

CURRENT STATUS OF ASTEROSEISMOLOGY

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ABSTRACT

Oscillation frequencies are the most accurate properties one can measure for a star, potentially allowing detailed tests of stellar models and evolution theories. We briefly review asteroseismology for two classes of stars. In δ Scuti variables, the main problems are the identification of the observed modes and the theoretical treatment of rotation. In solar-like stars the main difficulty is the tiny amplitudes, but credible detections are now being made. These confirm that stars are oscillating at the approximately the expected levels, but suggest that amplitudes scale as $1/g$ rather than L/M . We also stress the importance of multi-site campaigns. Several space missions will be launched over the coming years, promising an exciting future for asteroseismology.

Key words: asteroseismology; δ Scuti stars; solar-like oscillations.

1. WHY IS ASTEROSEISMOLOGY SO FAR BEHIND HELIOSEISMOLOGY?

Asteroseismology involves an interplay between observations of stellar oscillations and theoretical model calculations. It can be done when a set of oscillation frequencies is known for a given star and, at the same time, a set of theoretical model frequencies can be calculated. The motivation for doing asteroseismology is that oscillation frequencies are the most accurate properties one can measure for a star and we may therefore, at least in principle, be able to perform a detailed test of stellar modelling and evolution theories.

This potentially very promising tool has motivated a huge observational effort with the aim of obtaining accurate oscillation frequencies. At the same time, a substantial amount of work has been put into improvements of stellar modelling with the goal of being able to fit model frequencies to the observed oscillation frequencies.

In helioseismology, as can be seen from the papers presented in these proceedings, most current work concentrates on the details. We are already able to measure accurately many important properties of the solar interior.

Unlike asteroseismology, helioseismology is founded on an immense amount of high-quality data supported by an equally detailed set of state-of-the-art models.

It is impossible to imagine that asteroseismology will ever reach a level similar to that in which we find helioseismology today, concerning analysis techniques, data quality and the level of the results. The reasons for this lie in the main differences between the two subjects:

- Asteroseismology works on distant stars whose basic properties will always be less well determined than those of the Sun. These include age, composition, radius, mass, atmospheric properties and neutrino flux. The uncertainties will affect the quality of the calculated stellar models. One example is age, which is known for the Sun from radioactive dating of the solar system. To illustrate the importance of this parameter for the current solar model, consider the following simple question: What age would we determine for a solar model – based on the observed properties of the Sun – if we did not already know the age of the solar system?
- The surfaces of stars are essentially unresolved, which limits asteroseismology to modes of low degree. Much of what we have learned about the Sun is based on high degree modes.
- The Sun is a relatively simple system. This makes it very interesting, since we may have a chance to understand it! Many stars seem to be much more complicated. Hopefully we will find some important physical properties that are not known at present, which may turn out to be important for understanding the details of those stars.
- There is only one Sun, while there are billions of other stars. Many people work on the details in helioseismology, but we can't expect several billion astronomers to be working in asteroseismology!
- In helioseismology we see some big networks and dedicated telescopes (GONG, IRIS, BiSON), and we have many years of space research (SOHO, SolarMAX, IPHIR). In asteroseismology we find many smaller campaigns and networks, but very few dedicated telescopes. The space projects are just beginning. So far, there is a tremendous lack of high-quality data.

- Asteroseismology works on fainter stars and so has lower sensitivity than helioseismic observations. One will therefore generally be restricted to oscillations with relatively high amplitudes.

To explain why asteroseismology is so far behind helioseismology, we could identify three important elements from the above list:

- The imprecision of basic stellar properties.
- The complication of the stellar physics.
- The lack of high-quality oscillation data.

2. A REVIEW OF ASTEROSEISMOLOGY

In this review we will discuss what has been learned and finish by evaluating what we can hope to do in the next 10 years. When trying to review such a huge scientific field, there is always the risk of being remembered for the areas we did not discuss. So let us begin by saying what we do not intend to review. The application to white dwarfs is probably the biggest success of asteroseismology (see, e.g., Vauclair, 1997; Kawaler, 1998), but we do not intend to mention any techniques and results from this field. The same is true for a number of classical pulsating stars, such as β Cephei stars and roAp stars, which will not be discussed in this review. On seismology of giants and subgiants we refer to a paper by Guenther in these Proceedings.

