AsteroFLAG – from the Sun to the Stars

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Abstract.

We stand on the threshold of a critical expansion of asteroseismology of Sun-like stars, the study of stellar interiors by observation and analysis of their global acoustic modes of oscillation. The Sun-like oscillations give a very rich spectrum allowing the internal structure and dynamics to be probed down into the stellar cores to very high precision. Asteroseismic observations of many stars will allow multiple-point tests of crucial aspects of stellar evolution and dynamo theory. The aims of the asteroFLAG collaboration are to help the community to refine existing, and to develop new, methods for analysis of the asteroseismic data on the Sun-like oscillators.

1. Introduction

Acoustic oscillations are excited in stars with sub-surface convection zones, like the Sun. While the stochastic excitation mechanism limits the amplitudes of the modes to intrinsically weak levels, it does, however, give rise to an extremely rich spectrum of modes. The excited pressure (p) modes probe different interior volumes, with the radial and other low-degree modes probing as deeply as the core. This differential penetration of the modes allows the internal structure and dynamics to be inferred, as a function of position, to exotic levels of precision not usually encountered in astrophysics. The Sun has not surprisingly been the exemplar for the development of seismic methods for probing stellar interiors. The study of the global, p-mode oscillations of the Sun – the field of global helioseismology – recently celebrated its Silver Anniversary. The detection and observation of Sun-like oscillations in other stars offers the prospect of our being able to test theories of stellar evolution and stellar dynamos using many stars, rather than just one (the Sun) at different epochs along stellar evolutionary life cycles. The theories will be subjected to a very exacting examination.

The fact that the Sun-like oscillations have such small amplitudes (*e.g.*, several centimetres-per-second in Doppler velocity, or a few parts per million in intensity, for the most prominent low-degree solar modes) has made the extension of observations to other stars very challenging. However, the ingenuity of the observers is bearing fruit, with data on Sun-like oscillations now available for more than a dozen stars, with the confirmed detections ranging from dwarf stars that, like the Sun, have not yet reached the end of the hydrogen core-burning phase, to evolved red-giant stars. These asteroseismic observations have been made at ground-based telescopes (using spectrographs such as CORALIE, ELODIE, HARPS, UCLES and UVES), and by satellite instruments (WIRE and MOST). With continuation of these high-quality observations (*e.g.*, [1, 2]), the recent launch of CoRoT [3], the upcoming launch of NASA's Kepler mission (in early 2009) [4], and planned extension of the ground-based capabilities (*e.g.*, the proposed SONG asteroseismic network [5]), we stand on the threshold of a large increase not only in the number of stars for which data are available, but also in the lengths of those datasets (which are at present typically measured in days to weeks, rather than the many-year sets available for the Sun).

The aims of the asteroFLAG collaboration are to help the community to refine existing, and to develop new, methods for analysis of the asteroseismic data on Sun-like stars. There is expertise from those involved in the cutting-edge ground-based asteroseismic observations; members of the CoRoT Data Analysis Team (DAT); members of the Kepler Asteroseismology Science Consortium (KASC); leading theoreticians on the interior structures of stars and the Sun-like oscillations; and those involved in the analysis of the so-called Sun-as-a-star helioseismology data. The asteroFLAG group is diverse, and we welcome new members.

2. The asteroFLAG activities

The input data for probing stellar interiors are the mode parameters (e.g., frequencies, frequency splittings etc.). Accurate mode parameter data are a vital prerequisite for robust, accurate inference on the internal structures of the stars. Our objectives are to test aspects of the complete analysis pipelines for stars, from extraction of estimates of the mode parameters through to the procedures used to draw inference on the fundamental stellar properties and the internal structures.

We will test a variety of techniques for extracting estimates of the mode parameters, including methods from the Sun-as-a-star helioseismology community (e.g., solarFLAG [6]), and the stellar community. Our asteroFLAG group contains key members of solarFLAG, several of whom have already been engaged in transfer of knowledge to the asteroseismic problem as part of the CoRoT DAT activities [7, 8].

Initially, asteroFLAG is concentrating on main-sequence stars and is conducting the work within a *hare-and-hounds* framework. Sets of artificial asteroseismic data will be made by *hares* in the group, to simulate observations by different instruments (both ground and space-based). Information for constructing the artificial data comes from several sources, including full stellar evolutionary codes and analytical descriptions of the stochastic excitation and damping of the Sun-like oscillations. The artificial data are then being analyzed blind by other members of the group, who are the *hounds*.

Our work is not just limited to the mode parameter data. The upcoming asteroseismic observations, particularly those in intensity, promise to yield precise estimates of the granulation parameters of the stars. These measurements will provide important information for testing theories of convection.

3. AsteroFLAG hare and hounds on Kepler-like Observations

The first round of asteroFLAG Hare-and-Hounds exercises is already underway. The exercises are based on analysis of artificial Kepler-like data for main-sequence stars.

