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The New Solar Minimum: How deep does the problem go

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Abstract. Although there are now some tentative signs that the start of cycle 24 has begun there is still considerable interest in the somewhat unusual behaviour of the current solar minimum and the apparent delay in the true start of the next cycle. While this behaviour is easily tracked by observing the change in surface activity a question can also be asked about what is happening beneath the surface where the magnetic activity ultimately originates? In order to try to answer this question we can look at the behaviour of the frequencies of the Sun's natural seismic modes of oscillation - the p modes. These seismic frequencies also respond to changes in activity and are probes of conditions in the solar interior.

The Birmingham Solar Oscillations Network (BiSON) has made measurements of low-degree (low-ℓ) p mode frequencies over the last three solar cycles, and so is in a unique position to explore the current unusual and extended solar minimum. We compare the frequency shifts in the low-ℓ p-modes obtained from the BiSON data with the change in surface activity as measured by different proxies and show there are significant differences especially during the declining phase of solar cycle 23 and into the current minimum. We also observe quasi-biennial periodic behaviour in the p mode frequencies over the last 2 cycles that, unlike in the surface measurements, seems to be present at mid- and low-activity levels. Additionally we look at the frequency shifts of individual ℓ modes.

1. Introduction

The magnetic activity of the Sun is known to follow an approximately 11-year cycle ranging from quiet periods to much more active periods. Starting in March 1755 these cycles have been labeled with a number and we are currently in the minimum between cycles 23 and 24. However, this current minimum is proving to be somewhat unusual, both in terms of how long it is lasting and just how quiet the Sun is, at least in terms of the more recently observed cycles.

Surface measures of solar actively such as the number of visible sunspots and 10.7cm radio flux, all suggest that we are still in (or possibly just leaving) an extended minimum. Therefore, the question presents itself is there anything different about this minimum that we can learn from looking at the activity of the solar interior.

This can be investigated by looking at the acoustic modes of oscillation of the Sun (known as p modes). Modes with low angular degrees (low-ℓ) travel deeply into the solar interior and so sample the conditions below the solar surface. Also, low-ℓ modes are truly global in nature and therefore are sensitive to a large fraction of the solar disc. It has been known for some time that the frequencies of these oscillations vary during the solar cycle, with the frequencies being highest when the magnetic activity is at a maximum. Therefore, by looking at the change in frequencies we can gain insight into cycle related processes that are occurring beneath the solar surface.

The Birmingham Solar Oscillations Network (BiSON) has been collecting unresolved (Sun-as-a-star) Doppler velocity observations for over three decades. These types of observations are sensitive to the large scale 'global' oscillations of the sun, (i.e., those modes with the lowest angular degrees, ℓ). Due to the fact the BiSON has observations going back into the 1970's, these data offer a unique opportunity to study the last three solar cycles. However, when the network was first established there was only one station and as such the early observations are sporadic and so the data quality is relatively poor. The quality and duty cycle of the data greatly improves after 1986 once three stations were operating and this allows us to study the last two solar cycles in their entirety.

2. Method

The precision with which one can measure the p-mode frequencies is directly related to the length of the time series. Therefore, one often wants to take as long a time series as possible in order to give the most precise estimates of the frequencies. However, when trying to track the change in frequencies over the solar cycle, one must strike a balance between length of time series and the time resolution of each frequency measurement. To this end an 8577-day BiSON time series starting on 14 April 1986 and ending on 7th October 2009 was split into a set of 365-day time series. Each series was allowed to overlap the following by 91.25 days (i.e., a 4-time overlap), resulting in a total of 91 (non-independent) data sets. The power spectrum of each time series was parameterised using a modified Lorentzian model which was fitted to the data using a standard likelihood maximisation method (eg., see Chaplin et al. 1999) enabling the mode frequencies to be determined.

For each mode a minimum activity reference was taken from the fits to a data set lying on the boundary between cycle 22 and 23. The frequency shifts were then defined as the difference between this reference value and the frequency of the corresponding mode observed at different epochs. The size of the frequency shift has a known dependence on frequency and this dependence was removed in the manner described in Chaplin et al. (2007). A weighted average of the frequency shift for each time series was then determined, enabling the shift to be plotted over time. The average was made over modes ranging from $12 \leq n \leq 25$ and $0 \leq \ell \leq 3$.

