Session 3

Comparative Solar Minima from Sun to Earth

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Comparative Magnetic Minima:
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Helioseismology - a clear view of the interior

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Abstract. Helioseismology is a very powerful tool that allows us to explore the interior of the Sun. Here we give particular emphasis to the justification for the likely location of the zone that is most sensitive to cycle-related changes. For the low degree modes we find that more than one timescale for changes in the oscillations is discovered. We also note the successive cycles have differing sensitivities to the activity. We end with a warning of the risk of being misled with short datasets such as are seen with stellar data.

Keywords. Sun: helioseismology, Sun: interior, Sun: magnetic fields, Sun: oscillations

1. Introduction

The Sun's natural resonant oscillations, known as solar p modes are trapped in cavities below the surface of the Sun and their frequencies are sensitive to properties, such as temperature and mean molecular weight, of the solar material in the cavities. The basic principle governing the fundamental period of oscillation has been known for a long time and is that the period is related to the sound travel time. This period is similar to the dynamical timescale and is of order one hour for the Sun. The period scales as the inverse square root of the mean density. On the Sun we see not the fundamental but a higher overtone with a typical period of five minutes. It is no accident that this is a similar timescale to the turn-over time for a granule. Different modes of oscillations see different cavities with the lower boundary being very sensitive to the degree (or ℓ) of the mode and the upper boundary being mainly a function of frequency. A consequence of this is that the high degree modes are sensitive to just the outer regions of the Sun, while the low degree modes are sensitive to almost the complete volume. There are modes that are not global but only local. We do not consider them further here. In order to observe the high degree modes, in general one has to image the surface. However, no imaging is required for the low degree modes. Although one might think that, without imaging, one would observe just the lowest degree mode with $\ell = 0$, this is not true as there is some degree of inherent Doppler imaging.

By using a combination of measurements from high and low degree modes it is possible to build up maps of the sound speed and density in the interior of the Sun. It is also possible to determine the rotation profile with depth and latitude. Such images (see discussion in later section) point to the existence of several zones of high radial shear. One such zone lies at the base of the convection zone and is known as the Tachocline. Another radial shear zone is located at the surface.

It has been known since the mid 1980s that p-mode frequencies vary throughout the solar cycle with the frequencies being at their largest when the solar activity is at its maximum(e.g. Woodard & Noyes 1985; Pallé *et al.* 1989; Elsworth *et al.* 1990; Libbrecht &

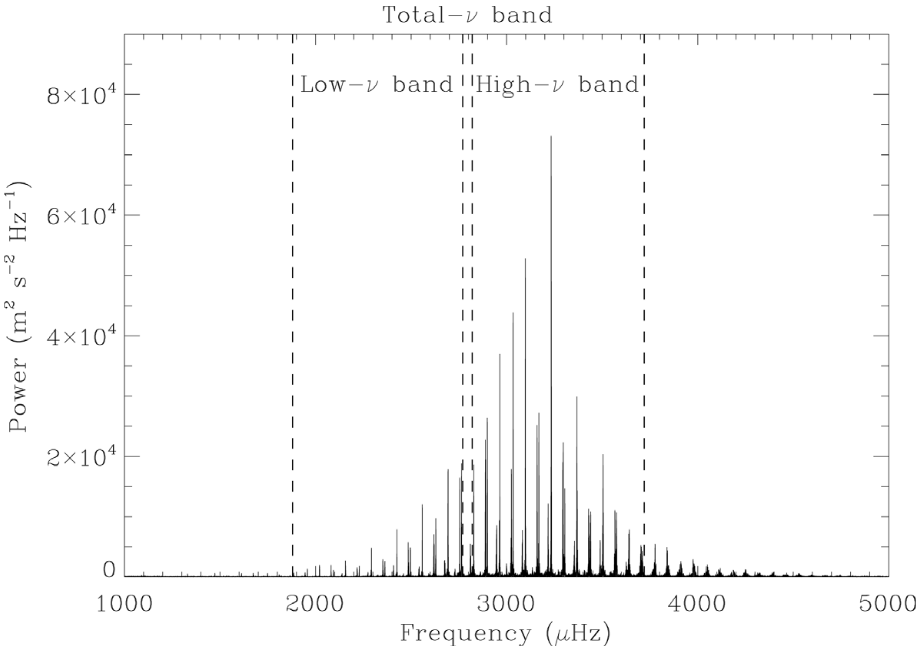

Figure 1. A frequency-power spectrum of BiSON data. The time series used to create this spectrum was 182.5 d in length. The vertical lines mark the low-, high- and total-frequency bands used when calculating the solar cycle frequency shifts.

