Challenges and Opportunities for Helio- and Asteroseismology

W. J. Chaplin

School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

Received XX Xxx 2010, accepted XX Xxx 2010
Published online later

Key words  stars: oscillations – Sun: helioseismology

I consider some of the challenges and opportunities facing helio- and asteroseismology, which reflect major themes of presentation and discussion from the HELAS IV international conference “Seismological Challenges for Stellar Structure”. I concentrate in particular on the exciting prospects for asteroseismology, now that the field is being provided with data of unprecedented quality and in unprecedented volumes.

1 Introduction

The HELAS IV international conference “Seismological Challenges for Stellar Structure” marked the successful conclusion of the European-Commission Sixth Framework Programme (FP6) phase of the European Helio- and Asteroseismology Network, “HELAS”. The international helioseismology and asteroseismology communities have benefitted from HELAS in many significant ways: HELAS has supported a diverse program of meetings and workshops, providing forums for facilitating international collaboration, the exchange of knowledge and expertise, and the development of new techniques for analyzing the increasing volumes of high-quality data (with resulting benefits in particular regarding provision of training of graduate students and young scientists in the field).

Much has changed since the first HELAS international conference was held at the University of Sheffield in 2006. Notable progress was then being made in asteroseismology, thanks to ongoing programs of episodic, ground-based telescope campaigns, observations by the MOST microsatellite, and the successful exploitation of the WIRE star-tracker data for asteroseismic studies. In helioseismology, important developments continued thanks to data being collected by the suite of helioseismic instruments on the ESA/NASA SoHo spacecraft, and by the ground-based Birmingham Solar-Oscillations Network (BiSON). CoRoT had not yet been launched, although that event was only a few months away. The asteroseismology programme of the NASA Kepler mission – what would become the Kepler Asteroseismology Investigation (KAI) – was still in the early stages of being formulated. And the Sun was heading towards its next solar minimum, with no unusual behaviour forecast for that upcoming period.

Fast-forward to 2010, and the picture is much altered. CoRoT (Michel et al. 2008) and Kepler (Gilliland et al. 2010) are now providing stellar photometric data of unprecedented quality and length for asteroseismology, and in unprecedented volumes. It is no understatement to say that these missions are revolutionizing the field. One of the highlights of the HELAS IV conference was a special session devoted to first asteroseismology results from Kepler, spanning solar-like stars (Christensen-Dalsgaard et al. 2010; Chaplin et al. 2010), red giants (Bedding et al. 2010), δ-Scuti and γ-Dor pulsators (Grigahcène et al. 2010), and oscillations in open clusters (Stello et al. 2010) and eclipsing binaries (Hekker et al. 2010).

With regards to the Sun, there has of course been the unusually deep and extended solar minimum between cycles 23 and 24, and helioseismology has cast important light on this unusual behaviour. The SoHo spacecraft is now almost at the end of its operational life, and its helioseismic imaging capabilities have very recently been superseded by the HMI instrument on board NASA’s Solar Dynamics Observatory (SDO), which was launched in 2010 February; while the CNES PICARD satellite was launched in 2010 June.

My objective in this review is to comment on some of the opportunities and challenges facing helio- and asteroseismology in the next few years. I follow the tenor, emphasis and focus of presentation and discourse at the HELAS IV conference, and I have used results on highlights from the meeting to illustrate and set the context of my discussion. I have grouped the highlights into a few overarching themes (reflecting of course my personal views on what were the main themes of the meeting). Because I have had to be selective the list of issues I present is by no means exhaustive, but hopefully provides a fair reflection of the meeting.

I begin close to home, with the Sun, and the unusual recent solar minimum.

* e-mail: w.j.chaplin@bham.ac.uk


2 The Unusual Solar Minimum

The unusual behaviour during the current solar minimum of many diagnostics and probes of solar activity has raised considerable interest and debate in the scientific community (e.g., see the summary by Sheeley 2010). The minimum has been unusually, and unexpectedly, extended and deep. Polar magnetic fields have been very weak, and the open flux has been diminished compared to other recent minima.

Helioseismology has been used to probe the behaviour of sub-surface flows during the solar minimum. Howe et al. (2009) found that the equatorward progression of the lower branches of the so-called torsional oscillations (east-west flows) was late in starting compared to previous cycles. They flagged this delayed migration as a possible pre-cursor of the delayed onset of cycle 24. The meridional (north-south) flow also carries a signature of the solar cycle, which converges towards the active-region latitudes and also intensifies in strength as activity increases. González-Hernández (2010) found that during the current minimum this component had developed to detectable levels even before the visual onset of magnetic activity on the solar surface.

