The History of g-mode Quest

T. Appourchaux¹ and P. L. Pallé²,³

¹Institut d’Astrophysique Spatiale, UMR8617, Université Paris-Sud, Bâtiment 121, 91405 Orsay Cedex, France
²Instituto de Astrofísica de Canarias, La Laguna, Tenerife, E-38205 Spain
³Departamento de Astrofísica, Universidad de La Laguna, La Laguna, Tenerife, E-38206 Spain

Abstract. The quest for the solar gravity modes (or g modes) is key for the understanding of the structure and dynamics of the solar core. We review the history of the solar g-mode searches which is separated in three nearly distinct eras which correspond to: the theory of g modes, the search from the ground and the search from space. The prospects of definitive solar g-mode detection are also discussed.

1. Introduction

Since the discovery of solar oscillations by Leighton et al. (1962), the interest in measuring the associated solar pressure modes (p modes) and gravity modes (g modes) has been waning. While the p modes provide extensive information on the structure and dynamics of the convection and radiative zones, the g modes promise access to the structure of the solar core. Whereas the first detection of the global p modes was achieved by Claverie et al. (1979), the first unambiguous detection of the g modes remains to be achieved. The goal of this paper is to review the history of g-mode detection.

In the first section, we will review the theory of the g modes (frequency, amplitude, lifetime). In the second section, we will review the first ground-based attempts at detecting the g modes, while the last section will review the space-based attempts. Each section has been bravely named after Isaac Asimov’s Foundation trilogy.

2. Foundation

“It is the chief characteristic of the religion of science that it works...”
Isaac Asimov, in Foundation (1942)

For a complete review of the theory of solar oscillations, the reader may refer to Appourchaux et al. (2010) and references therein. The solar oscillations have two restoring forces, compressibility and buoyancy, characterized respectively by the sound speed c and the buoyancy (Brunt – Väisälä) frequency N. The oscillation frequency of the gravity modes modes (g modes) is smaller than the Brunt – Väisälä frequency. As a result the amplitude of the eigenfunction of the g modes is large in the radiative zone and core of the Sun (where N is not negligible), whereas the eigenfunction is large in its convective zone for the p modes (See Figure 1).
Figure 1. Kinetic energy density as function of the radius for modes \( g_3, g_2, g_1, p_1, p_2 \) and \( p_3 \) of degree \( l=1 \) for a reference solar model. (From Provost et al. 2000, reproduced with permission © ESO).

Figure 2 plots the normalised kinetic energy of the modes, which is proportional to the mode inertia, as a function of frequency. Under the assumption of equipartition of the energy in the modes, the surface amplitudes would be approximately inversely proportional to the square root of the mode energy (e.g. Berthomieu & Provost 1990). For \( g \) modes with frequencies less than 200 \( \mu \)Hz, the lower the degree, the smaller is the energy, and the higher is the surface amplitude. Around 280 \( \mu \)Hz, modes of mixed character have smaller energies and therefore higher surface amplitudes than modes adjacent in frequency. Note the transition from \( p \) to \( g \) modes around 450 \( \mu \)Hz, and the existence of a set of modes of mixed character around 280 \( \mu \)Hz, having lower energies than modes in the neighbouring frequency regions. These latter modes, known as mixed modes, have a significant amplitude in both the interior of the Sun and in the convective zone. These mixed modes are extremely interesting since their potential for detection is larger (they can be excited by convection) and their diagnostic potential is as good as for the proper \( g \) modes. The detection of these mixed modes in other stars has led to great advances in the knowledge of the internal dynamics of these stars (Deheuvels et al. 2012).

Low-degree \( g \) modes with frequencies less than \( \nu_{n,l} \leq 200 \mu \)Hz may be described by an asymptotic relation (Vandakurov 1968; Tassoul 1980; Olver 1956). For small frequency, the second-order asymptotic expression for the period \( P_{n,l} (P_{n,l} = 1/\nu_{n,l}) \) can be represented by

\[
P_{n,l} \sim \overline{P}_{n,l} = \frac{P_0}{L} \left( n + \frac{l}{2} - \frac{1}{4} + \vartheta \right) + O\left( \frac{P_0^2}{P_{n,l}} \right),
\]

