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Kepler

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Abstract

Kepler is a NASA mission, scheduled for launch in April 2009, whose principal purpose is to investigate extra-solar planetary systems, through the detection of planetary transits across their parent star. An important goal is to determine the prevalence of Earth-size planets in Earth-like orbits. The required photometric precision also makes the mission very well-suited for asteroseismology, with the important purpose of characterizing the central stars in planetary systems. An extensive asteroseismic programme is planned for Kepler, organized in an international collaboration in the Kepler Asteroseismic Science Consortium.

Introduction

Kepler is a NASA Discovery mission to characterize extra-solar planetary systems using the transit technique. The mission requirements on photometric precision and mission duration ensure that a planet of the size of the Earth can be detected in a one-year orbit around a star like the Sun. In fact, substantial emphasis is placed on obtaining statistics on the number of planets of a nature conducive to the development of life, in the habitable zones around their central stars (Borucki et al. 2007). Kepler will carry out high-precision photometry, at better than 20 parts per million averaged over 6.5 hours at $V = 12$, of approximately 170,000 stars in a field covering around 105 square degrees in the region of Cygnus and Lyra, observing them nearly continuously for the duration of the mission, at least 3 1/2 yr. The data will be transmitted to the ground in the form of small images centred on each target, such that the detailed photometry can be optimized on the ground. Most of the stars will be observed with a 30-min cadence. However, at any given time 512 stars will be observed with a cadence of 1 minute, allowing detailed characterization of transits in already detected planetary systems and, of relevance to the present note, observations of short-period stellar pulsations. Kepler is scheduled for launch in April 2009, into a solar orbit trailing the Earth, similar to the Spitzer orbit. Thus the increasing distance to the Earth will impose some limitations on the data rate in a possible extended mission. Further details on the mission and its development status are provided by Borucki et al. (2008) as well as on the Kepler website: `http://kepler.nasa.gov/`.

The high photometric precision of Kepler will yield exquisite data for asteroseismology. Solar-like oscillations of main sequence stars will be observable in stars down to magnitude 12, while data of unprecedented quality are expected for other types of variable stars. This includes the very large sample of stars, including red giants showing solar-like oscillations, which can be observed with the 30-min cadence. This is the basis for the establishment of the Kepler Asteroseismic Investigation (KAI) through a Letter of Direction from the Science Principal Investigator Borucki to the asteroseismic community. A central goal of the KAI is to use asteroseismology to characterize central stars in planetary systems detected by Kepler. An important characteristic of the star, which can be constrained with asteroseismology, is the stellar radius which is required to infer the radii of planets from the magnitude of the light curve dip they cause in transit. Furthermore, the asteroseismic analysis is expected to provide information about the evolutionary state and hence age of the stars, of importance to the understanding of the evolution of planetary systems. However, the Kepler asteroseismic data will also allow detailed investigations of the internal properties of a broad sample of stars; also, it will provide information about stellar rotation, including the inclination of the rotation axis and the rotation of stellar interiors, and it may reveal frequency changes associated with stellar cycles. Thus the mission will provide major contributions to our understanding of the structure, dynamics and evolution of stars, including the physics of stellar interiors.

The Kepler Asteroseismic Investigation will be based at the Kepler Asteroseismic Science Operations Centre (KASOC) which is being established at the University of Aarhus, and which will distribute the asteroseismic data after receiving it from the Kepler Data Archive. To ensure the full utilization of the Kepler data, the Kepler Asteroseismic Science Consortium (KASC) has been set up. KASC is open to any interested scientist, and membership of KASC provides access to all data made available through KASOC.

Christensen-Dalsgaard et al. (2007) gave an introduction to the Kepler mission and the asteroseismic investigation. Here we provide further details on the organization of the KAI and the expected results. Additional information can be found on the KASC home page: `http://astro.phys.au.dk/KASC`. This includes DASC/KASOC reports which are referred to in the following.

Targets for Kepler asteroseismology

The operations schedule of Kepler allows upload of new target lists every three months, when the spacecraft is rolled to realign the solar cells towards the Sun. Each target will be observed for at least one month; however, in many cases it is probably advantageous to observe a target for the full duration of the mission. Also, a careful selection of targets is obviously needed to optimize the use of the 1-min cadence targets. According to the Letter of Direction, the KAI can use all 512 1-min slots in the initial phase of the mission. Later some of these slots will be allocated to planet-transit investigations, but throughout the mission the KAI can choose at least 140 1-min targets. Asteroseismic analysis, to determine basic stellar parameters, will in addition be carried out at KASOC for selected stars where planetary systems are discovered by Kepler. Furthermore, the KAI can choose of the order of 1000 long-cadence targets, and an additional 1000 red giants, chosen as astrometric references and observed at the long cadence, will also be available for asteroseismology.

The target selection has been broadly divided into two phases. During the first three roll periods (i.e., the first 270 days of the mission) the asteroseismic observations will predominantly concentrate on *survey targets*, typically observed for one month each and selected to provide broad coverage of the possible targets. These targets will be used to characterize the properties of the mission and, in particular, the properties of stellar pulsations observed at an unprecedented level of precision. The results of this survey will then be used to select *specific targets* which will be observed for extended periods, in many cases probably over the remainder of the mission, and carefully selected to optimize the scientific return of the KAI.

The initial target selection was carried out in the autumn of 2008, through a call for target proposals within the KASC, to provide a list of targets well before the launch. Details on the target-selection procedure are available in the report DASC/KASOC/0006.