We will discuss two areas of asteroseismology:

- Oscillations in δ Scuti stars, which are pulsating A and F stars found on the main sequence or in the subgiant phase of their evolution, inside the classical instability strip. They have masses between 1.5 and 2.5 solar masses.
- Solar-like oscillations, which are conventionally defined as those excited stochastically by turbulent convection (e.g., Houdek et al., 1999). These are expected in all stars on the cool side of the δ Scuti instability strip, since it is these stars which have significant convection in their outer regions.

It is hoped that asteroseismology on these two classes of stars should answer a number of central questions related to stellar structure and evolution:

- Where, exactly, is the border between stars with and without a convective core? We believe it to be at a mass just slightly higher than the solar (around $1.1 M_{\odot}$).
- Stellar modelling suggest that stars on the main sequence can be divided into non-evolved stars that contain fusion in the core of the star and evolved subgiant stars that contain a fusion zone in a shell around the core. We expect to be able to locate the exact boarder between star having core and shell hydrogen fusion.

- In general we of course expect to test details of the models and also be able to test a number of special features such as mixing, diffusion, magnetic fields and rotation.

- Finally, one may hope to be able to measure stellar ages.

3. δ SCUTI STARS

Asteroseismology of δ Scuti stars has been reviewed several times (Matthews, 1993; Däppen, 1993; Handler, 2000) and there have also been workshops dedicated to these objects (Breger & Montgomery, 2000). The number of detected and accurately known frequencies is very large, but these are only useful if one is able to calculate an equally accurate model frequency, which can only be done if the mode has been identified. Mode identification has been one of the major obstacles to producing reliable seismic results on δ Scuti stars. A related problem is the fact that only a small fraction of the possible oscillation modes seem to be excited to a detectable level in a typical δ Scuti star. Several techniques to overcome the mode identification problem have been tried. One should in this respect be careful about assumptions (in some cases even prejudice) that are used to eliminate the mode identification problem. However probably only a fully open-minded attitude will move us towards a solution to this serious problem.

3.1. Fitting frequencies without knowing the identity of the modes

A way through this has been to calculate a huge set of models without assuming any identity for any of the observed modes, and then by a simple χ^2 calculation, locate the optimised solution. This approach have been used by Pamyatnykh et al. (1998) for the δ Scuti star XX Pyxidis. Based on frequencies for 13 oscillation modes in XX Pyx, they constructed 40 000 sets of model frequencies based on stellar evolution calculations that included rotation. In the search for the best input model and the optimised mode identification, Pamyatnykh et al. were able to locate 8 local minima in χ^2 space corresponding to 8 quite different solutions. Although they identified these as reasonable solutions, it is also clear than none of the 40 000 sets of models frequencies was able to reproduce exactly the observed frequencies. The reason is probably that the physics in the models does not describe the real properties of the star. It therefore seems clear that mode identification is needed before one can move forward in constructing seismic models of δ Scuti stars.

3.2. Mode identification in FG Vir

A new technique for mode identification was introduced by Viskum et al. (1998), based on oscillation amplitudes measured via changes in the equivalent widths of hydrogen and metal absorption lines. They applied this technique to the δ Scuti star FG Vir and were able to assign

l values to the eight strongest oscillation modes. Two modes turned out to be radial, allowing a match to theoretical models and hence precise determination of mean density, luminosity, mass and distance (the latter of which agreed very well with the Hipparcos parallax). Work by Breger et al. (1999) on FG Vir agrees quite well with that of Viskum et al.. Breger et al. fitted all known 24 oscillation frequencies in FG Vir to detailed models using the mode identity of the 8 strongest modes. Even when they included convective overshoot and modified opacities, they were not able to match all observed frequencies. They identified a number of very good fits, but none was perfect. The reason is probably the treatment of rotation in the models.

3.3. Rotation in δ Scuti stars

Rotation has a very strong effect on the observed frequency spectrum. Templeton et al. (2000) illustrated this nicely using model calculations on a number of models representing the δ Scuti star θ Tucanae. Based on 10 observed frequencies, they attempted to calculate the rotationally split frequencies assuming uniform rotation. They concluded that although one is able to match the observed frequencies when rotationally split frequencies are included in the models, one can actually find several solutions if the rotational velocity is kept free in the analysis.

It is important to note that rotation not only affects the frequencies, but also the basic stellar properties. This has been studied for stars in the Praesepe cluster by Michel et al. (1999), who were able to correct for the rotational effect on the measured temperature and luminosity. They created a complete seismic picture of all known δ Scuti stars in the Praesepe star cluster, most of which were observed by the STEPHI network (e.g., Hernández et al., 1998). Although Michel et al. were able to correct for rotation and, to some extent, limit the number of free parameters by a kind of differential seismology between oscillating stars in the cluster, they could not reach a satisfactory fit between the models and the observed frequencies.

