THE AMPLITUDE OF SOLAR OSCILLATIONS USING STELLAR TECHNIQUES

HANS KJELDSEN,1 TIMOTHY R. BEDDING,2 TORBEN ARENTOFT,1 R. PAUL BUTLER,3 THOMAS DALL,3 CHRISTOFFER KAROFF,1 LÁSZLÓ L. KISS,2 C. G. TINNEY5 AND WILLIAM J. CHAPLIN6

Submitted to ApJ

ABSTRACT

The amplitudes of solar-like oscillations depend on the excitation and damping, both of which are controlled by convection. Comparing observations with theory should therefore improve our understanding of the underlying physics. However, theoretical models invariably compute oscillation amplitudes relative to the Sun, and it is therefore vital to have a good calibration of the solar amplitude using stellar techniques. We have used daytime spectra of the Sun, obtained with HARPS and UCLES, to measure the solar oscillations and made a detailed comparison with observations using the BiSON helioseismology instrument. We find that the mean solar amplitude measured using stellar techniques, averaged over one full solar cycle, is $18.7 \pm 0.7 \, \text{cm s}^{-1}$ for the strongest radial modes ($l = 0$) and $25.2 \pm 0.9 \, \text{cm s}^{-1}$ for $l = 1$. In addition, we use simulations to establish an equation that estimates the uncertainty of amplitude measurements that are made of other stars, given that the mode lifetime is known. Finally, we also give amplitudes of solar-like oscillations for three stars that we measured from a series of short observations with HARPS ($\gamma$ Ser, $\beta$ Aql and $\alpha$ For), together with revised amplitudes for five other stars for which we have previously published results ($\alpha$ Cen A, $\alpha$ Cen B, $\beta$ Hya, $\nu$ Ind and $\delta$ Pav).

Subject headings: Sun: helioseismology — stars: oscillations — stars: individual ($\gamma$ Ser, $\beta$ Aql, $\alpha$ For, $\alpha$ Cen A, $\alpha$ Cen B, $\beta$ Hya, $\nu$ Ind, $\delta$ Pav)

1. INTRODUCTION

The list of stars in which solar-like oscillations have been observed is growing rapidly, thanks to improvements in high-precision velocity measurements (for a recent review see Bedding & Kjeldsen 2007). While most excitement centres on the frequencies of the oscillations, there is also considerable interest in the amplitudes (e.g., Christensen-Dalsgaard & Frandsen 1983; Kjeldsen & Bedding 1995; Houdek et al. 1999; Houdek & Gough 2002; Samadi et al. 2005, 2007a,b; Houdek 2006). This is because the excitation and damping are both controlled by convection and so the study of oscillation amplitudes will hopefully lead to an improvement in our understanding of the underlying physics.

Theoretical calculations of oscillation amplitudes, such as those cited above, are calibrated with reference to the Sun. It is therefore crucial to establish the amplitudes of the solar oscillations. There is an abundance of solar observations from helioseismology projects such as BiSON (Birmingham Solar Oscillations Network) and GOLF (Global Oscillations at Low Frequencies). However, these velocity measurements are made using a single spectral line, such as sodium ($\lambda$5896 Å, used by GOLF) or potassium ($\lambda$7699 Å, BiSON), and the measured oscillation amplitude depends on the height in the solar atmosphere at which the spectral line is formed (e.g., Isaak et al. 1989, Baudin et al. 2005, Houdek 2006). Velocity measurements of other stars, on the other hand, employ a wide wavelength range that includes many spectral lines, mostly from neutral iron. The iron lines are formed lower in the atmosphere than sodium and potassium and so we might expect solar amplitudes measured using stellar techniques to be lower than those from helioseismic measurements such as BiSON and GOLF. On the other hand, BiSON and GOLF measure velocities using a resonance scattering cell, whereas the stellar technique involves measuring line centroids. These approaches have different sensitivities as a function of the mode angular degree $l$ (Christensen-Dalsgaard 1989), which must be corrected for when interpreting measured amplitudes.