where \( n \) is the order of the mode, \( l \) is the degree of the mode, with \( P_0 \) given by:

\[
P_0 = \frac{2\pi^2}{\int_0^{r_c} (N/r)dr}.
\]
The History of g-Mode Quest

Figure 2. Logarithm of the normalized energy \(\omega^2 I_{nl}\) of low-frequency g and mixed modes (open symbols) and low-frequency p modes (filled symbols) for a reference solar model M1 of Provost et al. (2000), plotted as a function of frequency, for modes of degree \(l=0, 1, 2, 3, 4, 5, \) and 6. (The normalization is taken assuming that the modes have equal amplitudes at the photospheric level, where the temperature equals the effective temperature level). (From Provost et al. 2000, reproduced with permission © ESO).

\(N^2\) is assumed to vanish proportionally to the power \(p\) of the distance to the convection zone; then \(\vartheta\) tends at low-frequency to a constant \(-0.5/(p + 2)\). For the standard solar model, a linear behaviour of \(N^2\) may be assumed and \(\vartheta\) tends to \(-1/6\). The asymptotic expression above tells us that the frequencies of g modes are related closely to the Brunt–Väisälä frequency, particularly through \(P_0\). Typical values of \(P_0\) for a reference solar model are, \(P_0 \approx 35\) to 36 min. The periods of g modes of a given degree \(l\) are then proportional, in the first order, to \(P_0/L\), where \(L = l(l + 1)\). These asymptotic properties of g modes may be exploited in attempts to detect the modes, i.e., by searching for signatures of near-regular patterns in period, as we shall discuss in the Second foundation section.

The lifetime and amplitude of the g modes were extensively discussed by Appourchaux et al. (2010) and references therein. The theoretical mode lifetimes are of the order of 1 million years! The main source of the g-mode damping is related to the radiative damping for \(n > 3\), while for lower order g modes the source is still debated (See Appourchaux et al. 2010, and references therein). It is assumed that the g modes are excited by turbulent convection. The optimistic and the pessimistic values of g-mode amplitude differ by nearly 3 orders of magnitude: from \(1 \text{ cm s}^{-1}\) to \(10^{-3} \text{ cm s}^{-1}\) for \(l = 1\)!

This large variation is primarily due to the way that the turbulent eddies are time-correlated, i.e. with a Gaussian or a Lorentzian profile (Appourchaux et al. 2010).

The theoretical framework set for the p-mode oscillation was put to test with the detection of the p modes by Deubner (1975). From this point of view, the measured \((k, \omega)\) diagram of solar oscillations confirmed the theoretical work of Ulrich (1970). The success achieved with the p modes was expected to be useful for the detection of g modes. In other words, the g-mode theoretical predictions described in this section

\[\vartheta = \frac{1}{2} \left(1 + \frac{1}{p+2} \right)\]
would be put to test by the observations. The detection of low-frequency modes (not to say g modes) was to mark the start of the next era.

3. Foundation and Empire

“It is the invariable lesson to humanity that distance in time, and in space as well, lends focus. It is not recorded, incidentally, that the lesson has ever been permanently learned.” Isaac Asimov in *Foundation and Empire* (1945)

The first detection of low-frequency oscillations is attributed to Severnyi et al. (1976) who claimed having detected a 160-min oscillation using 9 days of solar radial velocity derived from a modified differential Babcock solar magnetograph, contemporaneously confirmed by Brookes et al. (1976) using a full-disk resonance spectrometer. Severnyi et al. (1976) identified this oscillation as being the \( l = 2 \, g_{11} \) mode of 2 m s\(^{-1}\) amplitude. This oscillation was later detected by several other instruments: differential Babcock solar magnetograph (Scherrer et al. 1979), full-disk resonance spectrometer (Grec et al. 1980). The mode sensitivity of the differential magnetograph to solar oscillations was the highest for \( l = 3, 4 \) modes unlike the full-disk spectrometers that are not sensitive to these modes (Kosovichev & Severnyi 1986). Since the mode sensitivity was different, a common source different from the Sun could explain the oscillation: the Earth’s rotation. The main problem of that oscillation is that it was very close to the ninth harmonics of the day which at 104.09 \( \mu \)Hz. Last but not least, the excitation of that single mode was not easily explained; for instance Kosovichev & Severnyi (1986) listed 13 different explanations as excitation process. Back in the 80’s; it was then realized that in order to confirm the detection of any low-frequency oscillation, there would be a need for long observation either performed from ground or (even more likely) from space.