A similar analysis was performed recently with BiSON data (see Broomhall et al. 2009). Here we extend in time the results of that paper and additionally present the shifts of individual ℓ modes. This allows us to make comments about the location of the solar variability, since each ℓ has different latitudinal sensitivities.

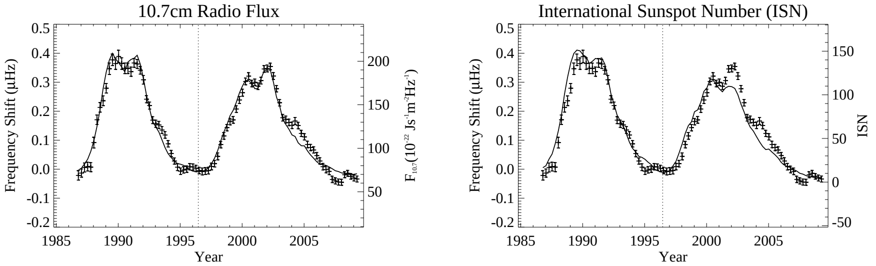

Figure 1. Compariosn between the frequency shifts as determined from BiSON data and two different surface activity proxies. Left: The 10.7cm radio flux. Right: The International Sunspot number, both shown by the solid black line.

3. Analysis and Results

In this section we concentrate on the last two cycles (22 and 23) where the BiSON data are of sufficient quality to do meaningful statistical tests. It is widely known (see Elsworth et al. 1990; Howe 2008, and references therein) that there is a good correlation between the shifts in the p-mode frequencies and other proxies that can be used to track the solar cycle. In Fig. 1 we compare the shifts with two of the more commonly used proxies, the 10.7cm radio flux ($F_{10.7}$) and the International Sunspot Number (ISN). The shifts show very good agreement with the 10.7cm radio flux up until around 2003, after which there is a significant disagreement relative to previous epochs. The agreement between the shifts and the ISN is not as good. This is thought to be because the ISN is predominantly sensitive to the strong component of the Sun's magnetic field, whereas the frequency shifts and radio flux are sensitive to both the strong *and* weak components. However, even with the poorer fit, it is still clear that the largest differences still occur over the latter part of cycle 23.

Looking more closely at the final few points shown in Fig. 1, it appears that there is a significant rise in the frequency shifts at the start of 2008, that may be pointing to the start of cycle 24. We do not see a similar rise in either the radio flux or the ISN. However, this rise in the shifts did not continue, and looking back at the boundary of the last cycle we can see there are similar rises and dips in the shifts throughout the last minimum too.

If these dips and rises in the shifts are not associated with the main solar cycle then they do highlight an interesting notion in their own right. There are clearly bumps and dips at higher activity in both the shifts and other proxies, but if these continue into low activity periods too, then it might be a an indication of short-term pseudo periodic behaviour.

To investigate this more thoroughly we have looked at the difference between heavily smoothed and unsmoothed data. The residuals of this comparison are shown in the left panel of Fig. 2. Short term periodic variations appear to occur on a scale of around two years. The variations seem to be stronger in the oscillations during the minimum periods but of similar magnitude to the radio flux during high activity. We can also look at a power spectrum of these residuals as shown in the right panel of Fig. 2. Although there is not a clear and obvious peak at short time periods there are a cluster of peaks around a

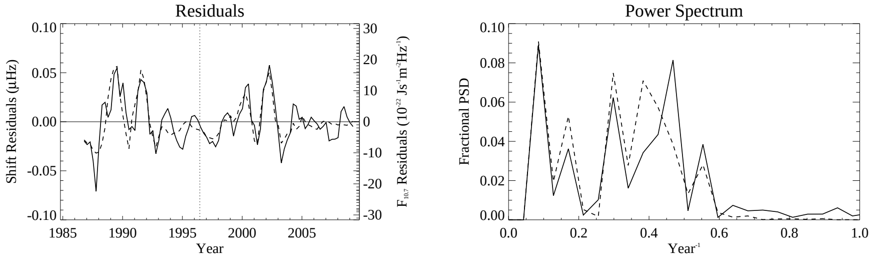

Figure 2. Left: The residuals obtained when subtracting the unsmoothed frequency shifts (solid line) and radio flux (dotted line) from heavily smoothed values. Right: The power spectrum of these residuals.

