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The Kepler Mission: Finding the Sizes, Orbits and Frequencies of Earth-size and Larger Extrasolar Planets

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Abstract. The first step in discovering the extent of life in our galaxy is to determine the number of terrestrial planets in circumstellar habitable zones (HZ). The *Kepler Mission* is designed around a 0.95 m aperture Schmidt-type telescope with an array of 42 CCDs. The photometer is designed to continuously monitor the brightness of 100,000 solar-like stars to detect the transits of Earth-size and larger planets. It is scheduled to be launched into a heliocentric orbit in 2007. Measurements of the depth and repetition time of transits provide the size of the planet relative to the star and its orbital period. When combined with ground-based spectroscopy of these stars to fix the stellar parameters, the true planet radius and orbit, semi-major axis, hence the position relative to the HZ, are determined. The spectra are also used to discover the relationships between the characteristics of planets and the stars that they orbit. In particular, the association of planetary size and occurrence frequency with stellar mass and metallicity will be investigated. At the end of the four year mission, hundreds of terrestrial planets should be discovered in and near the HZ of their stars if such planets are common. Extending the mission to six years doubles the expected number of Earth-size planets in the HZ. A null result would imply that terrestrial planets in the HZ occur in less than 1% of the stars and that habitable planets might be quite rare. Based on the results of the current Doppler velocity discoveries, detection of the reflected light from several hundred short-period giant planets is also expected. Information on the albedos and densities of those giants showing transits will be obtained.

1. Introduction

A knowledge of other planetary systems that includes information on the number, size, mass, and spacing of the planets around a variety of star types is needed to deepen our understanding of planetary system formation and the processes that give rise to final planetary configurations (Lissauer 1999). Recent discoveries show that approximately 10% of Sun-like stars possess planetary systems quite different from the solar system in that they include giant planets, in highly elliptical or short period orbits. The inferred evolution of these planets and their orbital characteristics imply the absence of Earth-like planets near the habitable zone. Information on the properties of the giant inner planets is now being obtained by both the Doppler velocity and the transit photometry techniques. The combination of the two techniques provides the mass, size, and density of the planets. For the planet orbiting star HD209458, transit photometry (Charbonneau et al. 2000; Henry et al. 2000) provided the first measurement of the diameter of an extrasolar planet. The measured size of 1.3 that of Jupiter provides a critical datum to check the theories of planetary structure (Hubbard et al. 2001).

Small rocky planets in the Habitable Zone (HZ) near 1 AU are more likely to harbor life than are the gas giant planets that are now being discovered. New technology is needed to find Earth-like planets that are a factor of several hundred times less massive than jovian-mass planets. The *Kepler Mission* is a space mission designed to use the transit method to discover hundreds of Earth-size planets in and near the HZ around a wide variety of stars. The *Kepler Mission* was selected as Discovery Mission #10 in December 2001 and is expected to launch in 2007. A description of the mission and the expected science results are presented here.

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 and larger planets in or near the HZ 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. Mission Overview

The *Kepler Mission* uses differential ensemble photometry to detect planets not detectable with ground-based techniques. The spacecraft is placed in an Earth-trailing heliocentric orbit by a Delta II 7425 launch vehicle. The mission lifetime needed to meet the goals is four years. The mission is robust because it includes: detection based on a periodic signal, use of both spatial and temporal differential measurements to reject noise sources, and a large statistical sample so that even a null result is significant.

Our approach is to use differential ensemble photometry to detect the periodic decreases in brightness of a star that occur when a planet crosses the stellar disk. Differential ensemble photometry is based on frequent comparisons of the brightness of each star relative to many nearby stars on the same portion of the CCD detector. Laboratory tests (Robinson et al. 1995; Koch et al. 2000) of CCD detectors show that such operation provides a measurement precision better than 1×10^{-5}. Transits by terrestrial planets produce a change in stellar brightness of 5×10^{-5} to 40×10^{-5} lasting for 4 to 16 hours. The geometric probability that a particular orbit is properly aligned to show transits is about 1/2% in or near the HZ.

