Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 56 (2015) 2706–2712

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Solar cycle variations in the powers and damping rates of low-degree solar acoustic oscillations

A.-M. Broomhall [a,b,*], C.E. Pugh [b], V.M. Nakariakov [b,c,d]

[a] Institute of Advanced Studies, University of Warwick, Coventry CV4 7HS, UK

[b] Centre for Fusion, Space, and Astrophysics, Department of Physics, University of Warwick, Coventry CV4 7AL, UK

[c] School of Space Research, Kyung Hee University, Yongin 446-701, Gyeonggi, Republic of Korea

[d] Central Astronomical Observatory at Pulkovo of RAS, St Petersburg 196140, Russia

Received 22 December 2014; received in revised form 30 March 2015; accepted 15 April 2015
Available online 23 April 2015

Abstract

Helioseismology uses the Sun's natural resonant oscillations to study the solar interior. The properties of the solar oscillations are sensitive to the Sun's magnetic activity cycle. Here we examine variations in the powers, damping rates, and energy supply rates of the most prominent acoustic oscillations in unresolved, Sun-as-a-star data, obtained by the Birmingham Solar Oscillations Network (BiSON) during solar cycles 22, 23, and the first half of 24. The variations in the helioseismic parameters are compared to the 10.7 cm flux, a well-known global proxy of solar activity. As expected the oscillations are most heavily damped and the mode powers are at a minimum at solar activity maximum. The 10.7 cm flux was linearly regressed using the fractional variations of damping rates and powers observed during cycle 23. In general, good agreement is found between the damping rates and the 10.7 cm flux. However, the linearly regressed 10.7 cm flux and fractional variation in powers diverge in cycles 22 and 24, indicating that the relationship between the mode powers and the 10.7 cm flux is not consistent from one cycle to the next. The energy supply rate of the oscillations, which is usually approximately constant, also decreases at this time. We have determined that this discrepancy is not because of the first-order bias introduced by an increase in the level of background noise or gaps in the data. Although we cannot categorically rule out an instrumental origin, the divergence observed in cycle 24, when the data were of high quality and the data coverage was over 80%, raises the possibility that the effect may be solar in origin.

Keywords: Sun; Helioseismology; Solar cycle

1. Introduction

Natural resonant oscillations of the Sun and stars can be used to study solar and stellar interiors using helioseismic and asteroseismic techniques. In the Sun the most prominent oscillations are acoustic p modes, so called because the main restoring force is a pressure differential. Properties of the oscillations, such as their frequencies, allow profiles of the solar interior to be constructed. Since p-mode oscillations are stochastically excited and intrinsically damped by the near-surface turbulent convection, observations of the powers and damping rates of the oscillations also provide information on the Sun's internal convection.

It has been known for some time that the frequencies of p modes vary systematically throughout the Sun's 11 yr magnetic activity cycle, with the frequencies being at a maximum when magnetic activity on the Sun is also at a maximum (e.g. Woodard et al., 1985; Elsworth et al., 1990; Pallé et al., 1990). However, they are not the only

* Corresponding author at: Institute of Advanced Studies, University of Warwick, Coventry CV4 7HS, UK.
E-mail address: a-m.broomhall@warwick.ac.uk (A.-M. Broomhall).

http://dx.doi.org/10.1016/j.asr.2015.04.018
0273-1177/

parameter of p-mode oscillations that vary with time: damping rates and powers are also observed to depend on the level of solar activity, with damping rates being at their highest and powers being at their lowest at solar maximum (e.g. Jefferies et al., 1990; Chaplin et al., 2000; Komm et al., 2000; Jiménez et al., 2002; Salabert et al., 2007). The exact cause of the variations remains uncertain; for example, active regions are known to affect mode lifetimes and suppress mode powers, but the associated mechanisms are not totally understood (Woods and Cram, 1981; Lites et al., 1982; Brown et al., 1992; Rajaguru et al., 2001; Komm et al., 2002; Howe et al., 2004). Meanwhile Houdek et al. (2001) theorized that during times of high activity magnetic structures have a sufficient enough effect on convection to noticeably alter mode damping rates.

