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The *Kepler Mission* Design Overview

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Abstract

The *Kepler Mission* is in the development phase with launch planned for 2008. *Kepler* is a principal investigator-lead Discovery-class mission. It is specifically designed to be capable of detecting Earth-size planets in the habitable zone of solar-like stars. The technique is to use differential photometry to simultaneously monitor the same set of more than 100,000 dwarf stars for four years looking for a sequence of transits. The photometer is basically a classical Schmidt telescope with a >100 square degree field of view and a focal plane of about 100 megapixels. The photometer is launched into an Earth-trailing heliocentric orbit.

Overview

The primary mission goal is to reliably detect a significant number of Earth-size planets in the habitable zone of solar-like stars (Borucki, this conference). The mission design allows for exploring the diversity of planetary sizes and orbital periods from Mars-size planets and orbital periods as short as a few days to gas giants and orbital periods of years, and for stellar spectral types from A-stars, which are much hotter and more massive than the Sun to the M-dwarfs, which are much dimmer and cooler than the Sun.

Kepler uses differential-ensemble photometry to detect the change in brightness caused by transits of planets at least as small as Earth. (The Earth is 100 times smaller than Jupiter.) A Sun-Earth transit analog produces a periodic change in brightness of 84 parts per million (ppm) lasting 13 hours every time it crosses the center of its parent star as viewed from our solar system. The stars are selected from our extended solar neighborhood and are roughly from 200 pc to 1 kpc away. By continuously monitoring more than 100,000 stars for four or more years, we will be able to determine the frequency of other Earths.

The planet's size, orbit and characteristic temperature can all be calculated from the depth and period of the transits, the size, mass and temperature of the star and use of Kepler's Third Law. Results from this mission allow us to place our solar system within the context of planetary systems in the 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.

The Photometer

The photometer consists of a classical Schmidt telescope with an 86% light-weighted ULE primary mirror and a focal plane consisting of 42 CCDs with 1024x2200 27mm pixels, providing >100 square degrees of active field of view.

The CCDs are readout about every five seconds and co-added on-board for 15 minutes. Only data from the pixels of interest associated with each target star are stored and telemetered to the ground. Measurements of bias and smear are also recorded, because there is no shutter. These are used later to "calibrate" the data.

Field of View Selection

An early study was made to define how the mission would operate. The trade considered trying to construct a "fish-eye" photometer with nearly all sky coverage, a photometer system that would periodically search multiple fields of view by repointing every 15 minutes or so and a photometer that stared at just a single region of the sky. It was found that the simplest and most efficient system was one that stared at a single region of the sky. The photometer system design that was found to be feasible has about a one-meter aperture with a stellar dynamic range of about 9-14 magnitude for terrestrial planet detection.

There were a number of criteria that have defined the field of view selection. The first was that the field of view must be accessible throughout the year. The sunshade sun avoidance angle of 55 degrees limited by the launch vehicle payload fairing defines two regions about the North and South ecliptic poles. The southern field was rejected, given that all of our supporting ground based telescope resources are in the North. The second criterion was to find the richest star field. This was narrowed down quickly to that portion of the galactic plane that is above 55-degree ecliptic latitude. The final criterion was to minimize the chances of background eclipsing binary stars causing a significant number of false positives. It was found that the background of distant stars drops dramatically when looking slightly out of the galactic plane. The final field center was found to be at $19^h22^m40^s$ +44°30′ equal to galactic l=76.5°, b=13.3°. The field rotation was selected to place the maximize number of bright stars that saturate and bloom in the gaps between the CCD modules. The field is shown in Figure 1.

Data Processing

The data from the 42 CCDs are read out about every five seconds. These data are co-added on board to form 15-minute integrations of every pixel in the field of view. At the end of the 15-minute accumulation only the pixels of interest forming the photometric aperture for each object are read out from accumulation memory and stored on the solid-state record for transmission to Earth. The data are processed on the ground to produce flux time series (light curves) for each target star using both aperture photometry and difference image analysis. Both series are then analyzed for both transit events and for reflected light events.