The motivation for g-mode detection was so high that it lead to the study of a space mission, the Dual Spectral Irradiance and Solar Constant Orbiter (DISCO), which showed what could be achieved were the g modes to be detected (Bonnet et al. 1981; Balogh et al. 1981). The prospects of g-mode detection were pushed forward by Delache & Scherrer (1983) who claimed the detection of tens of g modes, also using a modified Babcock solar magnetograph. In the mid-80s, the enthusiasm for a space mission was extremely active as several reports were written for the promotion of space-based observations (Noyes & Rhodes 1984; Marquedant et al. 1985), and also publicized by the famous Snowmass conference (Ulrich et al. 1984). Following the non-selection of DISCO, a new mission was proposed: the Solar and Heliospheric Observatory (SoHO). It was selected by the European Space Agency (ESA) in November 1982 for an assessment study.

The promotion for a space mission then became a transatlantic affair with support from the whole European and American helioseismic community. The first author of this paper can vividly remember that when presenting my first conference paper (Appourchaux 1984) having been asked by a high-ranking official from CNES (Centre National d’Etudes Spatiales, the French space agency) *to show that the g modes cannot be detected from the ground*. More important and less personal, the possible excitation of the 160-minute oscillation by the Geminga object was advanced not in a scientific journal but in the main stream French newspaper *Le Monde* (October 12, 1983). This
finding was relayed in the scientific journal *Nature* (October 20, 1983) as a *News and Views*. In this same issue of *Nature*, it was reported that the SoHO mission was selected by ESA for a Phase-A study. *Nature* asked a selection committee member whether [...] *the announcement influenced* [them], and the answer was: *It helped but was by no means decisive, SoHO would have been approved anyway.* The possible excitation of the 160-min oscillation was in fact neither confirmed (Anderson et al. 1984) nor even theoretically possible (Bonazzola et al. 1984; Carroll et al. 1984; Fabian & Gough 1984; Kosovichev 1984; Kuhn & Boughn 1984; Deruelle 1984). The SoHO Phase-A was eventually carried out under an ESA and NASA (National Aeronautics and Space Administration) collaboration for a selection as a mission in 1986 (Antonucci et al. 1981).

Space missions were not the only solution for having long-duration observations, high data fill and low noise. There were several initiatives that led to the creation of ground-based networks such as the Global Oscillation Network Group (GONG) funded in 1984 by the National Science Foundation, USA (Harvey et al. 1996); the Birmingham Solar Oscillation Network (BiSON) operating in July 1981 (Elsworth et al. 1991); or the International Research on the Interior of the Sun (IRIS) network operating in July 1984 (Fossat 1991).

In that same decade, the fate of the 160-min oscillation was definitely settled as it was shown that it was an artefact due to spurious solar velocity induced by atmospheric extinction (Elsworth et al. 1989). In the following years, the g-mode identification by Delache & Scherrer (1983) could never be reproduced showing again the dire needs for space-based observations.

With the selection of the SoHO payload in 1988, the Global Oscillations at Low Frequency (GOLF) instrument (Gabriel et al. 1995), the Michelson Doppler Imager for the Solar Oscillation Investigation (MDI/SoI; Scherrer et al. 1995) and the Variability of Irradiance and Gravity Oscillations instrument (VIRGO; Fröhlich et al. 1997) together with the aforementioned ground-based networks constituted a formidable armada of instruments that was the start of *The Empire* of helioseismology. In those days, the detection of g modes was thought to be a only matter of time.

