Asteroseismology with the *Kepler mission*

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Abstract

NASA's *Kepler mission* will fly a photometer based on a wide-field Schmidt camera with a
0.95 m aperture, staring at a single field continuously for at least 4 years. Although the mission's principal aim is to locate transiting extrasolar planets, it will provide an unprecedented
opportunity to make asteroseismic observations on a wide variety of stars. Plans are now
being developed to exploit this opportunity to the fullest.

Introduction

The *Kepler mission* was selected for NASA's discovery programme in 2001, with a launch
now planned for November 2008. The goal of the mission is to search for extrasolar planetary
systems with the transit method, by detecting the slight decrease in the brightness of a star as
a planet in orbit around it passes in front of the star. This is probably the most efficient method
to detect substantial numbers of planets of modest size, and a key goal of the mission is in
fact the search for 'Earth analogs', planets of roughly Earth size in year-long orbits around
solar-like stars. More generally, planets in the 'habitable zone', where conditions are such
as to allow liquid water, are emphasized; thus the mission is a key component of NASA's
Exploration Roadmap. These goals require very high differential photometric precision and
observations of a given field for several planetary orbits, i.e., several years. Also, to achieve
a reasonable probability for the detection of planets a very large number of stars must be
observed, requiring a large field of view of the photometer.

The requirements for planet-transit detection also make the *Kepler mission* very well suited
for asteroseismology. The photometric precision required to study solar-like oscillations is
similar to that needed to detect Earth-size planets, and the large field ensures that a very
substantial number of interesting targets will be available, both solar-like pulsators and other
types of pulsating stars. Consequently an asteroseismic programme is being established within
the *Kepler* project.

Pulsations are found in stars of most masses and essentially all stages of evolution. The
frequencies are determined by the internal sound-speed and density structure, as well as rotation and possibly effects of magnetic fields, and the amplitudes and phases are controlled
by the energetics and dynamics of the near-surface layers, including effects of turbulent convection. Observationally, the frequencies can be determined with exceedingly high accuracy
compared with any other quantity relevant to the internal properties of the stars. Analysis of
the observed frequencies, including comparison with stellar models, allows determination of
the properties of the stellar interiors and tests of the physics used in the model computation
(e.g. Kjeldsen & Bedding 2004).

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. Also, the extensive experience from analyses of solar oscillations can be applied in the analysis of data for these stars, which have oscillation periods of minutes to hours. Furthermore, the properties of the oscillations (amplitudes, frequencies, mode lifetimes) show long-term variations caused by stellar activity.

Here we give a brief description of the *Kepler mission* and the planned asteroseismic investigations. Further details on the mission were provided by Basri et al. (2005) and Koch et al. (2006), as well as on the mission web page (`http://kepler.nasa.gov/sci/`).

Kepler instrumentation

The *Kepler* photometer is a classical Schmidt design with a 0.95 m diameter corrector passing light to a 1.4 m primary and then on to the focal plane mounted near the instrument centre (see Fig. 1). The focal plane is populated with 42 CCDs with 2200 columns and 1024 rows each that will be read out through two amplifiers per CCD. Pixel sizes of 27 μ will provide full-well depths of approximately 1.0×10^6 electrons for these backside-illuminated, thinned and anti-reflection coated devices. The resulting pixel scale of 3.98 arcsec results in a large field of view subtending over 100 square degrees. The spacecraft is three-axis stabilized with an expected jitter of less than 1 per cent of the pixel scale.