All planetary candidates must pass a rigorous set of tests to prove that they are not false-positive events. The following data consistency checks are performed:

1. Total SNR $\geq 7\sigma$ and at least three individual transits must be detected;
2. Individual transits must be statistically consistent in amplitude and duration;

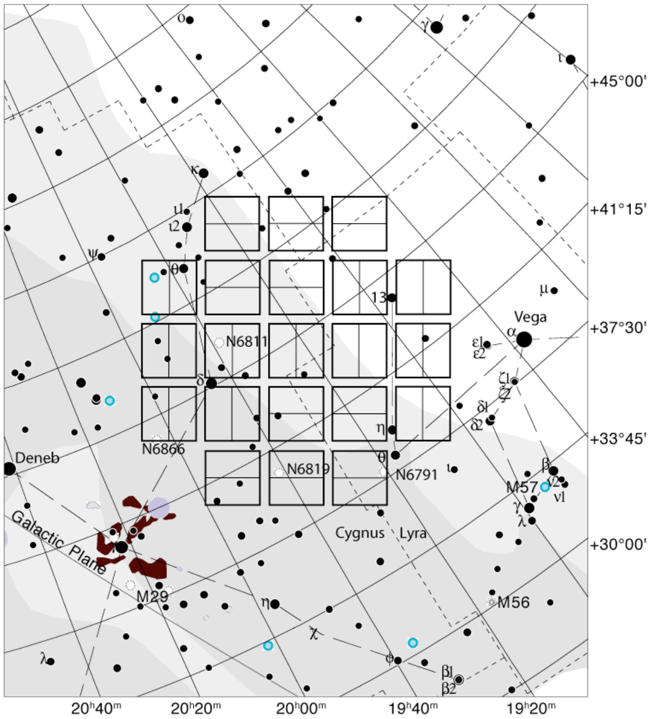

Figure 1 Layout of the 42 CCDs on the celestial sphere, which defines the *Kepler* field of view. The layout is four-fold symmetric except for the central CCDs. This permits 90° rotation of the photometer every three months to maintain the Sun on the solar arrays and the radiator used to cool the CCDs pointed to deep space.

3. Period timing from all transits must be consistent to within statistics;
4. Difference image analysis must not show a discernible shift in the image centroid, which would be indicative of a background eclipsing binary;
5. Individual pixel and time sample data for the transits must be statistically consistent; and
6. For SNR>16, the shape of the transit must be consistent with a U shape, not a V shape characteristic of an eclipsing binary.

As a statistical test, faint regions between the selected target stars will be continuously monitored to access the probability of faint background eclipsing binaries that could potentially produce false positives if they were spatially unresolved from a target star.

Follow-up Observing Program

For giant planets the Follow-up Observing Program (FOP) will use the radial velocity method to both confirm the planet's existence as well as obtain its mass. Combining the mass with the size obtained from the transit, the density of the planet can be calculated.

For terrestrial planets, one can show from moderate precision radial velocity data (~300 m/s) that the object is neither a grazing-eclipsing binary nor a white dwarf. The FOP will look for evidence of a blended-faint background object from high spatial resolution images. If one exists, it will be necessary to check to see that it is not an eclipsing binary with the same period. Finally, for short period orbits, M. Mayor (this conference) predicts that one should be able to confirm large terrestrial planets given the known star and the planet's period and phase.

Using spectra obtained from the radial velocity work, more precise stellar masses and sizes will be determined for each parent star. Finally, for terrestrial cases, a high-precision radial velocity campaign (~3 m/s) will be initiated to search for any non-transiting giant planets that may also exist in each system.

Detection Capability

The point design for the mission is the ability to reliably detect a sequence of 1.0 Earth-size transits of a 12th magnitude solar-like star, where we have defined reliable as a 4σ transit lasting 6.5 hours. Four transits provide a total SNR of 8 and we have set the threshold for detection at 7σ. The noise can be grouped into three types:

1. Shot noise from photon counting statistics, which depends on the stellar apparent brightness, aperture and quantum efficiency of the detectors;
2. Stellar variability, which we have assumed to be 10 parts per million (ppm) for solar-like stars in the time domain for transits; and
3. Measurement noise due to both the instrument and background noise caused by such things as stray light, zodiacal light and faint unresolved background stars.

