Precision Asteroseismology
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Concluding remarks

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Abstract. We cannot presume to summarize all of the science we've discussed in the talks, posters, and informal discussions. Here, we discuss a few of the themes that emerged, concentrating on the theoretical basis that Wojtek Dziembowski and his colleagues have developed and explored over the past 40+ years. We connect those with observational results – especially those from recent ground-based surveys and space-based missions that have revolutionized the study of stellar variability.

1. Introduction

This five-day science conference was organized around the themes that Wojtek Dziembowski has explored in his exceptional career in astrophysics. In reality, though, we could only briefly touch upon the enormous strides in those fields that have been enabled by his work. In parallel with theoretical developments made by Wojtek and his friends in the theoretical and computational stellar astrophysics community, the observers have produced data at an ever-increasing rate. We now face a fire-hose of data coming from space-based observatories (*Kepler*, *CoRoT*, and hopefully soon *Gaia* and *TESS*) that can provide, long, continuous high-precision photometry. Ground-based large-scale variability surveys such as OGLE (described nicely by Grzegorz Pietrzyński on Monday) add to this deluge of data, as do data products from planet search projects such as WASP (as we heard from Barry Smalley).

Over 60 talks and over 70 posters discussed many aspects of stellar pulsation and stellar variability across the H-R diagram. Summarizing all of this work in a few pages is neither possible nor useful – the presenters have provided some excellent write-ups of their work in the pages of this volume, and we encourage you to take some time and enjoy reading through them. In this short summary, we highlight a few themes that emerged that illustrate the influence that Wojtek has had on the field. We close with a way to "measure" our links to Wojtek's specific contributions in a quantitative way.

2. Pulsation physics

It is fair to say that Wojtek's main scientific interest is in essence a simple one: the physics of stellar pulsations, inspired by the observed properties of pulsating stars. Application of stellar pulsations to the physics of stars and their evolution (what we now call "asteroseismology" — see Gough 1996), while also of interest, comes second. He admitted as much during his talk on the second day of the conference. However, the understanding obtained from investigating the properties of stellar pulsation is central to asteroseismology. A very important example is the development of the asymptotic theory of stellar pulsations to which Wojtek has played such a key role, and which is central to the analysis of observed frequencies. Although the early basis was established by the Belgian group (e.g. Ledoux 1962; Smeyers 1968) and by Vandakurov *et al.* (1967), Wojtek was probably the first to apply the results to the understanding of the properties of real stars. An important example is Wojtek's work on the pulsations of evolved stars in 1971 (Dziembowski 1971). † Although the paper uses a Cepheid model as the primary example, it essentially provides the foundation for the very rich investigations of red giants made possible by observations by *CoRoT* and *Kepler* nearly 40 years later.

Large-scale numerical computations of stellar internal hydrodynamics are becoming increasingly powerful, and perhaps increasingly realistic, as a tool to understand the properties of stellar pulsations. The potential for direct computation of the interaction between pulsations and convection, discussed by Friedrich Kupka on Wednesday, is promising significant progress on this otherwise intractable problem. Similarly, the computations presented by Irina Kitiashvili, also on Wednesday, point the way to a direct investigation of stochastically excited modes in solar-like pulsators, including the effects of magnetic fields and hence addressing the issues of stellar activity discussed in Travis Metcalfe's talk.

A very different area of research, but a similar level of computational effort, is represented by the huge grids of stellar models that are being created for the interpretation of stellar-oscillation data to obtain the underlying stellar parameters. This direction was exemplified by the studies of pre-main-sequence stars presented on Tuesday by Konstanze Zwintz. However, such computations do not guarantee insight or understanding and should be complemented with simpler treatments which might provide such insight from the computations.