The target selection obviously requires as much information as possible about the stars in the Kepler field. These issues were discussed at the 2nd KASC Workshop in Aarhus in June 2008. The presentations from the workshop can be consulted at `http://astro.phys.au.dk/KASC/kasc2/Report.htm`. An important background for the selection of both planet-search and asteroseismic targets is the *Kepler Input Catalogue* (KIC; for brief presentations, see Latham et al. 2005; Brown et al. 2005). This is based on dedicated five-colour photometry of a huge number of stars in the Kepler field, backed up by spectroscopy of selected stars, and combined with data from other catalogues, in particular the Two Micron All Sky Survey (2MASS). The data are analyzed to produce estimates of effective temperature, gravity, composition, reddening and distance. In addition, dedicated observations have been carried out for potential solar-like asteroseismic Kepler targets (Molenda-Żakowicz et al. 2007, 2008).

It is evident that surveys of stellar variability in the Kepler field may play an important role in identifying potential targets. This can be based on existing surveys that include the field or dedicated surveys specifically aimed at supporting the target selection (e.g., Pigulski et al. 2008). As discussed at the 2nd KASC Workshop extensive efforts are under way to characterize the populations in the Kepler Field of particularly interesting targets, such as white dwarfs, subdwarf-B variables and rapidly oscillating Ap stars. A tool for automated classification of variable stars, developed by Debosscher et al. (2007), will undoubtedly be crucial for the proper identification of the different types of variables in such surveys. For example, Blomme and collaborators are applying the technique to a major survey of stars in the Kepler field. To support the target selection simulations of the expected behaviour of, in particular, solar-like oscillations are also very important. This is being organized in the AsteroFLAG collaboration (Chaplin et al. 2008a, 2008b), a major international collaboration to test procedures for asteroseismic data analysis. A detailed characterization of the expected properties of various seismic parameters from such simulations was presented by Chaplin et al. (2008c).

The KAI pipelines

The original Kepler data are archived at the Data Management Center/Kepler Data Archive (DMC) at the Space Telescope Science Institute. From there the data are transferred to the KASOC after a transit-removal filtering (see below) to be made available to the KASC. The KASOC data-analysis pipeline will produce data at different levels, available to the KASC in the KASOC archive, including the original filtered time series, Fourier and power spectra, as well as oscillation characteristics and individual frequencies. In addition, the KASOC will contain a data-interpretation pipeline to determine global characteristics of the stars, based on the frequencies and other available information, including data from the Kepler Input Catalogue.

It has been a condition for the open data policy within KASC that the data made available should not be usable for searching for planet transits. Thus a procedure has been developed to filter the short-cadence time series in such a way that information about possible planets, in transit or seen in reflected light, is removed. The procedure was illustrated in detail by Kjeldsen & Arentoft (2008). Briefly, the Transit Removal Filter (TRF) involves the following steps:

1. The first part is a search for single transit signals using a match-filter algorithm. Any signals that are transit-like will be removed by fitting a model transit curve and subtract the model from the data.

2. After the large transits are located and removed the TRF process performs a search for coherent oscillations below a defined threshold frequency of 160 μHz (corresponding

to a period of 1.7 hours, as required for removing the shortest known transit). The frequencies for those oscillations are located and stored.

3. Based on the position of those coherent modes the TRF determines the frequency areas below the threshold frequency, in the vicinity of the identified frequencies, that are affected by the oscillations, as a fixed fraction (typically a total of 10%) of the frequency region below the threshold. No frequencies above the threshold are affected by the TRF process.

4. The Fourier components for the remaining part (e.g., 90%) of the frequency region below the threshold are then calculated and all phases for those frequencies are randomized.

5. The data are then regenerated from the randomized Fourier components by use of the inverse Fourier transformation.

The result of this process is a set of data where: (a) No strong transits are present. (b) Any weak transits are effectively destroyed by the Fourier phase randomization. (c) No oscillations and noise background are being modified for frequencies above 160 microHz. (d) Below 160 μHz all strong modes (and their surroundings in the power spectrum) are untouched. (e) The phases in the background between oscillations below 160 μHz are being destroyed effectively, however the background power level is unchanged. Analysis in the power spectrum is not affected by the TRF process.

Tests based on both artificial and real data have shown that this procedure has little influence on the use of the data for asteroseismology, while effectively suppressing the information about transits.

Concluding remarks

The Kepler mission offers unprecedented possibilities for surveying stellar variability to a very high level of sensitivity, as well as to probe stellar internal properties and hence advance our understanding of stellar structure and evolution. The realization of these possibilities will require concerted efforts by the broad international community. We hope that as many as possible will join the Kepler Asteroseismic Science Consortium and contribute to the utilization of this spectacular resource.

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BRITE-Constellation

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Abstract

BRITE-Constellation, a project developed since 2003 by researchers* at Canadian and Austrian Universities presently consists of UniBRITE and BRITE-Austria/TUG-SAT1, which are two 20 cm cube nanosatellites. Each will fly a 30 mm aperture telescope with a CCD camera equipped with either a red (550 to 700 nm) or a blue (390 to 460 nm) filter, to perform high-precision two-color photometry of the brightest stars in the sky ($\leq$ 4th mag) for up to several years. Stars of up to two magnitudes fainter will be observed simultaneously with reduced accuracy in an on-board photometric mode. Depending on the orbit and the position of the BRITE targets the photometry can be obtained contiguously during many orbits for many months, with gaps during individual orbits, or only for certain periods of the year.