Evidence for activity-cycle variations in mode parameters has been observed in stars other than the Sun (García et al., 2010). However, despite the large amount of high-quality data produced by CoRoT and Kepler the expected evidence for similar cycles in solar-like stars has not been forthcoming. The frequency-lifetime-power relationship observed in solar p modes could be crucial for identifying stellar activity cycles. It is therefore important to fully understand the activity cycle variations in mode parameters observed for the Sun.

We present variations in the lifetimes, powers and the energy supply rate of global solar p modes throughout cycles 22, 23, and the rising phase of cycle 24. In Section 2 we describe the data and analysis procedures employed in this study. The main results are presented and discussed in Section 3. A summary is provided in Section 4.

2. Data and analysis

The Birmingham Solar Oscillations Network (BiSON; Davies et al., 2014) has been making spatially unresolved (Sun-as-a-star) observations of the Sun for more than 30 yrs. However, the early data have relatively poor coverage and so here we use data that extend from January 1st 1985 until March 26th 2014. This allows us to compare two and a half solar cycles, making BiSON unique in helioseismic terms as the longest running helioseismic observatory. We have used the most recent data release from BiSON, which were produced using new procedures that improved the signal-to-noise ratio of the oscillations (Davies et al., 2014).

Although Sun-as-a-star (unresolved) helioseismic observations, such as those made by BiSON, are only sensitive to modes with the largest horizontal scales (low degree, or low-l) a rich spectrum of oscillations still exists. In this study we concentrate on modes with $l = 0$, 1, and 2 as these modes have the largest amplitudes in the BiSON data. We only consider modes in the frequency range $2400 \leqslant \nu_{n,l} \leqslant 3500\,\mu\text{Hz}$. These are the most prominent modes of oscillation, which means that parameters of the modes can be obtained accurately and precisely. These are also the modes that experience the largest variation in mode damping as the Sun's magnetic activity varies from maximum to minimum (e.g. Komm et al., 2000). Finally, this range includes 8 modes from each l (24 modes in total that correspond to different radial orders, n).

Frequency-power spectra of the data were fitted using a Maximum Likelihood Estimation technique (Fletcher et al., 2009), where the asymmetric profile of Nigam and Kosovichev (1998) was used. The width of the fitted profile, $\Delta_{n,l}$, is then proportional to the damping rate of the oscillations. while the power, P, is commonly defined as

$$P_{n,l} = 0.5\pi H_{n,l}\Delta_{n,l}, \tag{1}$$

where H is the height of the fitted profile. We note that Eq. 1 gives the power of a symmetric peak. We neglect the asymmetries since the asymmetric approximation of Nigam and Kosovichev (1998) is only valid in the vicinity of the mode and the integral of the profile tends to infinity. Since the asymmetries are small (Jiménez-Reyes et al., 2007), Eq. 1 is a good approximation; however, large errors in the asymmetries could affect the determined powers. This is discussed further in Section 3. The uncertainties associated with $\Delta_{n,l}$ and $H_{n,l}$ are those obtained from the fitting procedure. However, $\Delta_{n,l}$ and $H_{n,l}$ are highly anti-correlated and this must be taken into account when determining the uncertainty associated with $P_{n,l}$. We do so in the manner described by Chaplin et al. (2000).

The energy of the oscillations, $E_{n,l} \propto M_{n,l}P_{n,l}$, where $M_{n,l}$ is a measure of the interior mass affected by the oscillation as given by Christensen-Dalsgaard and Berthomieu (1991). The rate at which energy is supplied to the oscillations, $\mathrm{d}E_{n,l}/\mathrm{d}t \equiv \dot{E}_{n,l}$, is proportional to the product of $\Delta_{n,l}$ and $E_{n,l}$ (see Chaplin et al. (2000), for details).

In order to study solar cycle variations in the helioseismic parameters a compromise must be struck. The data series need to be of sufficient length in time to obtain a good enough resolution in the power spectrum to allow the parameters of the oscillations to be obtained accurately and precisely; however, if the data series are too long one loses sensitivity to solar cycle variations. Therefore, we have used a running sequence of 365 d spectra that overlap by 273.75 d. The frequency-power spectrum of each subset of data was fitted independently, producing 114 sets of mode parameters.