Classical signal detection algorithms that whiten the stellar noise and fold multiple transits to form a single event are used to search for the periodic signatures down to the statistical noise limit (Jenkins et al. 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.

4. Photometer and Spacecraft Description

The sole scientific instrument aboard Kepler is a wide field-of-view (FOV) differential photometer with a 100 square degree FOV. The photometer will continuously and simultaneously monitor the brightnesses 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 14. The photometer is similar in design to a Schmidt telescope and has a focal plane composed of 42 1024x2200 format backside-illuminated CCDs. Figure 1 is a schematic diagram of the photometer. The photometer has a corrector of 0.95 m and a 1.4 m primary. 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 signal 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.

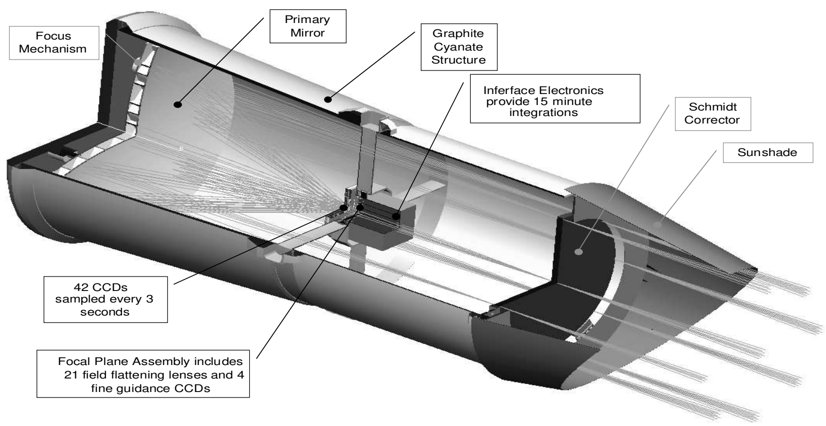

Figure 1. Schematic diagram of the *Kepler* photometer.

The spacecraft shown in Figure 2 encloses the base of the photometer and provides solar panels for power and contains the communication, navigation, and power equipment. Several antennas with different frequency coverage and gain patterns are available for uplink commanding and for data downlink. A moveable high gain antenna operating at Ka band is used for high-speed data transfer to the Deep Space Network (DSN). A total of 1GB of data per day is transferred to the ground for processing. The spacecraft provides very stable pointing using fine guidance sensors mounted in the photometer focal plane. Small cold-gas thrusters are used to desaturate the momentum wheels.

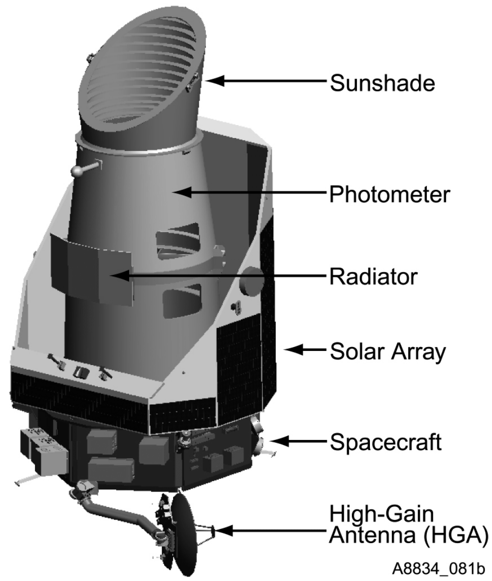

Figure 2. Integrated spacecraft and photometer.

5. Differential Ensemble Photometry

To obtain the precision needed to detect the small transit signals produced by terrestrial-size planets orbiting solar-like stars, differential ensemble photometry is employed. Several steps are used to remove the common-mode noise, but no attempt is made to obtain absolute accuracy. Only variations of a star's relative brightness on the time scale of transits (3-16 hours) are of interest. In particular the following steps are used to attain the necessary precision:

1) Target stars are always measured relative to an ensemble of nearby stars.
2) Only the time change of the ratio of the target star to the ensemble is of interest.
3) Time variations of the ratio that are substantially outside the transit passband are of little interest.
4) Stars are read out every three seconds to avoid saturation.

