The *Kepler* Asteroseismic Investigation

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Abstract. The NASA *Kepler* mission for studies of extra-solar planets, with expected launch early in 2009, will provide a large set of excellent data for asteroseismology. Here we provide a brief presentation of the mission and discuss some aspects of the expected results of the asteroseismic investigations and the organization of the effort in the Kepler Asteroseismic Science Consortium (KASC).

1. Introduction

The *Kepler mission* was selected for NASA’s discovery programme in 2001, with a launch now planned for February 2009. The primary goal of the mission is to search for extra-solar 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 purpose of the mission is in fact the search for ‘Earth analogs’, or, more generally, planets in the ‘habitable zone’ where conditions are such as to allow liquid water; 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 observations of stellar oscillations, with the aim of carrying out asteroseismic investigations of stellar interiors. 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 has been established within the *Kepler* project.

Stellar pulsations provide unique diagnostics of the internal properties of stars. Their 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 [1].

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. Such oscillations occur in stars across the cool side of the HR diagram, with oscillation periods of minutes to hours and increasing amplitudes and periods for increasing luminosity [2]. The extensive experience from analyses of solar oscillations can be applied in the analysis of data for these stars. Furthermore, the properties of the oscillations (amplitudes, frequencies, mode lifetimes) show long-term variations caused by stellar activity.

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 [3]. Extracting these quantities from the oscillation signal allows precise determinations of stellar radii (relative accuracy of 2–3 per cent) and ages (better than 5–10 per cent of the total main sequence lifetime). Such information is of obvious importance to the characterization of potential planet-hosting stars detected by the Kepler mission.

Here we give a brief description of the Kepler mission and the planned asteroseismic investigations. Further details on the mission were provided by Borucki et al [4], Basri et al [5] and Koch et al [6], as well as on the mission web page (http://kepler.nasa.gov/sci/).

2. Kepler instrumentation and observing programme

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 instrument centre. 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 × 10⁶ 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 smaller than the excellent levels realized for the Hubble Space Telescope when measured on the scale of pixels.

Since tight focus is 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. The result will be that some modules provide sharp point-spread functions in which the large pixels undersample the provided light distribution, while other modules will be near critical sampling. On the other hand, focus stability will be tightly constrained.

A single field near right ascension 19.4 h and declination 44° North will be monitored for the full 3.5-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° four times a year. Figure 1 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.

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 $5 \times 10^9$ electrons at 12th mag without saturating the CCDs, they will be read out every 2.5 to 8 seconds (the currently preferred value is 5 seconds) and accumulated on board into 30-minute sums.

For the extra-solar 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, resulting in the very extensive *Kepler Input Catalogue* (KIC). The goal is to provide 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 a 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; with the collection of $10^{12}$ electrons per month, which will occur at $V = 11.4$, the combined effect of photon noise and other noise sources is expected to reach this level. 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, *HST* experience 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.

3. Asteroseismology with *Kepler*

The Kepler Asteroseismic Investigation (KAI) is based on a Letter of Direction from the Kepler Principal Investigator to the KAI. This letter describes the data products provided by the Kepler Project for asteroseismic investigation, as well as the obligations of the KAI including that of providing asteroseismic characterization, in particular radii, of planet-hosting stars to the Kepler Project.

Throughout the mission, the KAI will be allowed to select targets for both short- and long-cadence observations. During the initial roll segment of the mission, which is expected to last somewhat less than three months, all 512 short-cadence targets will be selected for asteroseismology. This number will decrease as planet candidates are discovered through the long-cadence observations and put on short cadence for better coverage of the transits. However during the entire mission 240 short-cadence targets will continue to be reserved for asteroseismology. Of those, 140 will be selected through KAI while up to 100 targets can be selected by the Kepler Science Working Group in order to observe planet-hosting stars which are also promising asteroseismic targets. In addition, at least 100 targets at long cadence will be reserved for asteroseismology which may include both giant stars and long-period classical pulsators such as, for example, Cepheids.