We begin by creating a "reference" set of line widths, powers, and energy supply rates. These are constructed by determining the weighted mean line widths, powers and energy supply rates across all 365 d subsets observed after 1993, as this data has a higher fill and lower noise than preceding subsets (see below). The mean line width ($\overline{\Delta_{n,l}}$), power ($\overline{P_{n,l}}$), and energy supply rate ($\overline{\dot{E}_{n,l}}$) are determined individually for each mode (n, l). Since the mode parameters we are considering are dependent on the frequency of the mode we determine the relative shift with time:

$$\delta\Delta_i = \frac{\Delta_{n,l,i} - \overline{\Delta_{n,l}}}{\overline{\Delta_{n,l}}}, \quad (2)$$

$$\delta P_i = \frac{P_{n,l,i} - \overline{P_{n,l}}}{\overline{P_{n,l}}}, \quad (3)$$

$$\delta \dot{E}_i = \frac{\dot{E}_{n,l,i} - \overline{\dot{E}_{n,l}}}{\overline{\dot{E}_{n,l}}}, \quad (4)$$

where the subscript i denotes the time subscript for the 114 subsets.

As BiSON is a ground-based network, gaps in time occur in the BiSON data, because of poor weather conditions and instrument failure. The fill of a particular time series is the proportion of the time series that contains data (as opposed to null points), where a fill of unity means that there was 100% data coverage. Fig. 1 shows the fill of the 114 subsets as a function of time. One can clearly see the improvement in the fill as BiSON increased the number of sites in the network. After September 1993 the fill remained approximately constant, at around 0.8.

Gaps in the data cause biases in the mode widths and heights estimated from the resulting power spectrum (Chaplin et al., 2003), which has a knock on effect for the determined powers and energy supply rates. Since we wish to compare results from data obtained over a large range of fills it is necessary to correct for the fill. We now briefly describe how these corrections are made.

2.1. Corrections for bias introduced by fill

The Global Oscillations at Low Frequencies (GOLF, Gabriel et al., 1995; Garcia et al., 2005) instrument onboard the ESA/NASA SOlar and Helioseismic Observatory (SOHO) satellite also makes Sun-as-a-star line-of-sight velocity observations of the Sun. However, SOHO was only launched in 1995, meaning that to date it has only accumulated one and a half solar cycles. SOHO data, therefore, cannot yet be used to compare variations observed from one cycle to the next. GOLF is, however, space-based and so its data has very high fill. We use a 365 d section of GOLF data with a fill of 1.0 to constrain the bias observed in the BiSON data by artificially imposing the BiSON window functions on the GOLF data. This was done by making the GOLF data zero at times when no BiSON data were recorded. Some interpolation of the window function was required as the time cadences of the BiSON and GOLF data are not the same. We determined the variation in Δ, P, and $\dot{E}$ as a function of fill compared to the values obtained when the fill was 1.0, i.e. when the BiSON window functions were not imposed. This variation is approximately linear with fill and so can be used to correct the values of the relevant parameters obtained in the BiSON data to the theoretical values that would be obtained if the fill were 1.0. The methodology used here is similar to that employed by Chaplin et al., 2003.

We must remember that the effect of the fill is slightly more complicated than implied by a simple linear correction. As the fill decreases, power in a frequency-power spectrum is redistributed into noise, thereby decreasing the signal-to-noise of the data. Not only does this lead to the above-mentioned bias but it also makes the mode profiles more difficult to fit accurately and precisely, leading to an increase in scatter in the values of the determined parameters.

2.2. Comparison with 10.7 cm radio flux

We compare the variations observed in the parameters to the 10.7 cm radio flux, a well-known global proxy of the Sun's magnetic activity cycle. The total variation between solar cycle minimum and maximum in the 10.7 cm flux is orders of magnitude larger than the minimum-to-maximum variation in the helioseismic parameters. Therefore, to allow comparisons to be made, we perform a linear regression between the helioseismic parameters and the 10.7 cm flux. The linear regression was performed using data from cycle 23 only, which spans from June 30th 1995 until June 26th 2008. This allows us to determine whether the behavior of the parameters changes from one cycle to the next, with respect to the 10.7 cm flux. Furthermore, for the reasons outlined above the signal to noise and fill of the data observed during cycle 23 is better than cycle 22. Linear regressions were performed independently for the fractional variation in Δ and P. The resulting linearly regressed values of the 10.7 cm flux can be considered as retrospective predictions of the fractional changes in Δ and P.