Only data from pixels illuminated by target stars are saved. Data for each pixel are co-added onboard to produce one brightness measurement per 15 minute integration. This results in an initial on-board data reduction of 10,000:1. Data for target stars that are monitored for p-mode analysis are returned at a cadence of 1 per minute.

6. Influence of Stellar Variability on the Detectability of Transit Signals

Stellar variability can significantly reduce the detectability of small signals if the amplitude is sufficiently high in the temporal passband of interest.

Stellar variability can reduce the signal detectability in two important ways:

1) The variability introduces noise into the detection passband and thereby reduces the signal to noise ratio (SNR) and thus the statistical significance of transits.
2) The variability of the stars used in the normalization introduces noise into the target star signal because the flux of every star is ratioed to the fluxes of many surrounding stars to reject common-mode instrument noise.

Only the variability of main sequence dwarfs will be discussed here, as only they will be used as target stars. Stellar variability 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 interaction is stronger when the star is rotating rapidly, both spectral class and rotation rate influence the variability of stars. 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 spectral class and age.

The calculations for the number of planets expected to be detected depends directly on the number of target stars that have sufficiently low variability in the passband of interest that the SNR will be high enough to make a statistically valid detection. The age and rotation rate of the Sun are approximately 4.6 Gyr and 27 days, respectively. Because the age of the Galaxy is about 15 Gyr, about 2/3 of the stars are older than the Sun and are expected to be at least as quiet as the Sun. Results of the continuous observations of all the target stars allows the variability of each to be derived from inter-comparisons. Only those stars found from these observations to be very quiet will be used to generate the time series used in the transit search.

7. Expected Results

After the mission ends, the results can be summarized in graphs analogous to those shown in Figure 3. Because both the size and mass of the stars that are found to have planets will be determined by complementary observations (see below), 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 ($0.9\ R_{\oplus} < R < 1.2\ R_{\oplus}$) 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 50 planets. If most stars have two such planets (like Earth and Venus) in that region, then the point will show 100 planets detected in that region. If stars often have planets 30% larger, then because such planets are more readily detected, then points along the curve marked “1.3 Earth” will be recorded and about 200 planets will be plotted for a semi-major axis near 1 AU. Planets twice the diameter of the Earth (i.e., approximately 10 times the mass of the Earth) are readily detected even if they are orbiting large or dim stars, so about 600 planets should be detected near 1 AU.

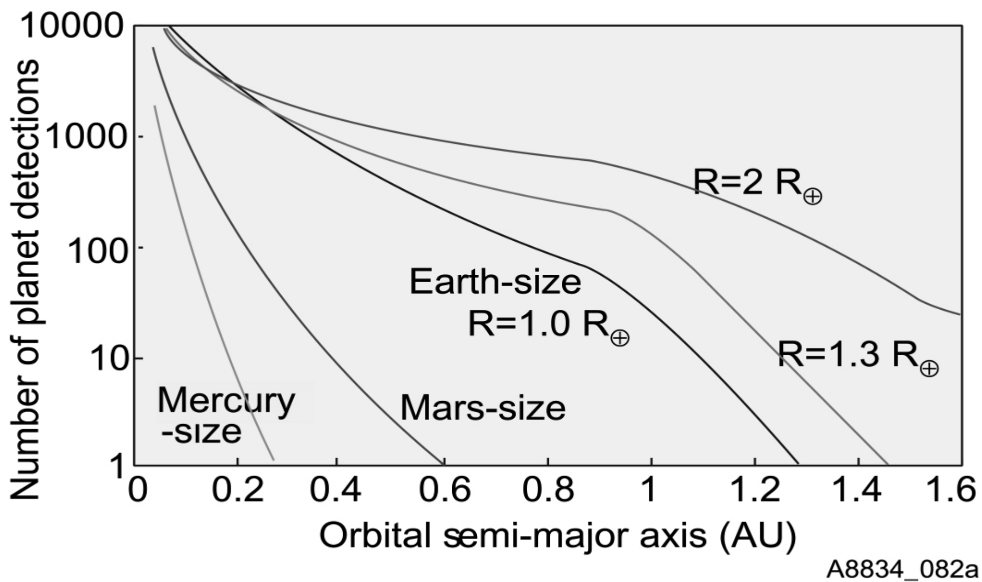

Figure 3. Loci of discoveries if all stars have one planet at the noted position.