Since tight focus in not required for obtaining optimal time-series photometry the individual CCD modules are allowed to have significant focus offsets relative to each other easing integration of this large focal plane. Modules with the best focus will have point spread functions (PSF) with full width at half maximum (FWHM) less than one pixel resulting in undersampling, while other modules with larger focus offsets will provide PSFs with FWHM of about two pixels resulting in critical sampling of the PSF. On the other hand, focus stability will be tightly constrained.
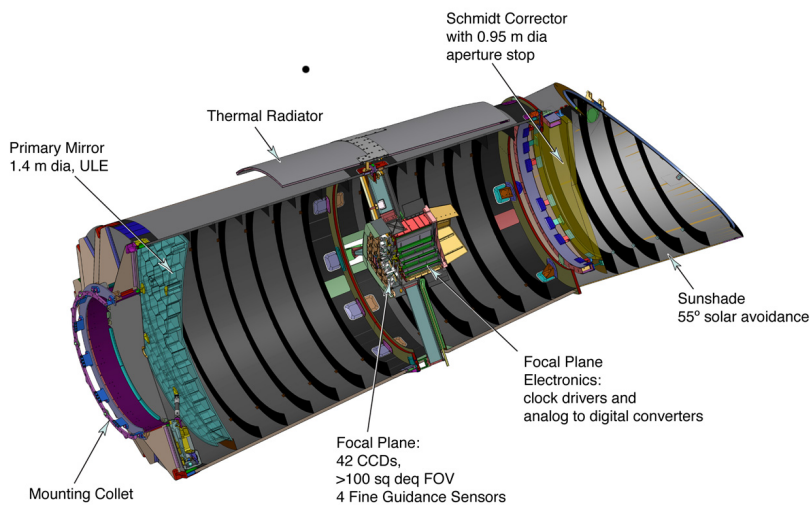

Figure 1: Primary components of the *Kepler* Photometer shown in cut-out. For a higher resolution, colour version see `http://kepler.nasa.gov/sci/`. This web site provides a wealth of technical and scientific information about the mission.

The *Kepler* observing programme

A single field near right ascension 19.4 h and declination 44° N will be monitored for the full 4-year mission (with option for a 2-year extension). The spacecraft will be in an Earth-trailing heliocentric orbit, similar to *Spitzer*. To keep the solar arrays illuminated and the focal-plane radiator pointed towards deep space the spacecraft is rotated 90° every three months. Figure 2 shows the CCD coverage superposed on the sky in the Cygnus-Lyra region; the CCD layout is four-fold symmetric so that the quarterly roll will not change the sky coverage. Transfer of the accumulated data to ground stations, in the form of small images around each target, will require body-pointing the high-gain antenna once per month resulting in data gaps less than one day, in addition to the similar gaps at the quarterly rolls.
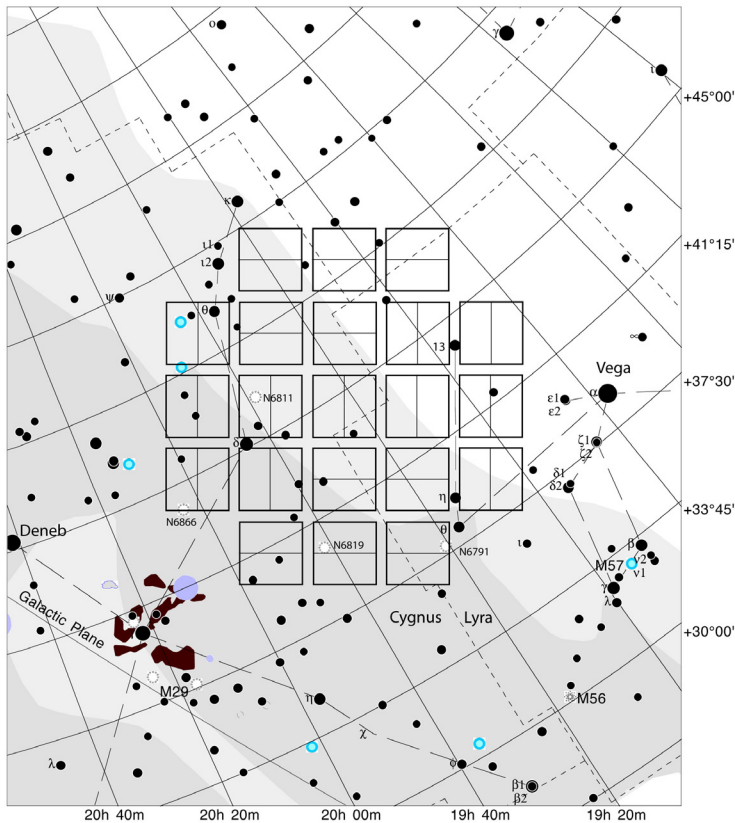

Figure 2: Region of galaxy to be monitored with *Kepler* showing in detail the layout of the 42 science CCDs. From `http://kepler.nasa.gov/sci/`.

