The Kepler Asteroseismic Investigation: Scientific goals and the first results

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Kepler is a NASA mission designed to detect exoplanets and characterize the properties of exoplanetary systems. Kepler also includes an asteroseismic programme which is being conducted through the Kepler Asteroseismic Science Consortium (KASC), whose 400 members are organized into 13 working groups by type of variable star. So far data have been available from the first 7 month of the mission containing a total of 2937 targets observed at a 1-min. cadence for periods between 10 days and 7 months. The goals of the asteroseismic part of the Kepler project is to perform detailed studies of stellar interiors. The first results of the asteroseismic analysis are orders of magnitude better than seen before, and this bodes well for how the future analysis of Kepler data for many types of stars will impact our general understanding of stellar structure and evolution.

1 Introduction

Kepler is a NASA Discovery mission with the primary goal to investigate the properties of extrasolar planetary systems (exoplanets). Of particular importance is the characterization of habitable systems, i.e., rocky planets, up to a few times the mass of the Earth, in a suitable distance from the central star. The mission detects exoplanets with the transit technique: using a 95 cm Schmidt telescope a 100 square degree field in Lyra and Cygnus is observed continuously to look for small reductions in observed stellar luminosity when a planet passes through the line of sight between the star and the observer. In practice, more than 150,000 stars are observed to ensure a reasonable detection probability. From repeated detections of such minute dimmings of the light, and additional follow-up observations, it may be confirmed that the signal is due to a planet in orbit around the star and the properties of the planet, in particular its diameter, can be determined (see Borucki et al. 2010, for further details). A planet of the size of the Earth in orbit around a star like the Sun gives rise to transits with a relative decrease in the stellar flux of around 10−4. Such an effect is readily detectable with Kepler (Borucki et al. 2009).

The requirement of exquisite photometric precision for the transit observations also makes the mission perfectly suited for asteroseismology (Christensen-Dalsgaard et al. 2008). In fact, the potential for combining exoplanet search and asteroseismology has already been demonstrated by the CoRoT mission (Michel et al. 2008). Thus the mission has established the Kepler Asteroseismic Investigation (KAI), with two main goals: the direct use of asteroseismology to characterize central stars of planetary systems, and in particular determine the radius and age of the stars; and the use of high-quality data on a very large and diverse sample of stars to study stellar properties and improve our understanding of stellar interior physics, evolution and oscillations.

To make full use of the possibilities offered by the KAI, we have set up the Kepler Asteroseismic Science Consortium, with direct access to the Kepler asteroseismic data. The benefits of this organization were demonstrated by the very efficient use of the initial data, allowing rapid publication of results of the first month of Kepler data (Gilliland et al. 2010a) (see also Karoff et al. 2010, for an example of the schedule of the analysis). Here we briefly describe the Kepler mission and the organization of the work within KASC, as well as the parallel efforts to utilize Kepler asteroseismology in support of the exoplanet research.

2 The Kepler mission

Details on the design of the Kepler instrumentation and the operations were provided by Koch et al. (2010). The Kepler photometer is of Schmidt design, with a corrector with a 95 cm aperture and a 1.4 m primary mirror. The curved focal plane contains 42 CCD detectors, each with a field-flattening lense. The active field on the sky is 105 square de-
Fig. 1 The Kepler FOV and location of the CCDs in the sky

790 Kjeldsen et al.: Asteroseismology with Kepler

grees; the field is placed such that the brightest stars, which could otherwise cause trailing problems, are placed in the gaps between the CCDs. The field and the location of the CCDs are shown in Fig. 1.

Kepler was launched on 7 March 2009 into a heliocentric Earth-trailing orbit, with a period of 372.5 days. Commissioning was carried out until 11 May 2009 and science operations started on 12 May 2009. To keep the solar panels pointed towards the Sun the satellite is rotated by 90° every 93 days. The detector plane is four-fold symmetric such that the CCDs always cover the same areas on the sky. Data downlink requires repointing of the satellite; this takes place at 32-day intervals and gives rise to 24 h interruptions in the observations. The nominal duration of the mission is 3.5 years. This may be extended; the maximum duration of the mission, limited by onboard consumables and telemetry limitations with increasing distance is about 7-8 years.