Woodard 1990; Jiménez-Reyes *et al.* 2003; Chaplin *et al.* 2007; Jiménez-Reyes *et al.* 2007). [Please note here that the references listed are not exhaustive and while the references do not always include the earliest example we have tried to include useful ones whose reference lists themselves are informative.] For a low-degree mode at about 3000 μHz, the change in frequency between solar maximum and minimum is about 0.4 μHz. By examining the changes in the observed p-mode frequencies throughout the solar cycle we can learn about solar-cycle-related processes that occur beneath the Sun's surface.

The Birmingham Solar-Oscillations Network (BiSON) (Chaplin *et al.* 1996) makes Sun-as-a-star (unresolved) Doppler velocity observations, which are sensitive to the p modes with the largest horizontal scales (or the lowest angular degrees, ℓ). Consequently, the frequencies measured by BiSON are of the truly global modes of the Sun. These modes travel to the Sun's core, however, their dwell time at the surface is longer than at the solar core because the sound speed inside the Sun increases with depth. Therefore, the low-ℓ modes are most sensitive to variations in regions of the interior that are close to the surface and so are able to give a picture of the influence of near-surface activity.

BiSON is a network of autonomous ground-based observatories that are strategically positioned at various longitudes and latitudes in order to provide nearly continuous coverage of the Sun. The network began with just one station and gradually expanded over the course of 17 years, finally becoming a six-site network in 1992. There are four sites in the southern hemisphere and two in the northern hemisphere. The quality of the early data is poor compared to more recent data because of limited time coverage.

2. Determining variations in p-mode frequencies throughout the solar cycle

BiSON is in a unique position to study the changes in oscillation frequencies that accompany the solar cycle as it has now been collecting data for over 30 years. Here, we have analyzed the mode frequencies observed by BiSON during the last two solar cycles in their entirety i.e. from 1986 April 14 to 2010 October 8. To obtain solar cycle frequency shifts the BiSON data must be split into shorter subsets. However, the longer the time series the more precisely the mode frequencies can be obtained. Therefore, the length in time of the subsets must represent a balance between being long enough to accurately and precisely extract mode frequencies and short enough to resolve solar cycle variations. Here we show the results obtained when the BiSON data were divided into 182.5-day-long independent subsets. Figure 1 shows a frequency-power spectrum of 182.5 d of BiSON data. We now describe how solar cycle frequency shifts are obtained from BiSON data.

Estimates of the mode frequencies were extracted from each subset by fitting a modified series of Lorentzian models to the data using a standard likelihood maximization method, which was applied in the manner described in Fletcher *et al.* (2009). We first defined a frequency range of interest. For this range, a reference frequency set was determined by averaging the frequencies in subsets covering the minimum activity epoch at the boundary between cycle 22 and cycle 23. It should be noted that the main results described here are insensitive to the exact choice of subsets used to make the reference frequency set. Frequency shifts were then defined as the differences between frequencies given in the reference set and the frequencies of the corresponding modes observed at different epochs (Broomhall *et al.* 2009). This gives one value of the frequency shift for each epoch and frequency range. Note that it is, in general, not possible to get a spot reading of the frequency shift. It may require several months of observations to obtain a frequency shift value.