The globally coherent acoustic properties of the recent solar minimum have been studied extensively with low-degree p modes (by Broomhall et al. 2009 and Salabert et al. 2009) and medium-degree p modes (Tripathy et al. 2010). These studies have shown that while the surface proxies of activity (e.g., the 10.7-cm radio flux) were quiescent and very stable during the minimum, the p-mode frequencies showed much more variability. Tripathy et al. (2010) noted further surprising behaviour compared to the previous minimum, i.e., an apparent anti-correlation of the p-mode frequency shifts and the surface proxies of activity, during the epoch covered by the current minimum.

Broomhall et al. (2009) had suggested the possible presence of a quasi-biennial modulation of the frequencies of the low-degree modes, superimposed upon the well-established ~11-yr variation of the frequencies. This has since been confirmed by further in-depth analysis, which reveals a signature that is consistent in the frequencies extracted from BiSON and GOLF data (Fletcher et al. 2010). The fact that this biennial signature has similar amplitude in the low-frequency and the high-frequency modes used in this analysis suggests that its origins lie deeper than the very superficial layers responsible for the 11-year shifts.

With regards to the recent solar minimum, the challenge now is to try to make sense of the unusual behaviour revealed by the helioseismic data, and to follow the acoustic signatures and flows as the Sun emerges from the minimum. An important avenue of investigation will be to compare results with those from the previous minimum, e.g., by direct analysis of the differences of the frequencies observed at the two epochs (Basu et al. 2010).

3 Ensemble Seismology

Kepler and CoRoT are providing exciting new opportunities to conduct ensemble seismology thanks to the large number of stars being observed. (In the spirit of the Greek asteroseismology, we might be tempted to instead adopt the phrase synasteroseismology.) The prospects for solar-like stars are particularly exciting. The large, homogeneous Kepler ensemble will for the first time allow a proper seismic survey of a population of solar-type field stars to be made. A statistical survey of trends in important seismic parameters will allow tests of basic scaling relations, comparisons with trends predicted from modelling, and lead to important insights on the detailed modeling of stars. This work is now in progress.

One may also pick from a large ensemble pairs, small groups or sequences of stars that share common stellar properties, e.g., mass, composition, or surface gravity. This opens the possibility to perform what we might call differential (or comparative) seismology of stars, e.g., in analyzing the selected stars one may eliminate or suppress any dependence of the modelling or results on the common property, or properties. By selecting, for example, a sequence of stars of very similar mass and composition it will be possible to produce an exceedingly accurate and robust relative age calibration, and give the potential to map evolutionary sequences of internal properties and structures, allowing exquisite tests of stellar evolutionary models. By selecting stars with very similar surface gravities, one may potentially probe differences in near-surface physics and convection.

Further inferences on near-surface physics may potentially be acquired by differential seismic analyses of simultaneous observations of the same star made in photometry and Doppler velocity. For example, there is the exciting prospect of our having simultaneous data on the solar-type binary 16 Cyg from observations made in photometry by Kepler and in Doppler velocity by the Stellar Observations Network Group (SONG) (Grundahl et al. 2009). The opportunities for collecting simultaneous data in photometry and Doppler velocity may be limited in the near future to only a small number of stars, and as such it also behoves us to look for twins of Kepler and CoRoT stars in data already collected by ground-based telescopes.

Finally, even when stars do not share common properties, comparative seismology still has the potential to aid accurate mode identification, without which inferences drawn from the seismic data would be greatly limited (e.g., see Bedding & Kjeldsen 2010).

Notable successes for CoRoT have come from asteroseismic studies of red giants. Data on large numbers of stars observed in the exoplanet channel reveal ubiquitous signatures of red-giant oscillations. Studies of this ensemble have shown clear observational evidence for new seismic scaling relations (e.g., Hekker et al. 2009, Mosser et al. 2010) predicted by theory (Stello et al. 2009a). The studies are being extended to make inference on the red-giant population –
which is dominated for the CoRoT sample by red-clump stars – and to thereby use the ensemble to test population synthesis models of the evolution of the galaxy (Miglio et al. 2009).