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 transit increases as the inverse of the orbital diameter and second, the number of transits that occur during the mission lifetime increase. Thus the detectability of transit patterns rapidly increase with the 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., ~0.05 AU, many 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 during a four year mission will be quite large (~400).

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 Figure 3. Nevertheless, if planetary frequencies are 1% or higher, many terrestrial-size planets should be found.

Giant planets with orbits of less than seven days, like 51 Pegasi b, are also detectable by the periodic phase modulation of their reflected light without requiring a transit (Borucki et al. 1997). 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. Transits by white dwarf stars can be recognized by their microlensing signatures (Sahu and Gilliland, ApJ in press.) 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 transit photometry and either of the other methods can be calculated since both the size and mass will be known.

Based on a 1% fraction of main sequence stars having a giant planet with a period less than a week, a geometric probability of 0.87 of the orbital pole having an inclination of at least 30 degrees, and 100,000 dwarfs being observed for four years, about 870 giant planets should be found from variations of their reflected light.

Transit signals from giant planets will produce a SNR of 400 per transit for Jupiter- or Saturn-sized planets and a SNR of 40 for Neptune- and Uranus-size planets. Such single transits will be very easy to detect. Hence the detection of about 125 transiting giant planets with orbital periods less than one year is expected. Giant planets with longer orbital periods will produce additional detections, but those planets with orbital periods too long to show two transits will need to be followed up by other facilities.

In addition to the detection of planets, the data can be used to obtain the rotation rates and activity cycles of the monitored stars. For stars brighter than m_v =11.5, the stellar age and mass can be derived from measurements of p-mode oscillations. Spectral observations of the stars with planets will be made in order to develop the relationships between stellar type and metallicity and characteristics of their planets.

The results from this mission are meant to test the hypotheses that most stars have terrestrial planets in their HZ. The *Kepler Mission* is designed to observe a large sample of stars to capture the richness of the unexpected and to provide a statistically significant null result if there are no detections of terrestrial planets.

8. Mission Organizations and Their Functions

To be successful, the mission must accomplish several tasks after launch and commissioning. An outline of the tasks is shown in Figure 4. A sustaining engineering center at BATC will manage the Mission Operations Center at Honeywell, provide health and safety checkups for the satellite, and will resolve any anomalies aboard the satellite.

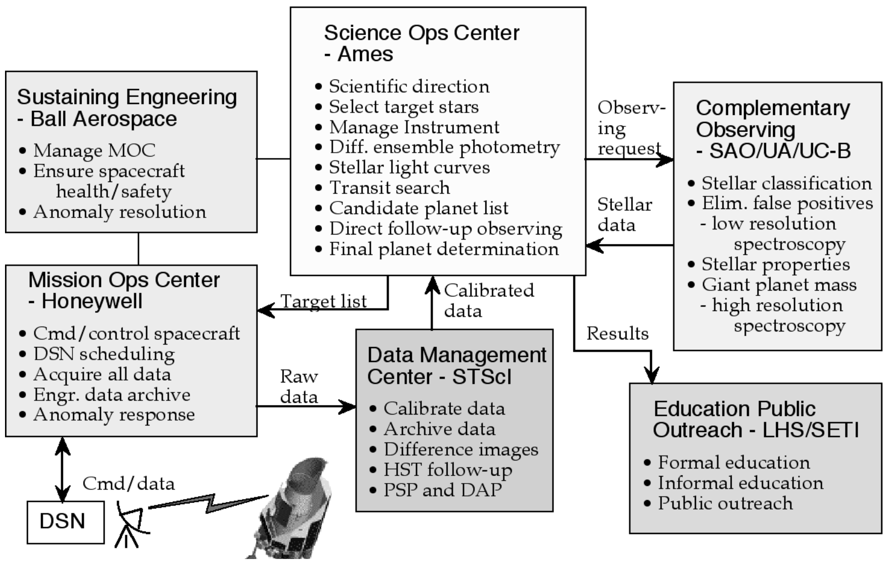

Figure 4. Organizations and their tasks during the operations phase of the *Kepler Mission*.