For each subset in time, three weighted-average frequency shifts were generated over different frequency intervals, where the weights were determined by the formal errors on the fitted frequencies: first, a "total" average shift was determined by averaging the individual shifts of the $\ell = 0$, 1, and 2 modes over fourteen overtones (covering a frequency range of $1.88 - 3.71$ mHz, see Figure 1); second, a "low-frequency" average shift was computed by averaging over seven overtones whose frequencies ranged from 1.88 to 2.77 mHz; and third, a "high-frequency" average shift was calculated using seven overtones whose frequencies ranged from 2.82 to 3.71 mHz. The lower limit of this frequency range (i.e., 1.88 mHz) was determined by how low in frequency it was possible to accurately fit the data before the modes were no longer prominent above the background noise. The upper limit on the frequency range (i.e., 3.71 mHz) was determined by how high in frequency the data could be fitted before errors on the obtained frequencies became too large due to increasing line widths causing modes to overlap in frequency.

Figure 2 shows mean frequency shifts of the p modes observed by BiSON (also see Broomhall *et al.* 2009; Salabert *et al.* 2009; Fletcher *et al.* 2010). A scaled version of the 10.7 cm flux is also plotted in Figure 2. The flux has been scaled by fitting a linear relationship between the 10.7 cm flux and the frequency shifts observed in the total-frequency band. The eleven-year cycle is seen clearly.

What causes the observed frequency shifts? Broadly speaking, the magnetic fields can affect the modes in two ways. They can do so directly, by the action of the Lorentz force on the gas. This provides an additional restoring force, the result being an increase of frequency, and the appearance of new modes. Magnetic fields can also influence matters

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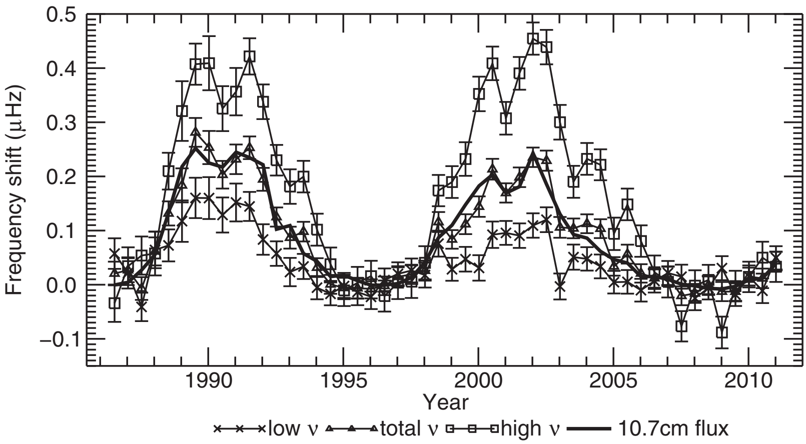

Figure 2. Average frequency shifts of "Sun-as-a-star" modes with frequencies between 1.88 and 3.71 mHz, 1.88 and 2.77 mHz, and 2.82 and 3.71 mHz (see legend). The results were obtained from 182.5 d time series. Also plotted is a scaled version of the 10.7 cm flux.

indirectly, by affecting the physical properties in the mode cavities and, as a result, the propagation of the acoustic waves within them. This indirect effect can act both ways, to either increase or decrease the frequencies.

The observed frequency shifts show dependencies on both frequency and ℓ. We now look in more detail at these dependencies and discuss what they tell us about the origin of the perturbation.

3. Dependence of solar cycle frequency shifts on frequency

Solar cycle frequency shifts, $\delta\nu_{n,\ell}$, have well-known dependencies on both angular degree, ℓ, and frequency, $\nu_{n,\ell}$, (see e.g. Libbrecht & Woodard 1990; Elsworth *et al.* 1994; Chaplin *et al.* 1998; Howe *et al.* 1999; Chaplin *et al.* 2001; Jiménez-Reyes *et al.* 2001). Figure 2 shows that the high-frequency band is much more sensitive to the solar cycle than the low-frequency band. The frequency dependence of the frequency shifts is a telltale indicator that the observed eleven-year signal must be the result of changes in acoustic properties in the few hundred kilometres just beneath the visible surface of the Sun, a region that the higher-frequency modes are much more sensitive to than their lower-frequency counterparts because of differences in the upper boundaries of the cavities in which the modes are trapped (Libbrecht & Woodard 1990; Christensen-Dalsgaard & Berthomieu 1991). We now go into more detail.