CoRoT also revealed clear, unambiguous evidence for non-radial modes in many of the red-giant stars (De Ridder et al. 2009). This general property has been confirmed and inferences from it extended by Kepler observations of red giants. Bedding et al. (2010) reported results on low-luminosity (H-shell burning) red giants, exploiting the ensemble properties of the stars by presenting the seismic spectra in so-called scaled, and semi-scaled, échelle diagrams (Bedding & Kjeldsen 2010). These diagrams reveal clear ridges due to radial and non-radial modes, and show that for these stars the displacements in frequency of the \( l = 1 \) modes from the midpoints of the adjacent \( l = 0 \) modes are negative in sign, unlike the positive displacements seen in many main-sequence stars; moreover, the large width in frequency of the \( l = 1 \) ridge is likely due to mixed modes (see Montalbán et al. (2010) for theoretical discussion of both issues).

Observations of classical \( \delta \)-Scuti and \( \gamma \)-Dor pulsators have provided further opportunities for ensemble studies by Kepler. Analysis revealed that nearly all members of the observed ensemble were hybrid pulsators, showing both types of oscillation (Grigahcène et al. 2010). This unexpected result has implications for how the stars are classified, and also for the theoretical descriptions of the excitation of the modes.

Another obvious application of ensemble seismology is in the study of oscillating stars in clusters. These stars of course share a common history and, to within small uncertainties, may be regarded as lying at the same distance. Stello et al. (2010) reported on oscillations of red giants observed in one of the open clusters (NGC6819) in the Kepler field. They found that the asteroseismic parameters could be used to test cluster membership of the stars, i.e., by comparing the observed frequency of maximum mode power with the frequency predicted from the locations of the stars in the cluster colour-magnitude diagram. In spite of having only limited data to hand when the study was made, it was already possible to identify four possible non-members despite those stars having a better than 80% membership probability from radial velocity measurements.

Opportunities also exist for using ground-based observations to perform ensemble seismology of clusters. Saesens et al. (2010) have studied classical pulsations of \( \beta \) Cephei stars in the open cluster NGC6910. When cluster members are ordered by intrinsic brightness, a clear systematic progression of the detected oscillation periods is revealed, just like that seen in the NGC6819 red giants. This suggests that simple inspection of the oscillation spectra of the ensemble of classical pulsators may be used to diagnose cluster membership, like the oscillation spectra of solar-like pulsators in Stello et al. (2010).

There are also opportunities for applying ensemble approaches in helioseismic studies, an obvious example being in the use of local helioseismology data products. Komm & Hill (2009) used local helioseismology to perform an ensemble study of 1009 active regions. They measured the subsurface flow properties beneath the regions, and a statistical analysis of the results showed that the inferred vorticity of the flows could help to distinguish flaring and non-flaring active regions, discrimination that would not be possible using, for example, X-ray flux data. Ensemble local helioseismology has also been used to study differences (again, in a statistical sense) in the properties found beneath active and quiet-Sun regions (e.g., see Komm, Howe & Hill 2009).

4 New Data – New Diagnostics, New Challenges

With new data of unprecedented quality and length come new challenges for data analysis, and new opportunities for making accurate and precise inference on the stellar properties that were not possible with older, inferior data products. There is the potential to develop and apply new diagnostic data analysis tools to ensure that contemporary data are exploited to their full potential. However, incumbent on the scientist in any such endeavour is to understand the limitations and biases inherent in those tools, dependent on the quality of data that is available.

New asteroseismic data from the likes of Kepler and CoRoT, and new helioseismic data from the likes of SDO and PICARD, will naturally drive developments in data analysis. A useful strategy to help in development and testing of analysis tools is to apply those tools to artificial data. The data must of course be realistic, and due care must be taken when applying conclusions drawn to results on real data. Nevertheless, tests like these can be extremely instructive – even vital – in aiding, and steering appropriately, the development of new tools; and for avoiding over-interpretation of results on real data.

Inference from local helioseismology requires intensive work on modelling the propagation of acoustic waves in the presence of magnetic fields. Realistic numerical simulations play a key rôle in these studies (e.g., see Schunker (2010) and references therein). Cameron et al. (2010) made numerical simulations of wave propagation through cylindrically symmetric model sunspots, and found good qualitative agreement between the modelled seismic signature and the observed signature of the sunspot in active region NOAA 9787.

