Differences between the current solar minimum and earlier minima

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Abstract.

The Birmingham Solar-Oscillations Network (BiSON) has collected helioseismic data over three solar cycles. We use these data to determine how the internal properties of the Sun during this minimum differ from the previous two minima. The cycle 24 data show oscillatory differences with respect to the other two sets, indicating relatively localized changes in the solar interior. Analysis of MDI data from Cycle 23 and Cycle 24 also show significant signs of differences.

1. Introduction

The minimum before Solar Cycle 24 has been much quieter than many before, with the lowest sustained 10.7cm radio flux since observation of this proxy began in 1947. Other differences have been observed too, as has been discussed in detail in other articles of this volume. Most of the discussions concern observations at or above the solar surface. In this paper we try to determine whether or not there were changes in the solar interior between this minimum and others before it using helioseismic data.

The Birmingham Solar-Oscillations Network (BiSON) has been collecting helioseismic data for over three solar cycles (Broomhall et al. 2009). No other helioseismic data set spans such a long time interval. We analyze data for one-year periods starting 1986/04/01, 1995/11/01 and 2008/05/01 to determine whether there are detectable differences between the thermal structure of the Sun during these epochs. These epochs correspond to the minima of cycles 22, 23 and 24 respectively.

2. Analysis

The BiSON project makes Sun-as-a-star (i.e., unresolved) observations, and hence can determine frequencies of only low-degree modes, principally modes with degree $\ell = 0, 1, 2$ and 3. Thus we cannot invert the frequency differences to determine differences in solar structure between the three epochs. We there-
fore, have to use indirect methods. We begin by calculating the differences in solar oscillation frequencies for the three minima. The pair-wise differences are shown on Fig. 1. As is clear from Fig. 1, the differences are small. However, the differences do not look completely random — they show a small frequency dependence. The differences appear to show a small periodicity as a function of frequency. This leads us to believe that the frequency differences arise from differences in deeper layers of the Sun.

To try and understand the frequency differences we look at the frequency differences between two solar models. We use model BP04 of Bahcall et al. (2005) and BSB(GS98) of Bahcall et al. (2006). These are two up-to-date solar models. However, they differ in their input opacities and in the $^{14}N(p,\gamma)^{15}O$ reaction rate. These give rise to small differences between the models both in the outer layers and in the core (see Basu et al. 2009). The frequency differences between the low-degree modes of these two models are shown in Fig. 2(a). As can be seen, the predominant frequency difference is a smooth function of frequency and is much larger than the difference in Fig. 1. However, the differences in Fig. 2(a) are a hallmark of differences in the very near-surface layers (see Christensen-Dalsgaard & Berthomieu 1991). Frequency differences that arise from deeper differences in structure can be revealed after subtracting a low-order polynomial in frequency from the frequency-differences. The residuals following such a removal are shown in Fig. 2(b). As can be seen, the differences are of the same order as those between the different BiSON sets. Furthermore the residual differences look very similar to the BiSON differences. This strengthens our initial conclusion about the differences in solar structure between the three minima.

Basu et al. (1996) had shown that removing a function of frequency from the frequency differences is equivalent to filtering out near-surface information.
from the set. What remains is information from the deeper layers. We use that analysis and determine that the residuals are a result of removing information from layers above \( r \simeq 0.98R_\odot \), i.e., from layers above the second helium ionization zone.

As noted by Basu & Mandel (2004), changes in the region of the HeII ionization zone can be identified in BiSON low-degree modes (Verner et al. 2006). Our initial analysis of BiSON data did find differences in the frequencies of solar modes for layers at or below the HeII ionization zone, the other being the base of the convection zone (CZ). The oscillatory signature can be amplified by taking the second differences of the frequencies, i.e., \( \delta^2\nu_{n,\ell} = \nu_{n+1,\ell} - 2\nu_{n,\ell} + \nu_{n-1,\ell} \).