We have recently pointed out the importance of establishing the oscillation amplitude of the Sun using stellar techniques (Kjeldsen et al. 2005). In that paper, we reported a limited set of observations of the solar oscillations obtained from spectra of the full moon. The results gave some support to the conclusion that Fe I measurements give lower amplitudes than both GOLF and BiSON, but we emphasized the desirability of obtaining more measurements of the Sun, in order to better calibrate the relationship between stellar and solar amplitudes. That is the main purpose of this paper.

2. OBSERVATIONS

We have obtained solar spectra by observing the daytime sky. Although detailed line profiles of daytime spectra show differences from the actual solar spectrum (Gray et al. 2000), and the bisector varies with solar activity, there is no reason to suspect any systematic effects on mean velocities on the timescale of the 5-minute oscillations.

We made the observations in 2005 September during a dual-site asteroseismology campaign on the star $\beta$ Hya (Bedding et al. 2007). Figure 1 shows the full set of data. At the European Southern Observatory on La Silla in Chile we used

---

1 Danish AsteroSeismology Centre (DASC), Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark; hans@phys.au.dk, karoff@phys.au.dk
2 School of Physics A28, University of Sydney, NSW 2006, Australia; bedding@physics.usyd.edu.au, laszlo@physics.usyd.edu.au
3 Carnegie Institution of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Road NW, Washington, DC 20015-1305; paul@dtm.ciw.edu
4 Gemini Observatory, 670 N. Aohoku Pl., Hilo, HI 96720, USA; tdall@gemini.edu
5 School of Physics, University of NSW, 2052, Australia; cgt@phys.unsw.edu.au
6 School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK; wjc@bison.ph.bham.ac.uk
7 Based on observations collected at the European Southern Observatory, La Silla, Chile (ESO Programme 075.D-0760)
the HARPS spectrograph with the 3.6-m telescope. A thorium emission lamp was used to provide a stable wavelength reference. We obtained 626 spectra over 9.7 hr spread over four consecutive afternoons, with typical exposure times of 25 s and a median cadence of one exposure every 56 s (which corresponds to a Nyquist frequency of 8.9 mHz). The velocities were processed using the standard HARPS pipeline.

At Siding Spring Observatory in Australia we used UCLES (University College London Echelle Spectrograph) with the 3.9-m Anglo-Australian Telescope (AAT). An iodine absorption cell was used to provide a stable wavelength reference, with the same setup that we have previously used with this spectrograph (Butler et al., 2004). With UCLES we obtained 265 spectra of the Sun over about 8.5 hr, spread over three non-consecutive afternoons. Typical exposure times were 45–60 s, with a median cadence of one exposure every 115 s (which corresponds to a Nyquist frequency of 4.35 mHz).

In addition, we have analysed velocities obtained by BiSON (Birmingham Solar Oscillations Network) over the first 10 days of 2005 September, which covers the period in which the UCLES and HARPS data were taken. We also examined a 14-year time series (1992.6 to 2006.9) from the BiSON archive, which allows us to follow variations in amplitude with the solar activity cycle (see §3.3). The BiSON data have 40-second sampling. They had also been high-pass filtered by subtracting a moving mean calculated in a boxcar of length 1000 s (which corresponds to a Nyquist frequency of 8.9 mHz).

As mentioned above, the night-time target for this asteroseismology campaign was the star β Hyi. However, β Hyi was not accessible to HARPS for the first part of each night due to hour-angle restrictions on the ESO 3.6-m telescope. We used this time to observe two other stars, taken from the list of target priorities presented by Bedding et al. (1996). The first was γ Ser (HR 5933, HD 142860, HIP 78072), which has spectral type F6 IV-V and magnitude V = 3.85, and was observed for about 75 minutes at the start of each of three consecutive nights. The second star was β Aql (HR 7602, HD 188512, HIP 98036), spectral type G8 IV and magnitude V = 3.71, which was observed on four consecutive nights for periods of 65, 95, 10 and 70 minutes, respectively.

This limited set of observations was not sufficient to allow us to measure oscillation frequencies, but we were able to estimate the amplitudes, in the same way as we have previously done for the star δ Pav (Kjeldsen et al., 2005). In addition, we also analysed observations of the star α For (HR 963, HD 20010, HIP 14879), which has spectral type F8 IV and magnitude V = 3.85. Those observations were taken with HARPS in 2007 January for about 20-30 minutes at the start of each of seven consecutive nights, during a multi-site campaign on Procyon (T. Arentoft et al., in prep.). Note that the behaviour of the line bisections for these observations of γ Ser and β Aql were already discussed by Dall et al. (2006).