It is well known in the field of δ Scuti seismology that the stellar rotation is probably the main problem. Rotation affects the models (both the stellar evolution and via frequency perturbations), implying that we only calculate accurate theoretical frequencies if we are able to describe the internal (differential!) rotation of the star. As pointed out above, rotation also affects the stellar parameters, so once again we can only calculate accurate values for temperature and luminosity if we know the rotation (and the shape) of the star. Without this knowledge, we have enough freedom to reach a reasonable fit to any combination of observed frequencies. However, even this freedom is not enough in most cases to reach a perfect fit, which may be one of the most interesting conclusions we can draw at present: the theoretical models do not describe δ Scuti stars accurately enough to fit the observed oscillation frequencies.

4. SOLAR-LIKE OSCILLATIONS

Observers have worked hard in the last decade on searching for solar-like oscillations in other stars. Reviews of those efforts have been given by Brown & Gilliland (1994), Kjeldsen & Bedding (1995), Heasley et al. (1996) and Bedding & Kjeldsen (1998). The problems which limit the usefulness of δ Scuti oscillation frequencies do not apply to the solar-like case. For one thing, most solar-type stars are slow rotators. Also, in the Sun we find that all possible modes within a broad frequency range are excited. The frequencies form a fairly regular series which is well approximated by the so-called asymptotic relation. It is generally assumed that the same will apply to other solar-like oscillations, which means that mode identification will not be a problem.

The single most important problem with solar-like oscillations lies in their extremely small amplitudes. Detection therefore requires extremely sophisticated techniques. Such techniques are now available via high-precision Doppler measurements, but a drawback is the difficulty in arranging multi-site observations that are crucial to obtaining a decent window function.

4.1. Recent observational results

We may define four different levels of detections in relation to solar-like oscillations:

1. No detection.
2. Detection of excess power.
3. Detection of average frequency separations ($\Delta\nu$ and $\delta\nu_{02}$) by fitting to the asymptotic relation.
4. Detection of individual frequencies (including mode identifications, departures from the asymptotic relation, rotational splitting, etc.).

Many unsuccessful attempts have been made during the last decade, all of which must be placed at the first level. Five years ago, a review by Kjeldsen & Bedding (1995) concluded there was little evidence for any published data to be placed at any level higher than the first. Such a conclusion cannot be maintained today! A number of observing campaigns have now produced significant evidence for oscillations:

η Boo Kjeldsen et al. (1995) detected excess power in this G0 subgiant from measurements of Balmer-line equivalent widths. The excess was at the expected level, and these authors were able to extract frequency separations and individual frequencies which agreed well with theoretical models (Christensen-Dalsgaard et al., 1995; Guenther & Demarque, 1996). A more detailed discussion of theoretical models for η Boo can be found by Di Mauro & Christensen-Dalsgaard (these Proceedings). We should note, however, that a search for velocity oscillations in this star by Brown et al. (1997)

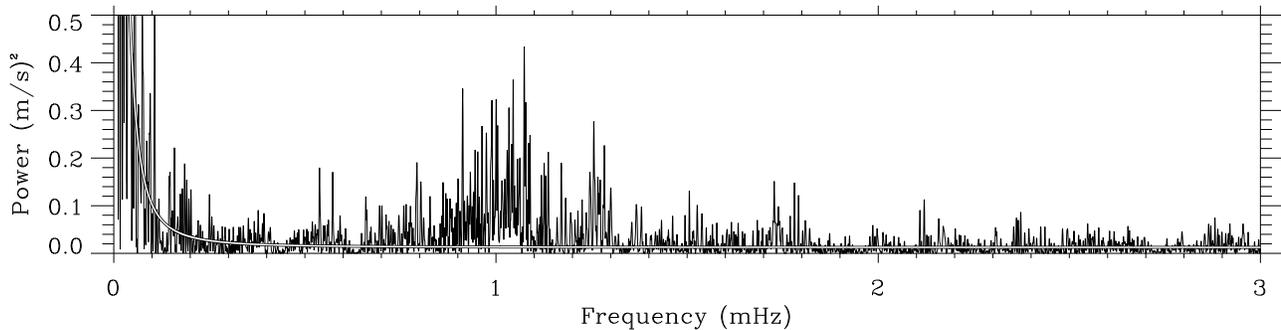


Figure 1. Power spectrum of AAT velocity measurements of β Hydri. There is a clear excess of power around 1 mHz which is a striking signature of solar-like oscillations (from Bedding et al., 2000).

failed to detect a signal, setting limits at a level below that expected on the basis of the Kjeldsen et al. result.