Figure 2 illustrates a possible scenario for the asteroseismic observations. The target lists for both the short- and long-cadence observations can be modified every three months. In Fig. 2 the 140 KAI targets observed at short cadence, as well as the long-cadence targets, have been divided into stars to be observed throughout the entire mission as well as stars observed for shorter time, down to the three months between each upload of modified target lists. Obviously the actual distribution will develop during the mission. In particular, great care is required in the selection of targets to be observed continuously throughout the mission. In addition to these, it is likely that some targets will be observed repeatedly to determine possible changes in frequency that might be associated with stellar activity.

3.1. Pipeline development for solar-like oscillations

As part of the Letter of Direction, KAI has committed itself to develop a pipeline for deriving stellar parameters for solar-like oscillating stars. Specifically, the large and small frequency separations, determined from the *Kepler* time-series observations, will be used to provide precise estimates of stellar radii and ages. A major task for KAI will therefore be to develop tools for automatic extraction of oscillation parameters for stars observed at both short and long cadence, and in particular for planet-hosting stars.

We are currently developing methods for automatic extraction of frequency spacings and we are performing simulations in order to estimate the limiting magnitudes, as a function of position in the HR diagram, to which we can successfully extract parameters such as the large frequency separation $\Delta \nu$, which allows a precise determination of the corresponding stellar radius. In this context we have developed a new method for extracting the large frequency separation from power spectra of solar-like oscillating stars.

The method, which resembles the Matched Filter approach known from planet transit searches, makes use of the fact that solar-like oscillations follow the asymptotic relation, at least for low-degree modes [7]. Modes of same degree $l$ but adjacent radial order $n$ are separated
Figure 2. An example of asteroseismic observations with *Kepler*; short-cadence targets are at the top and long-cadence targets at the bottom. Dark red denotes targets selected for asteroseismology by KAI. Throughout the mission 140 short-cadence targets are selected by KAI; during the first roll segment all 512 short-cadence targets are available. In the remainder of the mission up to 100 short-cadence targets may be selected, owing to their interest as planet hosts, by the Kepler Science Working Group (SWG) for asteroseismic investigation (light red), whereas the remainder of the short-cadence targets are used for detailed investigations of planet transits (blue), or, after the first year, for the 25 Guest Observer targets (magenta). In addition, at least 100 long-cadence targets may be selected by KAI for asteroseismology. Finally, the figure indicates the *Kepler* main targets for the search for planetary transits (pale green). An example is shown of how the targets selected by KAI can be distributed into targets observed during the entire mission and targets observed for shorter periods, down to single three-month segments. The nominal mission life time is 3.5 years, but with a possible extension of two years.

by the large separation, while modes of the same *n* but adjacent *l* are separated by half the large separation. Starting from an estimate of the *n*-value of maximum power (see [2]), the procedure is the following: The candidate ∆ν values are constrained from the star’s position in the HR diagram – for a solar-like star the search range may typically be in an interval ∆ν ~ 100–160 µHz. For each candidate ∆ν a corresponding frequency range is then selected in terms of a predefined range in *n*-values. Thus, a different frequency range is used for each tested value of ∆ν, but the radial orders included in the analysis are the same. We note that different ranges of *n*-values can easily be tested for each star in order to select the optimal values.

For each ∆ν the part of the power spectrum covering the selected *n*-values is cut in bins of ∆ν/2 which are then summed and the highest peak in the summed spectrum is found. This is
done for each value of $\Delta \nu$ and the results are displayed as normalized maximum peak power as a function of candidate $\Delta \nu$ as shown in Fig. 3. Thus, when the correct large separation is used to construct the bins, the peaks in the power spectrum of both $l = 0, 1$ modes will end up at the same position in the summed spectrum, giving a high value of maximum power. In the case shown in Fig. 3, the detected large frequency separation of $\sim 136 \mu$Hz is consistent with the input value to the simulations.

This method has the advantage that it uses an optimized frequency range for each candidate $\Delta \nu$, and the method has been demonstrated to be very robust based on the simulations performed up to now. Another result of the simulations is that the magnitude range in which doubtful results are obtained is very small. In most cases we find either a convincing signal or a null result due to too high noise. Further simulations will be performed to establish how well this method performs compared with other techniques relying on, for instance, cross correlations, but the method does indeed seem very promising.