3. ANALYSIS AND RESULTS

3.1. Time series and power spectra

The first step in the analysis of the solar velocities from HARPS and UCLES was to remove slow trends from each data set by a high-pass filter that only affected frequencies below 1 mHz. Figure 2 shows a close-up comparison of HARPS and BiSON for one afternoon of data (160 min). There is excellent agreement and we see that the two data sets are of comparable quality. The UCLES data have somewhat poorer precision per data point.

The next step was to calculate the power spectra of the velocities. For HARPS and UCLES, we used the measurement uncertainties, σi, as weights in calculating the power spectrum (according to $w_i = 1/\sigma_i^2$). No uncertainty estimates were available for the BiSON velocities and so all points were given equal weight. The power spectrum of the HARPS time series is shown in the upper panel of Fig. 5, while the lower panel shows the spectrum of the segment of BiSON data taken at the same times. We see that the HARPS and BiSON power spectra are very similar. Figure 4 shows a similar analysis for the UCLES data and the corresponding BiSON segment. The UCLES power spectrum has higher noise but, taking this into account, we again see good agreement between the two. A comparison of Figures 5 and 4 shows that the solar power spectrum was quite different for the two time series, reflecting the intrinsic variations in the solar oscillations. Given that the HARPS data have lower noise than the UCLES data, we do not show results for UCLES in the remainder of the analysis.

3.2. Calculating smoothed amplitude spectra

The amplitudes of individual modes are affected by the stochastic nature of the excitation and damping. To measure the oscillation amplitude in a way that is independent of these effects, we have followed the method introduced by Kjeldsen et al. (2005). In brief, this involves the following steps: (i) heavily smoothing the power spectrum (by an amount defined in the next paragraph), to produce a single hump of excess power that is insensitive to the fact that the oscillation spectrum has discrete peaks; (ii) converting to power density by multiplying by the effective length of the observing run (which we calculate as the reciprocal of the area under the spectral window in power); (iii) fitting and subtracting the background noise; and (iv) multiplying by $\Delta \nu/c$ and taking the square root, in order to convert to amplitude per oscillation mode. Here, $\Delta \nu$ is the large frequency separation, which has a value of 135 $\mu$Hz in the Sun, and $c$ is a factor that measures the effective number of modes per order.

The amount of smoothing affects the exact height of the smoothed amplitude spectrum. To establish a standard that allows comparisons, we propose that smoothing be done by convolving (in power) with a Gaussian having a full width at half maximum of 4$\Delta \nu$. We have adopted this convention for all the figures and measurements in this paper.

3.2.1. The value of $c$

In our previous work, we used a value of $c = 3.0$ (Kjeldsen et al., 2005; Bedding et al., 2006, 2007). However, $c$ depends on the sensitivity of the observations to the various low-degree modes, which in turn depends on the method used to observe the oscillations. We therefore reconsider the calculation of $c$, as follows. Let $S_l/S_0$ be the spatial response of the observations to modes with degree $l$, relative to those with $l = 0$. Table 4 of Christensen-Dalsgaard (1989) allows us to calculate $S_l/S_0$ for BISON velocity observations and these are shown in Table II. We have also calculated values for velocity observations using the stellar technique, using the results in Bedding et al. (1996) for an adopted mean wavelength of 550 nm. These are also shown in Table II. The difference from
the BiSON values arises from the way the BiSON resonance scattering cell measures velocities, as discussed in detail by Christensen-Dalsgaard (1989). Finally, Table 1 also shows the response factors for intensity measurements at the three wavelengths of the SoHO VIRGO instrument, again derived from the results in Bedding et al. (1996). For BiSON, Christensen-Dalsgaard (1989) has calculated $S_0 = 0.724$, while for stellar velocity measurements we have used the results in Bedding et al. (1996) to derive $S_0 = 0.712$ (again, for an adopted mean wavelength of 550 nm).