Because the photometer points at a single star field for the duration of the mission and because the data downlinks occur only once every four days, the mission operations are infrequent and there is no need for a mission operations center devoted solely to the *Kepler Mission*. Hence the already existing Mission Operations Center (MOC) at Honeywell will do the command and controlling of the satellite and acquire data from the spacecraft from the DSN in addition to their existing tasks. Every three months there will be somewhat more activity as the satellite is rotated 90 degrees around the center of the field of view to keep the solar panels pointed towards the Sun and the radiator pointed toward deep space.

These data from the MOC will be sent to the Data Management Center (DMC) at the Space Telescope Science Institute (STScI) for calibration and archiving. Here, corrections will be made for defective pixels, smearing due to shutterless operation, dark current, and other instrumental effects. STScI will also be responsible for the p-mode analysis to characterize the brighter stars and for examining stars with planetary candidates to rule out background eclipsing binary stars.

The calibrated data will be forwarded to the Science Operations Center (SOC) at NASA Ames. The SOC team will be responsible for coordinating the science team, for target selection prior to, and during mission operation, for generating the light curves for all target stars and for detecting transits. When a star is found to have a pattern of transits consistent with the presence of a planetary companion, a program to validate the detection will be initiated. To pass the first test, the orbital periods determined from at least three transits must agree to approximately one part per 100,000, the durations and depths of the transit must be consistent (within statistical uncertainty) among the transit pattern, and the transit duration must consistent with a Keplerian orbit for the mass of the target star. The target star will be placed on the list of stars that will be observed with a one-minute cadence rather than the usual 15-minute cadence. For brighter stars, this step allows a better definition of the shape of the transit. With sufficient SNR, it is possible to use the shape of the transit to distinguish between a grazing occultation of two stars versus a near-central transit of planet. In the first instance, the transit is more “V” shaped whereas in the second instance, the transit is more “U” shaped (Borucki et al. 2001).

The second test is to do image subtraction photometry and search for the jump in position of the target centroid that occurs if a background star is responsible for the transit signal. If there is no evidence of a background star, then the third test is to determine the size of the target star to verify that it is a dwarf rather than a giant and thereby show that the companion size is consistent with that of a planet. If a catalog lookup is insufficient, then a request to do moderate precision spectroscopy of the star will be sent to the Complementary Observations (CO) center at the Smithsonian Astrophysical Observatory (SAO). The spectra obtained can be used to classify the spectral type and luminosity class of the star and then use stellar models to estimate its size. The spectrum will also be used to determine the mass of the companion if it is a low mass star or brown dwarf. Follow up observations using high-precision Doppler spectroscopy are employed to determine planetary masses or provide an upper limit to the planetary mass.

A final check is made using the HST or a telescope with active optics capability to examine the possible existence of an extremely close background star. A pattern of transits that passes all these tests is considered evidence of a planetary companion.

9. Mission Team

To perform these tests and to accomplish the mission goals, expertise in many areas is needed. Table 1 lists the areas of expertise and the Science team members associated with each area. The first group satisfies the need for experience in doing high precision photometry with CCDs. The investigators in the second group have extensive experience in stellar spectroscopy and Doppler velocity measurements. Stellar variability limits the ultimate photometric precision for bright stars so it will be actively investigated to develop methods of reducing its effect. As the science results accumulate, it will be important to understand their implications. Here theoretical models will be important. Experience in mission operations will direct mission resources to resolve issues. The last group in the table is responsible for disseminating the discoveries to the general public.