Considering the second differences of the frequencies of the two solar models, we expect very small differences between the BiSON data sets. While the second differences amplify the oscillatory signal, they also amplify errors. As a result we found that we cannot, at this time, get reliable results from the frequencies of the minimum of Cycle 22. The results from Cycles 23
and 24 are shown in Fig. 3(b). Also shown are fits to the data using the model of Basu et al. (2004). The model has three components, an oscillatory part for the HeII ionization zone, one for the CZ base and a smoother term to account for near-surface signals.

The amplitudes of the oscillatory terms are frequency dependent and hence we deal with the average amplitude over the fitting interval of 1.7 mHz to 3.8 mHz. For Cycle 23, we find that the amplitude of the Helium term is $0.699 \pm 0.020$ µHz, while that for Cycle 24 it is $0.743 \pm 0.020$ µHz. The differences are not large, but formally significant at the 2σ level. If these changes are taken at face value, it would imply that Cycle 24 has a higher amplitude. This is consistent with results of Basu & Mandel (2004) and Verner et al. (2006) who found that the amplitude increases as the level of activity decreases. This test might therefore be sensitive enough to distinguish between the small difference of activity between the two sets. The errors for Cycle 22 are large (mostly because only 3 of the 6 stations in the BiSON network were operating during that period and we have found several systematic errors that need to be removed from the data), and we find an amplitude of $0.723 \pm 0.04$ µHz. The wavelength of the HeII signal is a measure of its acoustic depth and we find a value of $\tau = 690.2 \pm 5.6$ s for Cycle 23 and $693 \pm 5.5$ s for Cycle 24. The differences are not statistically significant, however, if we just considered the central value, the results
would indicate lower sound-speed between the surface and the HeII ionization zone during the minimum of Cycle 24 compared with Cycle 23. Cycle 22 has \( \tau = 690.5 \pm 26 \text{s} \), and the uncertainties are too large to draw any conclusions. The differences in the amplitudes and acoustic depths of the CZ signature is not statistically significant. Cycles 23 and 24 have amplitudes of 0.283 ± 0.042 \( \mu \text{Hz} \) and 0.287 ± 0.042 \( \mu \text{Hz} \) respectively. The acoustic depths are respectively \( \tau = 2301 \pm 15 \text{s} \) and \( 2317 \pm 15 \text{s} \).

As mentioned earlier, the oscillation power spectrum for the minimum of Cycle 22 shows evidence of some systematic effects, and hence, we are in the process of re-analyzing the data.

The Michelson Doppler Imager (MDI) on board SOHO has observed helioseismic data for Cycle 23, and hence we also use those data to determine the differences in the Sun between the minimum of Cycle 23 and the current minimum. These data have \( p \)-modes up to \( \ell \simeq 200 \) and hence we can invert the differences. The frequency differences between Cycle 23 and 24 are shown in Fig. 4(a) and the sound-speed differences obtained by inverting the frequency differences are shown in Fig. 4(b).

From Fig. 4(a) we see that the frequencies for the minimum of Cycle 23 were higher than those of Cycle 24. This is consistent with the fact that the minimum of Cycle 23 was more active than that of Cycle 24. The frequency differences in Fig. 4(a) were inverted using two methods, the Regularized Least Squares (RLS) method (see Basu & Thompson 1996) and the Subtractive Locally Optimized Averages (SOLA) method (Pijpers & Thompson 1994; Rabello-Soares et al. 1999). The results are more significant when the two methods give the same result. The inversion results show that for the region we can resolve, the
Sun had a somewhat higher sound-speed during the minimum of Cycle 23 than during the minimum of Cycle 24. While the differences are small, they do appear to be statistically significant, at least over a part of the solar interior. We are unable to resolve the structure of the outer 10% due to the lack of higher-degree modes. The limited number of low-degree modes in the data sets limits our inversion results in the deeper layers.

3. Conclusions

Using data from the Birmingham Solar Oscillation Network and the Michelson Doppler Imager on board SoHO, we find evidence that suggests the structure of the Sun may have been different during the the minimum of Cycle 24 compared with the minimum of Cycle 23. There is some evidence that it was different compared to the minimum of Cycle 22 too, however, Cycle 22 data need to be re-analyzed before we can make firm conclusions. The evidence points to a lowered sound-speed during Cycle 24 in layers deeper than 0.98R⊙.

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