INPUTS FROM HELIOSEISMOLOGY TO SOLAR PHYSICS

SOLAR ACTIVITY AND SOLAR OSCILLATIONS

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1. Introduction

Helioseismology provides us with the tools to probe solar activity. So that we can consider how the solar oscillations are influenced by that activity, we first consider the phenomena that we associate with the active Sun. The surface of the Sun is not quiet but shows evidence of convection on a wide range of scales from a few hundred kilometres through to several tens-of-thousands of kilometres. The surface temperature shows signs of the convection structures with the temperature in the bright granules being some 100 K to 200 K hotter than the surrounding dark lanes. Sunspots, which are regions of high magnetic field that suppress convective flows, are clearly visible to even quite crude observations. They are several tens-of-thousands of kilometres in diameter and about 2000 K cooler than their surroundings. Ultraviolet and X-ray pictures from satellites show that the higher layers of the solar atmosphere are very non-uniform with bright regions of high activity. Contemporaneous magnetograms show that these regions are associated with sunspots. Flares – regions of magnetic reconnections – are seen at all wavelengths from X-ray through the visible to radio. They are the non-thermal component of the radio emission of the Sun. There are many other indicators of activity on the Sun.

Precise correlations between individual regions of solar activity and the observations of solar oscillations are still scarce and in this paper we consider principally the correlations between activity and the average behaviour of the Sun. We are concerned with how solar oscillations probe solar activity and we seek correlations between these signatures of activity and some characteristics of the oscillations. The oscillations themselves can be described by the "degree" and frequency of the modes. In general, instruments which are good at making measurements on the very low-degree modes are not sensitive to the higher-degree modes, while those instruments

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that have spatial resolution to measure the higher degrees do not produce very precise measurements of the low-degree modes. Modes of different degrees probe different volumes in the Sun. According to asymptotic theory, the inner turning point is determined by $\nu/[\ell(\ell+1)]$, where ν is the frequency of the mode and ℓ is its angular degree. The upper turning points are also a function of the mode under consideration, but in this case, up to moderate ℓ, the modes are essentially vertical at the surface and their behaviour is a function of frequency alone and not angular degree. The lower-frequency modes have upper turning points deeper in the Sun than do higher-frequency modes and so, for a phenomenon localised very near to the surface of the Sun, we can expect that its effect will depend principally on the frequency of the mode.

2. Solar Cycle

Activity levels on the Sun are well known to vary on many different timescales. In order to characterise the activity we use various proxies – the most famous and longest measured of which is the sunspot number. There are other several other measures that can be used: for example the 10.7-cm radio flux, which comes primarily from the higher levels in the solar atmosphere; the MPSI magnetic plage strength index from the Mount Wilson magnetograms; KPMI, the magnetic index from Kitt Peak; and UVI, a measurement of the solar UV variability as determined by the Mg II 280 nm core-to-wing ratio. The historical sunspot record shows that the activity levels on the Sun vary with a periodicity of about 11 years. The investigation of the magnetic field associated with the sunspots shows that the underlying magnetic cycle has a period of twice that indicated by the sunspot number. As a matter of interest, there was a long interval in the second half of the 17th century when no sunspots were recorded and which coincided with a period of extreme cold in Europe. We wish to probe this magnetic activity using observations of solar p-mode oscillations.

The frequency of a given p mode depends, among other parameters, on the cavity within which the mode is "constrained". It is plausible to suggest that the cavity will in some way be altered during the solar cycle and hence one might expect that the frequency of a mode would change with solar cycle. Moreover, as different modes see different cavities, the size and even the sign of the change will vary from mode to mode. Note that the magnetic effects are limited to a band of active latitudes and are not spread over all the Sun. According to Spörer's law, the latitude at which sunspots first appear is itself a function of the phase within the solar cycle. At the beginning of a new solar cycle, sunspots appear at latitudes of about ±40°, and at lower latitudes of $\sim \pm 5°$ at the minimum. Thus we might also expect some latitude dependence in oscillations variation. The earliest observations of the p-modes were of modes of medium degree using instruments which resolved the Sun. However, these were short data sets not well suited to the study of the variability of the modes.