The primary science goals are studies of massive and luminous stars in our neighbourhood, representing objects which dominate the ecology of our Universe, and of evolved stars (giants) to probe the future development of our Sun. The wide field cameras (24°) will also obtain data from other scientifically interesting stars to investigate their stellar structure and evolution.

All of this is enabled by innovative technology currently developed in collaboration between Canada and Austria. A launch of UniBRITE and BRITE-Austria in 2009 is envisioned and an expansion proposal of the BRITE-Constellation by two additional spacecrafts of the same construction, to be funded by the Canadian Space Agency (CSA), is currently under review.

A comprehensive description of scientific and technical aspects of BRITE-Constellation is being prepared for publication in Communications in Asteroseismology. The BRITE-Constellation web site can be found at www.brite-constellation.at. A first Announcement of Opportunity for submitting BRITE-Constellation observing proposals was issued at
http://ams.astro.univie.ac.at/BRITE_AO/BRITE_AO.html

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PLATO: PLAnetary Transits and Oscillations of stars

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Abstract

PLATO is a preselected candidate mission for the Cosmic Vision programme 2015–2025 if the European Space Agency. If ultimately selected (decision end 2011), it will be launched in the 2017/2018 timeframe. The mission was designed to answer the question: *How do planetary systems form and evolve?*, i.e., it aims to reach a serious improvement in our understanding of the formation and evolution of planets and planetary systems, including systems with Earth-like planets in the "habitable zone".

PLATO will detect and fully characterise planetary systems by long duration (3 year), short cadence (30 sec) uninterrupted photometric monitoring of ≈100,000 bright stars of all spectral types, using the signature of transits of planets in front of their parent stars, seismic interpretation of the oscillation frequencies of the parent stars, ground-based high resolution spectroscopy and interferometry, and data from the ESA mission Gaia. The primary targets of PLATO are bright stars ($m_V \leq 11$). In addition, PLATO will also perform an extensive survey of planetary transits in front of ≈400,000 stars down to $m_V = 14$. Two long runs of three, respectively two years on primary target fields will be performed. The two long runs will be followed by a set of shorter ones (of a few months each) on different target fields, either to revisit and confirm planetary transit candidates of the long runs or to study population II stars as well as stars in open clusters, with the goal to improve stellar evolution models.

The present talk is presented by various members of the PLATO science study team of ESA; it will be published only once in *Catala et al., CoAst, volume 158* to which we refer for further information.

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Stellar Observations Network Group

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Abstract

SONG is a Danish-led initiative to construct a global network of 1m telescopes devoted to carrying out time-series observations for asteroseismology and to search for extra-solar planets. To pursue these goals the telescopes of the network will be equipped with a high-resolution spectrograph for measuring very precise radial velocities, and with a CCD camera for carrying out photometry of microlensing events observed towards the Galactic Bulge. Currently, funding has been obtained for construction of a full prototype network node. In this contribution we shall describe the current status of the project, and the instrumental setup as well as the software code needed for measuring precise radial velocities through the use of an iodine cell as velocity reference.

Network – brief overview and ongoing work

SONG is a project to build a global network of telescopes which are designed to address two primary science goals: 1) to carry out asteroseismology through long, uninterrupted, time-series velocity measurements and 2) to search for low–mass extra–solar planets through photometric observations of microlensing events towards the Galactic Bulge. Briefly put, SONG will be a facility dedicated to studying phenomena occurring in the time domain. The project was initiated in 2006 (see Grundahl et al. 2007 and Grundahl 2008). Jørgensen (2008) gives an overview of the microlensing aspects of SONG.

In order to obtain the needed, long, time-series data from the ground, it is necessary to have a network of telescopes. Currently our work is focusing on the design and construction of a prototype node for such a network.

Ultimately, the network should consist of 8 identical nodes distributed in longitude and latitude to provide full sky and time coverage. At each network node a 1m telescope will feed light to a high-resolution spectrograph and an imaging CCD camera located at a Coudé focus. In addition, the focal plane will have a port for future auxiliary instrumentation. All instruments and computers will be located in a temperature-controlled container (inspired by the GONG project); this will lead to a more stable environment than a dome can provide.

In the focal–plane assembly, optical field de-rotation and atmospheric dispersion correction (ADC) will be provided, as well as calibration lamps, filters and shutters. As part of the design, space wil be available to add a second, identical, CCD camera to the focal plane, such that dual-colour imaging becomes possible.

The spectrograph has been designed by Paolo Spanò (INAF-Brera) and it resembles closely the principles behind modern high-resolution spectrographs, such as UVES, HARPS and SARG. The standard working resolution will be 100,000 but several slitwidths will be available.

During the past year significant progress has been achieved for the SONG project. The most important news is that funding has been secured for the development of a prototype network node, including hardware and software for control and automated data-reduction.

It is worth to mention here that the project acronym SONG, originally for Stellar *Oscillations* Network group, now stands for Stellar *Observations* Network Group, in order to emphasize that the main focus will be stars and not only the study of stellar oscillations.

Spectrograph design

For the asteroseismic observations precise radial velocities are to be extracted from the spectroscopic time-series observations. SONG will employ an iodine cell as velocity reference. In order to exploit this to its fullest during data reduction, it is necessary to model the spectrograph point-spread-function to high accuracy. To make this feasible it is highly recommended that the PSF is as uniform as possible across the CCD which makes the PSF modelling less complex. Thus, a very uniform PSF is one of the design goals for the spectrograph.