3.3. The solar amplitude

The smoothed amplitude spectrum for our solar observations with HARPS is shown in Fig. 8 together with that from BiSON from exactly the same observation times. Note that here we did not use the weights when calculating the HARPS power spectrum, since these were not available for BiSON and we wanted to make the window functions exactly the same. The amplitude of solar oscillations measured using the stellar technique is slightly lower than that measured by BiSON, by a factor of 1.07 ± 0.04. The error bar comes from the uncertainty in fitting the background to the HARPS spectrum. However, we must keep in mind that our observations of the Sun were made over only a few hours, and at a single epoch during the 11-year solar cycle. To correct for this and hence determine the mean amplitude of the Sun, we have made use of the full set of BiSON observations.

We have analysed the 14-year time series from the BiSON archive, measuring amplitudes in ten-day segments in the way described above. In practice we chose all segments to have the same number of data points, which meant that the lengths of most segments were in the range 8–12 d, reflecting variations in the filling factor of the network. The result is shown in Fig. 6 where each point represents the peak amplitude in one segment. We see clearly the variations in amplitude with the solar activity cycle, as has been well studied from these BiSON data by Chaplin et al. (2000, 2003).

Note that the scatter in the amplitudes in Fig. 6 is not measurement error, but rather reflects the intrinsic variability of the modes. We see that both the amplitude and the scatter on the amplitude are smallest at solar maximum (2001), which is explained by the shorter mode lifetime during periods of high solar activity. Any changes in the excitation rate during the solar cycle would also contribute to amplitude variability, but no evidence for such changes has so far been reported.

The mean BiSON amplitude over one 11-year solar cycle, measured from the data in Fig. 6, is 20.0 ± 0.1 cm s$^{-1}$. Combining this with the result in the previous section, we conclude that the mean amplitude of the radial oscillations in the Sun, measured using stellar techniques, is 18.7 ± 0.7 cm s$^{-1}$. This is the quantity that we were seeking to measure. It is important to remember that this is based on the process we used (including the 4$\Delta\nu$-smoothing described in §3.4) and is normalized to the mode with $l = 0$. Values for non-radial modes can be calculated from the ratios in column 3 of Table 1. For example, the mean peak amplitude for $l = 1$ modes is significantly higher than for $l = 0$, and both are given in the first line of Table 1.

Figure 7 shows smoothed amplitude spectra for 10-day segments of BiSON data for one full year, starting at 2005.0. This period covers the solar minimum and so the variations are dominated by the stochastic nature of the excitation and damping, rather than by variations due to the solar cycle. Note that the curves show less spread at the higher frequencies than at the lower frequencies, reflecting the fact that the mode lifetimes in the Sun increase with frequency.

The mean of these curves is shown in Fig. 8 after scaling so that the peak is 18.7 cm s$^{-1}$, which is the solar mean as measured with stellar techniques.

3.4. Amplitudes for other stars

In Figure 8 we show the amplitude curves for the three stars described in Table 2 ($\beta$ Aql, $\alpha$ Ser, and $\gamma$ Ser), together with five other stars for which we have previously published amplitudes: $\alpha$ Cen A, $\alpha$ Cen B and $\delta$ Pav (Kjeldsen et al. 2005), $\nu$ Ind (Bedding et al. 2006) and $\beta$ Hyi (Bedding et al. 2007). All the curves were calculated using the revised method described in §3.2.

Table 2 summarizes our results for the Sun and these eight stars. Column 2 gives the large frequency separation that we used in the calculation (there are no measurements of $\Delta\nu$ for $\alpha$ Ser, $\alpha$ For, $\beta$ Aql and $\delta$ Pav and so we estimated a value from the stellar parameters). Column 3 of Table 2 gives our measurement of $\nu_{\text{max}}$, the frequency of the envelope peak, and column 4 gives the peak height (the amplitude per radial mode, as plotted in Fig. 8). Column 5 gives the peak amplitude of the $l = 1$ modes, using the calibration factor of $S_1/S_0 = 1.35$ (see Table 1), which we include to emphasise that the strongest peaks will generally be those with $l = 1$.