Observations of the low-degree p modes started in 1975 with the Birmingham measurements made from Tenerife. Those measurements have been continued and augmented until up to present day. There are also measurements from the late 1970's by Fossat (Gelly *et al.* 1988). It is not only the oscillation observed in velocity which we have to consider. The total solar irradiance in the ecliptic plane varies by about 0.1 per cent during the solar cycle with the luminosity being highest at solar maximum. (Wilson & Hudson 1988; Foukal & Jean 1990). Solar Irradiance oscillations were seen by ACRIM on SMM from mid February 1980 until the loss of the spacecraft fine pointing in December 1980 (Woodard & Noyes 1985). Medium and high-ℓ observations have been made by several teams in the years since 1979 (e.g., Duvall *et al.* 1988; Rhodes, Cacciani & Korzennik 1991; Libbrecht & Woodard 1991, Bachmann & Brown 1993). Details of the observations – including details of the precise epoch for which data are available from each instrument – are given in the review by Rhodes *et al.*.

There were trends visible in the observations of the frequencies which indicated that the frequencies were decreasing with time, but there was some confusion in the reports. However, in 1989 at the Hakone meeting Libbrecht (see Libbrecht & Woodard 1990) presented strong evidence for a solar cycle variation in frequencies based on BBSO observations in 1986 and 1988 of moderate degree data ($5 \leq \ell \leq 60$). The scale of the variation had, in fact, been predicted by Kuhn (1989), using limb-photometry data and an analysis of temporal changes in the even-Legendre frequency splittings. Closely following the moderate degree analysis came the publication of the Birmingham data (Palle *et al.* 1989, Elsworth *et al.* 1990) from the BiSON network in a data set which extended back to before the solar maximum in 1981. The observed shift was in these low degree modes was of the order of 3 nHz per Rz (i.e., per sunspot number). Taking into account the rather weak ℓ-dependence seen, this value was not incompatible with the higher-ℓ shifts.

The question now is how do we interpret the observations in terms of an understanding of how the Sun is changing during the solar cycle? The main features of the BBSO results are as follows. The year 1986 – which is near the low point in solar activity – is taken as the reference year with which all other years are compared. The frequencies increase progressively as the the solar activity increases: the shift between 1986 and 1989 is greater than that between 1986 and 1988. With high-quality data, it is possible to determine that the observed shift is a function of frequency as well as solar activity, with the shift effectively disappearing below about 1.5 mHz. The shifts themselves are small: the observed shift at about 4 mHz in 1989 is 800 nHz, i.e., an effect at the level of 2 parts in 10,000.

An important step in the understanding of what it is in the Sun that is changing comes from the fact that it can be shown that the observed frequency shifts up to a certain frequency appear to be inversely proportional to the mode inertia. The mode inertia itself is strongly dependent on the conditions which hold in the outer layers where the mode is evanescent, and not on the structure of the deep interior. This is because the normalisation of the eigenfunction is carried out at the surface of the star where the mode is observed and not in the interior where most of the energy is. Very near to the surface of the Sun, all p modes of low and moderate degree have essentially the same spatial structure and so those modes sample the near-surface layers of the Sun in the same way. So the mode-mass dependence suggests that the structural changes are located in the outermost layers of the Sun. Theoretical analyses by various authors showed and that both magnetic and thermal influences are required to explain the observations. The authors have considered either the influence of the chromospheric magnetic cavity (Campbell & Roberts 1989) or sub-photospheric flux tubes (Goldreich *et al.* 1991) or changes in the mixing length (Gough & Thompson 1988). For an up-to-date discussion of the theory see also the review by Roberts (1996).

Above about 4 mHz, where the shifts get smaller, leakage into a chromospheric cavity is invoked. Interestingly, this places the seat of the variation away from the region where one might expect the solar dynamo to be sited. An evolving magnetic field at the base of the convection zone could, in principle, influence the frequencies – especially those of the low-order modes. However, unless the fields are of the order of a mega-Gauss, the implied frequency change is small. At the base of the convection zone, a field of 10^6 G would contribute a magnetic pressure of only 7×10^{-4} of the gas pressure. The balance is different high in the atmosphere where the gas pressure is much lower.

Activity on the Sun does not change in a completely smooth way – there are fluctuations of the timescale of days and months as well as years. As an indication that there are short-term fluctuations, consider the scatter in the estimate of a frequency with the formal errors derived from the fit to the data. Formal errors are underestimate the observed scatter on the frequency measurements (Chaplin *et al.* 1996). This is, in part, due to the random nature of the excitation and the consequent variation in the line shape. Many people have considered direct correlations between shift and activity indices. Woodard *et al.* (1991) show very clear correlations between magnetic activity as measured by the mean magnetic field, smoothed to remove effects of the solar rotation. Palle (1996) has shown that the shifts observed in the rising and falling phases of a given cycle are not always the same, even for the same level of magnetic activity. However the magnetic activity in the two phases are also different – strictly speaking, it is therefore not enough just to correlate with an activity index.

