ASTEROSEISMOLOGY: THE NEXT FRONTIER IN STELLAR ASTROPHYHSICS

A Science White Paper for the Astro 2010 Decadal Survey
Submitted for consideration by the Stars and Stellar Evolution Panel

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1. Introduction

The foundation of modern astrophysics, most especially the distance scale to the galaxies and the ages of stellar clusters, is based on a quantitative understanding of the fundamental parameters of stars: mass, age, chemical composition, and mixing length. The detection and measurement of acoustic (*p*-mode) oscillations in solar-type stars offers a new approach to measuring these parameters with significantly higher precision than has previously been possible, thus enabling quantitative comparison of data with stellar models.

The study of the interior structure of stars historically has relied on a combination of photospheric spectral diagnostics and models. However, with the now mature development of the techniques of helioseismology, along with technological advances that yield high-precision measurements of intensity fluctuations and spectral line positions in stellar spectra at high cadence, the emerging field of asteroseismology now enables us to embark upon the direct, observational study of stellar interiors.

Asteroseismology allows us to obtain quantitative information on the internal structure of stars, to compare stellar models to real stars more extensively than heretofore possible, to explore the behavior of matter under conditions that cannot be achieved on Earth, and to confront discrepancies between stellar ages and estimates of the cosmological age from a new perspective. Thus, the direct study of stellar interiors through the techniques of asteroseismology is of broad astrophysical relevance and importance.

While this white paper is focused on the seismology of solar-like stars there are several other types of pulsating stars that are distinctly non-solar, and that have been very successfully probed with seismic methods for some time. Examples of these stellar classes are the pulsating white dwarfs, the rapidly oscillating Ap stars, and the δ Scuti stars. The diagnostic and observational approaches described herein are applicable throughout the H-R diagram.

Stars can be characterized by five intrinsic parameters, plus distance: mass, helium fraction, metallicity, age, and the mixing length ratio. In principle, measurement of the frequency separations of *p*-mode oscillations (i.e., sound waves) permits estimation of the age and mass of a star with useful precision if the metallicity is known from other means. However, the uncertainty in stellar metallicity determinations increases the uncertainties in masses and ages determined from oscillation frequencies to significant levels. Additional information, such as the actual individual oscillation frequencies or other data which can help constrain the intrinsic parameters, is needed. In their study of the application of oscillation data to the determination of stellar parameters, Brown et al. (1994) concluded that the determination of ages, mixing lengths, and masses can be substantially improved when oscillation data can be included with traditional measures, especially for more distant stars for which astrometric distances cannot be obtained. *The application of asteroseismology techniques to stars in clusters will ultimately allow us to obtain more accurate distances and ages for the calibration of the distance scale and for comparison to stellar evolution models.*

2. Background

Stellar oscillations can be described (for spherical stars) as radial eigenmodes multiplied by a spherical harmonic, with two quantum numbers, *n* and *l*. The radial order *n* is the number of nodes in the eigenfunction between a star's center and its surface. For typical solar-type stars, *n* is of order 20. The angular quantum number *l* describes the number of nodal planes that intersect the surface of the star. For observations in integrated light, *l* is usually small (l = 0,1,2, or perhaps, 3). Differences in frequency of oscillation of these modes are related to the intrinsic stellar parameters. Frequency separations of the *n*-modes are typically large, and are related to the time for a sound wave to cross the star. Through further consideration of the virial theorem, it can be shown that this travel time is related to the mean density of the star. Thus, the separation of the *n*-modes, known as the "large separation", is easily interpreted in terms of stellar structure and it is relatively straightforward to observe.

Frequency separations of the *l*-modes are smaller and are related to the radial gradient of the sound speed, particularly in the stellar core. Since these gradients change as nuclear burning alters the molecular weight distribution in and around the core, the so-called "small separation" contains information about the evolutionary state of the star. Measurement of the *l*- and *n*-mode frequency separations can yield good estimates of mass and age when combined with stellar models and other observational parameters. The information content for stars in these frequency separations is summarized in Fig. 1 below from Christensen-Dalsgaard (2004).