two to three year period. Similar "quasi-biennial" variation have been remarked upon before, specifically in the green coronal emission line at 530.3nm at high solar activity (Vecchio & Carbone 2008). Additionally, an explanation of such quasi-biennial behaviour has been put forward by two different types of dynamos operating at different depths (Benevolonskaya 1998a,b).

We can gain further insight into what the shift in the frequencies are telling us by looking at the shifts of individual angular degrees. We show this for $\ell = 0$ - 3 in Fig. 3. The $\ell = 0$ shifts seem to fit the radio flux very well, with a reduced χ^2 value of only 1.8 (which is considerably lower than the averaged ℓ value of 3.5). This may be partly due to the fact that the $\ell = 0$ modes are more sensitive to the whole disc of the Sun than the higher ℓ modes.

For the $\ell = 1$ modes there is more structure than in the $\ell = 0$ case and this results in a poorer fit with the radio flux (the reduced χ^2 is 3.3). The $\ell = 2$ mode shifts show more similarity with $\ell = 0$ than $\ell = 1$. However the fit to the radio flux is again poorer (a reduced χ^2 of 3.1). This correlation between $\ell = 0$ and $\ell = 2$ modes and also $\ell = 1$ and $\ell = 3$ modes is an intriguing result. It might be due to the fact that correlated modes have somewhat similar latitudinal sensitivities. Both $\ell = 0$ and $\ell = 2$ modes have an $m = 0$ zonal component which is sensitive to higher latitudes, whereas $\ell = 1$ and 3 modes only have sectoral components. Or alternatively, the effect could be an artifact of the fitting procedure since $\ell = 0$ and 2 modes and $\ell = 1$ and 3 modes are fitted together in pairs. These ideas will be investigated further in the future.

Again, we can look more closely at the final few points in each of the plots in order to investigate how the current solar minimum and start of cycle 24 is developing. For $\ell = 0$ we see a clear jump in the shifts at the beginning of 2008, but there is no obvious decline after this. For $\ell = 1$ the rise at the start of 2008 is much less pronounced than for $\ell = 0$, and there is a definite decline after this. The $\ell = 2$ shifts appear to start rising before the beginning of 2008 and continue upwards thereafter. Finally, for $\ell = 3$ we see a short rise during 2008, although the error bars are sufficiently large that the rises and dips are not significant.

These results match quite closely with what is seen in an analysis of GOLF data (see Salabert et al. 2009). However, in the GOLF data there was a clearer rise in the $\ell = 0$ and 2 modes and less of a dip in the $\ell = 1$ data ($\ell = 3$ modes were not included in this analysis). Salabert et al. (2009) gave an explanation for this based on the latitudinal sensitivity of the modes. They suggest that, if it is assumed that at the time of the final few measurements the start of cycle