In asteroseismology, the asteroFLAG collaboration (Chaplin et al. 2008) has been very active developing tools for application to solar-like oscillators. A particular focus has been to develop tools for automated analysis of many stars to meet the demands of the Kepler survey phase, which will ultimately provide data on more than 1000 solar-like stars. The first application of some of these tools to three bright, solar-like Kepler targets was reported in Chaplin et
al. (2010). The collaboration has also tested methods for estimating radii of solar-like stars (Stello et al. 2009b), using artificial Kepler-like data. The main goal of the Kepler Mission is to characterize extrasolar planetary systems, particularly Earth-like planets in the habitable zones of their host stars, and accurate and precise stellar radii are required to constrain the sizes of the detected exoplanets. Christensen-Dalsgaard et al. (2010) report the first application of asteroseismology to known planet-hosting stars in the Kepler field.

CoRoT data on F-type solar-like oscillators have challenged pre-conceived ideas of how asteroseismic data are analysed (Appourchaux et al. 2008; Barban et al. 2009; García et al. 2009; Mosser et al. 2009). The large mode linewidths uncovered in these stars forced modifications to “peak bagging” strategies for extracting estimates of the mode parameters, and have posed challenges for angular degree identification. Tests on artificial data are a vital pre-requisite for improving the analysis applied to these stars (e.g., see Benomar et al. 2009).

Experiments with artificial data on rapidly rotating intermediate and high-mass stars have proven particularly instructive for helping to understand the appearance of the observed classical oscillation spectra in the presence of rapid rotation (Ballot et al. 2010a). The impact of rapid rotation also cannot be ignored in some solar-like oscillators, i.e., in young F-type stars. Here, modelling of the seismic spectra must also account for second-order terms, which are usually neglected in any analysis (Ballot 2010b).

Regions of stellar interiors where the structure changes abruptly perturb the frequencies or periods of the oscillations (e.g., see Houdek & Gough 2007). The characteristics of the signatures imposed on the oscillations depend on the properties and locations of the regions of abrupt structural change. When the regions lie well within the mode cavities, the near regular spacing of modes in frequency (for p modes) or period (for g modes) are given periodic displacements. There are, for example, signatures left by the ionization of helium in the near-surface layers of solar-like stars. Measurement of these signatures allows tight constraints to be placed on the helium abundance, something that would not otherwise be possible in such cool stars (because the ionization temperatures are too high to yield usable photospheric lines for spectroscopy). There are also signatures left by the locations of convective boundaries. It is therefore possible to pinpoint the lower boundaries of convective envelopes in cool stars. These regions are believed to play a key rôle in stellar dynamos, and so this information is of great importance to stellar dynamo modelers.

The key to extracting the signatures in solar-type stars is to have sufficient precision in estimates of the mode frequencies. Multi-month datasets are required, and tests undertaken with artificial asteroseismic data (or real Sun-as-a-star helioseismic data) are essential for elucidating diagnostic limits under different data quality scenarios (e.g., see the tests undertaken by Basu et al. 2004; Ballet, Turck-Chièze & García 2004; and Verner, Elsworth & Chaplin 2006). Mazumdar & Michel (2010) report attempts to extract periodic signatures from CoRoT frequency data on the F-type solar-like star HD49933.

Frequencies of classical pulsations may be measured to much higher precision than their intrinsically damped, solar-like cousins. However, only recently has the first evidence been presented (by Degroote et al. 2010) for a periodic displacement of the m-mode frequencies of a classical pulsator (the B3V star HD50230). It was the almost unbroken sequence of multi-month observations made by the CoRoT spacecraft that provided the data quality necessary to uncover the signal in the g-mode periods. This signal is thought to be a signature (e.g., due to mixing) from the boundary of the convective core and radiative envelope.

When regions of abrupt structural change do not lie well within the mode cavities, the signatures they leave are more subtle. This is the case for the signatures left by small convective cores in solar-type stars slightly more massive than the Sun (Cunha & Metcalfe 2007). The measurement of the frequency dependence of prominent frequency separations of the low-degree modes provides a potential diagnostic of both the presence and size of a convective core (Brandão & Cunha, 2010). The mixing implied by the convective cores, and the possibility of mixing of fresh hydrogen fuel into the nuclear burning cores – courtesy of the regions of overshoot – affects the main-sequence lifetimes. Tests on artificial seismic data are essential to understand the prospects, and potential limitations, for inference on convective cores.