The photometric data are downlinked in the form of small images around each target star, the size depending on the brightness of the star. For stars brighter than V magnitude 11.7 the central pixels in the image are saturated and a larger area is required to capture the overflowing photo-electrons; given this, however, accurate photometry is possible for stars as bright as magnitude 6 (Gilliland et al. 2010b), although at the expense of telemetry. For most targets the data are integrated over around 30 minutes, in what is known as Long Cadence (LC) mode; this is adequate for detecting planetary transits. However, for up to 512 targets the data can be transmitted at a 1-minute cadence (Short Cadence; SC); this is required for the study of pulsations of main-sequence stars and is also used further to characterize the planetary transits. Of the 512 SC slots, at least 140 are reserved for targets selected by the KASC for asteroseismology; additional 100 slots can be used for asteroseismic targets selected for their exoplanet interest by the Kepler Science Team. In addition, KASC is guaranteed the right to select 1700 LC slots for asteroseismology of more slowly pulsating stars, as well as access to LC data on 1000 red giants selected as astrometric references.

Target lists are uploaded to Kepler once a quarter. Each target (short cadence) is observed for a minimum of 1 month, although after the initial 10 month of operations most often a target is kept for the full quarter. The target lists have to be ready 8 weeks before the next quarter begins. This gives very substantial flexibility in the choice of targets for asteroseismology, including taking into account results obtained in earlier phases of the mission, to select the optimum targets for long-term observations. It will often be the case that a given target is observed in several consecutive quarters.

The Kepler Input Catalogue (KIC) is a key tool for selecting stars for the Kepler programme. The KIC-10 (Kepler Input Catalog, version 10) is placed in the Multi-mission Archive at the STScI (MAST) with the aim to provide information useful for the selection of optimum targets for the mission, not just for the Kepler planet searches, but also for other users, such as the KASC and the Guest Observer Program. The KIC reports every known object in a footprint that covers the entire Kepler field, including the gaps between the Kepler CCDs. It relies on the USBO-B for the information on faint stars. New multiband ground-based photometry in the Sloan g, r, i, and z bands, plus D51 (a custom intermediate-band filter that includes the gravity-sensitive Mg b features) was included for essentially all the entries in the 2MASS Catalog, and this photometry has been used to estimate effective temperatures, surface gravities, metallicities, reddening, and photometric distances. Masses and radii estimated with the aid of stellar models are also included in the KIC.

A characteristic precision of the KIC-10 photometry is 0.015 mag in r and in the various colours, e.g. g–r, r–i, and i–z. This is the median error derived from multiple visits to the same stars. Based on just the photometry, the effective temperatures for solar-type stars are uncertain by about 150 K, with larger errors towards the hotter and cooler ends of the range covered.

3 Organization of the Kepler Asteroseismic Investigation

The goal of the KAI is to ensure fast and efficient utilization of the unique resource provided by the Kepler asteroseismic

1 http://archive.stsci.edu/kepler/kepler_fov/search.php
The very large number of stars that are being observed motivates the involvement of a broad community in the analysis, with direct and flexible access to the asteroseismic data. In addition, it is important that the data are analysed in a coordinated manner, to optimize the investigations and ensure timely publication of the results, properly reflecting the underlying efforts. This is the background for the establishment of the Kepler Asteroseismic Science Consortium (KASC). Full access to the asteroseismic data is open to all active members of the KASC. A concern for this open data policy, however, has been the possibility of detection of apparent planetary transits by the KASC members. Reliable identification of exoplanets with the transit technique requires extensive analyses beyond the initial detection of a possible transit, and hence is carefully controlled by the Kepler Science Team; similarly, this represents a high-profile goal of the mission, and hence announcements of planet detections are the responsibility of the Science PI. To avoid premature announcements of planet detections all KASC members have signed a Nondisclosure Agreement, stating that evidence for planet transits found in the data will be communicated only to the Science Team, for further analysis. In addition, the data are checked for obvious exoplanet signatures before being released to KASC. During the initial release of data from the first quarters (Q0, Q1 and Q2) the short cadence data were modified through a Transit Removal filter (TRF) aiming at destroying any transit-like features in the time series. However, this filter also modified some of the oscillation features at low frequencies and it was decided to release all Kepler asteroseismic data without the TRF modification. All KASC data are now used in a version without filtering (TRF), including Q0, Q1 and Q2 data.