The primary *Kepler* science searching for transits of Earth-like planets will be fulfilled by collecting data on 170 000 stars for the first year, reduced to 100 000 later as high-noise stars are dropped, to accommodate the lower data rates as the spacecraft drifts away from the Earth. These targets will range in magnitude from about 9th to 15th with the design point

being the ability to detect the 85 parts-per-million (ppm) transits of an Earth analog. The design point is a combined differential photometric precision of less than 20 ppm in 6.5 hours (half the length of a central passage of an Earth analog) for a $V=12$ G2V host when all noise terms are included, assuming an intrinsic 10 ppm noise from the solar-like star. In order to accumulate the 5×10^9 electrons at 12th mag without saturating the CCDs, they will be read out every 2.5 to 8 seconds (exact value yet to be set) and accumulated on board into 30-minute sums.

For the extrasolar planet detection, targets that are dwarfs are strongly preferred over giants; hence a full ground-based, multi-band photometric screening will be completed before launch, capable of providing a target list dominated by F, G and K dwarfs with as many M dwarfs, to a limit of $V=16$ in this case, as possible. Due to the 30-minute observing cadence asteroseismology from these primary observations will be limited to red giants that have slipped through the screening process (or intentionally left in), and classical oscillators for which this long cadence allows Nyquist sampling.

The capability of *Kepler* to provide also excellent results for asteroseismology on solar-like stars has been recognized from the time of initial mission proposals, and a small complement of 512 targets that can be changed on a quarterly basis will be followed with 60-second data accumulations. For detailed study of solar-like oscillations the goal should be to reach a mean photon-noise level in the amplitude spectrum of 1 ppm after three months; this requires the collection of 10^{12} electrons per month, which will occur at $V=11.4$. Stars brighter than this, with photon noise below 1 ppm per month, are likely the prime targets for asteroseismology. Such targets are saturated in individual readouts; however, experience from *HST* observations has been that saturated data can support near photon-noise-limited differential time-series photometry, with a detector set-up such as will be used for *Kepler*. At $V=9$, usually taken to be the bright limit for *Kepler* observations, the photon-noise limit will be $\sim$70 ppm per minute, and experience from *HST* and simulations for *Kepler* suggest that we should be able to do better than 100 ppm per minute, allowing the mean noise level over a three-month data segment to reach less than 0.5 ppm in the amplitude spectrum.

Early in the mission the 512 one-minute cadence targets will be dedicated to those deemed best for asteroseismology. After the detection of planet candidates from the 170 000 long-cadence targets, many of these providing high S/N will be switched to the short cadence to allow refinement of transit shape, timing of transits for detection of other planets, and also for asteroseismology, since a prime motivator for the latter is the exquisite refinement of stellar parameters (especially radius) thereby obtained. A substantial number of targets will be reserved for asteroseismology throughout the mission, however.

Asteroseismology with *Kepler*

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 (e.g. Christensen-Dalsgaard 2004). Extracting these quantities from the oscillation signal allows precise determinations of stellar radii (relative accuracy of $2-3$ per cent); also, ages can be determined with a precision of better than $5-10$ per cent of the total main sequence lifetime, although the accuracy may be somewhat compromised by uncertainties in stellar physics and composition. We are currently developing techniques for extracting this information; the large separation can be determined from the power spectrum of the time-series using cross-correlation and peak comb analysis, and having obtained that, the small separation can be obtained by a folding of the power spectrum based on the large separation.