The frequencies of the oscillations are a measure of the conditions inside the Sun. Inversion techniques are used to infer the interior structure. To get the best quality data over a wide range of frequencies and degrees, it is often convenient to combine data sets. However, given that the frequencies are actually changing with activity levels on the Sun and hence with time, it is very important to use contemporaneous data sets if the inferred structure of the interior is not to be corrupted by activity effects (Basu *et al.* 1996). The problem does not stop there. Because the activity is concentrated at certain latitudes, one must also take account of the degree dependence of the frequency shift (Dziembowski & Goode 1996).

There are many more observations to be made. The existing groups can build on their historical records and there are the observations to be made from the SOHO satellite. As many of the posters at this meeting, and in particular those in the session, testify we can expect to improve our understanding in the near future. Perhaps we will even see a signature of the 22-year magnetic cycle of the Sun.

3. Sunspots

Leighton (1962), in the paper which announced the observation of local solar oscillations, commented that the oscillation amplitude appeared to be suppressed in active regions. Later Braun (1987) showed strong evidence for the absorption in sunspots for modes of degree 200 and higher. It seemed likely that the absorption was a property of strong magnetic fields. The f mode was most strongly absorbed. Much more recent work by Braun suggests that the 5-minute power is from forced oscillations of the surrounding photosphere, whereas the 3-minute power is due to actual resonance in sunspots. These effects are strongest in chromospheric lines (Thomas *et al.* 1984). It is hoped that the work will lead to an observation of the magnetic field strength as a function of depth in thin flux tubes and sunspots. However, there needs to be a proper understanding of the mechanism as right now one cannot disentangle temperature and magnetic field. There is clearly a strong interaction between sunspot magnetic fields and p-modes. (See Spruit 1996; Braun 1987; 1988; 1994).

In 1909, at the Kodaikanal Observatory in India, Evershed studied the horizontal outflows in sunspots. These flows are observed in the penumbral photosphere but stop abruptly at the boundary to the undisturbed photosphere. There are flows in the dark lanes which constitute the background for the bright penumbral grains. The flow variable, tends to increase outwards, and may reach velocities of several kilometres per second. The observations have been interpreted as a siphon flow along magnetic flux tubes. Thus there is an imbalance in the system. The Evershed flows take material away from the centre of the spot and magnetic pressure also pushes outwards, therefore there must be something to stabilise the system. This could be provided by a downward flow and studies of sunspot have searched for such a flow.

Time travel maps of sound waves propagating in local regions of the convection zone provide for such an observation. Measurements are made by estimating the cross correlation functions of fluctuations of brightness on the solar surface caused by solar oscillations. Because of the high noise level, the data must be averaged over large surface areas. Typically mean travel times are obtained between a central point and surrounding annuli. A sort of tomography is then used to interpret the data. In the data observed by Duvall and co-workers (Duvall 1995,1996), the four annuli chosen trace rays which propagate through the upper 30 per cent of the convection zone. The data can be interpreted to show strong downflows of order of 1km/s around the sunspot studied. This is a very important piece of evidence in our understanding of why sunspots can exist.

4. Solar noise

The limit to the solar oscillation modes which can be detected is set by the background solar noise in velocity or intensity. The Harvey model attempts to quantify the components of the noise which are important to helioseismology. The velocity field is considered to be determined by granulation, mesogranulation, supergranulation and active regions. Convection cells have magnetic fields on the boundaries and the flow is restricted to the edges. Auto-correlation analyses suggest that it is appropriate to represent each of the these phenomena by a characteristic decay time and a strength. It was proposed that each component of the solar noise be represented by a function of the form

$$P(\nu) = \frac{4\sigma^2}{1 + (2\pi\nu\tau)^2}.$$

The combined effect of all these using the original estimates for the parameters is shown as the *Harvey model* in Fig. 1.

Observations from the BiSON instrument in the Canary Islands and analysed by the Tenerife group confirmed the general shape of the prediction (Regulo *et al.* 1994). There is the requirement that, for a mode to be observable, it must be detectable, against the noise background, within one