The experience from HARPS and UVES is that high spectral resolution is needed for the most precise velocities. We have therefore designed the spectrograph for a working resolution of $\sim 100,000$.

A measure of the image quality for the spectrograph is the diameter of the spot size as a function of wavelength and position on the CCD. Across the $2K \times 2K$ pixels of the detector the 80% encircled-energy diameter varies between 5 and 7 microns – the spectrograph camera is essentially diffraction-limited with very little PSF variation.

The wavelength coverage will be from 4800–6800Å, with some wavelength gaps between the reddest orders. In order to make it possible to access all wavelengths in the 4800-6800Å interval, a mechanism to tilt the grating will be included in the design.

Since the operating wavelength range for the spectrograph is limited to a ~2000Å interval it is possible to use highly optimized coatings on all surfaces which helps to produce a very high efficiency. Our calculations show that the spectrograph efficiency at blaze centres will be in excess of 50% (this figure does not include atmosphere, telescope and slit losses and CCD efficiency).

Iodine data-reduction software

As mentioned previously the SONG spectrograph will be used to obtain very precise radial velocities; our aim is to reach a precision better than 1m/s per minute of observations for the brightest ($V \approx 0$) stars. To reach this goal an iodine gas cell will be inserted in front of the spectrograph slit to imprint the iodine absorption spectrum on the stellar spectrum.

In our calculations of the velocity precision we can achieve, we have assumed that our velocity extraction code performs to the same level of precision as achieved by Butler et al. (2004), in observations of α Cen A with UVES at the ESO VLT. Consequently we have started the development of an iodine code for the SONG data reduction pipeline.

Our software is developed in IDL (Interactive Data Language) and the approach is to follow the procedures described in the papers by Butler et al. (1996) and Valenti et al. (1995). For extraction of the observed spectra we use the REDUCE package developed by Piskunov & Valenti (2002). We model the observed star+iodine spectrum as the convolution of the spectrograph point-spread-function (PSF) with the product of a stellar template and the iodine absorption spectrum.

For testing the performance of our developed software we used the α Cen A dataset obtained by Butler et al. (2004) which is available through the ESO archive. Our reductions started from the raw data in order to “mimic” the full process of data reduction and velocity

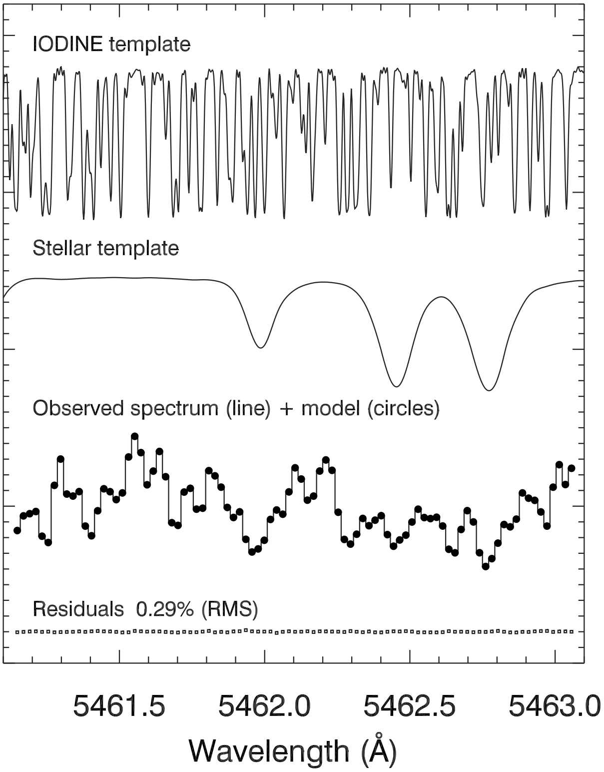

Figure 1: Illustration of the modelling process for spectra obtained through an iodine cell. The upper panel shows the spectrum of the iodine template used for the reductions. The next panel shows the (deconvolved) stellar template constructed from observations of α Cen A without the iodine cell in the beam. The third panel from the top shows the stellar spectrum, observed through the iodine cell (full curve), with the modelled spectrum overplotted as filled black circles. The lower plot shows the observed minus calculated spectrum and the rms dispersion of the residuals.

extraction. Furthermore, T. Bedding (private comm.) has made the velocities extracted by Butler et al. (2004) available to us, thereby allowing a direct comparison of results.

In order to construct the template for the observed star we used the Jansson deconvolution algorithm (Jansson 1984), also used by Butler et al. Instead of the original Jansson algorithm we used the updated version of Crilly et al. (2002) which has a faster convergence.

Our test sample consisted of 688 images obtained with UVES in its highest resolution mode ($0.''3$ slit, R$\sim$ 110,000). Each spectrum was divided into 774 chunks of 91 pixels each, and for each of these we modelled the observations and the PSF, including a velocity shift of the star. The final velocity of the star is then obtained as a robust average of all chunks; various schemes of weighting can be applied to improve the precision. For the results

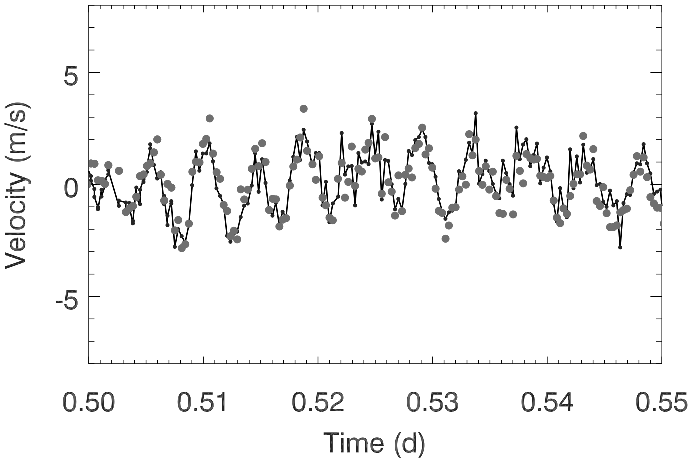

Figure 2: Comparison of measured velocities based on our code (black line with small dots) and (grey points) the velocities from Butler et al. (1996). Note that both reductions clearly show the oscillations of α Cen A.