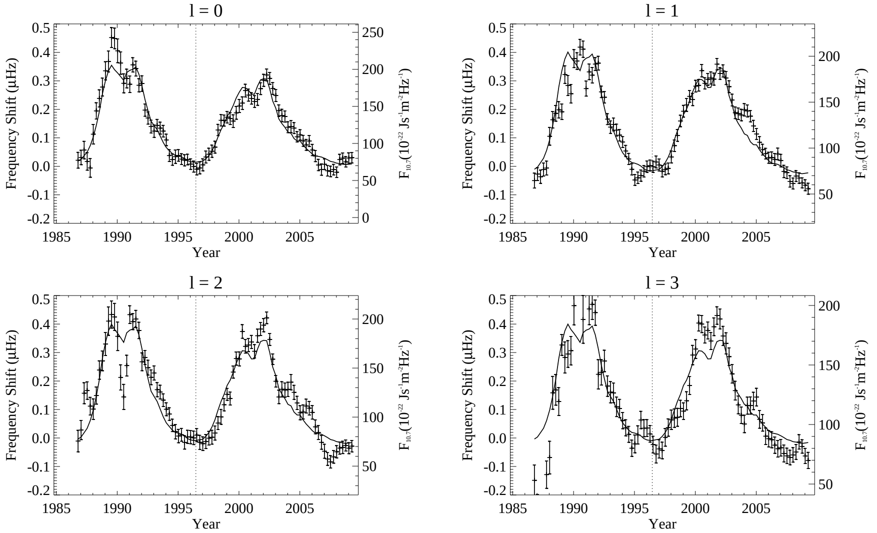

Figure 3. Compariosn between the frequency shifts as determined from BiSON data and the 10.7cm radio flux for each individual ℓ-mode in the range $0 \leq \ell \leq 3$

24 had begun, then we would expect any increased activity to occur at higher latitudes first. The $\ell = 0$ and $\ell = 2$ modes are more sensitive to these higher latitudes and hence may be seeing the effects of an increased activity due to the onset of cycle 24. The $\ell = 1$ modes, on the other hand, whose sensitivities are more confined towards the equator may not be seeing this increased activity yet.

The main argument against this explanation is that the zonal $m = 0$ components of the $\ell = 2$ multiplet, which will be the component most sensitive to higher latitudes, only contributes about 10% to the determination of the fitted frequency. The frequency fit is actually much more dependent on the sectoral $|m| = 2$ components, whose sensitivities are actually more concentrated around the equator than the $\ell = 1$ sectoral components. Therefore it would seem that there is more investigation needed into the shifts of the individual ℓ modes to try and understand these differences. Also, as described above, we will investigate the pair-by-pair nature of the fitting process to see whether it might be responsible for our observations.

4. Summary and Discussion

The shifts in oscillation frequencies over time is reasonably well correlated with other activity proxies such as the 10.7cm radio flux and ISN. However, there are some differences. The largest of which, at least over the two cycles we have data for, occur recently, starting on the downward part of cycle 23 and heading into the unusual and extended minimum between cycle 23 and 24. The current minimum in the frequency shifts is considerably deeper than in the proxies when compared with the previous minimum and there is clear structure in the shifts that does not appear in the proxies. Additionally, there is some evidence for pseudo-periodic short term (2-year) variations in activity on top of the 11-year cycle. Frequency shifts show sharper amplitude variations during the quiet sun periods compared with the radio flux.

Since the frequency shifts are sensitive to conditions below the surface it is likely that these differences are due to changes in the magnetic flux that are occurring in the solar interior. These changes then may have either yet to manifest on the surface, or are attenuated before ever reaching there.

Alternatively the differences could be due to zonal effects, since the oscillations are not all equally sensitive at different latitudes of the Sun. We have looked at the shifts of modes with different ℓ in order to gain a clearer picture of this. The $\ell = 0$ modes show the closest match with the radio flux. The higher degree modes all show greater discrepancies. The strongest regions of magnetic flux tend to start at latitudes near the poles and then drift towards the equator as the cycle progresses. Therefore, modes that are only sensitive to ceratin latitudes will see their frequency shift's respond to this drift in magnetic flux. This will ultimately add further structure into the plots of the frequency shifts that may not be apparent in the $\ell = 0$ modes or radio flux plots.

If we assume that cycle 24 had started at the time of the last few points in the data set used here, then the shape of the plots for $\ell = 0$, 1, 2, and 3 might also be explained by this latitudinal sensitivity argument as suggested by Salabert et al. (2009). Although the fact that the $\ell = 2$ modes showed a similar upturn to the $\ell = 0$ modes in the final few observations, may actually work against this theory since the zonal $m = 0$ component, which does have a greater sensitivity to higher latitudes, only has a small effect on the fitted frequency of the $\ell = 2$ multiplet.

It is clear that further work on the individual ℓ modes is needed to help clear up this matter. In the future we hope to continue the work on individual ℓ modes by comparing the frequency shifts with decomposed magnetic maps. This will allow us to compare the frequency shifts with the change in magnetic flux over time for similar zonal regions.

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