Procyon Velocity data for Procyon (F5 subgiant) have recently provided good evidence for oscillations (Barban et al., 1999; Martić et al., 1999) with a clear power excess around 1 mHz and peak mode amplitudes of about 0.5 m s^{-1} . The large frequency separation ($\Delta\nu = 56 \mu\text{Hz}$) seems to agree with expectations, but the single-site window function complicates the interpretation. These results indicate that the power excess seen earlier by Brown et al. (1991) — which implied similar peak amplitudes — may have been real, although the inferred $\Delta\nu$ of $71 \mu\text{Hz}$ does not agree with the more recent result.

ζ Herculis Martić et al. showed evidence at this conference for p-mode power in this G0 subgiant. A comb-response analysis apparently shows a large separation of $43.1 \mu\text{Hz}$. Based on their echelle diagram, one may even extract a value for the small separation of $\delta\nu_{02} = 3 \mu\text{Hz}$. Again, the single-site window function is problematic.

α Cen A Kjeldsen et al. (1999) measured Balmer-line equivalent widths in α Cen A with two telescopes over six nights and set an upper limit on oscillation amplitudes of only 1.4 times solar, with tentative evidence for p-mode structure. Photometry from the WIRE satellite by Schou and Buzasi (these Proceedings) appears to confirm oscillations at approximately this level.

β Hyi Bedding et al. (2000) have made what seems to be the best example of a detection of solar-like oscillations in another star. Their power spectrum of the G2 subgiant β Hydri can be seen in Fig. 1. The star was observed in velocity over five nights with the UCLES echelle spectrograph on the 3.9-m Anglo-Australian Telescope (AAT), using an iodine cell as the wavelength reference. The power excess is at the expected level and a fit to the asymptotic relation results in a large separation of $56.2 \mu\text{Hz}$. The oscillation frequencies seem to depart significantly from the asymptotic relation, but again there are big problems from the single-site window function.

Given that oscillations are now being reliably detected, it seems clear to us that the usefulness of single-site obser-

vations is severely limited. One may even say that further observations with single telescopes would be a waste of telescope time. The time has come to organise campaigns with two or more telescopes, and perhaps to think about a dedicated network.

4.2. Amplitudes of solar-like oscillations

Solar-like oscillations are excited by convection and the expected amplitudes have been estimated using theoretical models. Based on models by Christensen-Dalsgaard & Frandsen (1983), Kjeldsen & Bedding (1995) suggested that amplitudes in velocity should scale as L/M , where L and M are the stellar luminosity and mass in solar units. More recent calculations by Houdek et al. (1999) confirm this scaling relation, at least for stars with near-solar effective temperatures. However, it was pointed out by Kjeldsen & Bedding (1995) that the L/M relation predicted amplitudes for some F-type stars, namely Procyon and several members of the cluster M67, that were greater than observational upper limits. Despite this, the L/M relation has been quite widely adopted.

In order to resolve the problem for the hotter stars, we suggest a revised scaling relation. Noting that L/M is equal to T_{eff}^4/g (with all quantities in solar units), we propose a modified relation in which velocity amplitudes scale as $1/g$. Given the growing number of credible detections, we are now able to check these relations. Note that, although a single-site window function makes it difficult to extract frequencies, the estimates of oscillation amplitudes are not so badly affected.

Figure 2 shows the observed versus expected velocity amplitudes for the stars mentioned above, using both scaling relations. The upper limits in the figure are from photometric observations of stars in the open cluster M67 (Gilliland et al., 1993; Kjeldsen & Bedding, 1995). Those results, as well as observations in equivalent width (η Boo and α Cen A), have been converted to velocity amplitudes using the relations given by Kjeldsen & Bedding (1995).