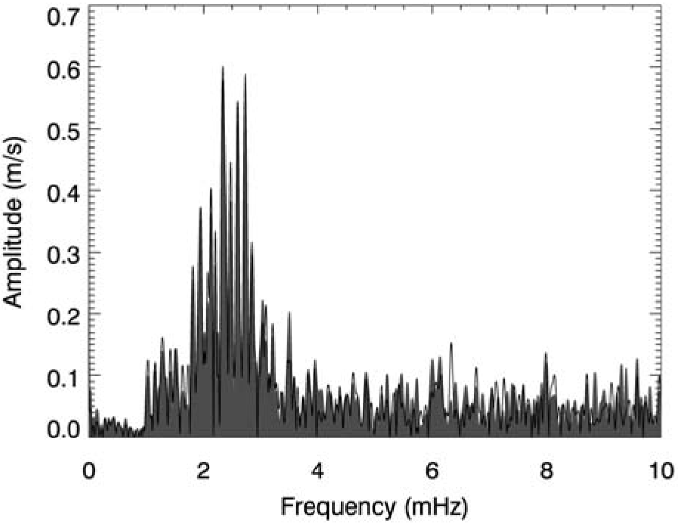

Figure 3: Comparison of amplitude spectra based on our velocities (filled grey "background" curve) and those of Butler et al. (1996) (black curve). We used the exact same data and thus the only differences arise from differences in the derived velocities.

presented here each chunk was weighted by the dispersion in the 688-point time series. The typical error in the modelling of a chunk is about 0.4% but varies somewhat with position on the CCD, the best modelled chunks show residuals (observed - calculated) below 0.3%. For the best chunks the measured rms dispersion, in the 688 point time series, was in the 8-10m/s range. The modelling process is illustrated in Fig. 1 (in a similar way to that of Fig. 1 in Butler et al. (1996)).

Figure 2 presents a comparison between the velocity curve obtained by us and by Butler et al. (1996). It is evident that the agreement is very good and that both time-strings show, directly, the oscillations of α Cen A. The figure only shows a quarter of the available data to avoid overcrowding the plot, the rest of the curve shows a similarly good agreement. A quantitative comparison is given below.

We have measured the velocity precision by constructing the amplitude spectrum of the time string, as shown in Fig. 3. At high frequencies (4.5-10mHz) we measured the rms scatter and converted this into a typical precision, per point. For the data from Butler et al. (2004) we find a precision of 71 cm/s and for our reductions a precision of 77 cm/s is found.

This exercise shows that the data-reduction code in its current state is capable of reaching 1m/s for data of high quality. It is important to note that we have not yet carried out tests of the *accuracy* of the code and the results presented here are for the *precision*. We expect that more work on the modelling of the PSF, and improvement of the weighting of chunks could lead to further improvement in the velocity precision.

The code is still under development and as such is not suited for use by others. We will, however, make it publicly available once it is in a more final state, and after subjecting it to further testing.

Project outlook

Currently (autumn 2008) the main focus for the SONG project is to establish a prototype network node. The work towards this goal is divided into several (overlapping) phases:

- **2008:** finish optical design and place orders for all the major components (telescope, optics etc.)
- **2009:** complete detailed mechanical design, start construction of instruments, development of control software.
- **2010:** assembly, integration and test of instruments, first light for telescope.
- **2011:** extended test of robotic observations and completion of the prototype development phase.

During this period of time, the setup of a broad consortium to develop the full network by $\sim$ 2014 will also be initiated.

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Conference summary: interpretations of asteroseismic data

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Abstract

My goals in this summary are to give my personal impressions, highlight significant developments, and list some of the remaining puzzles and challenges in asteroseismology as presented at this conference. I do not review future space- and ground-based observing programs discussed in the final morning session, but I was encouraged by the data that these promise to return in the near term that will keep asteroseismology an exciting research field for years to come.

Reviews and Tutorials

The meeting began with an introductory talk by Oskar von der Lühe about the conference's major sponsor, HELAS, the European Helio and Asteroseismology Network (http://www.helas-eu.org). We learned about their history, about their last-minute successful bid for funding as a "Coordination Action" under the European Commission's Sixth Framework Program, and the work of HELAS in sponsoring meetings, including those at Sheffield, Nice, Vienna, Porto, Göttingen, La Palma, and Freiburg, and in supporting upcoming space missions SDO, COROT, PICARD, Kepler, the Solar Orbiter, and PLATO. This program cannot exist as a Coordination Action beyond 2010, and needs to transition to an Integrated Research Infrastructure with new funding sources. Ideas and assistance in making this transition are welcome!

The review talks were outstanding, and I wish that we could document them for an asteroseismology course or textbook. It will be worth your time to read the proceedings papers for these talks, even though the space allotted is too short to convey all of the information.