Finally, we touch on the diagnostic potential of avoided crossings (Osaki 1975; Aizenman et al. 1977) in solar-like stars. These avoided crossings are a tell-tale indicator that the stars have evolved significantly. In young solar-type stars there is a clear distinction between the frequency ranges that will support acoustic (pressure, or p) modes and buoyancy (gravity, or g) modes. As stars evolve, the maximum buoyancy (Brunt-Väisälä) frequency increases. After exhaustion of the central hydrogen, the buoyancy frequency in the deep stellar interior may increase to such an extent that it extends into the frequency range of the high-order acoustic modes. Interactions between acoustic modes and buoyancy modes may then lead to a series of avoided crossings, which affect (or “bump”) the frequencies and also change the intrinsic properties of the modes, with some tacking on mixed p and g characteristics.

Measurement of the these avoided crossings has the potential to provide exquisite constraints on the fundamental stellar properties. Very little data have been available historically. Observational evidence for avoided crossings had been uncovered in ground-based asteroseismic data on two bright stars, η Boo and β Hyi (Christensen-Dalsgaard et al. 1995; Kjeldsen et al. 1995; Bedding et al. 2007; Doğan et al. 2009). Deheuvels et al. (2009) have also recently reported evidence for avoided crossings in CoRoT observations of the G-type star HD49385, with Deheuvels & Michel (2009) using an elegant analysis on coupled oscillators to discuss
the results. Kepler now promises dramatic changes in this area, because within the large Kepler ensemble of solar-like oscillators there is a clear selection of stars showing avoided crossings. One of the three solar-like stars selected for the first Kepler paper on solar-like oscillators – KIC 11026764 – is a beautiful case in point, and has been the subject of further in-depth study (Metcalfe et al. 2010). The data provided by Kepler will by necessity drive developments in analysis to allow the diagnostic potential of avoided crossings to be fully exploited.

Acknowledgements. The author would like to thank the SOC and LOC of the HELAS IV conference for their kind invitation to present the summary of the meeting. He acknowledges financial support from both HELAS, and the UK Science Technology and Facilities Council (STFC), and thanks C. Constantinidou and B. A. Millett for useful advice concerning Greek naming.