This point was made, quite elegantly, by Richard Townsend in his discussion of pulsations in rotating stars on Tuesday, with reference to the following quote from a related paper by F. Soufi, Marie-Jo Goupil, and Wojtek (Soufi *et al.* 1998):

> *"We feel perturbation theory calculations are still useful, because coding the formulae is in fact quite straightforward – far easier than deriving them. In contrats [sic], it is highly nontrivial to achieve a* 10^{-3} *precision in frequency calculations with a 2-D hydrocode, were one available. Undoubtedly, the use of such codes will ultimately be unavoidable, but then it will be very helpful to have a code based on the perturbational approach for comparisons at moderate equatorial velocities where both are valid."*

Townsend also introduced the very useful concept of "narrative" to describe, for a given problem, the complete and coherent story that contains both the detailed results and the broader understanding. It is obvious that Wojtek has contributed greatly to this narrative in the study of pulsating stars.

The conference featured interesting new developments in several areas of pulsation physics. The Blazhko effect in RR Lyrae stars is one of the most long-standing puzzles in the physics of stellar pulsations. *Kepler* observations of a substantial number of RR Lyrae stars showing this effect, including RR Lyrae itself, as illustrated by Katrien Kolenberg's talk on Thursday, have provided data of unprecedented precision and extent for the study of this phenomenon. As Robert Szabó showed in his talk earlier on Thursday, an unexpected feature is the prevalence of, at least intermittent, period doubling in these stars. Together with nonlinear modelling this points to resonances, remarkably including the 9:2 resonance between the fundamental radial mode and a 'strange' mode, as being

† One of the present authors was reminded that some of the calculations for that paper were carried out on a Danish-built GIER computer, of similar type to the one on which he started his computational efforts.

involved. With further analysis and hydrodynamical modelling we may soon get closer to an understanding of the Blazhko effect, revealing also an unexpected richness in the physical behaviour of pulsating stars.

The basic processes of mode excitation are reasonably well-understood. Amongst cool stars with convective envelopes, the dominant process is stochastic excitation, by convection, of otherwise stable modes, This includes the remarkably rich behaviour found in the red giants, extending to what Wojtek and his collaborators (Soszyński *et al.* 2007) have named the OSARGs (*O*GLE *S*mall *A*mplitude *R*ed *G*iants). The recently established link between the OSARGs and the most luminous *Kepler* red giants (Mosser *et al.* 2013) is extremely interesting in this regard. Also, the instability of modes caused by the heat-engine mechanism (the κ mechanism) can increasingly be understood in terms of opacity perturbations; for hotter stars the revision of the opacities from iron-group elements was crucial (e.g., Dziembowski & Pamyatnykh 1993). However, there are still problems in reproducing the modes observed in specific stars, as discussed by Wojtek in his talk (see also Dziembowski & Pamyatnykh 2008). On Thursday, Gilles Fontaine discussed the interesting example of the GW Vir variables, at the beginning of the white-dwarf cooling sequence, where the details of the observed modes can be understood as the effect on the instability of competition between mass loss and settling.

For stars whose oscillations are excited by a heat-engine mechanism the processes limiting the amplitudes, and hence selecting those modes that reach observable amplitudes, remain poorly understood. Wojtek and his group have made major contributions to the study of this problem, emphasizing the potential importance of resonant interactions between unstable and stable modes, going back to Dziembowski (1982). Radek Smolec † gave a comprehensive overview of these issues on Thursday. He also discussed the cases of multi-mode pulsators detected in large-scale surveys, in particular OGLE, and the difficulties in understanding and interpreting the space-based observations of δ Scuti stars. An important issue in the latter case is to distinguish between actual modes of the star and combination frequencies resulting from nonlinear interactions. The conclusion appears to be that the problem of understanding mode selection, despite the very rich space-based data revealing extremely small amplitude pulsations, is still not solved.