Marc-Antoine Dupret discussed the history and implementation of convection treatments in stellar models, including time-dependence, overshooting, semi-convection, nonlocal treatments, 1D, 2D and 3D simulations, and also managed to cover the history of microscopic diffusion and transport processes, and rotation, including differential rotation, and touch on B fields, all in one 40-minute introductory talk! M. Jerzykiewiecz gave the history of extracting frequencies from sparse data using Fourier analysis and prewhitening and window functions, starting from 1934, but concluded in the end that "if the data is ok, any method of analysis will do!" S.O. Kepler discussed the basics of ground-based multisite photometric data reduction. Conny Aerts gave the history of discovery of line profile variability. G. Handler discussed photometric mode identification, and John Telting discussed spectroscopic mode identification. S. Jeffery gave us a tour of the HR diagram and stellar evolution, highlighting the physical processes that could be probed by asteroseismology at each stage. Shibahashi showed us how to solve the wave propagation and pulsation equations including magnetic fields, including rotation as a perturbation. Samadi reviewed stochastic excitation of oscillations and mode lifetime predictions. Houdek discussed pulsation-convection interactions, the importance of turbulent pressure, and their role in determining instability strip edges and mode properties for solar-like and red giant oscillations. Zahn outlined the observational evidence necessitating extra mixing (outside of convective regions), and discussed the causes of mixing (rotation, diffusion, and angular momentum transport by waves) and implementation in model calculations.

Data Analysis Techniques

We heard about several techniques, such as a trend filtering algorithm, variable sine algorithmic analysis, Bayesian inference techniques, and Markov Chain Monte Carlo techniques used for extracting frequencies and for rigorous error analysis. As Brewer commented in his excellent explanation of Bayesian techniques, we must find "an intermediate between believing theoreticians and ignoring them." We want to caution the observers, though, not to trust stellar model predictions as a guide to signals (period spacings, frequency ranges, etc.) that you expect to find. You might otherwise smooth over or filter out a new discovery that the theorists didn't foresee. If you do process data in this way, at the least list the assumptions and processing steps, even if they are obvious to you and most observers; the modelers or theorists may not be familiar with them nor understand the implications. Please make available your raw data as well, so that modelers/theorists can gain an appreciation and understanding of your processing.

Some Interesting, Surprising, or Significant Results

The following section lists some discoveries that I found significant or surprising.

Dupret's review mentioned difficulties in convection models with higher fidelity than the mixing-length theory, in particular developing closure criteria for the equations. He said that there is a 30% uncertainty in microscopic diffusion coefficients due to collective effects that become important when the thermal energy is about the same order as the Coulomb energy. Could these effects be included in improved methods? He said that some of the 3D models including large eddy simulations by, e.g., Browning et al. have unrealistically small Reynolds numbers; why does this occur, and how useful are these models at present for understanding stars?

Kepler noted that we now have a few stars other than the sun with many modes, e.g., 79 modes for FG Vir, a main sequence δ Sct star, and 198 for the white dwarf PG 1159. Period changes can in principle be used to measure core composition and cooling rates in white dwarfs; Kepler measured the 2nd-order period change for one white dwarf of one part in 10^{20}; I wonder whether I should believe this number, and whether anything has ever been measured so precisely!

Soszyński discussed OGLE III survey results, and said that five triple-mode Cepheid pulsators have been detected (are these explained by models?). This survey identified fourteen separate sequences in the red giant Luminosity vs. Period diagram–do these correspond to different overtones, metallicities, or nonradial modes, or all of the above? Techniques for automated classification and period searching are being developed to process the one million variable stars they expect to find.

Kolenberg and Tsantilas discussed a variable sine algorithmic analysis technique that looks promising when there is an unknown physical mechanism causing a mode to change its period, amplitude or phase over time. They applied this technique to the Blazhko effect variations in RR Lyrae. Could this method be used to gain insight on variability caused by solar-like magnetic cycles?

Breger et al. reported that, for δ Sct stars, nonradial modes tend to cluster near the radial ones, as would be expected if driving is correlated with mode kinetic energy (mode trapping).

Guenther reported that there is now agreement that Procyon shows *p*-modes, but there is as yet no agreement between research groups on the exact frequencies. E. Michel reported that pulsation amplitudes of sunlike stars studied by COROT are, for some reason, 25% lower than theoretical estimates.

Gutiérrez-Soto et al. reported COROT detection of pulsations in Be stars (rapidly rotating B stars showing H emission lines), and that they are trying to understand origin of their circumstellar disks in terms of pulsations.

Kovács said that the incidence of field variable stars with significant Fourier spectra and $>$0.5 mmag amplitudes is only 5%. This conclusion came as a shock, since most of us, after attending so many variable star meetings and seeing the HR diagram filling out with variable star types, were beginning to believe that all stars are variable!

It was pointed out by Christensen-Dalsgaard and others in the discussions that one can constrain *surface* convection parameters with photometric color variations, and constrain *deep* convection parameters with instability strip edges if the driving is sensitive to that region, as is the case for γ Dor stars.

I learned from Handler that we can choose photometric filters to optimize ability to do photometric mode identification. I wondered whether we should be inventing new photometric filter systems for different types of variable star pulsations, as mode ID is so important for asteroseismic interpretations.