### 4. Second Foundation

“To any who know the star field well from one certain reference point, stars are as individual as people. Jump ten parsecs, however, and not even your own Sun is recognizable.” Isaac Asimov in *Second Foundation* (1948)

The prospects of g-mode detection was put to rest from the selection of SoHO to shortly before its launch. It was revived when Thomson et al. (1995) claimed having detected g modes in particle data in the *Ulysses* and *Voyager* missions. The detection was based upon the application of a patent widely used in cellular telephone (Lindberg & Thomson 1991). The idea was to detect if there were a signal above the noise at a known-in-advance frequency. Then Thomson et al. (1995) used theoretical g-mode frequencies and previously measured p-mode frequencies for detecting these modes. The finding of Thomson et al. (1995) were not confirmed by Riley & Sonett (1996); Denison & Walden (1999); Hoogeveen & Riley (1998). To date their detection has indeed not been confirmed.
Following the launch of SoHO on December 2, 1995, the perspective of g-mode detection started exciting times. Pallé et al. (1998) put a definite end to the existence of the 160-min oscillation as GOLF was not detecting anything at all. Two years after the launch, it was realized that the helioseismic instruments of SoHO could not individually detect the g modes. In 1997, the first author of this paper decided to follow the legacy of the late Philippe Delache (known as the ambassador of g modes) and started a working group composed of member of the teams of MDI/SOI, VIRGO and BiSON. The group was named after Gaston III Phoebus (Count of Foix) famous for having written *The Book of Hunt* (1388), a book very appropriate for hounds! The Phoebus group held 5 workshops from 1997 to 2002 which led to several publications of attempts at detecting the g modes (Chaplin et al. 2002; Wachter et al. 2003) amongst which one provided an upper limit to g-mode amplitude of $1 \text{ cm s}^{-1}$ (Appourchaux et al. 2000). The many different techniques devised for detecting the g modes can be found in Appourchaux et al. (2010) and references therein.

On the other hand, the GOLF team was separately trying to find the g modes in their own data. They reported having detected an $l = 1$ g$_1$ mode at $284.7 \mu$Hz but still provided an upper limit to the g-mode amplitude of $0.6 \text{ cm s}^{-1}$ (Gabriel et al. 2002); and the detection of several candidates (Turck-Chièze et al. 2004) of amplitude $0.6 \text{ cm s}^{-1}$ at around $220 \mu$Hz, akin to an $l = 2$ g$_3$ mode. At the time of writing, none of these finding are confirmed.

The Phoebus group was then enlarged with the addition of members of the GOLF team. The Phoebus group then held three additional workshops from 2005 to 2007 that led to additional attempts at g-mode detections especially with the introduction of Bayesian-type of detection (Appourchaux 2008; Broomhall et al. 2007, 2010). During that time, using the asymptotic property laid out in Equation (1), García et al. (2007) reported a collective detection of g-mode signature. They found a peak in the periodogram of the GOLF data performed in the range $[60,140] \mu$Hz. Using this collective detection of these peaks, they reported individual detection of the peaks using the *collapsogramme* technique with a typical signal-to-noise ratio of 2 for $l = 1$ g$_8$ mode and a splitting of about $890 \text{ nHz}$, resulting in an amplitude of $0.1 \text{ cm s}^{-1}$ (See also Salabert et al. 2009, for an application of the collapsogramme to the detection of low order p modes). At the time of writing, the collective detection has not been confirmed using techniques different from that of the periodogram of the periodogram (Broomhall et al. 2010).

The Phoebus activities were stopped in 2010 with the publication of a review paper which stated that *there was* indeed a consensus amongst the authors of this review that *there was* currently no undisputed detection of solar g modes. (Appourchaux et al. 2010). Unfortunately, the first author still believes that this consensus holds in 2013.

5. **Perspective**

“The observer influences the events he observes by the mere act of observing them or by being there to observe them” Isaac Asimov in *Foundation’s Edge* (1982)

At the time of the conference in Tucson, several of my colleagues provided me with recent results of their own g-mode search. Scherrer and Larson (2013, private communication) tried to find a coincident peak in the $l = 1$ MDI periodogram of the
Figure 3. Estimated amplitudes of stochastically excited g modes of low degree plotted against frequency $\nu$. The estimates are rms surface values for singlet modes (single values of $n$, $l$ and $m$), joined by lines: triple-dot-dashed for Gough (1985), dot-dashed for Kumar et al. (1996) and dashed for Belkacem et al. (2009). The continuous line is an estimate of the 10% limit from 17 years GOLF data (García et al. 2007). The thick grey lines are two estimates from Shiode et al. (2013) for two eddy sizes of 100% (dashed line) and of 30% (solid line) of the pressure scale height. For proper comparison, the effect of the spatial instrumental filter must be included, i.e. visibilities (Appourchaux et al. 2010).

periodogram with that of García et al. (2007) but could not find any evidence common peaks. Fossat (these proceedings) computed a time series of the mean location of the p-mode envelope and its associated power spectrum. He then used the periodogram of the periodogram in the range $[25,40]$ $\mu$Hz hoping to detect an $l = 1$ comb, thanks to the asymptotic properties given by Equation (1). Then using the likely frequency location of the modes, he co-added 8 possible g-mode spectra in order to enhance them that provided a splitting of 439 $\text{nHz}$. Needless to say that these two results show that there is still a lot of interest in the detection of the g modes.

