

# A seismic signature of a second dynamo?

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## ABSTRACT

The Sun is a variable star whose magnetic activity varies most perceptibly on a timescale of approximately 11 years. However, significant variation is also observed on much shorter timescales. We observe a quasi-biennial (2-year) signal in the natural oscillation frequencies of the Sun. The oscillation frequencies are sensitive probes of the solar interior and so by studying them we can gain information about conditions beneath the solar surface. Our results point strongly to the 2-year signal being distinct and separate from, but nevertheless susceptible to the influence of, the main 11-year solar cycle.

*Subject headings:* methods: data analysis - Sun: activity - Sun: helioseismology - Sun: oscillations

## 1. Introduction

The Sun is a variable star, whose magnetic activity shows systematic variations. The most conspicuous of these variations is the 11-cycle solar cycle (Hathaway 2010). Starting in 1755 March the 11-year cycles have been labelled with a number and we are cur-

rently moving into cycle 24 after just coming out of an unusually extended minimum.

Over the past twenty years it has become apparent that significant (quasi-periodic) variability is also seen on shorter timescales, between one and two years (e.g. Benevolenskaya 1995; Mursula et al. 2003; Valdés-Galicia & Velasco 2008). In this paper we investigate the origins of this so-called “mid term” periodicity by looking beneath the so-

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lar surface. We attempt to answer the following question: Is the periodicity the result of modulation of the main solar dynamo responsible for the 11-year cycle or is it caused by a separate mechanism?

To answer this question we have used helioseismology to investigate the solar cycle related changes of the Sun's interior. We study the variation with the solar cycle of the frequencies of the Sun's natural modes of oscillation, which are known as p modes (because internal gradients of pressure provide the restoring force for the oscillations). 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 (e.g. Christensen-Dalsgaard 2002, and references therein). The frequencies of p modes 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; Jiménez-Reyes et al. 2003; Chaplin et al. 2007; Jiménez-Reyes et al. 2007). 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.

We use oscillations data collected by making unresolved (Sun-as-a-star) Doppler velocity observations, which are sensitive to the p modes with the largest horizontal scales (or the lowest angular degrees,  $\ell$ ). Consequently, the observed frequencies are of the truly global modes of the Sun (e.g. Christensen-Dalsgaard 2002, and references therein). These modes travel to the Sun's core but, because the sound speed inside the Sun increases with depth, their dwell time at the

surface is longer than at the solar core. Consequently, p modes are most sensitive to variations in regions of the interior that are close to the surface and so are able to give a global picture of the influence of near-surface activity. The data were collected by the Birmingham Solar-Oscillations Network (BiSON; Elsworth et al. 1995; Chaplin et al. 1996) and the Global Oscillations at Low Frequencies (GOLF; Gabriel et al. 1995; Jiménez-Reyes et al. 2003; García et al. 2005) instrument onboard the ESA/NASA Solar and Heliospheric Observatory (SoHO) spacecraft.

## 2. Uncovering the mid-term periodicity

The observations made by BiSON and GOLF were divided into 182.5-day-long independent subsets. BiSON has now been collecting data for over 30 years. The quality of the early data, however, are poor compared to more recent data because of poor time coverage. 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 2009 October 7. GOLF has been collecting data since 1996 and so we have been able to analyze data covering almost the entirety of solar cycle 23 i.e. from 1996 April 11 to 2009 April 7. After 1996 April 11, when both GOLF and BiSON data were available, we ensured that the start times of the BiSON and GOLF subsets were the same. Note that at the time of writing we have more recent calibrated data available from BiSON than from GOLF.

Estimates of the mode frequencies were extracted from each subset by fitting a modified Lorentzian model to the data using a standard likelihood maximization method. Two different fitting codes have been used to extract the mode frequencies, both giving the

same results. For clarity we only show the results of one method, which was applied in the manner described in Fletcher et al. (2009). 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 of this paper 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).

For each subset in time three weighted-average frequency shifts were generated, 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 to 3.71 mHz); 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 linewidths causing modes to overlap in frequency.