Samadi pointed out something that is obvious if one thinks about it: For lower Z, there are lower mode excitation rates due to higher stellar surface density. Mathis showed that there should be a bias in mode excitation introduced by the Coriolis force, and an asymmetry between prograde and retrograde modes for *g*-modes. Can we find evidence for this bias in observations?

Montalban pointed out that, at fixed Z, with the new AGS05 (Asplund, Grevesse and Sauval) abundances, Fe is increased by 20%, since CNO abundances are significantly lower, and opacities actually increase. A new abundance mixture would change the theoretical instability strip boundaries for main sequence B stars. Could we test for different abundance mixtures by locating these edges and comparing with predictions?

Smolec revisited double-mode Cepheid models; he found that double-mode behavior disappears if buoyant forces are included in convectively stable regions, reopening the question of how to explain these stars.

Grevesse noted that non-local thermodynamics equilibrium (NLTE) effects, rather than the inclusion of three-dimensional model atmospheres, was the largest contributor to the oxygen abundance reduction in the AGS05 solar mixture. He speculated that a revised NLTE treatment would change the O abundance to 8.7 dex, intermediate between the old 8.8 and new 8.6 dex values.

Charpinet said that, to explain the driving of sub-dwarf B (sdB) stars, localized Fe enhancements of a factor of 12 due to gravitational settling and radiative levitation are needed. This abundance profile develops over time; instabilities appear after 10^5 y, fully set in at 10^6 y, and abundance profile equililbrium is reached by 2×10^8 y. It may be possible to use pulsation mode properties to gauge the evolutionary stage and approach to equilibrium as profile develops.

Fontaine discussed a new type of variable, the Hot DQ stars, and speculated that roAp stars could be their main sequence progenitors. These stars have effective temperatures of 18,000-23,000 K, between the DAV and DBV variables, and have megagauss magnetic fields and a carbon-dominated atmosphere.

Randall noted that for sdB stars one usually doesn't need mode identification to find a fit to the frequencies and determine mass, but for the brightest sdB, PG 1047, the mass is ambiguous, and an effort is underway to obtain mode IDs (fortunately it is the brightest sdB!)

Zahn explained that rotational mixing alone doesn't transport angular momentum, and that internal gravity waves are also needed. Talon and Charbonnel can match the observed Li abundance for stars and the sun, and can explain the slow rotation of the sun's interior, by including these gravity waves.

Mathis found that angular momentum is extracted for retrograde waves that are less damped, and is deposited for prograde waves that are damped more. Lee said that almost all retrograde g-modes are found stable theoretically. Does this conclusion hold up observationally?

Lignières applied acoustic ray dynamics and quantum chaos methods to rapidly rotating polytropic models. The theory introduces island modes and chaotic modes, a regular frequency patten with an irregular one superimposed. This additional or distorted mode spectrum occurs even for rotation rate 12% of breakup. The island modes are most observable for stars seen pole-on. Should we expect to see such frequency patterns in many of the stars that we have already observed? How will these effects complicate our mode identification and interpretations?

In Shibahashi's tutorial on including B fields and perturbative rotation in stellar models, we learned that B fields make the pulsation equations of 8th order! Damping due to B fields explains the lack of δ Scuti pulsations in roAp stars. Shibahashi showed that different lines are formed at different surface layers, with possibly different abundances. Standing as well as running waves can be observed in line profile variations. He emphasized that depth dependence is needed in line profile variability analysis, and that this dependence could be used to probe the 3D structure of Ap star atmospheres.

In Kochukhov's talk, we learned of the first validation of the oblique pulsator model, obtained by Doppler imaging of the B field at pole of a roAp star. Brandão discussed the potential to constrain B-field topology from pulsations.

Jeffery gave a tour of variables in the HR diagram, and listed additional types that should be included in the popular HR diagram created by J. Christensen-Dalsgaard: Hot DQV, sdO, exHe, WR, LBV, and RV Tau.

Pamyatnykh used observations of β Cep and SPB stars ν Eri and 12 Lac to test overshooting, opacity, and rotation models. He finds that an opacity increase of a factor of 1.5 at log T $\sim$5.45 is needed. He also finds from rotational splittings a core rotation 5× that of the envelope rotation. The predicted asymmetry of an ℓ=1 triplet is 4-5× smaller than observed. If this asymmetry is produced in the outer layers, could it be explained by some outer layers rotating faster than others?

Zwintz and Guenther found that pre-main sequence A, B, and T Tauri stars show different spacing for ℓ=1-2 periods than their main sequence counterparts. They analyze frequencies of candidate PMS stars, and find much better χ^2 fits for PMS models than for MS models. They also discussed HD 142666 (the "devil star"), for which circumstellar dust changes the amplitude by $\sim$1 mag, but pulsations at mmag are seen in the quiet phase. It is a problem that the unlikely ℓ=3 mode fits the dominant mode best.

Van Grootel showed how one could use frequency splittings in sdB stars to constrain the progress of spin-orbit synchronization. She found that synchronization is reached from the surface down to 0.22 $R_\star$ in Feige 48, and to 0.5 $R_\star$ in PG 1336–018. She noted that additional radial layers in the rotation profile, dependence on angle as well as radius, and second-order splittings must be included to extend the analysis.

Posters

Below are a few interesting facts gleaned from an incomplete look at the posters.