In addition to searching for Earth-like exoplanets (via the transit method), NASA's Kepler mission will also provide an unprecedented opportunity to study a wide range of stars by asteroseismology. The Kepler Asteroseismology Investigation (KAI) will be arranged around the Kepler Asteroseismic Science Operations Centre (KASOC), which will be based at the Danish AsteroSeismology Centre (DASC, Aarhus) and overseen by J. Christensen-Dalsgaard and H. Kjeldsen [9]. There is wide participation from the international community in the Kepler Asteroseismology Science Consortium (KASC).

The nominal mission lifetime is $\approx$ 4 years. There will potentially be a few hundred Sun-like asteroseismic targets, with *circa.* 50 eventually getting continuous coverage over the entire mission. This last element is crucial, in that it is only from extended observations that certain scientifically rich, but extremely subtle, elements of the oscillation spectra can be measured, *e.g.*, frequency asymmetries of mode peaks (diagnostics of granulation) and frequency asymmetries of mode splittings (diagnostics of magnetic dynamo signatures).

AsteroFLAG is already involved in helping to prepare for the asteroseismology component of Kepler, through its hare-and-hounds activities. Exercise #1 of the asteroFLAG hare and hounds is concerned with testing extraction of estimates of the large and small frequency spacings of the low-degree modes. These seismic frequency spacings will provide key results for complementing the exoplanet search data: the large spacings provide tight constraints for estimating radii of the exoplanet host stars, which may then be used to give precise estimates of the exoplanet radii; while the small spacings may be used to help constrain ages of the host stars.

When mode peaks observed in the power frequency spectra are of sufficient prominence it will be possible to obtain extremely precise estimates of *individual* mode frequencies, for example by application of "peak-bagging" fitting methods developed for Sun-as-a-star data (which we will test on the asteroFLAG data). Use of individual mode frequencies will then allow even tighter constraints to be placed on the stellar radii. The intention is to provide input and guidance to the KASC to help develop a robust strategy, or recipe, for estimation of stellar radii in Kepler observations, under different dataset scenarios (i.e., for different intrinsic stellar properties and noise levels).

WJC and four other asteroFLAG colleagues (T. Appourchaux, GH, RN and TS) have thus far acted as the *hares*, and have generated artificial data on a selection of main-sequence stars for other members of the group, the *hounds*, to analyse blind (T. Arentoft, JB, OC, STF, RAG, SJJ-R, CR and DS).

To give an idea of the expected quality of the data, we show some amplitude frequency spectra of artificial Kepler-like data made from timeseries generated by the asteroFLAG simulator. Figure 1 shows how Kepler would see the Sun, according to the asteroFLAG simulator, were the Sun to be observed continuously for 4 yr at apparent visual magnitude $m_v = 9$. This is

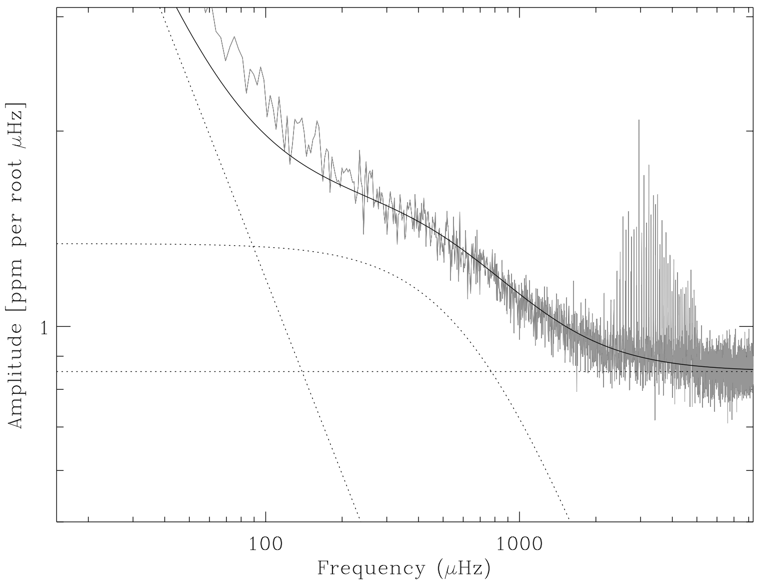

Figure 1. How Kepler would see the Sun, according to the asteroFLAG simulator, were it to be observed continuously for 4 yr at apparent visual magnitude $m_v = 9$. The amplitude frequency spectrum of the timeseries is rendered in light grey. The p modes have maximum amplitudes at $\approx 3000\,\mu$Hz. The individual limit contributions of photon shot noise, granulation, and active-region noise are shown as the dotted lines. The total contribution of these three "noise" components is plotted as a dark, continuous line.

at the bright m_v end of the target range, which extends down to brightness $m_v \sim 15$ (*e.g.*, [9]). The amplitude frequency spectrum has been plotted on a log-log scale to highlight the key components of the dataset. The spectrum of the timeseries is rendered in light grey. The p modes show their strongest amplitudes at $\approx 3000\,\mu$Hz. The individual limit contributions of photon shot noise, granulation, and active-region noise are shown as the dotted lines. The total limit contribution of these three "noise" components is plotted as a dark, continuous line.