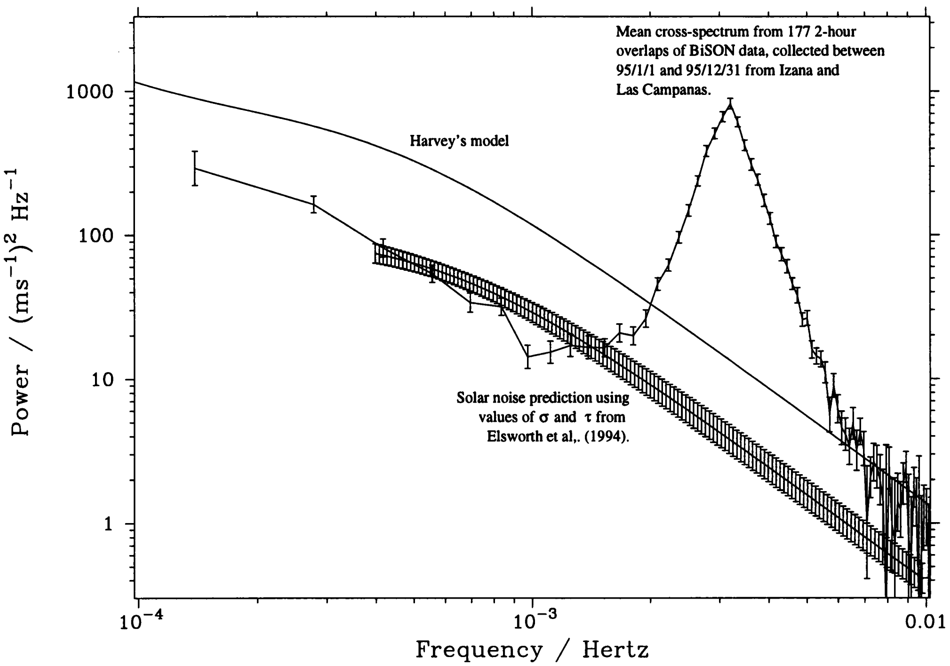

Figure 1. Solar noise power as measured by BiSON and compared with the original Harvey prediction.

lifetime of the mode. Longer observations improve on the signal to noise. If this condition is not met, then the signal to noise increases only as the fourth power of the observing time. The amplitude of the p modes is such that they are not difficult to observe. For g modes, the strength of the signal is weaker and the solar noise level is higher than in the p-mode region. The g modes are expected to be very coherent and so long observing times can be used. BiSON observations (Elsworth *et al.* 1993) have already shown that the solar noise levels are below those estimated by Harvey (see Fig 1). At 1 mHz, the value observed by cross-correlation of data from well-separated stations is about a factor of 5 below the original estimate. Recent BiSON data taken near solar minimum show that the observations have changed very little with solar cycle (Chaplin *et al.* 1996)

The GOLF and Virgo instruments on SOHO will shed further light on the signal levels in velocity and intensity. It is important to remember that the observed strength of the oscillation signal is a function both of the height in the solar atmosphere at which the oscillations are formed, and the frequency of the oscillation. To make comparisons for example between the BiSON value which is a measurement in the potassium line and the GOLF value which is a measurement in the sodium line, the different heights of formation must be taken into account. (Fossat 1996)

5. Individual events

What we have been discussing up to here is the averaged behaviour of modes. It is possible to study the evolution of single modes under certain circumstances. Before the global modes of the Sun had been observed, C.L. Wolff predicted (Wolff 1972) that oscillations of the Sun might be excited by a large solar flare. He compared the situation with that on the Earth after a big earthquake. For several years now, the BiSON data (Elsworth *et al.* 1995) and the IPHIR data (Toutain and Fröhlich 1992, Baudin *et al.* 1995) have been used to show the evolution of modes. The data show that the stochastic model for excitation (Chaplin et al. 1995; 1996) is at least consistent with the observations in that the distribution of the amplitudes follow the predictions. However, the BiSON data show indications of an excess of the highest power modes. The BiSON data were also used to explore the possibility that the activity of the Sun could be seen to be linked to individual excitations. No obvious correlations with flare activity have been seen. There is a previous report of high-ℓ data showing such a link (Haber *et al.* 1988) but calculations by Kosovichev (Kosovichev and Zharkova 1995) suggest that there is not enough energy in flares for them to significantly influence the excitation process. However, more energetic events such as coronal mass ejections or the demise of a sun-grazing comet (Isaak 1978) might provide enough energy.

6. Summary and Conclusions

Activity is clearly varying periodically. The future holds great potential for studying that variation However, to date, only the ground-based networks have long databases which go back beyond the beginning of the previous solar cycle in the case of the BiSON data. We have seen that the frequency of the solar oscillations varies with that activity. The amplitude of the modes also varies in a systematic way (Anguera Gubau *et al.* 1992, Elsworth *et al.* 1993). The modes are strongest when the activity is at its minimum For the behaviour of other aspects of the oscillations – there is little clear evidence for systematic trends in the observed values. For example, according to that data there is currently no evidence for changes in the widths (Chaplin *et al.* 1996) of the low-degree modes. Equally the solar noise background and the overall solar rotation rate do not appear to vary with the solar cycle (Fig. 1).

References

Anguera Gubau, M., Pallé, P. L., Perez Hernandez, F., Regulo, C. & Roca Cortes T.