A transit of a 1.0 Earth-size planet of a solar-like star produces an 84 ppm change in apparent brightness. Thus, a 4σ detection requires the photometric precision due to all noise sources to be less than 20 ppm. The noise allocation has been taken to be 1) 16 ppm for shot noise on a 12th magnitude G2V star, 2) 10 ppm for stellar variability as a typically conservative value for solar-like stars older than 1 Gyr and 3) 6.6 ppm for the measurement noise. To achieve this noise level, one must perform differential photometry to remove common mode noise in the measurement system. Thus, we refer to the combined differential photometric precision (CDPP), which takes into account all of the noise sources and removes common mode signal variations by performing ensemble normalization. The CDPP is unique for each star not only because of its inherent stellar variability, but because of many other factors in addition to the star's brightness, such as, the color dependence of the spectral response of the photometer to the stellar spectral type, the number of pixels associated with the stellar image, which depends on brightness, etc. A discussion of the many noise terms is given in a paper by Koch (2002).

For a CDPP of 20 ppm the minimum detectable planet size is shown in Figure 2 assuming the case for a grazing transit, that is, one that crosses a cord of the stellar disk equal to half of the stellar diameter. The detectable planet size scales directly with the CDPP. For example, for a 14th magnitude star the CDPP is expected to be 42 ppm and for a 9th magnitude star it is expected to be less than 11 ppm. Thus, a two Earth and a half Earth-area planet could be detected respectively in the habitable zone (1 AU orbit) of a solar-like star after four years. Planets smaller than Earth in short period orbits are detectable, since they produce more transits during the mission lifetime. Taking into account both transit duration and the number of transits, the minimum detectable planet size depends directly on the square root of the orbital semi-major axis. The mission allows for a wide range of possibilities, such as, finding Earth-size planets in just one month if they exist in short period orbits and planets as small as Mars.

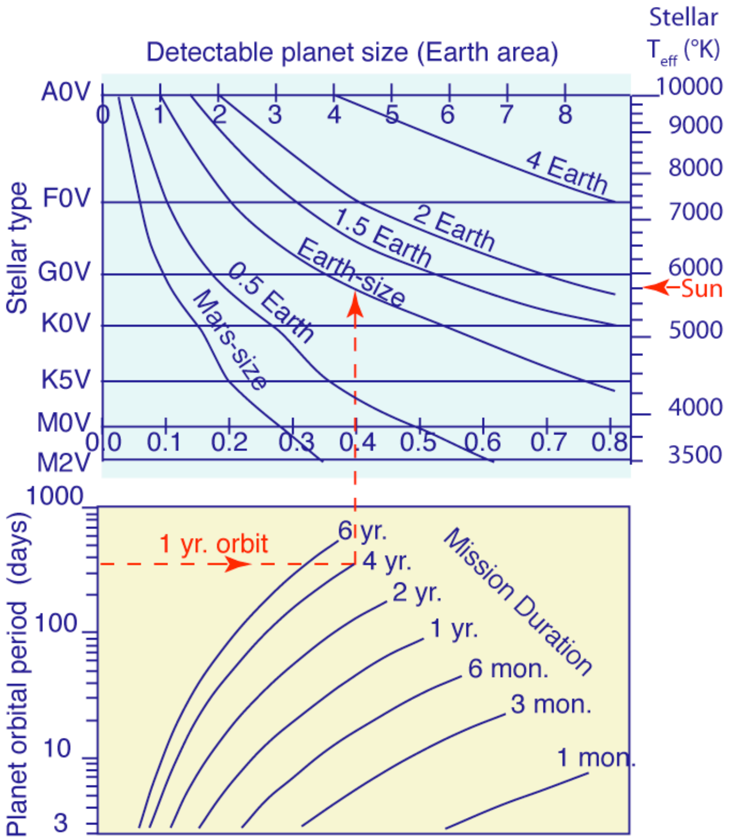

Figure 2 Detectable planet size for a total noise (CDPP) equal to 20 ppm and requiring at least four grazing transits. The dashed line illustrates, that for a one-year planetary orbit and a four-year mission duration, a 1.0-Earth-size planet is detectable for a solar-like star, G2V (Teff=5780°K).

Summary

The *Kepler Mission* is in the development phase with launch planned for June 2008. *Kepler* is NASA's first mission capable of finding Earth-size and smaller planets. The mission is specifically designed to detect Earth-size planets in the habitable zone of solar-like stars with the ability to detect a wide variety of possible planet sizes, orbits and parent stellar types leading to a new era in extrasolar planetary system discovery, exploration and understanding.

References

Koch, David, A Model for Estimating the Number of Stars for which Terrestrial Planets Can Be Detected Using Transits, *Bioastronomy 2002, Life Among the Stars, IAU Symposium 213*, p. 85, R. P. Norris and F. H. Stootman, ed. ASP