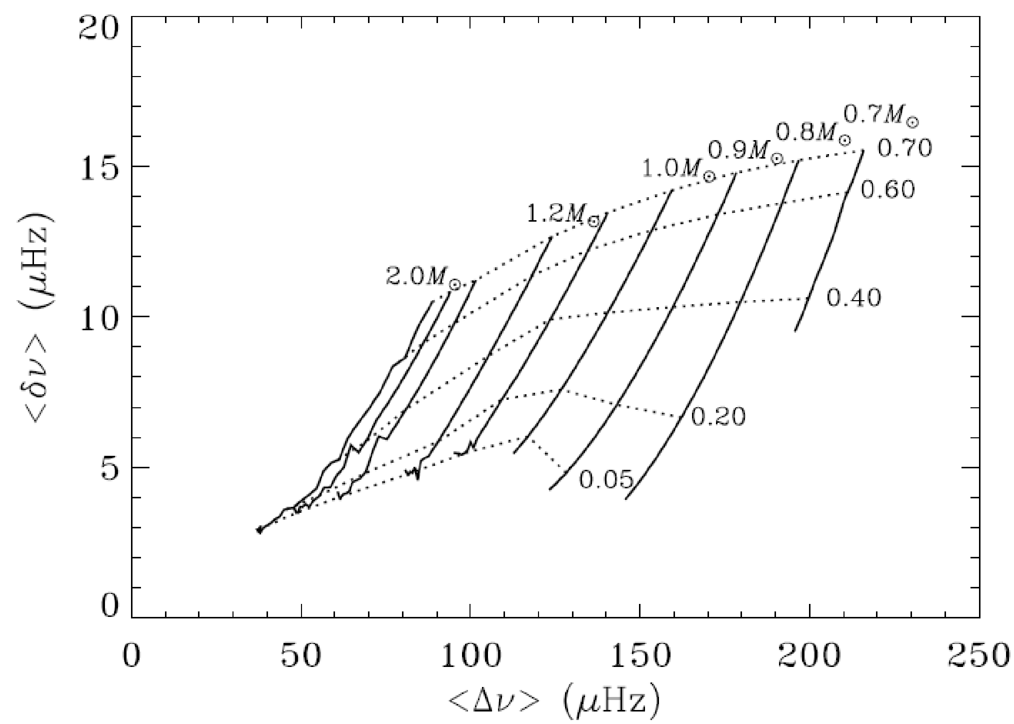

Figure 1 The "asteroseismic H-R diagram" showing the small frequency separation as a function of the large frequency separation along with stellar mass and age. Mass is constant along solid lines; age (parameterized by the central hydrogen abundance) is constant along dotted lines (adapted from Christensen-Dalsgaard 2004).

The source of energy for the *p*-mode oscillations themselves is acoustic noise generated by high-speed convective motions within a few scale heights of the stellar surface. Hence, stars later than about spectral type F5, i.e., stars with vigorous outer convection zones, should give rise to *p*-modes that are generally similar to those observed in the Sun.

3. Results

As helioseismology celebrates its diamond anniversary, we now find asteroseismology entering a rapid phase of development, similar to that of helioseismology ~ 25 years ago. Initially, though, progress was slow. As comprehensively reviewed by Aerts et al. (2008), the search for solar-like oscillations in stars in the solar neighborhood has been ongoing since the early 1980s. The first indication of stellar power with a frequency dependence similar to that of the Sun was obtained by Brown *et al.* (1991) in α CMi (Procyon, F5 IV). The first detection of individual frequencies of solar-like oscillations was achieved from high precision time-resolved spectroscopic measurements only in 1995 for the G5 IV star η Boo (Kjeldsen *et al.* 1995; Brown *et al.* 1997); however, a confirmation of this detection from independent measurements could not be established, but it was subsequently confirmed by Carrier et al. (2003) and Kjeldsen *et al.* (2003). It took another four years before solar-like oscillations were definitely established in Procyon (Martíc *et al.*, 1999). Since then, solar-like oscillations were found in two more stars: the G2 IV star β Hyi (Bedding *et al.* 2001) and the solar twin α Cen A (Bouchy and Carrier 2001; Schou and Buzasi 2001). These important discoveries led to several more subsequent detections, a summary of which is encapsulated in Fig. 2 below.