(1992) *A&A*, **255**, 363

Bachmann K. T. & Brown T. M. (1993) *ApJ*, **411**, L45

Basu S. *et al.* (1997) these proceedings

Baudin F., Gabriel A., Gibert D., Palle P. & Regulo C. (1995) in *Fourth SOHO Workshop: Helioseismology*, eds. Hoeksema J. T., Domingo V., Fleck B. & Battrick B., ESA SP-376, vol 2, p 323

Braun D. C. (1987) *ApJ* **319**, L27

Braun D. C. (1988) *ApJ* **335**, 1015

Campbell, W. R., and Roberts, B. (1989) *ApJ* **338**, 538

Chaplin W. J., Elsworth Y., Howe R., Isaak G. R., McLeod C. P., Miller B. A. & New R. (1995) in *Fourth SOHO Workshop: Helioseismology*, eds. Hoeksema J. T., Domingo V., Fleck B. & Batrick B., ESA SP-376 vol 2, p 335

Chaplin W. J., Elsworth Y., Howe R., Isaak G. R., McLeod C. P., Miller B. A. & New R. (1996) *MNRAS*, submitted

Chaplin W. J., Elsworth Y., Isaak G. R., McLeod C. P., Miller . B. A, New R. & Underhill. C. J (1997) these proceedings

Chaplin *et al.* (1996), in preparation

Duvall T. *et al.* (1988) *ApJ* **324**, 1158

Duvall T. L. Jr., Jefferies S. M. & Harvey J.W. (1995) *Bull. Am. Ast. Soc.* **25**, 950

Duvall T. L. Jr., D'Silva S., Jefferies S. M., Harvey J.W. & Schou J. (1996) *Nature* **379**, 235

Dziembowski W. A. & Goode P. R. (1996) *A&A* **317**, 919

Elsworth Y., Howe R., Isaak G. R., McLeod C. P. & New R. (1990) *Nature* **345**, 322

Elsworth Y., Howe R., Isaak G. R., McLeod C. P., Miller B. A., New R., Wheeler S. J. (1993) *MNRAS* **265**, 888

Elsworth Y., Howe R., Isaak G. R., McLeod C. P., Miller B. A., Wheeler S. J., New R. (1995) in GONG '94 ,*Helio- and Astero-Seismology from Space*, eds. Ulrich, R., Rhodes, E., & Däppen, W., p. 318

Fossat E. (1996), private communication

Foukal P. & Lean J. (1990) *Science* **247**, 556

Gelly, B.,Fossat., E., & Grec, G. (1988) in *Seismology of the Sun and sun-like stars*, eds. ESA SP-286, p. 275.

Goldreich P., *et al.* (1991) *ApJ* **370**, 752

Gough D. O. & Thompson M. J. (1988) in *Advances in Helio- & Asteroseismology*, Symp. IAU 123, eds. Christensen-Dalsgaard J. & Frandsen S., 175

Haber D. A., Toomre J., Hill F., &Gough D. O. (1988) in Proc. Symp. *Seismology of the Sun and sun-like stars*, Ed. Rolfe E. J., ESA SP-286, p. 301

Isaak G. R. (1978) *Physics Bulletin* **27**, 127

Kosovichev A. G. & Zharkova V. V. (1995) *Fourth SOHO Workshop: Helioseismology*, eds. Hoeksema J. T., Domingo V., Fleck B. & Battrick B., ESA SP-376, p. 341

Kuhn J. R. (1989) *ApJ* **339**, L45

Leighton, R. B., Noyes, R. W., & Simon, G., W. (1962) *ApJ* **135**, 474

Libbrecht K. G. & Woodard M. F. (1990) *Nature* **345**, 779

Palle P. L., Regulo C. & Roca Cortes (1989) *A&A* bf 169, 313

Palle P. L. *et al.* (1996) ApJ, submitted

Rhodes E. J., Cacciani A. & Korzennik S. C. (1991) *Adv. Space. Res.* **11** (4), 17

Roberts B (1996) *Bull. Astr. Soc. India* **24**, 199

Spruit, H. C. (1996) *Bull. Astr. Soc. India* **24**, 211

Toutain, Th., & Fröhlich, C. (1992) *A&A* **257**, 287

Wilson R. C. & Hudson H. S. (1988) *Nature* **319**, 654

Wolff C. L. (1972) *ApJ* **177**, L87

Woodard M. F., & Noyes R. W. (1985) *Nature* **318**, 449

Woodard, M. F., Libbrecht, K. G., Kuhn, J. R., & Murray, N. (1991) *ApJ*, **373**, L81