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I.5
In the United States: the long way to Kepler

W. Borucki

NASA Ames Associate, NASA Ames Research Center, Moffett field, CA 92035, USA

The Kepler Mission is a space observatory (Fig. I.5.1) launched in 2009 by NASA to monitor 170 000 stars for four years to determine the frequency of Earth-size and larger planets in and near the habitable zone (HZ) of solar-like stars, the size and orbital distributions of these planets and the types of stars they orbit (Borucki et al. 2010; Koch et al. 2010).

Kepler is the tenth in the series of NASA Discovery Program missions that are competitively-selected, PI-directed, medium cost missions. The Mission concept and various instrument prototypes were developed at the Ames Research Centre over a period of 18 yr starting with a small amount of funding in 1983. Beginning at the start of the NASA Discovery Program in 1992, the Mission concept was proposed five times to the NASA Discovery program before its acceptance for mission development in 2001. Prior to the launch of the Mission, a ground-based multiband survey of the 4 million stars in the selected field-of-view and an analysis program were conducted to classify the stars in order to select the most promising targets (Brown et al. 2011). An asteroseismology program was also conducted to determine the size and ages of brighter stars found to have transiting planets and for characterizing stellar structure.

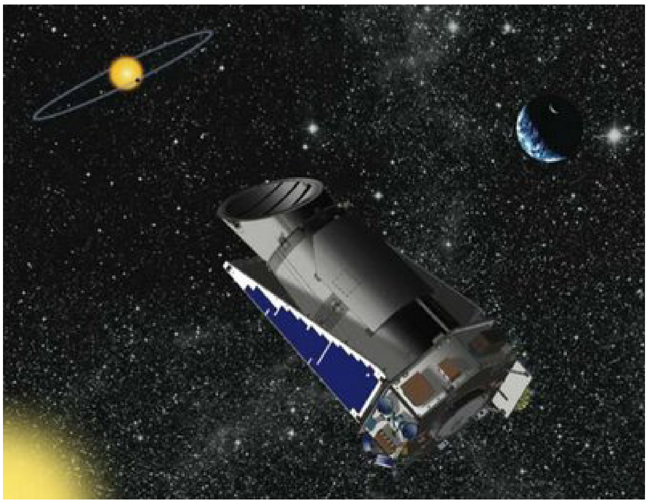

Fig. I.5.1. Artist's conception of the Kepler Mission observing an exoplanet transit. (NASA Image)

1. Mission description

The point-design for the Kepler Mission was based on a total noise value of 20 ppm for a 6.5-hour transit of a 12th magnitude solar-like star by an Earth-size planet in a 1 AU orbit using a 1-m aperture telescope. With shot noise of 14 ppm and a stellar variability of 10 ppm, an instrument precision of 10 ppm for a 6.5-hour transit duration is required to yield root-sum-square noise of 20 ppm. This performance provides a SNR of about 4 per transit (a transit duration of 6.5 hours is chosen because most transits will not be central and because it provides margin for unanticipated noise sources).

Because of the large number of stars surveyed and because the search is over periods between ∼1 day and 2 yr, about 10^{11} statistical tests must be executed to search for patterns of transits for 170 000 stars. Consequently, to reduce the number of false-alarms (FA) due to statistical fluctuations to less than 1 FA over the entire mission-duration, the stellar flux time-series data were examined only when the detected transit pattern exceeded 7.1σ significance. Transit patterns that just meet the threshold will be recognized only 50% of the time while those with a transit pattern of 8σ detection will be recognized about 84% of the time. To obtain at least 50 planets in the HZ of Sun-like stars, the Mission was designed to monitor 170 000 stars for a period of four years. Because statistical fluctuations in the data and astrophysical phenomena produce events that can mimic planetary transits, a very elaborate set of procedures was executed to identify and remove false alarms and false positive events.

In order to maximize the number of appropriate target stars in the instrument FOV, a study was conducted prior to the launch to identify the region of the sky with the highest density of bright stars. The ecliptic was excluded because the Sun and solar-system planets would intrude to prevent continuous observations. The chosen location was slightly north of the galactic equator to reduce the prevalence of giant stars; i.e., in the Cygnus region centred on Galactic coordinates N76.53°, +13.29° (Fig. I.5.2). A sunshield designed to allow pointing to within 55° of the Sun and to fit into the launch shroud of the Delta-2 booster was chosen.

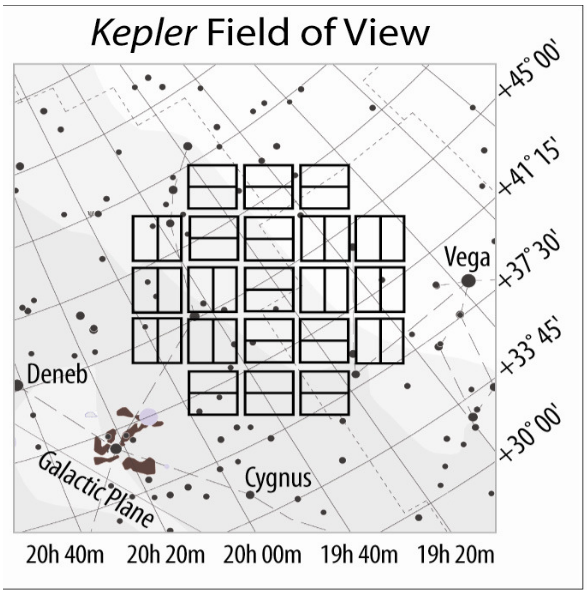

Fig. I.5.2. Kepler stared at the same FOV during the four-year mission to avoid missing transits of planets with long orbital periods. (Star chart from The Sky Software with permission from Bisque.com.)

