The New Solar Minimum: How deep does the problem go?

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Introduction to BiSON

Izana, Tenerife

Mt. Wilson, USA

Las Campanas, Chile

Sutherland, South Africa

Narrabri, Australia

Birmingham, UK

Carnarvon, Australia
Introduction to BiSON

Observations are made using a Resonance Scattering Spectrometer. (RSS). Light from potassium absorption line is detected using same elements held in a cell in the RSS. Measurements are made in both wings of solar line by splitting the lab line using a magnetic field (Zeeman effect).

Can measure velocity changes by measuring the intensity of solar absorption lines in the two wings.

\[ R = \frac{(I_b - I_r)}{(I_b + I_r)} \]

Effects of Earth’s orbit and rotation can be accounted for and removed leaving only the solar oscillations signal.
BiSON: Three Solar Cycles

BiSON has been collecting data for over 3 decades, but with a much improved duty cycle from 1986 onwards. This allows the shift in the oscillation frequencies to be tracked over the last three solar cycles. The shifts can be seen to closely match other activity proxies such as the 10.7 cm radio flux ($F_{10.7}$).
Calculation of Shifts

• An 8486-day BiSON time series starting on 14 April 1986 and ending on 8th July 2009 was split into 365-day series.
• Each time series was allowed to overlap the following by 91.25 days (i.e., a 4-time overlap), resulting in a total of 90 (non-independent) data sets.
• The power spectrum of each time series was parameterised using a modified Lorentzian model.
• This model was then fitted to the data using a standard likelihood maximisation method in order to extract estimates of the mode frequencies.
Calculation of Shifts

- 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 these reference values and the frequencies of the corresponding modes observed at different dates.
- The size of the frequency shift has a known dependence on frequency and this was removed.
- A weighted average of the frequency shift for each time series was then determined, enabling the shift to be plotted over time.
I averaged frequency shifts

Here we concentrate on the last two cycles (22 and 23) where the BiSON data is of sufficient quality to do meaningful statistical tests. The shifts show very good agreement with the 10.7cm radio flux up until around 2003 where there is significant disagreement relative to previous epochs.
I averaged frequency shifts

We can also look at other activity proxies such as the International Sunspot Number (ISN). It is clear that the agreement is less good than with the Radio Flux. We again see that the largest differences occur in this last cycle.
I averaged frequency shifts

The extent of the disagreement since 2003 onwards can be seen by looking at the $\chi^2$ value of the fit between the radio flux and the oscillations over a running series of 22 points (~1/4 of a cycle).
Short Term Periodic Variations

The “wiggles” seen in the oscillations, and to a slightly lesser extent the radio flux, might be a signature of short-term pseudo periodic motion. We can heavily smooth the data and look at the residuals between the smoothed and unsmoothed plot to get a better picture of this.
Short Term Periodic Variations

The 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.
Short Term Periodic Variations

We can also look at a power spectrum of these residuals. There is not a single obvious peak at shorter time periods but there are a cluster of peaks around the 2 year mark.
Frequency Shifts at l=0

We can also look at the shifts for individual angular degrees (l). The l=0 shifts seem to fit the radio flux rather well, with a reduced $\chi^2$ value of 1.8. For l=0 we see no significant decrease from the sharp rise that occurred at the end of 2008.
Frequency Shifts at l=1

Given that the error bars are of similar size, there appears to be more structure in the l=1 modes shifts than in the l=0. The fit to the radio flux is also not as good, the value of the reduced $\chi^2$ being 3.3. We do not see such a sharp rise at the end of 2008, and there is a definite decline after this.
Frequency Shifts at $l=2$

The $l=2$ modes show more similarity with the $l=0$, than $l=1$. However, there is still more structure than $l=0$ and the fit to the radio flux is poorer with a reduced $\chi^2$ of 3.1. The rise at the end of the last cycle is quite pronounced.
Frequency Shifts at l=3

The l=3 modes show more similarity with the l=1. Again the fit to the radio flux is relatively poor with a reduced $\chi^2$ of 3.7. There is a fairly sharp rise at the end of 2008, followed by a decrease, although the significance of these results is low.
Summary & Conclusions

• The shift in oscillation frequencies over time match reasonably well with other activity proxies, but there ARE differences.
  – Overall fits is better with 10.7cm radio flux than with international sunspot number.
  – Largest differences in data available seems to be occurring now. Starting on the downward part of cycle 23 and heading into the unusual and extended minimum.

• Differences may indicate magnetic effects that are happening below the surface of the Sun which are either yet to manifest on the surface or are attenuated before they arrive there.
  – Could also be due to zonal effects, since other than l=0 modes, the oscillations are not equally sensitive over the entire solar surface.
Summary & Conclusions

• 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.*
  – *Suggests the effect may be a sub-surface one that is attenuated before reaching the upper layers.*

• Can look at the shifts of individual l modes. The l=0 modes seem to show the closest fit with the radio flux proxy.
  – *This is perhaps to be expected since the l=0 gives a measure of activity across the entire surface just like the radio flux.*
  – *Lower l mode oscillations will have different sensitivities to different latitudes.*