![Figure 3](image-url) **Figure 3.** Peak power as a function of candidate large separations for a $V = 11$ solar-type star observed for 4 years with *Kepler*. The input simulation was a part of an asteroFLAG *hare-and-hound* exercise [8] which, in addition to the oscillations, included a number of stellar effects such as activity.

### 3.2. Simulations

We have performed simulations in order to determine the faint limit to which we can determine the large frequency separation, and hence the radius of the star. The baseline simulation was 99 stellar models in the mass-range $0.7–1.5 M_\odot$. For each stellar mass, in steps of $0.1 M_\odot$, we selected 11 models from the main sequence to the giant branch and simulated oscillation frequencies using the ASTEC code. For each model we then simulated 1-year light curves at short cadence using the algorithms described by De Ridder *et al.* [9] and added noise, including granulation, corresponding to $V = 9–14$ in steps of 0.2 mag. For each case, we ran 10 different realizations of the noise and only considered a detection successful when we could extract the correct large frequency separation, using the method described above, in *all* 10 realizations.

The results are displayed in Figs 4 and 5, for the low- and high-mass ranges (relative to the Sun), respectively, and they show that we will be able to determine the large separation in a major fraction of the *Kepler* (planet-hosting) stars observed at short cadence. For instance, for stars less massive than the Sun we will, from 1 year of data, be able to extract the large...
separation in stars fainter than $V = 13$ for an intrinsic brightness corresponding to the solar luminosity.

We have then performed further simulations in order to test how precisely we can determine the large separation. Depending on the position in the HR diagram, and hence the amplitude of the oscillations, we could determine the large separation to a precision well below 0.5% from just 90 days of observations for a star like the Sun down to $V = 11$, and we obtained a similar precision down to $V = 12$ from 3 years of observations. Such a precise determination of the large separation will allow a determination of the stellar radius to better than 2%.

The simulations performed so far have shown that Kepler will indeed provide excellent data for asteroseismology, and that the Kepler Project can expect to benefit greatly from the asteroseismic investigation in terms of characterization of planet hosting stars. We will, however, perform much more detailed simulations in order to develop the final asteroseismic pipeline and prepare for the scientific exploration of the Kepler data, also in terms of improved stellar modelling. This will be done within the framework of KASC (see Sect. 4), which includes the asteroFLAG collaboration that has already organized its first hare-and-hound exercise on simulated Kepler data [8].

**Figure 4.** Detection limits for stars of one solar mass and below based on 1 year of simulated Kepler data. Green squares denote a detection limit fainter than $V = 14$, blue triangles $V = 13−14$, light blue circles $V = 12−13$ and red stars brighter than $V = 12$. The numbers attached to the symbols detail the detection limit found in the simulations for the corresponding model.

### 3.3. Other investigations

The use of the Kepler time series for asteroseismology extends much further than the parameter determination discussed above. 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 have here concentrated on solar-like oscillations of main-sequence stars, to be observed with the short cadence. However, 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 long-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. Thus the resulting dataset will be an invaluable resource for studies of a very broad range of stellar variability.

4. Organization of the 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. The relevant Kepler data will be transferred from the Data Management Center 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. This will include analysis for the stars selected by the Kepler Science Working Group for asteroseismic analysis, to obtain the basic stellar parameters of planet-hosting stars. Further detailed analyses will be carried out for the stars selected by KAI 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. 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 have established a Kepler Asteroseismic Science Consortium (KASC), with broad community participation, to help with the preparations and take part in the analysis of the data. So far around 250 members have joined KASC, indicating the contributions to be made to the project and the planned uses of the data.

A very important task of the KASC will be to provide input towards the selection of Kepler asteroseismic targets, including the decision on how long each target should be observed. As a basis will be used the Kepler Input Catalogue as well as supplementary ground-based observations. Particularly important is the identification of suitable targets amongst relatively rare types of pulsating stars, such as rapidly oscillating Ap stars, slowly pulsating B stars, and γ Doradus stars.

5. 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 [10] 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 Kepler asteroseismic data will provide a major boost to the investigations of stellar internal structure and evolution. Furthermore, the results will be very valuable for the exoplanet part of the mission. As demonstrated above, we can 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.

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