While a deep understanding of the physics of stellar pulsations is of great interest in itself, it is important to emphasize the crucial need for comparison with asteroseismic observations or other diagnostic tools. A superficially simple example that came during the conference was the so-called p factor that relates the apparent and true velocity amplitude, illustrated by Nicolas Nardetto in his Tuesday presentation. The empirically determined p factor is essential for the use of the Baade-Wesselink method for distance determination. Also, the increasingly sophisticated understanding of the asymptotic properties of stellar oscillations has been crucial for interpreting of the observations of solar-like oscillations (for a recent example, see Goupil *et al.* 2013), and faces new challenges in the detailed interpretation of mixed modes in red-clump stars where composition discontinuities in the core give rise to very complex oscillation spectra. It should also be noted that a better understanding of the mode selection in, e.g., δ Scuti stars, as discussed above, could greatly help the asteroseismic use of observations of these stars for determining the properties of individual stars.

† Radek is Wojtek's 'grand-student' – his Ph.D. advisor was Paweł Moskalik, whose thesis advisor was Wojtek.

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3. Precision in asteroseismology

The exquisite data from *CoRoT* and *Kepler* have been a major breakthrough for asteroseismology; photometry (though with less precision) of the huge number of stars observed with the OGLE project allows characterization of a very broad range of stellar variability, including rare types of pulsating stars. The challenge is to make full use of these outstanding data.

These challenges were addressed by Bill Chaplin on Monday, with particular emphasis on solar-like oscillations. The analysis of these data sets, with durations from months to years, requires correction of the raw photometry for discontinuous changes in level, and other irregularities resulting from instrumental and other non-stellar causes, e.g., with the changing orientation of the spacecraft from quarter to quarter for *Kepler*. With corrected data in hand, preliminary analysis in solar-like pulsators can be made in terms of the large frequency spacing and the frequency of maximum power, using apparently reliable scaling relations (Kjeldsen & Bedding 1995, 2011; Huber *et al.* 2011). However fully exploiting the data requires determination of the individual frequencies and, very importantly, a proper statistical characterization of the results. Reliable determination of the accuracy of the results is essential in the subsequent asteroseismic analysis.

Chris Engelbrecht, in his address on Tuesday morning, gave a comprehensive overview of the various analysis techniques that are available for frequency analyses of time-series data. An important part of the analysis, particularly for solar-like oscillations, is the determination of the non-oscillatory background, which in many cases is dominated by stellar effects (and hence in itself provides scientifically very interesting information). The individual steps in this analysis are relatively well understood, although the statistical properties of the observed frequencies, including possible correlations particularly for derived quantities such as frequency separations, are probably in general not adequately treated. This understanding has been applied to the analysis of individual stars, through considerable effort and time. A serious challenge will be to develop reliable automatic tools that can carry out the analysis at a similar level of reliability for thousands of stars, or indeed to determine how best to make scientific use of the results of such an analysis.

In the subsequent analysis of asteroseismic data the availability of reliable non-seismic characterization of the target stars is crucial (e.g., Uytterhoeven *et al.* 2010; Molenda-Żakowicz *et al.* 2013). This includes effective temperature, composition and, if possible, radius, obtained from photometry and spectroscopy. When available, interferometry provides vital constraints, and will be a powerful tool combined with determinations of distances which will be revolutionized by the *Gaia* mission. In the case of *Kepler* this is complicated by the fact that most stars observed are quite faint and hence require long observations to reach the spectral resolution needed for precise determination of stellar composition. The need for such data is becoming increasingly clear with the growing realization that the asteroseismic data, even at the precision offered by *Kepler*, in themselves are not sufficient fully to characterize the stars. This is particularly evident in a degeneracy in the results of fits to solar-like oscillation frequencies between the mass and initial helium abundance Y_0 of the star. Also, there seems to be a tendency that the fits in some cases prefer presumably unphysically low values of Y_0 (Mathur *et al.* 2012). Sufficiently precise non-seismic information may help break such degeneracies and remove the specter of unphysical results.