Stellar p modes are trapped in cavities in the solar interior. While the lower turning point of these cavities is mostly dependent on ℓ, the position of the upper turning point is mostly dependent on frequency. As p modes travel towards the centre of the Sun, refraction causes the oscillations to follow a curved path which takes them back to the surface. The lower turning point, therefore, depends on the direction of travel and consequently ℓ. On the other hand, the upper turning point is relatively independent of ℓ as by the time the oscillations reach the photosphere all waves travel in an approximately radial direction (for low and intermediate ℓ). Instead the position of the upper turning point is dependent on frequency. The modes are reflected because of the sharp decrease

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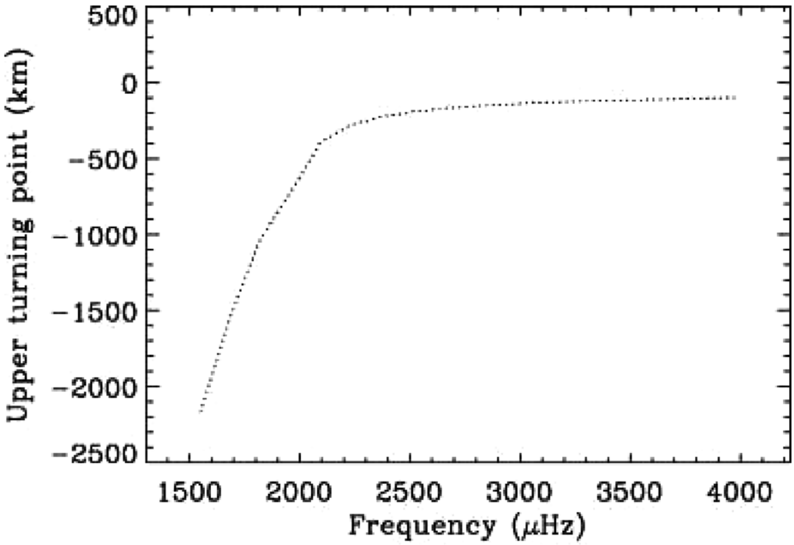

Figure 3. Taken from Chaplin *et al.* (2001). Upper turning point as a function of frequency for radial modes, as determined from model S of Christensen-Dalsgaard. Here, we define the zero-point location as that corresponding to where optical depth reaches unity at a wavelength of 500 nm.

in density of the plasma at the photosphere. If the density scale height is smaller than the lengthscale of the mode then the pressure changes required to make the mode cannot be maintained over the length of time that matches the wave period. As the density scale height decreases rapidly with altitude in the outer regions of the Sun the depth at which modes with different periods are reflected varies.

For a given ℓ the upper turning point of low-frequency modes is deeper than the upper turning point of high-frequency modes. At a fixed frequency lower-ℓ modes penetrate more deeply into the solar interior than higher-ℓ modes. Therefore, higher-frequency modes, are more sensitive to surface perturbations.

Libbrecht & Woodard (1990) discuss the origin of the perturbation. If the perturbations were to extend over a significant fraction of the radius, asymptotic theory implies that the fractional mode frequency shift would depend mainly on $\nu_{n,\ell}/\ell$. However, the observed $\delta\nu_{n,\ell}$ is not well described by a function of $\nu_{n,\ell}/\ell$. This implies that the relevant structural changes occur mainly in a thin layer. Thompson (1988) found that the effect of perturbing a thin layer in the propagating regions of modes, such as the HeII ionization zone, is an oscillatory frequency dependence in $\delta\nu_{n,\ell}$, which is not observed. This implies that the dominant frequency dependence is not the direct result of, for example, changes in the magnetic field at the base of the convection zone. If the perturbation was confined to the centre of the Sun the size of the frequency shift would increase with decreasing ℓ as lower ℓ modes penetrate deeper into the solar interior than high-ℓ modes. In fact, $\delta\nu_{n,\ell}$ increases with increasing ℓ.