3. Results and discussion

Fig. 2 shows the variations in the widths (which are proportional to the damping rates of the oscillations) and the powers with time. As expected the widths are at a maximum at solar maximum and the powers are at a minimum at solar maximum. The widths show good agreement with the

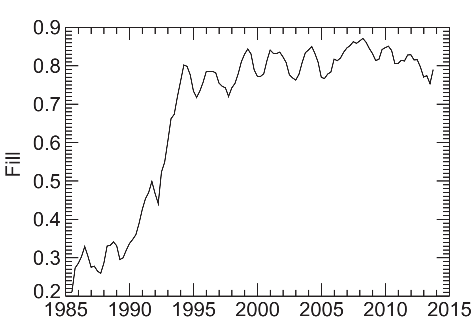

Fig. 1. Fill of the BiSON 365 d time series, which overlap by 273.75 d. The fill is defined as the proportion of the time series that contains data as opposed to null points.

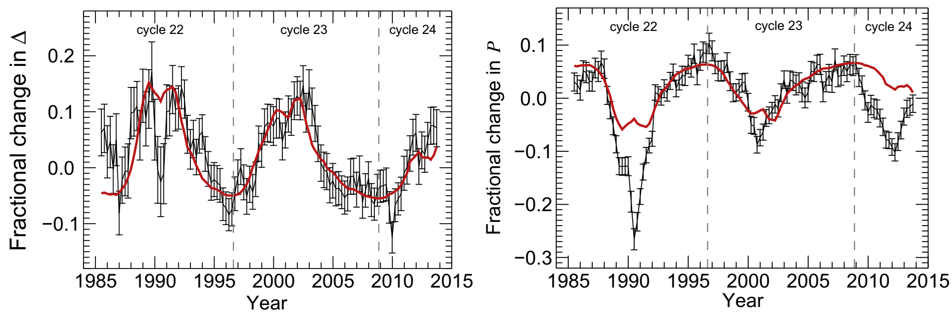

Fig. 2. Left: Fractional variation in the width of the Lorentzian mode profiles in a frequency-power spectrum as a function of time. Right: Fractional variation in the power of the p-mode oscillations as a function of time. The fractional variations in the widths and powers are determined by taking an average of p modes with $0 \leqslant l \leq 2$, and $2400 \leqslant \nu \leqslant 3500$ μHz. In each panel, overplotted in red, are linearly regressed versions of the 10.7 cm flux. The linear regressions were performed separately for the widths and powers. The dashed vertical lines separate the different solar cycles. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

linearly regressed 10.7 cm flux, with the exception of the maximum of cycle 22, where a large dip in the widths is observed. A large deviation from the powers predicted by the linear regression of the 10.7 cm flux is also observed at the maximum of cycle 22. The timing of the dip is consistent with the double maximum (sometimes referred to as the Gnevyshev gap, or an intrinsic part of the quasi-biennial oscillation, see Bazilevskaya et al. (2014) for a recent review). However, as we discuss, this may be coincidental.

To determine whether these deviations are real we considered further possible sources of bias in the data. We note that although the fill is still low during this period it is similar to the fill in preceding 365 d segments. We therefore considered the background noise in the data, which is plotted in Fig. 3 as a function of both time and fill. There is a definite peak in the background level, which is far above the background level expected given the fill of the data. This peak occurs at the same time as the observed deviations in the widths and powers of the oscillations. However, we find that, in the frequency range of interest, even this large increase in noise only results in a small change in the fitted heights and widths (within respective uncertainties). This is likely to be because in the frequency range we consider here the signal-to-noise is large even when the additional noise is present in the data.

An additional way in which the noise could affect the data is by perturbing the asymmetry parameter of the line fitting, which would have an effect on the fitted widths and heights. Although an in-depth study of the mode asymmetry is beyond the scope of this paper we note that when determining the average powers and widths we only consider modes for which reasonable values of the asymmetries (and, for that matter, all other parameters) were obtained. This was done by filtering the data for outliers and by checking each fitted profile by eye.