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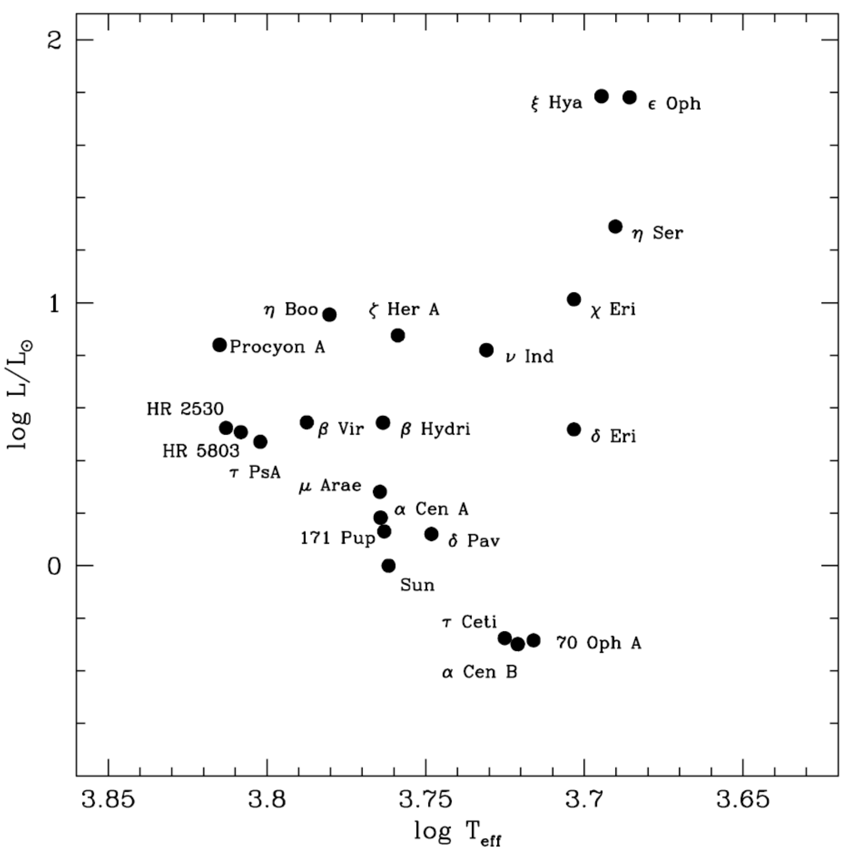

Figure 2 H-R diagram showing the stars in which solar *p*-mode oscillations have been detected (from Aerts et al. 2008, courtesy of Fabien Carrier).

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The oscillation frequencies and frequency separations detected in solar-like "pulsators" provide additional constraints with which to test models of stellar structure and evolution in conditions slightly different from those provided by the Sun. Such studies generally involve a fit of theoretical models, characterized by a number of model parameters, to the set of seismic and non-seismic data available for a given pulsator. Theoretical modeling of solar-like pulsators using this direct fitting approach has been carried out for several stars; so far, the main results of these fits are estimates of the stellar masses, ages, and initial metallicities, even though in some cases the results are still controversial and call for better data-sets.

Among the solar-like pulsators, the binary star α Cen A and B provides a particularly interesting test bed for studies of stellar structure and evolution, given the numerous and precise seismic and non-seismic data that are available for both components of the binary. Studies of α Cen A and B, including seismic and non-seismic data for both components, indicate that the age of the system is likely to be between 5.6 and 7.0 Gyr, the value derived being dependent on the seismic observables that are included in the fits. A study by Teixeira *et al.* (in preparation) found that the mixing length was slightly *smaller* for α Cen B than for α Cen A. The latter study also found that the best-fitting model for α Cen A was on the border of having a convective core (see Christensen-Dalsgaard 2005): even a slight increase in the mass of the model led to a significant convective core and hence a model that was quite far from matching the observed properties. In another example of the power of stellar oscillations as a diagnostic of fundamental stellar properties, Teixeira et al. (2009) report the detection of *p*-mode oscillations in the G8 V star τ Ceti. The detection includes a tentative identification of modes up to $l = 3$. These investigators used the frequencies to estimate the mean density of the star to an accuracy of 0.45% which, combined with the interferometric radius, gives a mass of $0.783 \pm 0.012\ M_{\mathrm{Sun}}$ (1.6%).

