Are short-term variations in solar oscillation frequencies the signature of a second solar dynamo?

Anne-Marie Broomhall¹, Stephen T. Fletcher², David Salabert³,⁴, Sarbani Basu⁵, William J. Chaplin¹, Yvonne Elsworth¹, Rafael A. García⁶, Antonio Jiménez³, and Roger New⁷

¹ School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
² Faculty of Arts, Computing, Engineering and Sciences, Sheffield Hallam University, Sheffield S1 1WB, UK
³ Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain
⁴ Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain
⁵ Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA
⁶ Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/SAp, Centre de Saclay, 91191 Gif-sur-Yvette, France

E-mail: amb@bison.ph.bham.ac.uk

Abstract. In addition to the well-known 11-year solar cycle, the Sun’s magnetic activity also shows significant variation on shorter time scales, e.g. between one and two years. We observe a quasi-biennial (2-year) signal in the solar p-mode oscillation frequencies, which are sensitive probes of the solar interior. The signal is visible in Sun-as-a-star data observed by different instruments and here we describe the results obtained using BiSON, GOLF, and VIRGO data. Our results imply that the 2-year signal is susceptible to the influence of the main 11-year solar cycle. However, the source of the signal appears to be separate from that of the 11-year cycle. We speculate as to whether it might be the signature of a second dynamo, located in the region of near-surface rotational shear.

1. Introduction

The Sun is a variable star, whose magnetic activity shows systematic variations. The most conspicuous of these variations is the 11-year solar cycle [1]. However, over the past twenty years it has become apparent that significant (quasi-periodic) variability is also seen on shorter timescales, between 1 and 2 years [e.g. 2–4]. Fletcher et al. [5] investigated the origins of this so-called “mid-term” periodicity by looking at variations in the frequencies of solar oscillations. Fletcher et al. used the Sun-as-a-Star observations made by the Birmingham Solar Oscillations Network [BiSON; 6; 7] and the Global Oscillations at Low Frequencies [GOLF; 8–10] instrument onboard the Solar and Heliospheric Observatory (SOHO) spacecraft. In this paper we extend the work of Fletcher et al. by examining data observed by the Variability of solar IRradiance and Gravity Oscillations [VIRGO; 11] instrument, which is also onboard SOHO. 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). We have examined each set of VIRGO data individually and find that the results are similar for each channel. Therefore, here we concentrate on the results found using the blue VIRGO data.

The frequencies of solar p modes vary throughout the solar cycle with the frequencies being at their largest when the solar activity is at its maximum [e.g. 9; 12–16]. 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 Sun-as-a-star observations, which are sensitive to the p modes with the largest horizontal scales (or the lowest angular degrees, l). Consequently, the observed frequencies are of the truly global modes of the Sun (e.g. 17, 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.

Recently García et al. [18] observed signatures of a stellar activity cycle in asteroseismic data obtained by the Convection Rotation and Planetary Transits [CoRoT; 19] space mission. With the prospect of longer asteroseismic data sets (~5 years) becoming available through, for example, Kepler [20] there will be opportunities to observe activity cycles in other stars. These observations will provide constraints for models of stellar dynamos under conditions different from those in the Sun.

2. Uncovering the mid-term periodicity

The observations made by BiSON, GOLF and VIRGO 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, is 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 and VIRGO have 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 all three sets of data were available, we ensured that the start times of the subsets from each observational program were the same.

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 [21]. 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 [22].

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 l = 0, 1, and 2 modes over fourteen overtones (covering a frequency range of 1.88 – 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. However, we note here that each of the fitted frequencies was checked for accuracy and this resulted in many of the low-n fitted frequencies from the VIRGO data being discarded. The lower signal-to-noise of the oscillations in the VIRGO data means that accurate fits to the data are only possible above approximately 2.3 mHz. 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.

The left-hand panels of Figure 1 show mean frequency shifts of the p modes observed by BiSON, GOLF and blue VIRGO, respectively [also see 5; 22; 23]. The 11-year cycle is seen clearly and its signature is most prominent in the higher-frequency modes. This is a telltale indicator that the observed
Figure 1. Left column: average frequency shifts of “Sun-as-a-star” modes with frequencies between 1.88 and 3.71 mHz (total-frequency band, solid line, and diamond symbols); 1.88 and 2.77 mHz (low-frequency band, dotted line, and cross symbols); and 2.82 and 3.71 mHz (high-frequency band, dashed line, and triangle symbols). Right column: residuals left after dominant 11-year signal has been removed (dotted and red dashed curves are displaced by −0.2 and +0.2, respectively, for clarity).