Significant deviations between the observed fractional variation in the mode powers and the linearly regressed 10.7 cm flux are observed in cycle 24. The exact time at which this deviation occurs very much depends on the linear regression used: If, for example, we had instead scaled the 10.7 cm flux using data from cycles 22 or 24 large discrepancies would be observed in cycle 23. Hence we can only conclude that the relationship between the mode powers and the 10.7 cm flux has changed from cycle to cycle. The fractional variation of the powers observed in cycle 24 is of a similar magnitude to the fractional variation

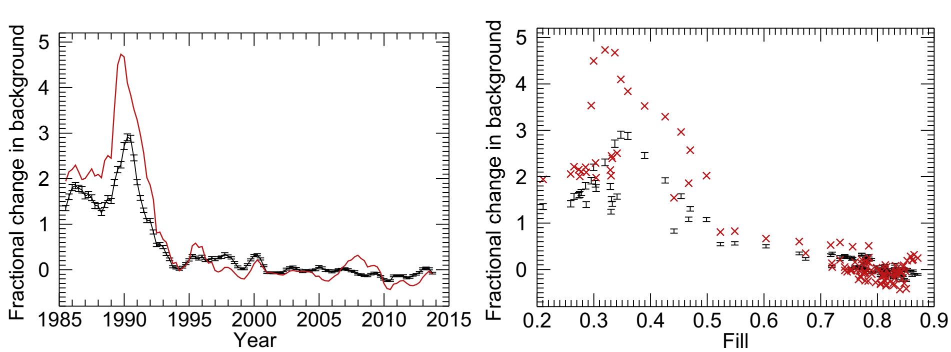

Fig. 3. Left: Fractional variation in the fitted background of the power spectra as a function of time (black with error bars). Right: Fractional variation in the fitted background of the power spectra as a function of fill. In each panel, overplotted in red, is the fractional variation in the level of noise above the acoustic cut-off frequency ($6000 \leqslant \nu < 12,500$ μHz). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

observed in cycle 23, despite almost all other proxies of the solar activity cycle, including the 10.7 cm flux, indicating that the maximum of cycle 24 is much smaller than the previous cycle. Once again the fitted asymmetries may play an important role here as they appear to be systematically lower at the maximum of cycle 24 than one might expect. However, in order to change the fitted asymmetry something must have changed in the data and such a change could be an instrumental noise effect or a real solar effect.

Table 1 shows the changes of the fractional variations in mode profile widths and mode powers between different solar minima and maxima, divided by the change in 10.7 cm radio flux over the same intervals. Cycle 24 has not been included in this analysis as the full maxima has not yet been observed. The changes in widths are all very similar, suggesting a similar relationship between the widths and 10.7 cm flux during all solar cycles. There is more variation in the values obtained for the changes in mode powers. The values for cycle 22 are greater than the values for cycle 23, due to the dip in mode power during the maximum of cycle 22: The rising phases differ by more than 3σ and the falling phases differ by more than 7σ. There is a slight difference (approx. 2σ) between the values for the first and second halves of both cycles, further suggesting a change of relationship between the powers and 10.7 cm flux between during this time.

Fig. 4 shows the variation in the energy supply rate as a function of time. During cycle 23 $\dot{E}$ is approximately constant and correlates poorly with the 10.7 cm flux. A Pearson's correlation coefficient of -0.22 is obtained, which is below a 10% confidence level. For this reason, the 10.7 cm flux has not been overplotted on Fig. 4 as a reliable linear regression could not be performed. The effect of the drop in powers around 1990 and, to a lesser extent, during the current solar cycle can clearly be observed.

Table 1
Ratios of changes of width and power shifts between solar minima and maxima with the change in 10.7 cm flux over the same interval.