Despite the case studies just outlined, in-depth seismic studies of stars with stochastically excited modes are currently still in their infancy compared with global helioseismology. However, given the recent detections and the continuing efforts to improve them, we expect very substantial progress in the seismic interpretation of such targets in the coming years. As seen in the example of α Cen A, it is noteworthy that the class of main-sequence, solar-like oscillators encompasses transition objects with respect to the development of a convective core on the main sequence at masses between 1 and 1.5 solar masses. Asteroseismology can provide crucial insights on the yet poorly understood physics that occurs near the core of the objects in this transition region. Also, data of the expected quality will provide information about the depth and helium content of the convective envelope (*e.g.*, Houdek and Gough 2007), as well as more reliable determinations of stellar ages (Houdek and Gough 2008).

Additional information from solar-like oscillations is available in the cases of relatively evolved stars that are beyond the stage of central hydrogen burning. Here the frequency range of stochastically excited modes may encompass *mixed modes* behaving as standing internal gravity waves, or *g* modes, in the deep chemically inhomogeneous regions, thus providing much higher sensitivity to the properties of this region. In fact, there is some evidence that such modes have been found in the subgiant η Boo (Christensen-Dalsgaard, Bedding, and Kjeldsen 1995).

4. Observational Techniques

The two principal techniques that are utilized for the detection of oscillations in late-type stars are Doppler spectroscopy and photometry, with advantages and disadvantages associated with each approach. For example, Doppler methods work best for stars with many narrow spectral lines (implying stars with low v sin i's) while photometric techniques should work with any star.

In addition, photometric techniques can be applied across a wide field of view, allowing asteroseismic data to be acquired for many stars simultaneously, while the requirement for the observation of many spectral lines at once means that Doppler spectroscopic techniques are practically feasible only for one star per observing sequence. Since vertical Doppler oscillations are naturally weighted more toward the disk center than the scalar intensity fluctuations, Doppler oscillations can be observed to degree l = 3 in stars while intensity oscillations can be seen only to degree 2. This difference in degree sensitivity could be used in principle to help identify the degree of modes observed on a star, which suggests that both intensity and Doppler observations should be carried out. From a purely asteroseismology perspective the Doppler observations are preferred because more modes are visible. In either case, high measurement precisions are required: of order meters per second for Doppler techniques with ~ 1000 spectral lines observed simultaneously, and sensitivities of parts per million for intensity oscillations.

The Sun exhibits non-oscillatory velocity and intensity fluctuations that produce a background "noise". The spectrum of this background noise depends on the average properties of the fluctuations and provides valuable information about these fluctuations. Nevertheless, this background limits the detection of oscillation modes. At the frequencies of *p*-modes in the Sun and sun-like stars, the background noise for both Doppler and photometric fluctuations is due almost entirely to granulation. With the Sun as a guide, we find that the signal-to-noise ratio of Doppler measurements compared to intensity measurements is ~ 40 times more favorable for Doppler measurements. Other stars may be different and the situation may differ at other frequencies, but it is reasonable to expect that Doppler observations are likely to reveal oscillations at lower amplitudes than intensity observations across a wide range of stars. We note that the French-European CoRoT mission is already beginning to acquire through intensity observations information on both the oscillation spectrum and the granulation "noise" spectrum of stars during the course of its search for extrasolar planetary transits. In some stars, the power in the granulation spectrum has been observed with CoRoT to be substantially enhanced at factors ~ 5 over that of the power in the solar granulation spectrum. It is likely that the soon-to-be-launched Kepler mission will obtain substantial quantities of intensity data that could be dominated by the pattern of granulation noise as well as signatures of stellar microvariability due to magnetic activity. From this experience, it is clear that complementary spectroscopic (Doppler) data are needed.