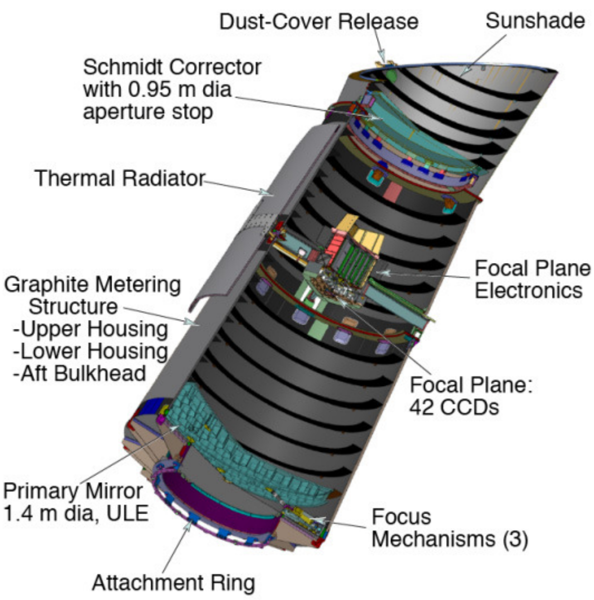

Fig. I.5.3. Cutaway view of the Kepler instrument (Courtesy of Ball Aerospace and Technology Corp.)

The telescope was a Schmidt design with a 0.95 m corrector and a 1.4 m mirror with a focal length of 1.47 m (Fig. I.5.3). To avoid mission failure due to a sticking shutter on the photometer, the instrument was designed to operate without a shutter. Instead the overwrite from the star images that trailed across the detectors during the short readout period was measured at every exposure and removed.

An Earth-trailing 372.5 day heliocentric orbit was chosen to keep the instrument in a thermally stable condition, to allow observations 24 hrs/day almost 365 days per year, and to avoid scattered light from the Earth and Moon.

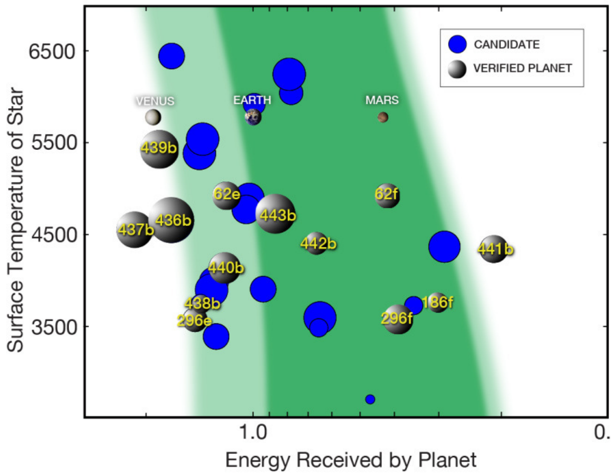

Fig. I.5.4. Small planets and planetary candidates in the habitable zone (HZ) published in Report on Progress to Physics (NASA Image).

Transmission of the data required a high-gain antenna and the loss of a day of data each month when the spacecraft was rotated to point the antenna toward Earth.

The active area of the 42 CCDs covered 105 square degrees. Each 2048 × 2200 format CCD had two outputs that each serviced a 2048 × 1100 section. Pixels were 27 × 27 square microns with a projected area on the sky of $3.8'' \times 3.8''$. Filters restricted the optical passband to a range of 420 to 850 nm. The short-wavelength limit was chosen to reject the stellar variability associated with the Ca II H & K spectral lines.

The cadence was 30 min for 170 000 targets. From these targets, a subset of 512 was also recorded at a 1-min cadence. This option was used to better define the timing of the transits when a planet was discovered and was also used for some of the asteroseismology investigations (Chaplin & Miglio 2013).

2. Highlights

During the four years of operation, Kepler made an unprecedented set of time-series observations of 190 000 stars (including those requested by Guest Observers). Analysis of the data has detected over 4600 planetary candidates, including several hundred Earth-size planetary candidates, over a thousand confirmed planets, Earth-size planets in the habitable zone (Fig. I.5.4), and has provided the information required for estimates of the frequency of planets in our galaxy (Batalha 2014).

The long term observations of the transiting planets allowed gravitational interaction among the planets in a planetary system to shift the times of transit depending on the masses of the planets and their orbital parameters. This variation in transit timing (TTV) was a very productive method of determining planetary masses and complemented those provided from radial velocity (RV) measurements using ground-based telescopes. By combining the Kepler observations with those of RV (Ford et al. 2012; Fabrycky et al. 2012) and TTV to get masses and densities, rocky planets were distinguished from low-density (water, gas, and ice) planets (Lissauer et al. 2014). Ten planets were found orbiting binary stars and several planets were found in orbits that are at large angles to the stellar equator.

The Kepler Mission results show that most stars have planets, many of these planets are similar in size to the Earth, and that planetary systems with several planets are common. With over 100 billion stars in our galaxy, we now know that there are billions of Earth-size planets in the HZ of their stars.

For an extensive discussion of the development of the Kepler Mission, see Borucki (2016).

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