3.5. The uncertainty in measuring oscillation amplitudes

Part of the uncertainty in each measured oscillation amplitude arises from the precision with which we can fit and subtract the background. This is a measurement error and is given in columns 4 and 5 of Table 2.

In addition, stars will presumably have variations with activity cycle, analogous to the $\sim \pm 5\%$ variation seen in the Sun, but for the moment we do not have enough information to estimate those effects. However, we can estimate the scatter on the measured amplitude that is caused by the finite lifetime of the modes. This arises because a typical stellar observing run does not last long enough to sample a large number of mode lifetimes.

For the BiSON data in Fig. 6 the relative scatter of the measured amplitude about the smoothed curve has an average value of $\sigma_A/A = 6.2 \pm 0.2\%$. This relative scatter $\sigma_A/A$ depends on
two parameters. One is $T/\tau$, where $T$ is the duration of the observations (10 d in this case) and $\tau$ is the mode lifetime. The other parameter is $N$, the number of independent low-degree oscillation modes that are excited within the smoothed envelope, which is about 30 in the Sun. We expect $\sigma_A/A$ to vary inversely with both of these parameters:

$$\sigma_A/A = k N \left(1 + \frac{T}{\tau}\right)^{-0.5}.$$  

(2)

We have verified that equation (2) holds, and that the constant of proportionality is $k = 0.75$, by using simulations with different values of the parameters. We simulated the stochastic nature of the oscillations using the method described by De Ridder et al. (2006).

Our decision to adopt a smoothing width of $4\Delta\nu$ (Equation 2) means that $N$ will be the same for all stars (provided there are not a large number of additional mixed modes in the power spectrum). Since we know the mode lifetime of the Sun, we can calibrate equation (2) using the solar value of $\sigma_A/A = 6.2 \pm 0.2\%$ for the 10-d segments of BiSON data. The average mode lifetime in the Sun, measured from the linewidths in the range 2.8–3.4 mHz, is $2.88 \pm 0.07$ d (Chaplin et al. 1997). Using this, we get

$$\sigma_A/A = (0.131 \pm 0.004) \left(1 + \frac{T}{\tau}\right)^{-0.5}.$$  

(3)

Equation 3 can be used to estimate the uncertainty of amplitude measurements that are made on other stars, provided $\tau$ is known.

The last column of Table 2 shows $\sigma_A/A$ for the observations. We have used published measurements of mode lifetimes for $\alpha$ Cen A and B (Kjeldsen et al. 2005), $\nu$ Ind (Carrier et al. 2007) and $\beta$ Hyi (Bedding et al. 2007). There are no measurements available for the other stars ($\gamma$ Ser, $\beta$ Aql, $\alpha$ For and $\delta$ Pav) and so we adopted the solar value.

To obtain the total uncertainties for the amplitudes in Table 2, the uncertainty from the background subtraction should be added in quadrature to $\sigma_A/A$ (although in practice, the latter dominates). Finally, we repeat that there is an additional source of uncertainty in these amplitude measurements, namely any variations with stellar activity cycle.

4. CONCLUSIONS

We have used daytime spectra of the blue sky, obtained with the stellar spectrographs HARPS and UCLesen, to measure oscillations in the Sun. We measured amplitudes by smoothing in power density and subtracting the background, as previously described by Kjeldsen et al. (2005). In this paper we propose two conventions in the use of this method. Firstly, we suggest the smoothing be done by convolution with a Gaussian having a FWHM (in power) of $4\Delta\nu$. Secondly, we have chosen to report mean amplitudes for the radial modes ($l = 0$), but stress that the highest peaks in the amplitude spectrum will generally correspond to $l = 1$.

In the daytime sky observations reported here, the solar oscillation amplitude was slightly lower than that measured simultaneously by BiSON, by a factor of $1.07 \pm 0.04$. This difference arises from two factors: (i) the stellar techniques measure a velocity that is dominated by neutral iron lines, which are formed lower in the solar atmosphere than the potassium line measured by BiSON; (ii) the two methods have slightly different spatial response functions.

A single-epoch measurement of the solar amplitude has a significant uncertainty due to the stochastic nature of the oscillations. We find the mean solar amplitude measured by BiSON over one full solar cycle (for radial modes) to be $20.0 \pm 0.1$ cm s$^{-1}$, implying a mean amplitude measured using stellar techniques of $18.7 \pm 0.7$ cm s$^{-1}$. The mean peak amplitude for $l = 1$ modes is $25.2 \pm 0.9$ cm s$^{-1}$.