Solar cycle phase	Change in width ($\times10^{-3}$)	Change in power ($\times10^{-3}$)
Cycle 22 rise	1.0 ± 0.3	1.90 ± 0.09
Cycle 22 fall	1.2 ± 0.3	2.2 ± 0.1
Cycle 23 rise	1.1 ± 0.2	1.4 ± 0.1
Cycle 23 fall	1.2 ± 0.2	1.1 ± 0.1

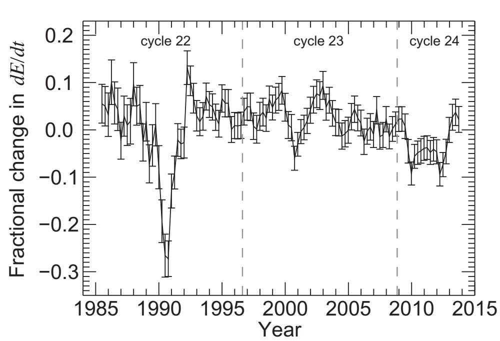

Fig. 4. Fractional variation in the energy supply rate of the oscillations as a function of time. The dashed vertical lines separate the different solar cycles.

4. Summary

As expected the line widths are at a maximum at solar maximum, implying that the modes are more heavily damped at solar maximum. The mode powers are at a minimum at solar activity maximum. We recall that the mode frequencies are at a maximum at solar maximum (e.g. Woodard et al., 1985; Elsworth et al., 1990; Pallé et al., 1990; Broomhall et al., 2014). Therefore the line widths (or damping rates) vary in phase with the frequencies, while the powers vary in anti-phase. This characteristic frequency-power-damping rate relationship may prove to be vital in identifying signatures of stellar activity cycles in asteroseismic data, for which little evidence has been found to date (García et al., 2010).

The variation in the line widths correlates well with the 10.7 cm flux across the epoch examined here, with the only notable deviation observed around the maximum of cycle 22 (c.1990). Similar deviations were observed in the mode powers at this time. Despite being coincident with a large increase in the background noise level it was found that changing the signal-to-noise of the mode alone was not sufficient to explain the observed drop in power and line width. It is however possible that the noise affects the fitted profile in a more complex way, and one possibility is in terms of the asymmetry of the mode profile.

The powers observed in cycle 24 also drop below the values predicted by the linear regression of the 10.7 cm flux, although, as mentioned in the previous section, the time at which the deviation appears to occur depends on the linear regression used. This deviation does not coincide with a change in background or a deviation between the observed line widths and those predicted by the linear regression of the 10.7 cm flux. It is possible that the deviation of the powers relates to the change in the magnitude of the frequency shifts observed in low-frequency modes between cycles 22 and 23 (Basu et al., 2012). A more up-to-date study of the mode frequencies, including those observed during the rising phase of cycle 24, has been conducted, and will be published elsewhere. Salabert et al. (2015) demonstrated that the frequencies of high-frequency modes varied by 30% less in the rising phase of cycle 24 than in cycle 23, which is in agreement with surface and atmospheric measures of the Sun's magnetic field. However, the frequencies of the low-frequency modes appear to change by the same amount in cycle 23 and the rising phase of cycle 24, implying that below 1400 km the magnetic field has not changed. Although we do not consider the dependence on mode frequency of the change in power here, the magnitude of the variation we have observed in cycle 24 thus far is comparable to that observed in cycle 23, despite surface proxies of the solar magnetic field indicating that cycle 24 is weaker than cycle 23.

A consequence of the deviation of the powers is that the energy supply rate also appears to decrease between 2009 and 2013. Once again we must consider the possibility that this deviation is related to the asymmetry of the fitted profile. However, even if this is the case something in the data must have changed to cause this, whether it be an instrumental artifact or a real solar effect. Mode asymmetries are believed to occur because the source that excites the oscillations is located in a restricted spatial extent, close to the upper boundary of the oscillations (e.g. Duvall et al., 1993; Roxburgh and Vorontsov, 1995). A further contribution comes from the effects of correlated background noise from the source (e.g. Nigam et al., 1998; Severino et al., 2001). A change in the asymmetry of the oscillations could, therefore, imply a change in the position of the dominant excitation source. However, the sign of the asymmetry is determined by the method of observation and more specifically whether one is using Doppler velocity or intensity measurements (Nigam et al., 1998). Furthermore, asymmetries are notoriously hard to fit accurately and precisely. Alternative explanations could be formulated in terms of the depth in the atmosphere at which the observations are made. Further investigations are, therefore, required to determine the exact nature of the deviation in power and energy supply rate. Nevertheless it will be interesting to see if the powers return to predicted values as cycle 24 progresses.