Very recently, Shiode et al. (2013) studied how g modes could be excited by convection in stars more massive than the Sun, stars having convective cores. They used their model to derive solar g-mode amplitudes which are indeed in the ball park of previous estimates (See Figure 3 for a comparison of the various estimates).

The four independent estimates of g-mode amplitude given in Figure 3 compared to the GOLF 17-year limit shows that it is very likely that the solar g modes have not been detected yet. If we were to trust the most optimistic value of Belkacem et al. (2009), we would have been able to detect the g modes with a signal-to-noise ratio of 2, a value commonly achieved in asteroseismology (See Appourchaux et al. 2008, as an example). It is then very likely that the g-mode amplitude are at least 10 times lower than the values provided for $l = 1$ by Belkacem et al. (2009).

What do you need in order to detect the solar g modes? There has been two possibilities: to dig deeper the current database of ground- and space-based observations, and to reduce the solar atmospheric noise with new instruments. As for the first solution, this has been done over the past 30 years and will likely continue for several
decades to come. As for the second solution, there has been two ideas that have not been yet implemented.

The first idea is developed under the concept of the Global Oscillations of Low-Degree modes (GOLD; Turck-Chièze et al. 2012) which aims at measuring solar radial velocities at different heights in the atmosphere, thereby hoping to reduce the solar noise using the cross spectrum technique of García et al. (1999). Unfortunately, it has been shown that even if the coherence between two signals is zero, the average of the cross spectrum will indeed be zero but the variance of the cross spectrum will not follow this behaviour (Appourchaux et al., 2007). Assuming that the g modes have very long lifetime then the advantage of the GOLD instrument is only for low-degree solar p modes with a lifetime shorter than the observing time (Appourchaux et al., 2007).

The second idea is to directly measure the gravitational perturbation generated by the g modes, that is the strain or the deformation of spacetime. This is what measures the ASTROD (Astrodynamical Space Test of Relativity using Optical Devices) mission proposed to ESA’s Cosmic Vision (Appourchaux et al., 2009). The strain sensitivity of ASTROD would allow to detect solar g modes with the lowest predicted amplitudes of Figure 3, a sensitivity at least 2 order of magnitude better than the LISA (Laser Interferometer Space Antenna) mission of ESA (Appourchaux et al., 2009). At the time of writing, LISA has not been selected as a mission but LISA pathfinder, a mission for testing in flight the concept of low-frequency gravitational wave detection, will be launched in 2015. As for the ASTROD mission, there is no programmatic window since it is not known when it will fly as no space agency has it in their long-term plans.

Finally, there remains the possibility of testing the current model of solar g modes amplitudes using the data from Kepler. If we could detect g modes in heavier stars, hoping thereby that the amplitudes are higher in more massive stars, then the excitation model could then be validated. With such a validation, it would be possible either to continue the search with the actual data or to devise more sensitive measurement techniques. With such a positive mind, we can then anticipate that we are to reach the Third foundation of g-mode detection.

Acknowledgments. TA would like to thank three important players who contributed to his helioseismic professional career: Jacques-Emile Blamont who introduced him to the world of space missions, of solar seismology and of tenacity; Pierre Connes who taught him the basics of proper and sound instrument design and last but not least David M. Rust whose confidence, openness and daring vision made him TA what he is today.