By using simulations, we have estimated the scatter in the amplitude measured from solar-like oscillations that arises from the stochastic nature of the excitation and damping. The result is given in Equation 3 which matches the scatter that we find from BiSON observations of the Sun. This equation can be used to estimate the uncertainty of amplitude measurements that are made on other stars, provided the mode lifetime is known.

Finally, Table 2 gives amplitudes for three stars ($\gamma$ Ser, $\beta$ Aql and $\alpha$ For) that were measured from a series of short observations with HARPS, together with revised amplitudes for five other stars for which we have previously published results. Now that the solar amplitude is established, these measurements should be valuable tests for theoretical models of solar-like oscillation amplitudes.

We thank Graham Verner for providing the time series of BiSON velocity measurements, and Yvonne Elsworth for comments on this paper. We thank ESO and the AAO for supporting the daytime observations. This work was supported financially by the Danish Natural Science Research Council and the Australian Research Council. We further acknowledge support by NSF grant AST-9988087 (RPB), and by SUN Microsystems. CK acknowledges support from the Danish AsteroSeismology Centre and the Instrument Center for Danish Astrophysics.

REFERENCES

Baudin, F., Samadi, R., Goupil, M.-J., Appourchaux, T., Barban, C., Bournier, P., Chaplin, W. J., & Gouttebroze, P., 2005, A&A, 433, 349.  
Bedding, T. R., Butler, R. P., Carrier, F., et al., 2006, ApJ, 647, 558.  
Bedding, T. R., & Kjeldsen, H., 2007, Commun. Asteroseismology, 150, 106.  
Bedding, T. R., Kjeldsen, H., Arens, T., et al., 2007, ApJ, 663, 1315.  
Bedding, T. R., Kjeldsen, H., Reetz, J., & Barbay, B., 1996, MNRAS, 280, 1155.  
Butler, R. P., Bedding, T. R., Kjeldsen, H., et al., 2004, ApJ, 600, L75.  
Carrier, F., Kjeldsen, H., Bedding, T. R., et al., 2007, A&A, 470, 1059.  
Chaplin, W. J., Elsworth, Y., Isaak, G. R., McLeod, C. P., Miller, B. A., & New, R., 1997, MNRAS, 288, 623.  
Chaplin, W. J., Elsworth, Y., Isaak, G. R., Miller, B. A., & New, R., 2000, MNRAS, 315, 32.  
Chaplin, W. J., Elsworth, Y., Isaak, G. R., Miller, B. A., New, R., & Toutain, T., 2003, ApJ, 582, L115.  
Christensen-Dalsgaard, J., 1989, MNRAS, 239, 977.  
Christensen-Dalsgaard, J., & Frandsen, S., 1983, Sol. Phys., 82, 469.  
Dall, T. H., Santos, N. C., Arens, T., Bedding, T. R., & Kjeldsen, H., 2006, A&A, 454, 341.  
De Ridder, J., Arens, T., & Kjeldsen, H., 2006, MNRAS, 365, 595.  
Gizon, L., & Solanki, S. K., 2003, ApJ, 589, 1009.  
Gray, D. F., Tycner, C., & Brown, K., 2000, PASP, 112, 328.  
Houdek, G., 2006, In Fletcher, K., editor, Beyond the Spherical Sun: a new era in helio- and asteroseismology. Proc. SOHO18/GONG 2006/HeIAs I, SP-624, page 28: astro-ph/0612024.  
Houdek, G., Balbus, M., Christensen-Dalsgaard, J., & Gough, D. O., 1999, A&A, 351, 582.  
Houdek, G., & Gough, D. O., 2002, MNRAS, 336, L65.  
Isaak, G. R., McLeod, C. P., Pallé, P. L., van der Raay, H. B., & Roca Cortés, T., 1989, A&A, 208, 297.  
Kjeldsen, H., & Bedding, T. R., 1995, A&A, 293, 87.  
Kjeldsen, H., Bedding, T. R., Butler, R. P., et al., 2005, ApJ, 635, 1281.
Samadi, R., Belkacem, K. B., Goupil, M.-J., Kupka, F. G., & Dupret, M.-A., 2007a, In Kupka, F., Roxburgh, I. W., & Chan, K. L., editors, IAU Symp. 239: Convection in Astrophysics. in press (astro-ph/0611760).