Acknowledgements

A-MB thanks the Institute of Advanced Study, University of Warwick for their support. VMN: This work was supported by the European Research Council under the *SeismoSun* Research Project No. 321141, STFC consolidated Grant ST/L000733/1, and the BK21 plus program through the National Research Foundation funded by the Ministry of Education of Korea. We thank the Birmingham Solar Oscillations Network, the GOLF/SOHO team, and NOAA NGDC for making their data freely available. The research leading to these results has received funding from the European Community's Seventh Framework Programme ([FP7/2007–2013]) under Grant agreement No. 312844 (see Article II.30 of the Grant Agreement).

References

Basu, S., Broomhall, A.-M., Chaplin, W.J., Elsworth, Y., 2012. Thinning of the sun's magnetic layer: the peculiar solar minimum could have been predicted. ApJ 758, 43.

Bazilevskaya, G., Broomhall, A.-M., Elsworth, Y., Nakariakov, V.M., 2014. A combined analysis of the observational aspects of the quasi-biennial oscillation in solar magnetic activity. Space Sci. Rev.

Broomhall, A.-M., Chatterjee, P., Howe, R., Norton, A.A., Thompson, M.J., 2014. The sun's interior structure and dynamics, and the solar cycle. Space Sci. Rev. 186, 191–225.

Brown, T.M., Bogdan, T.J., Lites, B.W., Thomas, J.H., 1992. Localized sources of propagating acoustic waves in the solar photosphere. ApJL 394, L65–L68.

Chaplin, W.J., Elsworth, Y., Isaak, G.R., Miller, B.A., New, R., 2000. Variations in the excitation and damping of low-*l* solar *p* modes over the solar activity cycle*. MNRAS 313, 32–42.

Chaplin, W.J., Elsworth, Y., Isaak, G.R., Miller, B.A., New, R., Pintér, B., Thiery, S., 2003. On the measurement bias of low-*l* solar *p*-mode excitation parameters: the impact of a ground-based window function. A&A 398, 305–314.

Christensen-Dalsgaard, J., Berthomieu, G., 1991. Theory of solar oscillations. Solar Interior Atmos., 401–478

Davies, G.R., Chaplin, W.J., Elsworth, Y., Hale, S.J., 2014. BiSON data preparation: a correction for differential extinction and the weighted averaging of contemporaneous data. MNRAS 441, 3009–3017.

Duvall Jr., T.L., Jefferies, S.M., Harvey, J.W., Osaki, Y., Pomerantz, M.A., 1993. Asymmetries of solar oscillation line profiles. ApJ 410, 829–836.

Elsworth, Y., Howe, R., Isaak, G.R., McLeod, C.P., New, R., 1990. Variation of low-order acoustic solar oscillations over the solar cycle. Nature 345, 322–324.

Fletcher, S.T., Chaplin, W.J., Elsworth, Y., New, R., 2009. Efficient pseudo-global fitting for helioseismic data. ApJ 694, 144–150.

Gabriel, A.H., Grec, G., Charra, J., Robillot, J., Roca Cortés, T., Turck-Chièze, S., Bocchia, R., Boumier, P., Cantin, M., Cespédes, E., Cougrand, B., Crétolle, J., Damé, L., Decaudin, M., Delache, P., Denis, N., Duc, R., Dzitko, H., Fossat, E., Fourmond, J., García, R.A., Gough, D., Grivel, C., Herreros, J.M., Lagardère, H., Moalic, J., Pallé, P.L., Pétrou, N., Sanchez, M., Ulrich, R., van der Raay, H.B., 1995. Global oscillations at low frequency from the SOHO mission (GOLF). Sol. Phys. 162, 61–99.

García, R.A., Turck-Chièze, S., Boumier, P., Robillot, J.M., Bertello, L., Charra, J., Dzitko, H., Gabriel, A.H., Jiménez-Reyes, S.J., Pallé, P.L., Renaud, C., Roca Cortés, T., Ulrich, R.K., 2005. Global solar Doppler velocity determination with the GOLF/SoHO instrument. Astron. Astrophys. 442, 385–395.