Garcia noted that the signal-to-noise background was larger than expected for the four solar-like stars observed by COROT. Bouabid reported on COROT finding a hybrid γ Dor/δ Sct star COROT (HD 49434). Breger and Lenz show that the amplitude variations of 44 Tau cannot be explained by resonance, mode coupling, or precession of the pulsation axis. Castanheira compared data of 72 DAV white dwarfs with seismic models (only 12 had been studied before), and deduced a $10^{-6.3\pm1.6}$ $M_\odot$ H layer mass and $10^{-2.5\pm0.6}$ $M_\odot$ He layer mass, with no evidence for mass loss or accretion in the instability strip. Diago studied B and Be stars in the LMC ($Z=0.007$) and SMC ($Z=0.002$); he found a smaller percentage of these stars: 2.9% and 4.9% incidence of B star variability in the LMC and SMC respectively, vs. 16% in the Milky Way; and 14.8% and 24.6% of Be stars, respectively, vs. 74% in the Milky Way. Fontaine explored Fe radiative levitation to explain sDO star pulsations. Moskalik found that, for the ω Cen fundamental mode RR Lyr stars, the incidence of presumed nonradial modes is 24%, twice that of the LMC, and the same as in the galactic bulge; for first overtone RR Lyr stars, 38% show nonradial behavior. Moskalik and Kołaczkowski report detection of nonradial modes in overtone LMC Cepheids. Théado showed that B fields suppress convection, and help enhance opacity-bump driving of roAp star pulsations. Zdravkov and Pamyatnykh found that they could get hybrid SPB/β Cep stars to exist with an opacity increase of a factor of 1.5 to 2 at $\log T\sim6.3$. Stello claimed that Kepler observations will be able to determine the radius of F to K stars based on the large frequency separation to within 1%! Sariano showed that small frequency separations can become negative for stars at the edge of main sequence or beginning of the supergiant branch; could this crossover be used to characterize convection in He cores, and constrain overshooting?

Questions and Unsolved Problems

Some unsolved problems mentioned in the talks and discussions are listed here.

Regarding convection, there is the question of appropriate closure models for the turbulence equations. There was some discussion on how to treat semi-convection–should one use the Schwarschild or the Ledoux criterion (or something else)? How and when should we include nonlocal and time-dependent convection treatments and turbulent pressure/energy? How do we make use of 3D results in 1D codes since it is inefficient or impossible with disparate space and timescales of different physical processes to do all modeling in 3D?

The interaction of physical processes made me wonder about energy balance and partition. Is the energy of modes conserved? How much energy is in waves, pulsation, rotation, turbulence, magnetic fields, thermal, gravitational, potential, or radiation?

Do red giants show nonradial modes?

What causes the activity of Herbig Ae stars? These shouldn't have chromospheres, they have no observable B field, and the circumstellar disk is decoupled from the star; can asteroseismology help?

What causes the Blazhko effect in RR Lyr stars? Are resonances between radial and nonradial modes, B fields, or turbulent convection responsible?

Can we accurately determine frequencies, and not just frequency spacings, for sunlike stars, when mode lifetimes are short?

How do we explain the hybrid γ Dor/δ Scuti pulsators? According to the theoretical driving mechanisms, these shouldn't exist. The deep convection zones required for γ Dor pulsation should prevent the He-ionization κ effect from working for δ Sct pulsations.

Is there observational evidence of the predicted asymmetry in excitation between prograde and retrograde *g*-modes due to Coriolis force?

Does the modeling explanation for double-mode Cepheids and RR Lyrae stars still work when negative buoyancy forces are included in the convectively stable regions?

What are the implications, beyond helioseismology, of the AGS05 solar mixture? How uncertain are stellar opacities, and what are the implications?

Is there a distinct separated sdO instability strip at $T_{eff}\sim71{,}000$ K? (Models are stable at 61,000 and 81,000 K.)

Do DQV pulsators with a strong magnetic field originate from roAp stars?

How are carbon atmosphere white dwarfs formed?

Could planets be responsible for extreme mass loss of sdB progenitors?

What are the excitation mechanisms, mode spectra, and amplitudes of gravity modes that are critical in transporting angular momentum?

For any amount of significant rotation, should we not expect the frequency spectrum to be variable due to quantum chaos? Have we observed this phenomenon in any stars to date?

Why do only some Ap stars pulsate?

Should we worry about the small discrepancy still existing between Cepheid pulsation and evolution masses?

How is mass lost in the RGB phase to produce sdB stars? Is any mass lost during the helium shell flash? (Jeffery claims that no models show any movement outside of the He/H boundary). Is binarity required?

Impressions

At this meeting, I was impressed by the high quality of the work, and the more than incremental progress exhibited. I was encouraged that both new and experienced researchers are taking on problems that seemed overwhelming in the past, such as differential rotation, time-dependent convection, mode identification, rigorous validation and uncertainty quantification, multidimensional modeling, mode coupling, amplitudes, excitation and damping, and magnetic fields. Many of these problems were beyond the capabilities of computational modeling ten or twenty years ago. Specific results are now being reported for realistic models, supported by observations.

I've been concerned about the effect of the internet and on-line publishing, and that we are in danger of developing habits of superficially skimming the literature, as we do with web news headlines. So I was pleased to see, particularly in the reviews, effort to research and document the history of major developments, and that participants are reading the literature carefully and building on previous work, not reinventing it.

I was impressed by the amount of high-precision data, available today and expected in the near future, from space- and ground-based networks and surveys; I was also impressed by the data analysis techniques and software being developed and made available to cope efficiently with large data sets.

At this meeting we learned most about advancement of techniques, and there was somewhat less emphasis than in previous asteroseismology meetings on point results for a specific star. It seems that we are on the verge of interpretation of the asteroseismic data.

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