For the G-type stars (η Boo, α Cen A, β Hyi, ζ Her) there is, of course, little difference between the two scaling relations. The agreement with observations is generally good. More data are clearly needed, but it is comforting to see that these stars do indeed appear to be oscillating

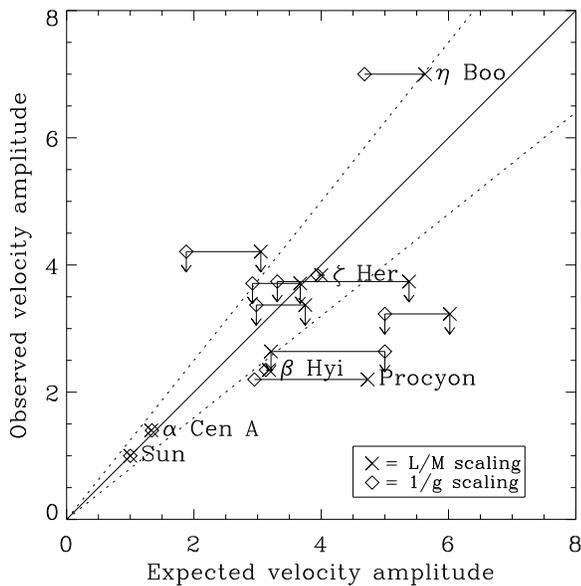


Figure 2. Observed amplitudes for solar-like oscillations compared with predictions based on the L/M and $1/g$ scaling relations. All amplitudes are relative to solar. The upper limits are for stars in the cluster M67. The diagonal line shows equality, with the dotted lines showing $\pm 25\%$.

at the expected levels. Turning to F-type stars, we see that the $1/g$ relation gives a much better prediction for the amplitude of Procyon, and also relaxes the problematic upper limits for the stars in M67. Again, more data are needed, but in the mean time we suggest using $1/g$ rather than L/M to predict oscillations amplitudes.

5. SPACE MISSIONS

The recent progress in ground-based observations, as well as results from the 52 mm star tracker on the otherwise-failed WIRE satellite (Buzasi et al., 2000, and these Proceedings), illustrate the potential of upcoming space missions:

MOST A Canadian project (Matthews et al., 2000).

MONS A Danish-led project with contributions from Australia and other countries (Kjeldsen, Bedding, & Christensen-Dalsgaard, 2000).

COROT A French/European project (Baglin et al., 1998).

Eddington A proposed ESA Flexi-mission, which has been selected as a reserve mission.

The future of asteroseismology is in space. One can perform wide-band photometry with high accuracy because of the absence of scintillation (fluctuations in the stellar light caused by the Earth's atmosphere). Even a small space-based telescope will do much better than even the largest ground-based telescopes. The other major improvement from moving to space is an excellent window function that is unaffected by weather. In space one can

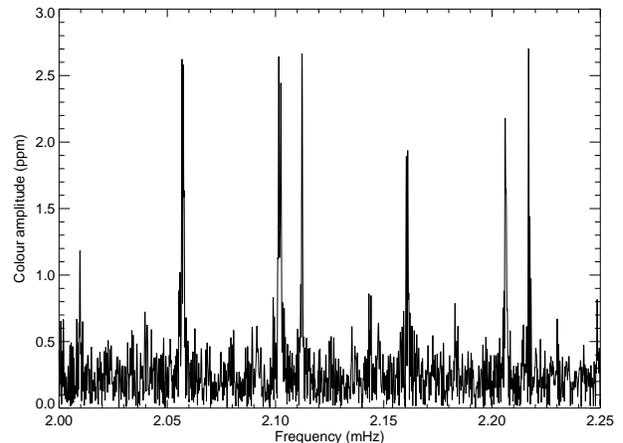


Figure 3. Simulated power spectrum for α Cen A, as expected from the MONS space mission.

reach duty cycles of 80–90%, which will result in very low side-lobes. As an example, we show in Fig. 3 a simulated data set for α Cen A as observed by MONS.

6. CONCLUSIONS

In this review we have described the current status of asteroseismology for A, F and G subgiants and main sequence stars. The main conclusions are as follows:

- Asteroseismology is far from helioseismology in terms of techniques and results.
- There are plenty of challenges for theoreticians, such as mixing, fluid motions, turbulent convection and deviations from spherical symmetry. The most important area to focus on is rotation.
- Asteroseismology is observationally driven. Ground-based velocity observations are now achieving believable detections, and it is time for multi-site campaigns. A large ground-based network is very desirable.
- A number of exciting space missions are in various stages of planning and construction (MOST, COROT, MONS and Eddington). If these succeed, it seems likely that asteroseismology will enter a golden age.