References

Anderson, J. D., Armstrong, J. W., Estabrook, F. B., Hellings, R. W., Lau, E. K., & Wahlquist, H. D. 1984, Nat, 308, 158
Antonucci, E., Balogh, A., van Beek, F., Christensen-Dalsgaard, J., Fröhlich, C., Gabriel, A., Harvey, C., Hoyng, P., Huber, M., Isaak, G., Lemaire, P., Malinovsky-Arduini, M., Patchett, B., Schwenn, R., & Tondello, P. 1981, SOHO Phase-A study, ESA SCI(85)7, Tech. rep., European Space Agency, Paris
Appourchaux, T. 1984, in Space Research in Stellar Activity and Variability (Observatoire de Paris-Meudon), 117
— 2008, Astron. Nachr., 329, 485
Appourchaux, T., Belkacem, K., Broomhall, A.-M., Chaplin, W. J., Gough, D. O., Houdek, G., Provost, J., Baudin, F., Boumier, P., Elsworth, Y., García, R. A., Andersen, B. N., Finsterle, W., Fröhlich, C., Gabriel, A., Grec, G., Jiménez, A., Kosovichev, A., Sekii, T., Toutain, T., & Turck-Chièze, S. 2010, A&A Rev., 18, 197
The History of g-Mode Quest

Appourchaux, T., Burston, R., Chen, Y., Cruise, M., Dittus, H., Foulon, B., Gill, P., Gizon, L., Klein, H., Kliiber, S., Kopeikin, S., Krüger, H., Lämmerzahl, C., Lobo, A., Luo, X., Margolis, H., Ni, W.-T., Patón, A. P., Peng, Q., Peters, A., Rasel, E., Rüdiger, A., Samain, É., Selig, H., Shaul, D., Sumner, T., Theil, S., Touboul, P., Turyshev, S., Wang, H., Wang, L., Wen, L., Wicht, A., Wu, J., Zhang, X., & Zhao, C. 2009, Exp. Astron., 23, 491

Appourchaux, T., Fröhlich, C., Andersen, B. N., Berthomieu, G., Chaplin, W., Elsworth, Y., Finsterle, W., Gough, D., Hoeksema, J. T., Isaak, G., Kosovichev, A., Provost, J., Scherrer, P., Sekii, T., & Toutain, T. 2000, ApJ, 538, 401

Appourchaux, T., Leibacher, J., & Boumier, P. 2007, A&A, 463, 1211

Appourchaux, T., Michel, E., Auvergne, M., Baglin, A., Toutain, T., Baudin, F., Benomar, O., Chaplin, W. J., Deheuvels, S., Samadi, R., Verner, G. A., Baudin, P., García, R. A., Mosser, B., Hulot, J., Ballot, J., Barban, C., Elsworth, Y., Jiménez-Reyes, S. J., Kjeldsen, H., Régulo, C., & Roxburgh, I. W. 2008, A&A, 488, 705

Balogh, A., Bonnet, R. M., Delache, P., Fröhlich, C., & Harvey, C. 1981, DISCO re-assessment study, ESA SCI(81)3, Tech. rep., European Space Agency, Paris

Belkacem, K., Samadi, R., Goupil, M. J., Dupret, M.-A., Brun, A. S., & Baudin, F. 2009, A&A, 494, 191

Berthomieu, G., & Provost, J. 1990, A&A, 227, 563

Bonazzola, S., Carter, B., Heyvaerts, J., & Lasota, J. P. 1984, Nature, 308, 163

Bonnet, R. M., Crommelynck, D., Delaboudinière, J. P., Delache, P., Fossat, E., Fröhlich, C., Gough, D. O., Grec, G., Simon, P., & Thuillier, G. 1981, DISCO assessment study, ESA SCI(81)3, Tech. rep., European Space Agency, Paris

Brookes, J. R., Isaak, G. R., & van der Raay, H. B. 1976, Nature, 259, 92

Broomhall, A., Chaplin, W. J., Elsworth, Y., Appourchaux, T., & New, R. 2010, MNRAS, 406, 767

Broomhall, A. M., Chaplin, W. J., Elsworth, Y., & Appourchaux, T. 2007, MNRAS, 379, 2

Carroll, B. W., McDermott, P. N., Reynolds, G. C., & Shore, S. N. 1984, Nature, 308, 165

Chaplin, W. J., Elsworth, Y., Isaak, G. R., Marchenko, K. I., Miller, B. A., New, R., Pinter, B., & Appourchaux, T. 2002, MNRAS, 336, 979

Claverie, A., Isaak, G., McLeod, C., van der Raay, H., & Roca Cortés, T. 1979, Nature, 282, 591