The asteroseismic inferences depend on making the best possible use of the data, ideally by devising diagnostics that provide information about global stellar properties or specific aspects of the stellar interior. For this purpose asymptotic analyses provide very valuable understanding of the oscillations and their dependence on stellar properties. As discussed by Sebastien Deheuvels in his talk on Monday afternoon, an important example for solar-like oscillations is the effect of acoustic glitches which have detectable signatures in the oscillation frequencies (e.g., Houdek & Gough 2007) and which are now being detected in data from *CoRoT* (Miglio *et al.* 2010; Mazumdar *et al.* 2012a) and *Kepler* (Mazumdar *et al.* 2012b). This may, for instance, provide an independent measure of the envelope helium abundance and hence help break the degeneracy between mass and initial helium abundance.

As we have struggled with for some time, δ Scuti stars present major problems for asteroseismic inferences with their very rich oscillation spectra and no clear systematics in the selection of the observed modes. As discussed by Katrien Uytterhoeven on Tuesday, additional observations that allow identification of at least some of the observed modes are very important. Not surprisingly, Wojtek's hand is present here, too, as the origin of these techniques, reflecting how the observational sensitivity to the modes depends on their degree, goes back to Dziembowski (1977) (see also Daszyńska-Daszkiewicz *et al.* 2005).

For other types of pulsating stars related procedures are available for asteroseismic inferences. A very interesting case are the subdwarf B stars, where fits to the observed frequencies provide very stringent constraints on the stars. In her talk on Thursday, Valerie Van Grootel (see also Van Grootel *et al.* 2013) discussed the case of acoustic modes in such a star and demonstrated a very high accuracy in the determination of the mass and radius of the star. The basis for the claim for accuracy, rather than only precision, was a careful analysis of the sensitivity of the results to uncertainties in the underlying stellar modelling. Such investigations, including potential numerical problems in the model and frequency computations, are indeed essential if we are to fulfill the full potential in precision asteroseismology. Another very interesting example is the analysis shown on Thursday by Noemi Giammichele of observations of a hydrogen-rich pulsating white dwarf. Based on five observed periods she was able to make a precise determination of several properties of the star, as characterized by, for example, mass, surface gravity and the thickness of the hydrogen and helium layers. In this case further investigations of the sensitivity to the model assumptions would probably be warranted.

4. Conclusion: the Dziembowski Number

Wojtek Dziembowski has been a steady influence on (now) generations of astrophysicists from Poland and many, many other nations throughout the world. His impact on stellar pulsation theory, and more generally on stellar astrophysics, has spanned over five decades. In that time, he has published many influential papers, and many astronomers have been honoured to collaborate with him and are proud to call themselves coauthors.

How can one quantify this reach of a single investigator's collaborations? Mathematicians have addressed this issue in at least one case – to recognize the extremely collaborative Paul Erdös (Goffman 1969), who published over 1500 papers in his career. The 'Erdös Number' was introduced to measure how closely one's coauthorship comes to a publication directly with Erdös: those who have published with Erdös directly have an Erdös number of 1; 511 scholars have an Erdös number of 1. Someone who has not published with Erdös but has published with someone who did coauthor a paper with Erdös earns an Erdös number of 2, and so on. Erdös himself has (had...) an Erdös number of 0. Currently, 9779 scholars have an Erdös number of 2. Interestingly, Wojtek has an Erdös number of 5, but his son, Stefan Dziembowski, has a 'better' Erdös number of 3 through his computer science collaboration with Ivan Damgård † (Cramer *et al.* 1999).

† Damgård (2) published with Pomerance (1) who published with Erdös (0).

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So, what is your Dziembowski number? To date, Wojtek has published papers with 161 direct collaborators. If you are one of us, then you have a Dziembowski number of 1. If your Dziembowski number is greater than 1, then you should seek him out, and write a paper with him. But beyond improving your Dziembowski number, you will have the chance to experience the pure joy of collaborating directly with Wojtek, and seeing how much fun stellar pulsation physics can be in the process.

Acknowledgements

We take this opportunity to thank Wojtek for his huge contributions to our field, for his enthusiasm and inspiration and for his friendship over very many years. We are very grateful to Jagoda and Andrzej for organizing an extremely interesting and productive conference, and for giving us the pleasure and honour of providing the closing remarks. Funding for the Stellar Astrophysics Centre is provided by The Danish National Research Foundation (Grant DNRF106). The research is supported by the ASTERISK project (ASTERoseismic Investigations with SONG and *Kepler*) funded by the European Research Council (Grant agreement no.: 267864).