Libbrecht & Woodard (1990), therefore, conclude that the oscillations are responding to changes in the strength of the solar magnetic activity near the Sun's surface. As modes below approximately 1800 μHz experience almost no solar cycle frequency shifts it is reasonable to conclude that the origin of the perturbation is concentrated in a region above the upper turning points of these modes. Figure 3 shows that the upper turning

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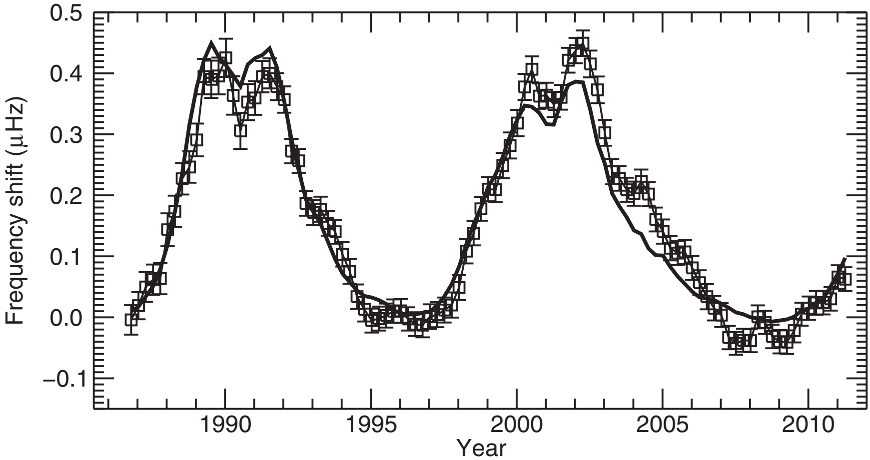

Figure 4. Oscillation frequency shifts in the high frequency band with the 10.7 cm flux overplotted as a thin line. The 10.7 and the frequency shifts are scaled to match in cycle 22

point of a mode with a frequency of $\sim$1800 μHz is about 1 Mm below the surface (which is defined as where optical depth reaches unity at a wavelength of 500 nm). Note that the upper turning point predicted by a model is strongly dependent on the properties of the model at the top of the convection zone.

4. Evidence for shorter-term variations in solar p-mode frequencies?

Over the past twenty years it has become apparent that significant (quasi-periodic) variability in activity is also seen on shorter timescales, between 1 and 2 years (e.g. Benevolenskaya 1995; Mursula *et al.* 2003; Valdés-Galicia & Velasco 2008). Is the periodicity the result of modulation of the main solar dynamo responsible for the eleven-year cycle or is it caused by a separate mechanism? Helioseismology can help to answer this question by looking for evidence of shorter-term variations in the p-mode frequencies, which, in turn, can provide information on solar-cycle-related processes that occur beneath the Sun's surface.

Shorter-term variations are indeed visible on top of the general eleven-year trend in p-mode frequencies (Broomhall *et al.* 2009; Fletcher *et al.* 2010; Broomhall *et al.* 2010). This is seen very clearly in Figure 4 which shows just the BiSON high-frequency data and the 10.7 cm radio signal. In this case the 10.7 is scaled to match the signal in cycle 22. The reason for this scaling will become apparent shortly. The period of this structure is approximately 2 years. Fletcher *et al.* (2010) showed that the signal was visible in both BiSON and GOLF data and Broomhall *et al.* (2010) demonstrated that the quasi-biennial signal was also evident in Variability of solar IRradiance and Gravity Oscillations (VIRGO; Fröhlich *et al.* 1995) data. VIRGO consists of three sun photometers (SPMs), that observe at different wavelengths, namely the blue channel (402 nm), the green channel (500 nm), and the red channel (862 nm). The results are similar for each individual channel.