García, R.A., Mathur, S., Salabert, D., Ballot, J., Régulo, C., Metcalfe, T.S., Baglin, A., 2010. CoRoT reveals a magnetic activity cycle in a Sun-like star. Science 329, 1032.

Houdek, G., Chaplin, W.J., Appourchaux, T., Christensen-Dalsgaard, J., Däppen, W., Elsworth, Y., Gough, D.O., Isaak, G.R., New, R., Rabello-Soares, M.C., 2001. Changes in convective properties over the solar cycle: effect on *p*-mode damping rates. MNRAS 327, 483–487.

Howe, R., Komm, R.W., Hill, F., Haber, D.A., Hindman, B.W., 2004. Activity-related changes in local solar acoustic mode parameters from Michelson doppler imager and global oscillations network group. ApJ 608, 562–579.

Jefferies, S.M., Duvall Jr., T.L., Harvey, J.W., Pomerantz, M.A., 1990. Helioseismology from the south pole: results from the 1987 campaign. In: Osaki, Y., Shibahashi, H. (Eds.), Progress of Seismology of the Sun and Stars, Lecture Notes in Physics, vol. 367. Springer Verlag, Berlin, p. 135.

Jiménez, A., Roca Cortés, T., Jiménez-Reyes, S.J., 2002. Variation of the low-degree solar acoustic mode parameters over the solar cycle. Sol. Phys. 209, 247–263.

Jiménez-Reyes, S.J., Chaplin, W.J., Elsworth, Y., García, R.A., Howe, R., Socas-Navarro, H., Toutain, T., 2007. On the variation of the peak asymmetry of low-*l* solar *p* modes. ApJ 654, 1135–1145.

Komm, R.W., Howe, R., Hill, F., 2000. Width and energy of solar *p*-modes observed by global oscillation network group. ApJ 543, 472–485.

Komm, R., Howe, R., Hill, F., 2002. Localizing width and energy of solar global *p*-modes. ApJ 572, 663–673.

Lites, B.W., White, O.R., Packman, D., 1982. Photoelectric observations of propagating sunspot oscillations. ApJ 253, 386–392.

Nigam, R., Kosovichev, A.G., 1998. Measuring the Sun's eigenfrequencies from velocity and intensity helioseismic spectra: asymmetrical line profile-fitting formula. ApJL 505, L51–L54.

Nigam, R., Kosovichev, A.G., Scherrer, P.H., Schou, J., 1998. Asymmetry in velocity and intensity helioseismic spectra: a solution to a long-standing puzzle. ApJL 495, L115–L118.

Pallé, P.L., Régulo, C., Roca Cortés, T., 1990. The spectrum of solar *p*-modes and the solar activity cycle. In: Osaki, Y., Shibahashi, H. (Eds.), Progress of Seismology of the Sun and Stars, Lecture Notes in Physics, vol. 367. Springer Verlag, Berlin, p. 129.

Rajaguru, S.P., Basu, S., Antia, H.M., 2001. Ring diagram analysis of the characteristics of solar oscillation modes in active regions. ApJ 563, 410–418.

Roxburgh, I.W., Vorontsov, S.V., 1995. An asymptotic description of solar acoustic oscillations with an elementary excitation source. MNRAS 272, 850–858.

Salabert, D., Chaplin, W.J., Elsworth, Y., New, R., Verner, G.A., 2007. Sun-as-a-star observations: evidence for degree dependence of changes in damping of low-ℓ p modes along the solar cycle. A&A 463, 1181–1187.

Salabert, D., Garcia, R.A., Turck-Chieze, S., 2015. Seismic sensitivity to sub-surface solar activity from 18 years of GOLF/SoHO observations. ArXiv e-prints.

Severino, G., Magrì, M., Oliviero, M., Straus, T., Jefferies, S.M., 2001. The solar intensity-velocity cross spectrum: a powerful diagnostic for helioseismology. ApJ 561, 444–449.

Woodard, M.F., Noyes, R.W., 1985. Change of solar oscillation eigen frequencies with the solar cycle. Nature 318, 449.

Woods, D.T., Cram, L.E., 1981. High resolution spectroscopy of the disk chromosphere. VII - Oscillations in plage and quiet sun regions. Sol. Phys. 69, 233–238.