The solar-like oscillations occur in stars across the HR diagram, with increasing amplitudes and decreasing periods for increasing luminosity (e.g. Kjeldsen & Bedding 1995). In order to test our ability to extract stellar parameters using solar-like oscillations, we calculated oscillation spectra from theoretical stellar models, and simulated 1-year *Kepler* time-series including
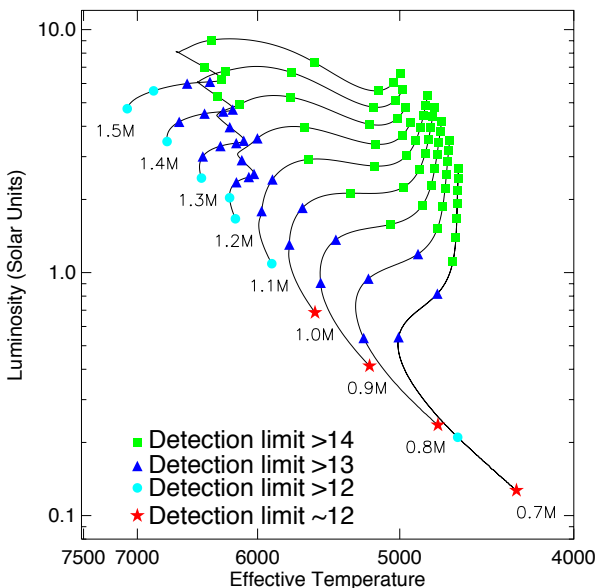
Figure 3: HR diagram of calculated models, with masses in solar units, indicating the limiting magnitudes to which the correct large separation could be retrieved from simulations of one year of Kepler data (see text).

stochastic excitation of the oscillations, realistic levels of photon-noise, and granulation. We calculated time-series for a total of 99 models in the mass-range $0.7 - 1.5 M_\odot$ from the main sequence to the giant branch. For each one, we added noise corresponding to $V = 9 - 14$ in steps of 0.2 mag, and for each magnitude value we simulated 10 time-series using different random numbers for generating the noise. We then used the analysis briefly discussed above to extract the large frequency separation to find, for each model, the limiting magnitude to which we could extract the correct separation in all 10 realizations of the noise. The results are shown in Fig. 3: from one year of *Kepler* data we will be able to determine the large separation, and hence stellar radii, in a very large fraction of the relevant stars in the *Kepler* field observed at the one-minute cadence. We also expect to be able to determine the small separation in most of the cases where we could determine the large separation, but this has not yet been quantified in any detail.

However, for asteroseismology we will be able to go much further. Using the *Kepler* time-series we will be able to extract the individual oscillation frequencies, measure amplitudes, phases and mode life-times, and use this information to interact with theoretical stellar modelling to measure stellar masses, luminosity, radii, ages, effective temperatures and rotation for each of the observed stars, as well as test the details of the physics of the stellar interiors.

We finally note that the time scale of pulsation varies widely between different types of stars. For several types of the classical variables (such as Cepheids), as well as for solar-like oscillations in giant stars, the pulsation periods are so long that the low-cadence data will be sufficient for detailed asteroseismic investigations. The long-term, continuous observations of *Kepler* will allow the determination of frequencies to very high precision.

The *Kepler* Asteroseismic Investigation (KAI)

The *Kepler* Asteroseismic Investigation will be arranged around the *Kepler Asteroseismic Science Operations Centre* (KASOC), which will be established at the Department of Physics and Astronomy, University of Aarhus. An agreement is being established to define the details of this part of the *Kepler* project.

The relevant *Kepler* data will be transferred from the Data Management Centre at Space Telescope Science Institute to KASOC; the data will be high-pass filtered, or in other ways modified, so as to contain no information about planet transits. At the KASOC amplitude spectra will be determined and the frequencies and other properties of the stellar pulsations will be extracted. Also, a preliminary asteroseismic analysis will be made to determine global parameters of the stars, such as radius, mass and age. Further detailed analyses will be carried out to determine properties of the stellar interiors and test stellar modelling, particularly for the relatively bright targets with high signal-to-noise ratio.

The quantity and quality of asteroseismic data expected from *Kepler* are overwhelming: time series extending over months to years for several thousand stars are expected. Also, very substantial development of procedures for data analysis and data interpretation has to take place before the start of the mission, and detailed ground-based observations are needed to characterize the prime targets of the asteroseismic investigation. These efforts far exceed the capabilities of KASOC and the directly involved Co-Investigators of *Kepler*. Consequently, we shall establish a *Kepler Asteroseismic Science Consortium* (KASC), with broad community participation, to help with the preparations and take part in the analysis of the data. A call will be made early in 2007 for applications to join the KASC, requesting indication of the contributions to be made to the project and the planned use of the data.