Information on KASC is available on the KASC web site. This includes a link to all the relevant documents describing the organization of the activity. In particular, the publication strategy and policy (DASC/KASOC/0009) should be noted.

3.1 KASC Working Groups

In order to organize the work among the 400 members of the Kepler Asteroseismic Science Consortium (KASC) a number of working groups (KASC WG) has been created. Each KASC WG has a chair who is responsible for managing and organizing the work related to that WG.

The following WG have been established, largely according to the relevant types of pulsating stars:

1. Solar-like p-mode oscillations
2. Oscillations in clusters
3. Delta Cephei stars
4. Delta Scuti stars
5. Rapidly Oscillating Ap stars
6. Slowly Pulsating B-stars
7. Cepheids
8. Red Giants
9. Pulsations in binary and multiple stars
10. Gamma Doradus stars
11. Compact pulsators
12. Miras and semiregulars
13. RR Lyrae stars

Most working groups are further subdivided into subgroups, with responsibility, e.g., for data analysis, modelling and ground-based support observations. Working Groups 2 and 9 clearly have a rather special status: they are intended to deal with those cases where membership of a cluster or a binary system is relevant for the analysis of a specific Kepler asteroseismic target. In general, it is likely that a KASC member belongs to several working groups and/or subgroups, depending on his/her interests. A detailed overview of the working-group structure, including names and contact information for working-group chairs, is available on the KASC web site.

Membership of a working group is a condition for access to the Kepler asteroseismic data through KASOC (see below). To join a working group a KASC member must supply a brief Letter of Intent to the relevant working group(s) stating his/her interest in the data and plans for using them. Access to any Kepler asteroseismic data is open to all KASC members, but publication has to be coordinated through the working groups, to ensure proper credit for the activities. In the likely not uncommon case that work on a dataset with a specific purpose uncovers aspects that are relevant to another working group, the KASC member simply has to join that working group.

The KASC WG are established to ensure an efficient and structured work within KASC focusing on data analysis, stellar modelling and publication of data. The chair of each working group (and subgroup) is responsible for organizing the work within the working group, defining specific tasks and deadlines and ensuring that all working group members are involved in the work in agreement with the individual intents expressed in their KASC Letters of Intent. The WG chairs are also responsible for internal information within a given working group and for keeping the KASC Steering Committee informed about the progress of the work within the working group. The working groups have very considerable autonomy on how to organize the work and the publications.

3.2 KASOC

To distribute the Kepler asteroseismic data and help coordinating the analysis and publications within KASC we have established the Kepler Asteroseismic Science Operations Centre (KASOC) This provides access to the Kepler time
series as well as other relevant information about the potential, and actually observed, Kepler asteroseismic targets. It is the intention that the KASOC site will also be used for exchange of results of the analysis of the Kepler data, such as modelling, and ground-based support observations, as well as serving for exchanging and discussing preprints based on KASOC analyses. Access to KASOC is controlled through an individual password that can be provided, once the KASC member has joined a working group. Data downloads are logged.

The SC data are provided to KASOC by Gilliland, after vetting the time series for possible transits or other conflicts with the Kepler exoplanet programme. The LC data are downloaded directly from MAST\(^4\) (Multimission Archive at Space Telescope Science Institute)

The data are typically made available around 4 months after the end of the corresponding quarter. For example, the data from Q3 (18 September 2009 – 17 December 2009) were released 22 April 2010. In total 362580 files (May 2010) have been downloaded from KASOC corresponding to 74 GBytes of uncompressed data (29 % of the data in FITS format and 71 % of the download as ASCII datafiles). Figure 2 shows the data download as a function of time indicating the peak downloads in relation to the release of new data.

The KASOC is currently hosted by the Department of Physics and Astronomy. The intention is that it will be moved to the Royal Library, Copenhagen, to increase the functionality, including careful version control and recording of the work processes involved in setting up the data. Also, by being archived at the Royal Library the long-term preservation and usefulness of the data can be ensured.