Deheuvels, S., García, R. A., Chaplin, W. J., Basu, S., Antia, H. M., Appourchaux, T., Benomar, O., Davies, G. R., Elsworth, Y., Gizon, L., Goupil, M. J., Reese, D. R., Regulo, C., Schou, J., Stahn, T., Casagrande, L., Christensen-Dalsgaard, J., Fischer, D., Hekker, S., Kjeldsen, H., Mathur, S., Mosser, B., Pinsonneault, M., Valenti, J., Christiansen, J. L., Kinemuchi, K., & Mullally, F. 2012, ApJ, 756, 19

Delache, P., & Scherrer, P. H. 1983, Nature, 306, 651

Denison, D. G. T., & Walden, A. T. 1999, ApJ, 514, 972

Deruelle, N. 1984, in Gravitation, Geometry and Relativistic Physics, edited by Laboratoire Gravitation et Cosmologie Relativistes, vol. 212 of Lecture Notes in Physics, Berlin Springer Verlag, 238

Deubner, F.-L. 1975, A&A, 44, 371

Ellis, A. N. 1986, in Seismology of the Sun and the Distant Stars, 173

Elsworth, Y., Howe, R., Isaak, G. R., McLeod, C. P., & New, R. 1991, MNRAS, 251, 7P

Elsworth, Y. P., Jefferies, S. M., McLeod, C. P., New, R., Palle, P. L., van der Raay, H. B., Regulo, C., & Cortés, T. R. 1989, ApJ, 338, 557

Fabian, A. C., & Gough, D. O. 1984, Nat, 308, 160

Fossat, E. 1991, Solar Phys., 133, 1

Fröhlich, C., Andersen, B. N., Appourchaux, T., Berthomieu, G., Crommelynck, D. A., Domingo, V., Fichot, A., Finsterle, W., Gomez, M. F., Gough, D., Jiménez, A., Leifsen, T., Lombaerts, M., Pap, J. M., Provost, J., Cortés, T. R., Romero, J., Roth, H., Sekii, T., Telljohann, U., Toutain, T., & Wehrli, C. 1997, Solar Phys., 170, 1

Gabriel, A. H., Baudin, F., Boumier, P., García, R. A., Turck-Chièze, S., Appourchaux, T., Bertello, L., Berthomieu, G., Charra, J., Gough, D. O., Pallé, P. L., Provost, J., Renaud,
Appourchaux and Pallé