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REFERENCES

- Baglin A., et al., 1998, In: Deubner F.L., Christensen-Dalsgaard J., Kurtz D.W. (eds.) Proc. IAU Symp. 185, New Eyes to See Inside the Sun and Stars, 301, Dordrecht: Kluwer, see also <http://www.astrsp-mrs.fr/projets/corot/>
- Barban C., Michel E., Martic M., et al., 1999, A&A, 350, 617
- Bedding T.R., Kjeldsen H., 1998, In: Donahue R.A., Bookbinder J.A. (eds.) Tenth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, vol. 154 of A.S.P. Conf. Ser., 301, San Francisco: ASP
- Bedding T.R., Butler R.P., Kjeldsen H., et al., 2000, Astrophys. J., Lett., submitted
- Breger M., Montgomery M. (eds.), 2000, Sixth Vienna Workshop in Astrophysics: Delta Scuti and Related Stars, vol. 210, ASP Conf. Ser.
- Breger M., Pamyatnykh A.A., Pikall H., Garrido R., 1999, A&A, 151
- Brown T.M., Gilliland R.L., 1994, ARA&A, 33, 37
- Brown T.M., Gilliland R.L., Noyes R.W., Ramsey L.W., 1991, ApJ, 368, 599
- Brown T.M., Kinnally E.J., Korzennik S.G., et al., 1997, ApJ, 475, 322
- Buzasi D.L., Catanzarite J., Laher R., et al., 2000, ApJ, 532, L133
- Christensen-Dalsgaard J., Frandsen S., 1983, Sol. Phys., 82, 469
- Christensen-Dalsgaard J., Bedding T.R., Kjeldsen H., 1995, ApJ, 443, L29
- Däppen W., 1993, In: Brown T.M. (ed.) GONG 1992: Seismic Investigation of the Sun and Stars, vol. 42 of A.S.P. Conf. Ser., 317, Utah: Brigham Young
- Gilliland R.L., Brown T.M., Kjeldsen H., et al., 1993, AJ, 106, 2441
- Guenther D.B., Demarque P., 1996, ApJ, 456, 798
- Handler G., 2000, In: Szabados L., Kurtz D. (eds.) IAU Colloquium 176: The Impact of Large-Scale Surveys on Pulsating Star Research, vol. 203, 408, ASP Conf. Ser.
- Heasley J.N., Janes K., Labonte B., et al., 1996, PASP, 108, 385
- Hernández M.M., Michel E., Belmonte J.A., et al., 1998, aa, 337, 198
- Houdek G., Balmforth N.J., Christensen-Dalsgaard J., Gough D.O., 1999, A&A, 351, 582
- Kawaler S., 1998, In: Deubner F.L., Christensen-Dalsgaard J., Kurtz D.W. (eds.) Proc. IAU Symp. 185, New Eyes to See Inside the Sun and Stars, 261, Dordrecht: Kluwer
- Kjeldsen H., Bedding T.R., 1995, A&A, 293, 87
- Kjeldsen H., Bedding T.R., Viskum M., Frandsen S., 1995, AJ, 109, 1313
- Kjeldsen H., Bedding T.R., Frandsen S., Dall T.H., 1999, MNRAS, 303, 579
- Kjeldsen H., Bedding T.R., Christensen-Dalsgaard J., 2000, In: Szabados L., Kurtz D. (eds.) IAU Colloquium 176: The Impact of Large-Scale Surveys on Pulsating Star Research, vol. 203, 73, ASP Conf. Ser., see also <http://astro.ifa.au.dk/MONS>
- Martic M., Schmitt J., Lebrun J.C., et al., 1999, A&A, 351, 993
- Matthews J.M., 1993, In: Brown T.M. (ed.) GONG 1992: Seismic Investigation of the Sun and Stars, vol. 42 of A.S.P. Conf. Ser., 303, Utah: Brigham Young
- Matthews J.M., Kuschnig R., Walker G.A.H., et al., 2000, In: Szabados L., Kurtz D. (eds.) IAU Colloquium 176: The Impact of Large-Scale Surveys on Pulsating Star Research, vol. 203, 74, ASP Conf. Ser., see also <http://www.astro.ubc.ca/MOST>
- Michel E., Hernández M.M., Houdek G., et al., 1999, A&A, 342, 153
- Pamyatnykh A.A., Dziembowski W.A., Handler G., Pikall H., 1998, A&A, 333, 141
- Templeton M.R., Bradley P.A., Guzik J.A., 2000, ApJ, 528, 979
- Vauclair C., 1997, In: Provost J., Schmider F.X. (eds.) Proc. IAU Symp. 181, Sounding Solar and Stellar Interiors, 367, Dordrecht: Kluwer
- Viskum M., Kjeldsen H., Bedding T.R., et al., 1998, A&A, 335, 549