3.3 Survey and specific targets

Kepler asteroseismology offers unique possibilities for extending our knowledge about stellar oscillations and stellar structure, and hence careful planning has been needed to ensure the optimal use of these possibilities. This requires a balance between obtaining information about a broad range of stars and carrying out in-depth investigations of carefully selected targets. This is being achieved by dividing the KAI into two, partly overlapping, phases. In the initial phase a large number of targets are surveyed, by being observed typically for one month each. This phase has occupied the first ten months, Q0 – Q4, of the mission, leading to the observation of about 5200 targets in SC and LC. It has been found that survey of some targets, in particular lower-mass unevolved solar-like pulsators and compact objects, requires longer periods, and hence such surveys are being continued in the subsequent quarters, with observations covering the full quarter. During Q0 – Q3 a total of 2937 SC targets were observed for KASC, spanning the HR diagram. 59 targets were observed for longer than one month and most of those (44 targets) were observed during the whole mission (Q0 – Q3). Based on KIC parameters we show in Figure 3 the HR diagram for all KASC targets observed during Q0 – Q3. SC targets are mostly main-sequence and dwarf stars (sdB and white dwarfs) while LC targets are mostly stars with a large stellar radius.

On the basis of the surveys, specific targets have been selected which will typically be observed for much more extended periods, to allow detailed studies of the stellar properties, including determination of aspects of the internal structure and internal rotation\(^4\) (Christensen-Dalsgaard 2010). A very interesting aspect, in the case of solar-like oscillations, is to search for variations of oscillation properties related to time-varying stellar activity\(^4\) (Karoff et al. 2009). The phase of observing the specific targets is now starting.

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\(^4\)http://archive.stsci.edu/kepler/
In the case of *Kepler* most of the central stars of the detected planetary systems are probably too faint for a detailed asteroseismic analysis. In some cases we can expect to be able to determine the mean density of the star and hence obtain a useful constraint on the properties of the system. Also, the detailed asteroseismic results obtained for brighter stars can be used to calibrate the Kepler Input Catalogue (KIC-10) and hence improve the general precision of stellar parameters. We note that for the PLATO mission (Catala 2009), under evaluation in the ESA Cosmic Vision programme, asteroseismic characterization of the central stars in extra-solar planetary systems is an integral part of the mission. The results already obtained with *Kepler*, illustrated above, clearly demonstrate the great value of this approach.

### 5 Summary and outlook

As pointed out in the sections above asteroseismology is and will become a very important tool for studying detailed properties of exoplanetary systems by characterizing the planet-host stars at a level of detail not possible from other astrophysical techniques. This requires improved knowledge of stellar structure and evolution and hence a general study of stellar oscillations in stars across a wide range of types. The first results of the asteroseismic analyses from *Kepler* were described by Gilliland et al. (2010a). These already showed the huge potential of *Kepler* for asteroseismology, including high-quality asteroseismology of a few solar-like stars (Chaplin et al. 2010), and analysis of a large number of red giants showing that high signal-to-noise photometry can provide direct detection of oscillation power for hundreds of stars, bringing red giant seismology a huge step forward (Bedding et al. 2010). Also, as discussed by Gilliland et al. (2010a) important results have been obtained for classical pulsating stars. The main improvement for those stars is the high stability of the *Kepler* photometer and the extended length of the time series, providing a great improvement in frequency accuracy of the detected modes and low-amplitude detectability (Kolenberg et al. 2010). An interesting feature is the large number of hybrid stars where one star shows simultaneous oscillations of different types, e.g., delta Scuti and gamma Doradus pulsations (Grigahcène et al. 2010). Just these early results are orders of magnitude better than seen before and this indicates how the future analysis of *Kepler* data for many types of stars will impact our general understanding of stellar structure and evolution. With *Kepler* going from the survey phase to the specific target phase (with stars being observed for extended periods of time) we will increase the frequency accuracy to a level where changes in the stellar structure may be observed for main-sequence stars. The KAI and KASC will play a key role in the continuing use and analysis of the *Kepler* asteroseismic data.

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