The top panels of Fig. 1 show mean fre-

quency shifts of the p modes observed by BiSON and GOLF respectively (see also Broomhall et al. 2009; Salabert et al. 2009). The 11-year cycle is seen clearly and its signature is most prominent in the higher-frequency modes. This is a tell-tale indicator that the observed 11-year signal must be the result of changes in acoustic properties in the few hundred kilometers 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). Despite the low- and high-frequency bands showing different sensitivities to the 11-year cycle there is a significant correlation between the observed frequency-shifts. The correlations between the low- and high-frequency band shifts is 0.82 for the BiSON data and 0.67 for the GOLF data. The errors on the correlations indicate that there is less than a 0.05 per cent chance that each of these correlations would occur by chance.

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 dominant 11-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 the bottom panels of Fig. 1, show a periodicity on a timescale of about 2 years.

The signal is reassuringly similar in the BiSON and GOLF datasets. The correlation between the two sets of frequency shifts was found to be highly significant in all three fre-

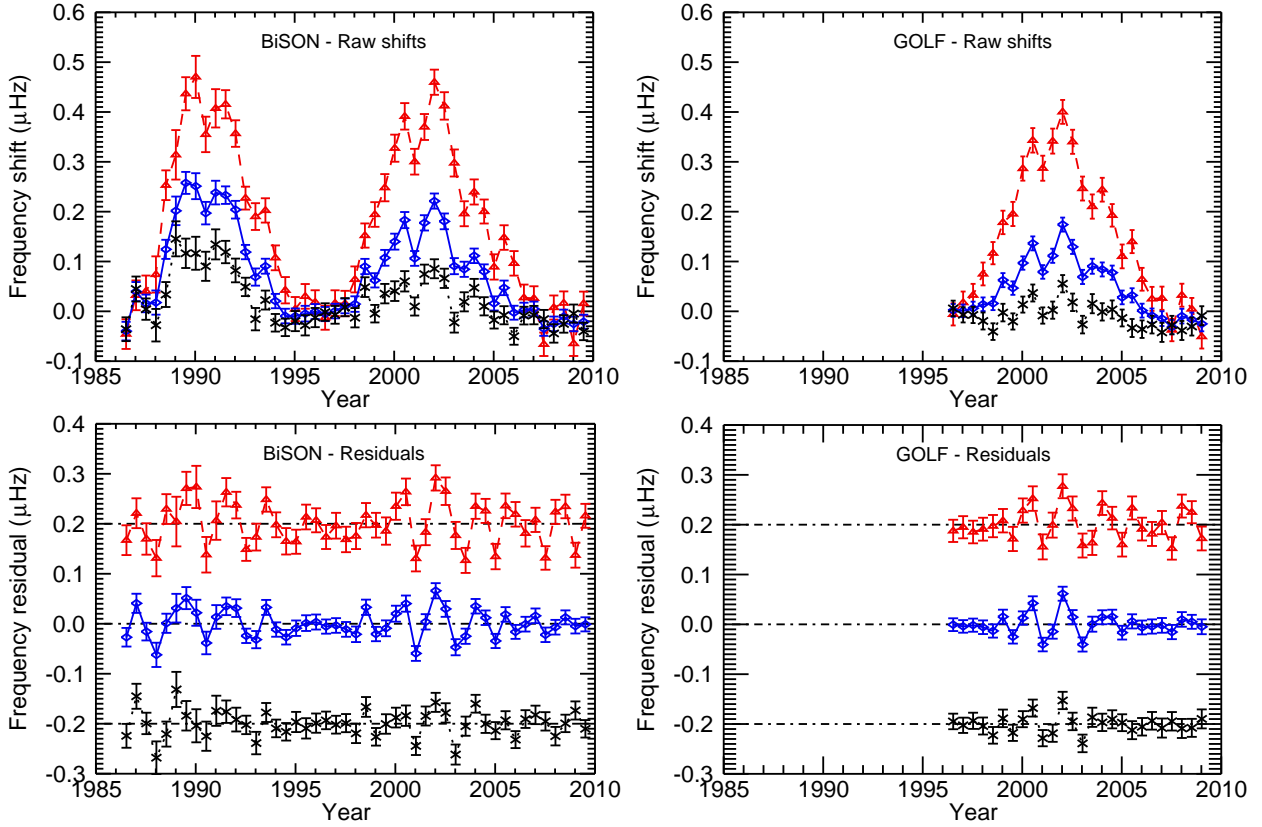


Fig. 1.— Top: average frequency shifts of “Sun-as-a-star” modes with frequencies between 1.88 and 3.71 mHz (total-frequency band, blue solid line and diamond symbols); 1.88 and 2.77 mHz (low-frequency band, black dotted line and cross symbols); and 2.82 and 3.71 mHz (high - frequency band, red dashed line and triangle symbols). Bottom: residuals left after dominant 11-year signal has been removed (black dotted and red dashed curves are displaced by  $-0.2$  and  $+0.2$ , respectively, for clarity).