References
Aizenman, M., Smeyers, P., Weigert, A., 1977, A&A, 58, 41 Appourchaux, T., Michel, E., Auvergne, M., et al., 2008, A&A, 488, 705 Ballot, J., Turk-Chièze S., García R. A., 2004, A&A, 423, 1061 Ballot, J., Lignières, F., Reese, D. R., Rieutord, M., 2010a, A&A, in the press Ballot, J., 2010b, AN, submitted (this volume) Barban, C., Deheuvels, S., Baudin, F., 2009, A&A, 506, 51 Basu S., Mazumdar A., Antia H. M., Demarque P., 2004, MNRAS, 350, 277 Basu, S., Broomhall, A.-M., Chaplin, W. J., Elsworth, Y., Fletcher, S. T., New, R., 2010, in: Proc. SOHO-23: Understanding a Peculiar Solar Minimum, eds. S. Crammer, T. Hoeksema & J. Kohl, ASPCS, in the press (arXiv1003.4262) Bedding, T. R., Kjeldsen, H., Arentoft, T., et al., 2007, ApJ, 663, 1315 Bedding, T. R., Huber, D., Stello, D., et al., 2010, ApJ, 713, L176 Bedding, T. R., Kjeldsen, H., 2010, CoAst, 161, 3 Benomar, O., Appourchaux, T., Baudin, F., 2009, A&A, 506, 15 Brandão, I. M., Cunha, M. S., 2010, AN, submitted (this volume) Broomhall, A.-M., Chaplin, W. J., Elsworth, Y., Fletcher, S. T., New, R., 2009, ApJ, 700, L162 Cameron, R., Gizon, L., Schunker, H., Pietarila, A., 2010, SolPhys, submittedCarrier, F., De Ridder, J., Baudin, F., et al., 2010, A&A, 509, 73 Chaplin, W. J., Appourchaux, T., Arentoft, T., et al., 2008, AN, 329, 461 Chaplin, W. J., Appourchaux, T., Elsworth, Y., et al., 2010, ApJ, 713, L169 Christensen-Dalsgaard, J., Bedding, T. R., Kjeldsen, H., 1995, ApJ, 443, L29 Christensen-Dalsgaard, J., Kjeldsen, H., Brown, T. M., et al., 2010, ApJ, 713, L164 Cunha, M. S., Metcalfe, T. S., 2007, ApJ, 666, 413 Degroote, P., Aerts, C., Baglin, A., et al., 2010, Nature, 464, 259 Deheuvels, S., Michel, E., 2009, Ap&SS, in the press (tmp.241) Deheuvels, S., Bruntt, H., Michel, E., et al., 2010, A&A, in the press De Ridder, J., Barban, C., Baudin, F., et al. 2009, Nature, 459, 398 Doğan, G., Brandão, I. M., Bedding, T. R., Christensen-Dalsgaard, J., Cunha, M. S., Kjeldsen, H., 2009, Ap&SS, in the press (tmp.251) Fletcher, S. T., Broomhall, A.-M., Salabert, D., Basu, S., Chaplin, W. J., Elsworth, García, R. A., New, R., 2010, ApJ, submitted García, R. A., Réguelo, C., Samadi, R., 2009, A&A, 506, 41 Gilliland, R. L., Brown, T. M., Christensen-Dalsgaard, J., et al., PASP, 2010, González-Hernández, I., Howe, R., Komm, R., Hill, F., 2010, ApJ, 713, L16 Grigahcène, A., Antoci, V., Balona, L., et al., 2010, ApJ, 713, L192 Grundahl, F., Christensen-Dalsgaard, J., Arentoft, T., Frandsen, S., Kjeldsen, H., Joergensen, U. G., Kjærgaard, P., 2009, CoAst, 158, 345 Hekker, S., Kallinger, T., Baudin, F., De Ridder, J., Barban, C., Carrier, F., Hatzes, A. P., Weiss, W. W., Baglin, A., 2009, A&A, 506, 465 Hekker, S., Debosscher, J., Huber, D., et al., 2010, ApJ, 713, L187 Houdek, G., Gough, D. O., 2007, MNRAS, 375, 861 Houk, R., Christensen-Dalsgaard, J., Hill, F., Komm, R., Schou, J., Thompson, M. J., 2009, ApJ, 701, L87 Kjeldsen, H., Bedding, T. R., Viskum, M., Frandsen, S. 1995, AJ, 109, 1313 Komm, R., Hill, F., 2009, JGR, 114, A06105 Komm, R., Howe, R., Hill, F., 2009, SolPhys, 258, 13 Mazumdar, A., Michel, E., 2010, AN, submitted (this volume) Metcalfe, T. S., Monteiro, M. J. P. F. G., Thompson, M. A., et al., 2010, ApJ, submitted Michel, E., Baglin, A., Auvergne, M., et al., 2008, Sci, 322, 558 Montalbán, J., Miglio, A., Noels, A., Scuflaire, R., Ventura, P., 2010, AN, in the press (this volume) Mosser, B., Michel, E., Appourchaux, T., 2009, A&A, 506, 33 Mosser, B., Belkacem, K., Goupil, M.-J., et al., 2010, A&A, in the press Osaki, Y., 1975, PASJ, 27, 237 Saesen, S., Pigulski, A., Carrier, F., et al., 2010, AN, submitted (this volume) (arXiv1004.2853) Salabert, D., García, R. A., Pallé, P., Jiménez-Reyes, S. J., 2009, A&A, 504, L1 Sheeley, N. J., 2010, in: Proc. SOHO-23: Understanding a Peculiar Solar Minimum, eds. S. Crammer, T. Hoeksema & J. Kohl, ASPCS, in the press (arXiv1005.3834v1) Schunker, H., 2010, AN, submitted (this volume) (arXiv1005.2626) Stello, D. S., Chaplin, W. J., Basu, S., Elsworth, Y., Bedding, T. R., 2009a, MNRAS, 400, L80 Stello, D., Chaplin, W., Bruntt, H., et al., 2009b, ApJ, 700, 1589 Stello, D., Basu, S., Bruntt, H., et al., 2010, ApJ, 713, L182 Tripathy, S. C., Jain, K., Hill, F., Leibacher, J. W., 2010, ApJ, 711, L84 Verner G. A., Chaplin W. J., Elsworth Y., 2006, ApJ, 638, 440