The various panels of Figure 2 show 4-yr amplitude frequency spectra for simulated observations of a solar twin at $m_v = 9$, 10 and 11 respectively. The plots, which are centered on the p-mode range, show average frequency amplitude spectra, made by dividing the full timeseries into short 4-day segments and co-adding the individual spectra.

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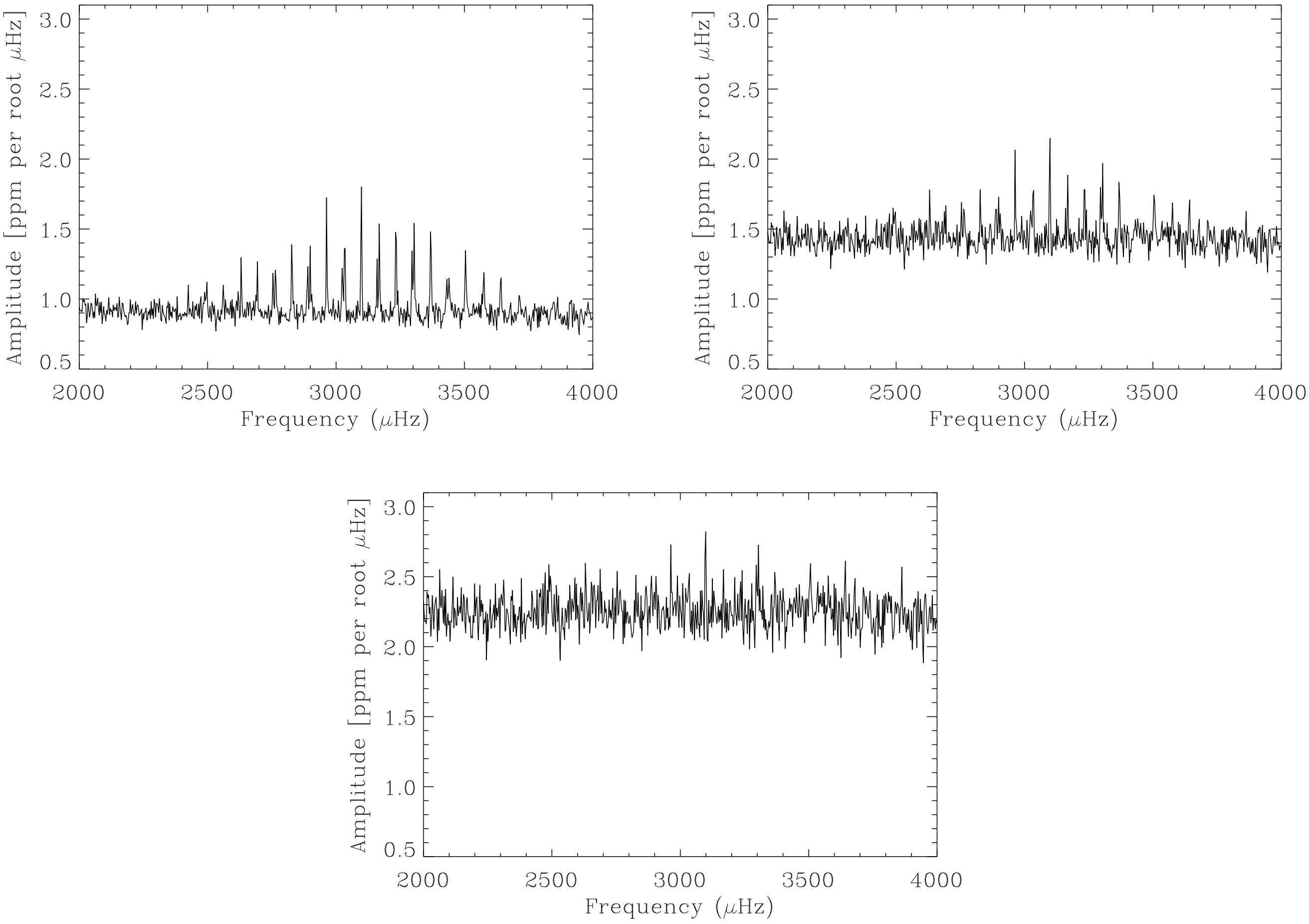

Figure 2. How Kepler would see the Sun, according to the asteroFLAG simulator, were it to be observed continuously for 4 yr at apparent visual magnitude $m_v = 9$ (top left-hand panel), $m_v = 10$ (top right-hand panel), and $m_v = 11$ (bottom panel). The plots show average amplitude frequency spectra, made by dividing the full timeseries into short 4-day segments and then co-adding the individual spectra.

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