11-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 [24; 25]. Note that the difference between the low- and high-frequency range shifts is less for the blue VIRGO data, compared to the BiSON and GOLF data. This is because the low-frequency range for the blue VIRGO data does not extend as low in frequency as for the BiSON and GOLF data. 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 are 0.82 for the BiSON data, 0.67 for the GOLF data, and 0.78 for the VIRGO data. The errors on the correlations indicate that there is less than a 1% chance that each of these correlations would occur by chance. The signal is reassuringly similar in the different data sets. The correlation between the BiSON, GOLF, and blue VIRGO frequency shifts was found to be highly significant in all three frequency bands with less than a 1% chance that these correlations would occur randomly.

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
There is a significant correlation between the low- and high-frequency band residuals for the BiSON (0.46), GOLF (0.55), and blue VIRGO (0.76) data and there is less than a 1% probability of these correlations occurring by chance. The correlations between the BiSON and GOLF residuals were found to be significant in all three frequency bands with less than a 1% probability of observing such correlations by chance. The BiSON and blue VIRGO residuals are also reasonably well correlated in all three frequency bands, with less than a 2% probability of observing the correlations by chance. However, the GOLF and blue VIRGO residuals are less well correlated.

The periodograms of the raw frequency shifts shown in the left-hand panels of Figure 1 were computed to assess the significance of the 2-year signal. Figure 2 shows the periodograms, oversampled by a factor of 10. Also plotted in Figure 2 are the 1% false alarm significance levels [26], which were determined using Monte Carlo simulations based on the size of the errors associated with the raw frequency shifts (see Figure 1). The large peak at 0.09 yr$^{-1}$ is the signal from the 11-year cycle. There are also large peaks at approximately 0.5 yr$^{-1}$ (indicated by the shaded regions denoted R1 in each panel of Figure 2). Statistical analysis of the BiSON periodograms established that the apparent 2-year periodicity was indeed significant, in the low-, total-, and high-frequency bands, with a false alarm probability of 1%. A peak at the same frequency is also significant in the high- and total-frequency bands in the GOLF and blue VIRGO data. Note that there is also a significant peak at a slightly lower frequency in the low-frequency band blue VIRGO data. The fact that the peaks in the GOLF and blue VIRGO data are not as prominent as the equivalent peaks observed in the BiSON data is expected because fewer GOLF and blue VIRGO data are available, particularly during periods of high activity when the 2-year signal is most prominent.

The examination of the VIRGO data supports the theory that there is a 2-year signal present in the
frequency shifts. One possible explanation for this signal is a dynamo action seated near the bottom of the layer extending 5% below the solar surface [see 5, for details]. The amplitude envelope of the 2-year signal observed in the BiSON and GOLF data appears to be modulated by the 11-year cycle (see the right-hand panels of Figure 1). This is particularly true for the low-frequency band. Interestingly this does not appear to be the case for the signal observed in the blue VIRGO data, which could be because fewer very low-frequency modes were used to calculate the blue VIRGO frequency shifts, thus indicating that the signal shows some frequency dependence. Note that although asymmetries in the Sun’s magnetic field have been used to explain the 2-year signal observed in other proxies of solar activity this would not explain why the amplitude of the signal observed in the p-mode frequency shifts is so similar in all frequency bands.

A prominent peak is observed at $\sim 0.9 \text{ yr}^{-1}$ in the blue VIRGO high- and total-frequency bands. However, there is no signal present at the same frequency in either the BiSON or GOLF data. This peak could, therefore, be instrumental in origin.

3. Evidence for a 1.3-year periodicity
We also draw attention to a significant peak at a frequency of approximately $0.8 \text{ yr}^{-1}$ or a period of $\sim 1.3 \text{ yr}$ (indicated by the shaded regions denoted R2 in Figure 2). This peak is visible most strongly in the blue VIRGO data but an excess of power is also visible in the high-frequency range in the BiSON and GOLF data (although the GOLF peak is only significant at a 2% level). Notice that the 1.3-year signal observed in the VIRGO data is significant in both the low- and high-frequency bands but almost fully suppressed in the total-frequency band. This is because the signal is out of phase in the two different regions of the frequency-spectrum.

A 1.3 yr periodicity has been observed in other solar data. For example, Howe et al. [27] observed variations in the rotation profile of the Sun, most predominately at low latitudes and with a period of 1.3 yr. However, the signal was found to be intermittent and has not been observed since 2001 [28]. Jiménez-Reyes et al. [9] observed a 1.3 yr modulation in the energy supply rate. Wang and Sheeley [29] observe a 1.3 yr quasi-periodicity in the Sun’s dipole magnetic moment and open magnetic flux. Wang and Sheeley [29] attribute this to the stochastic processes of active region emergence and a decay time of about 1 yr, which is determined by differential rotation, meridional flow and supergranule diffusion. The presence of excess power at this frequency in all three sets of data means that this feature warrants further investigation, as does the fact that the signal is out of phase in the low- and high-frequency band blue VIRGO data, and so the 1.3-year periodicity is the subject of ongoing work.

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