In order to extract mid-term periodicities, we subtracted a smooth trend from the average total shifts by applying a boxcar filter of width 2.5 years. This removed the

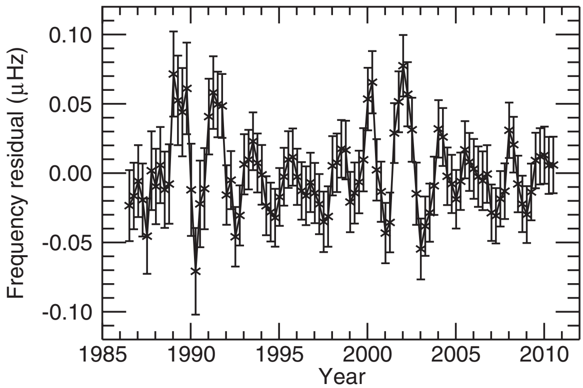

Figure 5. Rapidly varying component of the oscillation frequency shifts in the high frequency band

dominant eleven-year signal of the solar cycle. Note that, although the width of this boxcar is only slightly larger than the periodicity we are examining here, wider filters produce similar results. The resulting residuals, which can be seen in Figure 5, show a periodicity on a timescale of about 2 years.

The envelope of the two-year signal is modulated by the eleven-year signal. However there must be some addititive component because it is still present when the eleven-year signal is at minimum. Furthermore, the two-year signal must have its origin in significantly deeper layers than the eleven-year signal. Since the 2 year signal shows far less dependence on mode frequency, the origin of the signal must be positioned below the upper turning point of the lowest frequency modes examined (as the depth of a mode's upper turning point increases with decreasing frequency). The upper turning point of modes with frequencies of 1.88 mHz occurs at a depth of approximately 1000 km, whereas the influence of the eleven-year cycle is concentrated in the upper few 100 km of the solar interior. Put together, this all points to a phenomenon that is separate from, but nevertheless susceptible to, the influence of the eleven-year cycle.

One possibility is magnetic activity seated near the bottom of the layer extending 5% below the solar surface ($\sim 35,000$ km). This region shows strong rotational shear (see Figure 6), like the shear observed across the deeper-seated tachocline where the omega effect of the main dynamo is believed to operate (Corbard & Thompson 2002; Antia *et al.* 2008). The presence of two different types of dynamo operating at different depths has already been proposed to explain the quasi-biennial behaviour observed in other proxies of solar activity (Benevolenskaya 1998a,b). When the eleven-year cycle is in a strong phase, buoyant magnetic flux sent upward from the base of the envelope by the main dynamo could help to nudge flux processed by this second dynamo into layers that are shallow enough to imprint a detectible acoustic signature on the modes. The 2 year signal would then be visible. When the main cycle is in a weak phase, the flux from the second dynamo would not receive an extra nudge, and would not be buoyant enough to be detected in the proxies but could potentially be seen in the modes. While p-mode frequencies respond to conditions beneath the surface activity proxies respond to changes at or above the surface. The 2 year signals observed in other solar activity proxies are only detectible during phases of moderate to high activity (see, e.g. Vecchio & Carbone 2008; Hathaway 2010, and references therein). That the signal

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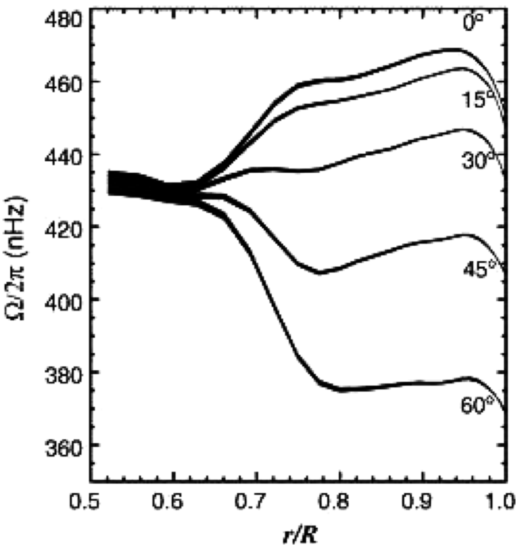

Figure 6. Taken from Howe *et al.* (2007). Mean rotation profile for RLS inversions of GONG data shown as slices ad constant latitude. Thickness of curves demonstrates the 3σ errors.

was also visible in the high-frequency modes during the recent extended minimum may also, therefore, point to behavioural changes in the main dynamo and its influence on the 2-year signal. We are currently exploring the latitudinal dependence of the two-year signal.