Conclusion

The *Kepler mission* promises unique opportunities for asteroseismology, in terms of the number and variety of stars that can be studied with very high differential photometric precision. This will provide a comprehensive overview of stellar properties across a large part of the HR diagram, including information about the excitation and damping of the modes, and detailed information about the internal structure of a substantial number of stars. Also, the long period over which the *Kepler* field will be observed offers the possibility of studying frequency variations associated with possible stellar activity cycles; thus a parallel investigation of the activity of stars in the *Kepler* field through measurement of the H and K indices (e.g. Baliunas et al. 1998) is highly desirable.

Kepler will follow two years after the launch of the *CoRoT* mission which shares many of the characteristics of *Kepler*, including very high photometric precision and observations over relatively long periods. Thus a collaboration with the *CoRoT* asteroseismic project would be very valuable; this could include experience with the optimal analysis of the time series to determine the oscillation frequencies, as well as improved information about the expected amplitudes and lifetimes of the modes in the potential *Kepler* targets.

The asteroseismic investigations based on the *Kepler* data will be very valuable for the exo-planet part of the mission. As demonstrated above, we expect to determine accurate radii for a substantial fraction of the planet-hosting stars discovered from planetary transits; this will substantially improve the determination of the planet radii from the properties of the transits. Also, in many cases the asteroseismic data will provide estimates of the age of the star, of obvious value to the understanding of the evolution of planetary systems. However, in the present context the main importance of the data is obviously their great potential value for our understanding of stellar structure and evolution.

References

Baliunas S. L., Donahue R. A., Soon W., Henry G. W., 1998, in Donajue R. A., Bookbinder J. A., eds, ASP Conf. Ser. Vol. 154, Activity Cycles in Lower Main Sequence and POST Main Sequence Stars: The HK Project. Astron. Soc. Pac., San Francisco, p. 153

Basri G., Borucki W. J., Koch D., 2005, New Astronomy Rev., 49, 478

Christensen-Dalsgaard J., 2004, Solar Physics, 220, 137

Kjeldsen H., Bedding T. R., 1995, A&A, 293, 87

Kjeldsen H., Bedding T. R., 2004, in Danesy D., ed., Proc. SOHO 14/ GONG 2004, Helio- and Asteroseismology: Towards a Golden Future. ESA SP-559, Noordwijk, p. 101

Koch D., Borucki W., Basri G., et al., 2006, in Hartkopf W. I., Guinan E. F., Harmanec P., eds, Proc. IAU Symp. 240, Binary Stars as Critical Tools and Tests in Contemporary Astrophysics, Cambridge University Press, #21

DISCUSSION

Roxburgh: Will you just have access to 500 windows or all the data?

Christensen-Dalsgaard: I think that initially we'll just be having 512 windows, although we have to negotiate on the giant stars. Asteroseismology with *Kepler* will actually be of some help to identify the giant stars because we will be measuring the large separations. So we will have some giant star data to play with. There is also a guest observer program, that is separate from this, and that will allow also studying "uninteresting" stars like B stars that some people tend to like.

Bedding: This mission will also provide excellent parallaxes for the main sequence stars from the astrometry.

Christensen-Dalsgaard: That's a very important point. We will be getting very precise, and maybe even very accurate, parallaxes from the Kepler data, so we should be able to get sufficiently accurate distances to determine the luminosities of the stars. From the photometry we should also be able to see rotation from spots on the surface, so we can compare this to pulsational spacings due to rotation.

Metcalfe: Did you say what is the policy and timeline for data release, and how this compares to the other space telescopes?

Christensen-Dalsgaard: The data-release scheme is very complicated and I was not able to discuss it. A complication is that it has to allow for enough time to detect and identify the planet transits, and for that you need at least three transits. There is hefty document that discusses all the rules on when and how the data are going to be released. However, I hope that we shall be able to operate with a simpler scheme for the asteroseismic data, managed through the Kepler Asteroseismic Science Operation Centre.

Aerts: I was thinking about the 3-minute integrations for the Gamma Dor stars. You should get them!

Christensen-Dalsgaard: Of course. We will use the Northern ASAS to start looking for candidates in the fields.