Table 1. Science Team Membership & Responsibilities	
Instrument & Mission Design	William Borucki, NASA Ames Research Center Timothy Brown, High Altitude Obs., UCAR Edward Dunham, Lowell Observatory John Geary, CfA, Smithsonian Astrophysical Obs. Ronald Gilliland, STScI Steve Howell, U. Arizona Jon M. Jenkins, SETI Institute Dave Koch, NASA Ames Research Center
Complementary Observations and Stellar Characterization	William Cochran, U. Texas David Latham, CfA, Smithsonian Astrophy. Obs. Geoffrey Marcy, U. California, Berkeley
Stellar Variability Studies	Gibor Basri, U. California, Berkeley Andrea Dupree, CfA, Smithsonian Astrophys. Obs. Dimitar Sasselov, Harvard University
Theoretical Studies	Alan Boss, Carneige Institute of Washington Jack Lissauer, NASA Ames Research Center
Mission Operations and Guest Investigator Program	Donald Brownlee, U. of Washington Yoji Kondo, Goddard Space Flight Center
General Overview	John Caldwell, York University, Canada David Morrison, NASA Ames Research Center Tobias Owen, Univ. of Hawaii Harold Reitsema, Ball Aerospace & Tech. Corp. Jill Tarter, SETI Institute
Education and Public Outreach	Alan Gould, UC Berkeley, Edna DeVore, SETI Institute

10. Coordination with Future Origins Program Missions

The *Kepler Mission* supports the Origins theme missions, in particular the Space Interferometry Mission (SIM) and Terrestrial Planet Finder (TPF) mission by finding the association between the frequency and characteristics of terrestrial planets and stellar type. Since the *Kepler* field of view is along a galactic arm at the same galactocentric distance as the Sun, the stellar population sampled with *Kepler* is indistinguishable from the immediate solar neighborhood. This permits planners for the TPF mission to design an instrument with enough range to search the appropriate number and types of stars to successfully measure the composition of the atmospheres of terrestrial planets in the HZ.

SIM is expected to launch several years after the *Kepler Mission* and thus will be able to immediately target those stars known to have planets. It will have the sensitivity to find giant planets in outer orbits for all orientations of their orbital plane. If SIM finds that such planets exist outside the orbits of the terrestrial planets, then we will know that the inner planets have some protection from impacts of comets and asteroids that could sterilize life on these terrestrial planets. The combining of the data from transit photometry, Doppler velocity, and interferometry should provide a wealth of data on planetary system structure and the interrelationships among terrestrial planets and giant planets. These data should allow us to put our Solar System in perspective and to determine the extent of possibly-habitable planets throughout our galaxy.

11. Conclusions

The Kepler Mission is optimized for finding Earth-size planets in the HZ of solar-like stars. Its unique aspects are that it:

1) Finds true Earth analogs,
2) Discovers thousands of planets,
3) Characterizes the planetary population within 1.5 AU,
4) Finds associations between stellar types and planetary systems,
5) Characterizes stars that have planets, and
6) Puts our Solar System in perspective.

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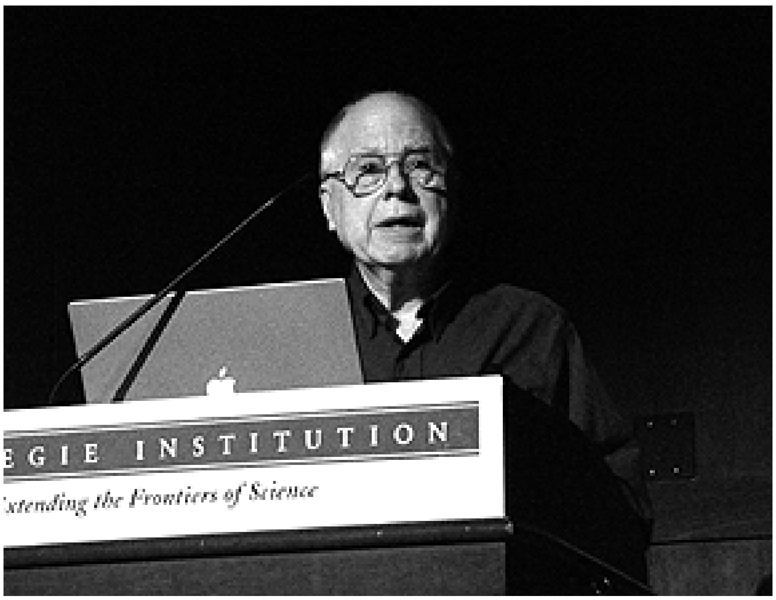

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