C., Robillot, J.-M., Roca Cortés, T., Thiery, S., & Ulrich, R. K. 2002, A&A, 390, 1119
Gabriel, A. H., Grec, G., Charra, J., Robillot, J.-M., Roca Cortés, T., Turck-Chièze, S., Bocchia, R., Boumier, P., Cantin, M., Cespédès, E., Courand, B., Crétolle, J., Damé, L., Decaudin, M., Delache, P., Denis, N., Duc, R., Dzitko, H., Fossat, E., Fourmond, J.-I., García, R. A., Gough, D. O., Grivel, C., Herreros, J. M., Lagardère, H., Moalic, J.-P., Pallé, P. L., Pétrou, N., Sanchez, M., Ulrich, R., & van der Raay, H. B. 1995, Solar Phys., 162, 61
García, R. A., Jefferies, S. M., Toner, C. G., & Pallé, P. L. 1999, A&A, 346, L61
García, R. A., Turck-Chièze, S., Jiménez-Reyes, S. J., Ballot, J., Pallé, P. L., Effer-Darwich, A., Mathur, S., & Provost, J. 2007, Science, 316, 1591
Gough, D. O. 1985, in Future Missions in Solar, Heliospheric and Space Plasma Physics (ESA Publication Division), 183
Grec, G., Fossat, E., & Pomerantz, M. 1980, Nature, 288, 541
Harvey, J. W., Hill, F., Hubbard, R., Kennedy, J. R., Leibacher, J. W., Pintar, J. A., Gilman, P. A., Noyes, R. W., Title, A. M., Toomre, J., Ulrich, R. K., Bhatnagar, A., Kennewell, J. A., Marquette, W., Patrón, J., Saa, O., & Yasukawa, E. 1996, Science, 272, 1284
Hoogeveen, G. W., & Riley, P. 1998, Solar Phys., 179, 167
Kosovichev, A. G. 1984, Soviet Astron. Lett., 10, 190
Kosovichev, A. G., & Severny, A. B. 1986, Soviet Astron. Lett., 12, 97
Kuhn, J. R., & Boughn, S. P. 1984, Nature, 308, 164
Kumar, P., Quataert, E. J., & Bahcall, J. N. 1996, ApJ, 458, L83
Leighton, R. B., Noyes, R. W., & Simon, G. W. 1962, ApJ, 135, 474
Lindberg, C., & Thomson, D. 1991, Method and apparatus for detecting control signals, Tech. rep., US patent 5442696
Marquedant, R., Litvak, M., Thorpe, T., Rhodes, E., Sepulveda, C., Smith, E., & Chrisp, M. 1985, Selection of a Wavelength Analyzer for a Solar Oscillations Imaging Experiment, JPL D-2018 (Jet Propulsion Laboratory, Los Angeles, CA)
Noyes, R., & Rhodes, E. 1984, Probing the Depths of a Star: The Study of Solar Oscillations from Space, NASA-JPL 400-234 (Jet Propulsion Laboratory, Los Angeles, CA)
Olver, F. W. J. 1956, Royal Soc. London Philosophical Transactions Series A, 249, 65
Pallé, P. L., Roca Cortés, T., Gelly, B., & GOLF Team 1998, in Structure and Dynamics of the Interior of the Sun and Sun-like Stars, edited by S. Korzennik, vol. 418 of ESA Special Publication, 291
Provost, J., & Berthomieu, G. 1986, A&A, 165, 218
Provost, J., Berthomieu, G., & Morel, P. 2000, A&A, 353, 775
Riley, P., & Sonett, C. P. 1996, Geophys. Res. Lett., 23, 1541
Salabert, D., Leibacher, J., Appourchaux, T., & Hill, P. 2009, ApJ, 696, 653
Scherrer, P. H., Bogart, R. S., Bush, R. I., Hoeksema, J. T., Kosovichev, A. G., Schou, J., Rosenberg, W., Springer, L., Tarbell, T. D., Title, A., Wolfson, C. J., & Zayer, I. 1995, Solar Phys., 162, 129
Scherrer, P. H., Wilcox, J. M., Kotov, V. A., Severny, A. B., & Tsap, T. T. 1979, Nature, 277, 635
Severny, A. B., Kotov, V. A., & Tsap, T. T. 1976, Nature, 259, 87
Shiode, J. H., Quataert, E., Cantiello, M., & Bildsten, L. 2013, MNRAS, 430, 1736
Tassoul, M. 1980, ApJS, 43, 469
Thomson, D. J., Maclellan, C. G., & Lanzerotti, L. J. 1995, Nature, 376, 139
Turck-Chièze, S., Carton, P.-H., Barrière, J.-C., Pallé, P. L., Robillot, J.-M., Ballot, J., Chenus, A.-C., Daniel-Thomas, P., Delbart, A., García, R. A., Granelli, R., Lahonde-Hamdoun, C., Loiseau, D., Mathur, S., Piret, Y., Salabert, D., Simonelli, R., & Davies, G. R. 2012, in Progress in Solar/Stellar Physics with Helio- and Asteroseismology, edited by H. Shibahashi, M. Takata, & A. E. Lynas-Gray, vol. 462 of ASP Conf. Ser., 240
Turck-Chièze, S., García, R. A., Couvidat, S., Ulrich, R. K., Bertello, L., Varadi, F., Kosovichev, A. G., Gabriel, A. H., Berthomieu, G., Brun, A. S., Lopes, I., Pallé, P., Provost, J., Robillot, J. M., & Roca Cortés, T. 2004, ApJ, 604, 455
Ulrich, R., Harvey, J., Rhodes, E., & Toomre, J. 1984, Solar Seismology from Space, JPL publication 84-84 (Jet Propulsion Laboratory, Los Angeles, CA)
Ulrich, R. K. 1970, ApJ, 162, 993
Vandakurov, Y. V. 1968, Soviet Astron., 11, 630
Wachter, R., Schou, J., Kosovichev, A. G., & Scherrer, P. H. 2003, ApJ, 588, 1199