References

Cramer, R., Damgård, I., Dziembowski, S., Hirt, M., & Rabin, T. 1999, *Lecture Notes in Comput. Sci.*, 1592, 311

Daszyńska-Daszkiewicz, J., Dziembowski, W. A., Pamyatnykh, A. A., Breger, M., Zima, W., & Houdek, G. 2005, *A&A*, 438, 653

Dziembowski, W. 1971, *AcA*, 21, 289

Dziembowski, W. A. 1977, *AcA*, 27, 203

Dziembowski, W. 1982, *AcA*, 32, 147

Dziembowski, W. A. & Pamyatnykh, A. A. 1993, *MNRAS*, 262, 204

Dziembowski, W. A. & Pamyatnykh, A. A. 2008, *MNRAS*, 385, 2061

Goffman, C. 1969, *American Mathematical Monthly*, 76, 791

Gough, D. O. 1996, *Observatory*, 116, 313

Goupil, M. J., Mosser, B., Marques, J. P., *et al.* 2013, *A&A*, 549, A75

Houdek, G. & Gough, D. O. 2007, *MNRAS*, 375, 861

Huber, D., Bedding, T. R., Stello, D., *et al.* 2011, *ApJ*, 743, 143

Kjeldsen, H. & Bedding, T. R. 1995, *A&A*, 293, 87

Kjeldsen, H. & Bedding, T. R. 2011, *A&A*, 529, L8

Ledoux, P. 1962, *Bull. Acad. roy. Belg. Cl. Science, 5e série*, 48, 240

Mathur, S., Metcalfe, T. S., Woitaszek, M., *et al.* 2012, *ApJ*, 749, 152

Mazumdar, A., Michel, E., Antia, H. M., & Deheuvels, S. 2012a, *A&A*, 540, A31

Mazumdar, A., Monteiro, M. J. P. F. G., Ballot, J., *et al.* 2012b, *AN*, 333, 1040

Miglio, A., Montalbán, J., Carrier, F., *et al.* 2010, *A&A*, 520, L6

Molenda-Żakowicz, J., Sousa, S. G., Frasca, A., *et al.* 2013, *MNRAS*, 434, 1422

Mosser, B., Dziembowski, W. A., Belkacem, K., *et al.* 2013, *A&A*, 559, 137

Smeyers, P. 1968, *Ann. d'Astrophys.*, 31, 159

Soszyński, I., Dziembowski, W. A., Udalski, A., *et al.* 2007, *AcA*, 57, 201

Soufi, F., Goupil, M. J., & Dziembowski, W. A. 1998, *A&A*, 334, 911

Uytterhoeven, K., Briquet, M., Bruntt, H., *et al.*, 2010, *AN*, 331, 993

Vandakurov, Yu. V. 1967, *Astron. Zh.*, 44, 786 (English translation: *Soviet Astron. AJ*, 11, 630)

Van Grootel, V., Charpinet, S., Brassard, P., Fontaine, G., & Green, E. M. 2013, *A&A*, 553, A97

PHOTOS FROM THE CONFERENCE

(taken by Alosha Pamyatnykh)

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Focusing on pulsation-convection interaction (or an LOC announcement).
[All figures courtesy of Alexey A. Pamyatnykh]

Phil Goode explaining how much fun it is to work with Wojtek.

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Paweł Moskalik demonstrating to Wojtek how easy seismology is.

Marie-Jo Goupil asking a difficult question.

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Wojtek answering an even more difficult question.

Gérard Vauclair's comment attracts enormous attention.

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Hideyuki Saio looking for a laser pointer speckle.


A happy Mike Jerzykiewicz.

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Wojtek providing one of his many insightful remarks.

Steve Kawaler introducing the Dziembowski Number.

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