quency bands: 0.71 for the low-frequency band, 0.99 for the high-frequency band, and 0.96 for the total-frequency band. There is less than a 0.05 per cent chance that these correlations would occur randomly. There is also a significant correlation between the low- and high-frequency band residuals for both the BiSON (0.46) and GOLF (0.55) data and there is less than a 1 per cent probability of these correlations occurring by chance.

Periodograms of the raw frequency shifts, as shown in the upper panels of Fig. 1, were computed to assess the significance of the 2-year signal. Fig. 2 shows the periodograms obtained from the BiSON data, oversampled by a factor of 10. The large peak at  $0.09 \text{ yr}^{-1}$  is the signal from the 11-year cycle. There are also large peaks at approximately  $0.5 \text{ yr}^{-1}$ . Statistical analysis of the BiSON periodograms established that the apparent 2-year periodicity was indeed significant, in both the low- and high-frequency bands, with a false alarm probability of 1 per cent (Chaplin et al. 2002). Excess power is also present in the GOLF periodograms around  $0.5 \text{ yr}^{-1}$ . However, none of the GOLF peaks are as prominent as the equivalent peaks observed in the BiSON data because fewer GOLF data are available, particularly during periods of high activity when the 2-year signal is most prominent.

### 3. Discussion

The 2-year signal is most prominent during periods that coincide with maxima of the 11-year cycle (although the high-frequency band continues to show changes through the most recent solar minimum). But what is most remarkable is that the 2-year signal has a similar amplitude in modes of all frequencies. This is in stark contrast to the 11-year

signal, which is about five times stronger in the higher-frequency modes (see Fig. 1).

The acoustic 2-year signal we see in the modes is, therefore, predominantly an *additive* contribution to the acoustic 11-year signal; nevertheless its amplitude envelope appears to be modulated by the 11-year cycle. The 2-year signal must have its origin in significantly deeper layers than the 11-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 11-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 11-year cycle.

One possibility is a dynamo action seated near the bottom of the layer extending 5 per cent below the solar surface. This region shows strong rotational shear, 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 behavior observed in other proxies of solar activity (Benevolonskaya 1998a,b). When the 11-year cycle is in a strong phase, buoyant magnetic flux sent upwards from the base of the envelope by the main dynamo could help to nudge flux processed by this second dynamo into lay-

ers 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 modes, or in other proxies (where the 2-year signals are also only detectible during phases of high activity) (see e.g. Vecchio & Carbone 2008; Hathaway 2010, and references therein). That the signal was also visible in the high-frequency modes during the recent extended minimum may also therefore point to behavioral changes in the main dynamo, and its influence on the 2-year signal.

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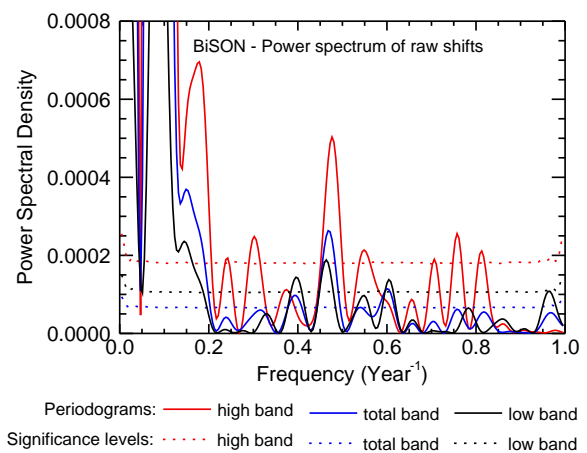


Fig. 2.— Periodograms of the BiSON frequency shifts. The solid lines represent the periodograms of the different frequency bands (see legend). The dotted lines represent the 1 per cent “false alarm” significance levels for the respective frequency ranges.