5. The Next Step for Asteroseismology

It is well known that asteroseismology (and the study of stellar oscillations in general) suffers from the lack of facilities to provide long, uninterrupted time-series observations.
This is essential in order to provide adequate accuracy for the measured frequencies and to separate closely spaced frequencies. Asteroseismology, and other fields of astrophysics depending on observations in the time domain, such as the search for extra-solar planets, need dedicated facilities to achieve the required extensive and nearly continuous observations. The Stellar Observations Network Group (SONG) is a Danish initiative dedicated to overcome the problems of short observing runs and non-continuous data, by building a telescope network which will study solar-like oscillations in nearby, bright stars and search for planets around other stars. SONG will consist of 8 identical telescope nodes, with 1-m class telescopes, distributed globally to provide maximum temporal coverage, with the aim to achieve full sky coverage. The

best observing duty cycle will be for the region around the celestial equator, where a duty cycle in excess of 80% will be possible. An overview of SONG can be found in Grundahl et al. (2008).

The instrumentation package will consist of a high-resolution spectrograph and an imaging camera which will be used for guiding during spectroscopic observations, but can also be used as a science imager. The high-resolution spectrograph will be optimized for measuring high-precision radial velocities and hence will be able to achieve very high precision despite the relatively modest size of the telescopes. The objective of the scientific operations is to observe targets for extended periods, up to ~ 4 months. This duration will enable exquisite frequency separation and precision to be achieved. Given an aperture of 1-m the asteroseismology targets for SONG will primarily be stars brighter than V = 6. This provides several stars in nearly all of the known classes of variables. We note here that since the targets are so bright it will be possible to measure precise radii for the SONG targets with existing interferometers. This will provide an important extra constraint on the stars under study which is not available from satellite missions such as CoRoT or Kepler. Furthermore, most stars will be quite close to the Sun, such that their parallaxes are well determined and, with spectroscopic data, oscillation modes with $l = 3$ can also be observed. SONG will not be limited to observing solar-like pulsators; it will also observe pulsating white dwarfs, RoAp stars, δ Scuti stars, etc.

We note that a recent campaign to measure solar-like oscillations in Procyon involved telescopes at 8 ground-based observatories (Arentoft et al. 2008; Bedding et al. 2009). This indicates the type of science that SONG would do routinely, and also the extent of international interest with more than 50 authors on the papers!

The design work for the SONG prototype unit consisting of the telescope and instrument was completed in 2008. Funding recently has been allocated for construction, assembly, integration and tests. The project anticipates that a fully tested and functioning prototype SONG node will be ready by the end of 2011, including the data reduction software. In parallel with the prototype development work, SONG wishes to establish an international collaboration, involving network sites and/or contribution of network nodes, such that the complete network can be established and ready for operation by 2014. In addition to the SONG initiative, the privately-funded Las Cumbres Observatory Global Telescope (LCOGT) is another notable example of a new facility that will pursue observations of stellar pulsations as part of its broader scientific program. LCOGT is now building a worldwide network of 1-meter telescopes that will be capable of both photospheric and spectroscopic measurements of classical pulsators, and also of stochastic pulsators that have relatively high amplitudes.

The SONG and LCOGT initiatives provide an excellent opportunity for the U.S. community to participate in, and contribute to, this forefront area of astrophysics, leveraging its resources through the investment already made in the development of the prototype instruments. The rich experience of helioseismology in the development of seismic data analysis techniques and interpretive approaches, combined with the advances in technologies for high precision measurements of stellar spectra, have placed us at the threshold of discovery. By obtaining oscillation spectra of stars based on data of high quality and extending over several months, asteroseismology will enable critical tests of stellar evolution theory and the determination of stellar ages and helium abundance. Without question, asteroseismology is the next frontier in stellar astrophysics.

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