5. Comparison between cycles

It is recognised that the minimum out of which we are just emerging was unusually deep and long. It is interesting to ask if the unusual behaviour occured just at that minimum or whether there are other indications of changes in the structure of the Sun. To explore this we look at the oscillations data for the last two complete cycles. We now see the reason for scaling the 10.7 data for cycle 22 alone. Figure 7 shows the high and low frequency bands for cycles 22 and 23 and the initial part of the rise into cycle 24. The high frequency band, as indicated previously, shows a much stronger response to the activity cycle than does the low frequency band. However, the low frequency band is very different in amplitude relative to the high frequency band. In the cycle which has just finished, the sensitivity of the low frequency band to the solar activity is much lower. It is possible that we are seeing evidence that the conditions in the solar interior have started to change. It may be that the upper turning point of the modes is moving deeper in the Sun away from the zones of activity. Alternatively, the radial location of the activity may be different.

6. Stellar Context

For the Sun we can measure both high and low degree modes and thereby obtain a very detailed picture of the conditions within the Sun. However, for most stars this is impossible. We must do what we can with just the low-degree modes. It is therefore

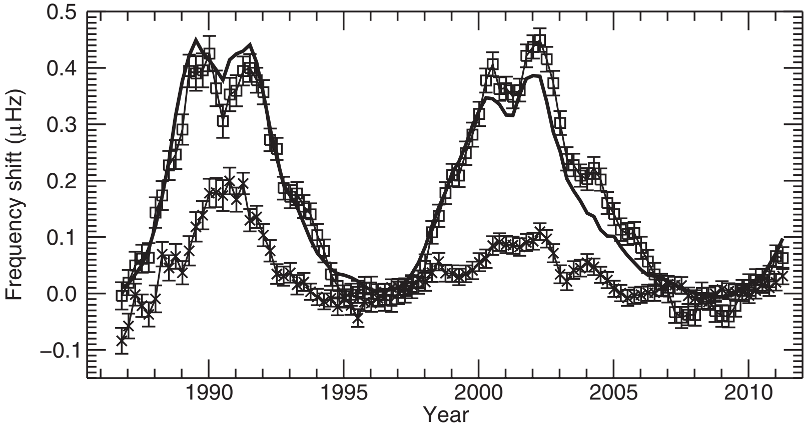

Figure 7. High and low frequency bands plus 10.7

useful to consider the inferences that we would draw from low-degree modes alone. We expect that magnetic activity will influence both the frequencies and the heights of the modes (Chaplin 2011). Effects that can be ascribed to activity were reported by Garcia for CoRoT observations of HD49933 (García *et al.* 2010). So we have clear expectations but what are the pitfalls. It is important to remember that the modes of oscillations are stochastically excited and we never see the underlying spectrum. This realisation noise is a big problem and a limiting factor in the inferences that can be drawn. It is very easy to be misled (Broomhall *et al.* 2011) into thinking that real changes are present when they are not.

7. Conclusions

We have seen that solar oscillations provide a window into the interior of the Sun. The global, low-degree modes have been measured for over two solar cycles and have the potential to allow us to compare one cycle with another. In the oscillations data, not only was the last minimum deep but there is clear evidence that the behaviour of the Sun at the peak of the last cycle was different from its behaviour in the previous cycle. We know that other indices are also seeing changes with, perhaps, the 10.7 cm radio flux and the sunspot number becoming somewhat decoupled and with the changes in the irradiance. This is a great opportunity to link the surface to the interior of the Sun. Furthermore the two-year signal seen in the oscillations and at times of high activity in some of the activity indices may be able to help us throw some light on the magnetic field generation in the Sun.

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Discussion

Janet Luhmann: (Comment) An alternative approach used by Lean, Sheeley and Wang was to use coronal EUV emission to "paint" potential source surface model lines. This may give you insight into magnetic geometry.

Yvonne Elsworth: Thanks a lot for this point. The research in this field will be followed in the future.

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Jeff Linsky: (Comment) Fontenla's models in 2011 are different from those in 2009. Lyman alpha wings are not properly modelled, we have encouraged him to consider Lyman alpha broadening.

Yvonne Elsworth: I appreciate this point. Indeed the wings of Lyman alpha are important for the continuum levels in the UV. We will use the updated models in the future.