Samadi, R., Georgobiani, D., Trampedach R., R., Goupil, M. J., Stein, R. F., & Nordlund, A., 2007b, A&A, 463, 297.

Samadi, R., Goupil, M.-J., Alecian, E., Baudin, F., Georgobiani, D., Trampedach, R., Stein, R., & Nordlund, Å., 2005, JA&A, 26, 171.

### TABLE 1

**SPATIAL RESPONSE FUNCTIONS**

|         | BiSON velocities | Stellar velocities | 402 nm | 500 nm | 862 nm |
|---------|------------------|--------------------|--------|--------|--------|
| $S_1/S_0$ | 1.37             | 1.35               | 1.26   | 1.25   | 1.20   |
| $S_2/S_0$ | 1.08             | 1.02               | 0.81   | 0.75   | 0.67   |
| $S_3/S_0$ | 0.58             | 0.47               | 0.25   | 0.18   | 0.10   |
| $S_4/S_0$ | 0.22             | 0.09               | −0.03  | −0.06  | −0.10  |
| $c$      | 4.43             | 4.09               | 3.31   | 3.16   | 2.91   |
### Table 2

**Amplitudes of velocity oscillations**

| Star     | $\Delta \nu$ (\(\mu\)Hz) | $v_{\text{max}}$ (mHz) | $v_{\text{osc}}$ (cm s\(^{-1}\)) | $I = 0$ | $I = 1$ | $\sigma_{A}/A$ |
|----------|-----------------------------|-------------------------|-----------------------------------|---------|---------|----------------|
| Sun...   | 134.8                       | 3.1                     | 18.7 ± 0.7                        | 25.2 ± 0.9 | 0.3%    |
| $\gamma$ Ser... | 90 1.6                       | 1.1                     | 34.2 ± 1.3                        | 46.2 ± 1.8 | 10%     |
| $\alpha$ For... | 60 1.1                       | 1.1                     | 34.8 ± 0.9                        | 47.0 ± 1.2 | 7%      |
| $\beta$ Aql... | 30 0.41                      | 2.4                     | 48.4 ± 1.3                        | 56.9 ± 1.5 | 9%      |
| $\alpha$ Cen A... | 106.2 2.4                    | 4.1                     | 7.2 ± 0.1                         | 9.7 ± 0.2 | 7%      |
| $\beta$ Aql... | 106.2 2.4                    | 4.1                     | 7.2 ± 0.1                         | 9.7 ± 0.2 | 7%      |
| $\nu$ Ind... | 25.1 0.32                    | 64.7 ± 0.9              | 87.4 ± 1.3                        | 10%     |
| $\delta$ Pav... | 93 2.3                       | 19.5 ± 0.4              | 26.3 ± 0.5                        | 8%      |

**Fig. 1.** — Velocity time series of the Sun measured from the blue sky by HARPS (red squares) and UCLES (black diamonds).

**Fig. 2.** — Close-up showing 160 min of the HARPS (red squares) together with contemporaneous measurements by BiSON (black diamonds).

**Fig. 3.** — Power spectrum of the HARPS velocities of the Sun (upper), and of the BiSON series taken at the same times (lower).
FIG. 4.— Same as Fig. 3 but for UCLES and the corresponding BiSON data.

FIG. 5.— Amplitude per mode of oscillations in the Sun, as measured from the power spectra in Fig. 3.

FIG. 6.— Amplitude of solar oscillations measured from BiSON data. The points were measured from independent 10-day segments of data and the thick line is after smoothing with a boxcar running mean of 50 points (500 days).
Fig. 7.— Smoothed amplitude spectra of solar oscillations measured from BiSON data in the year 2005. Each curve was measured from an independent 10-day segment of data.

Fig. 8.— Smoothed amplitude curves for oscillations in the Sun and other stars (see text for details).