Seismic comparison of the 11 and 2 yr cycle signatures in the Sun

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The solar magnetic activity consists of two periodic components: the main cycle with a period of 11 yr and a shorter cycle with a period of ≈ 2 yrs. The origin of this second periodicity is still not well understood. We use almost 15 yrs of long high quality resolved data provided by the Global Oscillation Network Group (GONG) to investigate the solar cycle changes in p-mode frequency with spherical degree ℓ = 0 − 120 and in the range 1600 µHz ≤ ν ≤ 3500 µHz. For both periodic components of solar magnetic activity our findings locate the origin of the frequency shift in the subsurface layers with a sudden enhancement in the amplitude of the shift in the last few hundred kilometers. We also show that the size of the shift increases towards equatorial latitudes and from minimum to maximum of solar activity. On the other hand, the signatures of the 2 yr cycle differ from the one of the 11 yr cycle in the magnitude of the shift, as the 2 yr cycle causes a weaker shift in mode frequencies and a slower enhancement in the last few hundreds kilometers. Based on these findings we speculate that a possible physical mechanism behind the quasi biennial periodicity (QBP) could be the beating between different dynamo modes (dipole and quadrupole mode).

1 Introduction

Stellar cycles can show all types of periodicities (Balun et al. 1995, Brandenburg, Saar & Turpin 1998, Oláh & Strassmeier 2002, Bohm-Vitense 2007) from none to multiple periods. Even our nearest star shows several periodicities. Sunspot time series dating back to the XVII century reveal that the amplitude and the length of the solar cycle are modulated on different timescales, among which the Gleissberg cycle is the most noticeable one (Kolláth 2009). Investigating time series of proxies extending back to 10⁴ yr ago, such as the cosmogenic isotopes Be⁴⁰ or C¹⁴, it is possible to investigate the level of solar activity in the distant past. In combination with sunspot data, these studies revealed intervals of very low solar activity, called grand minima (Usoskin et al. 2007). At the other end of the time scale, there are short and mid-term periodicities, between months and 11-years (Bai 2003). The one attracting a great deal of interest is the quasi-biennial periodicity (QBP) as it appears to modulate mainly all indices of solar activity proxies and is particularly strong over periods coinciding with solar maxima, although it doesn’t seem to characterize every solar cycle (Krivova & Solanki 2002, Vecchio & Carbone 2009). The discovery of a 1.6 year magnetic activity cycle in the exoplanet host star Horologii (Metcalf et al. 2010) has been recently reported. This is the shortest activity cycle so far measured for a solar-type star and it might be related to the mid-timescale magnetic variations recently identified in HD 49933 and in the Sun from astroseismic (García et al. 2010) and helioseismic measurements (Broomhall et al 2009a, Salabert et al. 2010, Simoniello et al. 2012). Conversely to solar activity indices, signatures of the QBP in helioseismic observations have shown its likely persistent nature throughout solar cycle 23 (Broomhall et al. 2012, Simoniello et al 2012). Several mechanisms have been proposed so far in an attempt to explain the origin of the QBP, but no clear evidences have been found. We decided to address this issue by investigating the origin and the latitudinal dependence of the shift, because differences or similarities of the seismic properties of the shift over two cycles might help us gaining a deeper insight on the mechanism behind the QBP signal. The findings will also help us improving our understanding on shorter cycles already observed in some stars.

2 Observations

2.1 Determination of mode frequency

The Global Oscillation Network Group (GONG) consists of six instruments deployed worldwide to provide nearly continuous and stable velocity images of the Sun. The GONG instrument is based on a Michelson interferometer called a Fourier tachometer. It works by using the Ni line at

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are produced. The modes frequencies for each \((n \, \ell \, m)\) mode are estimated from three months power spectra using the standard GONG algorithm (Anderson et al. 1990), which fits modes up to \(\ell=150\). The peak-fitting algorithm has two types of error flags related to the quality of the fit to a mode (Hill & Jefferies 1998). The individual frequencies of the azimuthal components are afterwards made publicly available [http://gong2.nso.edu/archive/]. In this work we investigate the temporal evolution of mode frequencies covering a period of observation from May 1995 up to December 2010.

2.2 Central frequency of the multiplets

The acoustic modes at the solar surface are described by associated Legendre functions \(P^m_\ell(x)\), where \(\ell\) is the degree, \(m\) is the azimuthal order, running from \(-\ell\) to \(\ell\), \(x\) is the cosine of the colatitude \(\theta\). Rotation and asphericity break the degeneracy among the modes of the same \(\ell\) and \(m\). The description of the mode is completed by the radial order \(n\), with modes of the same \(\ell\) and \(m\), having different frequencies. The frequencies of modes within an \(n,\ell\) multiplet are often described by using a polynomial expansion

\[
\nu_{n,\ell,m} = \nu_{n,\ell} + \sum a_j(n,\ell) P^j_\ell(m)
\]

where the basis functions are polynomials related to the Clebsch-Gordan coefficients (Ritzwoller and Lavelly 1991) \(C_{j0\ell m}\) by

\[
P^j_\ell(m) = \frac{\ell^j\sqrt{(2\ell - 1)!(2\ell + j + 1)!}}{(2j)!\sqrt{(2\ell + 1)}} C_{j0\ell m}^{\ell,m}
\]

The term \(\nu_{n,\ell}\) in this expansion is the so-called central frequency of the multiplet.

2.3 Frequency shift determination

The temporal variations of the \(p\)-mode frequencies were defined as the difference between the frequencies of the corresponding modes observed on different dates and reference values which is the average over the years 1995-1996. Since the frequency shifts have a well-known dependency on frequency and mode inertia (Jain, Tripathy & Bhatnagar 2001), we consider only those modes that are present in all data sets and the shifts are scaled by the mode inertia (Christensen-Dalsgaard & Berthomieu 1991). The mean frequency shifts is calculated from the following relation

\[
\delta \nu(t) = \frac{\sum_{n,\ell,m} Q_{n,\ell,m} \delta \nu(t)}{\sum_{n,\ell,m} Q_{n,\ell,m}}
\]

The weighted averages of these frequency shifts were then calculated in two different frequency bands:

1. low frequency band \(1600 \mu\text{Hz} \leq \nu \leq 2500 \mu\text{Hz}\);

2. high-frequency band \(2500 \mu\text{Hz} \leq \nu \leq 3500 \mu\text{Hz}\).

The frequency dependence analysis might help us localizing the region where the visible manifestation of the 2 yr signal starts to occur. In fact the mode frequency rules the position of the upper turning point of the waves (Chaplin et al. 2001). Seismic observations have shown that over the 11 yr activity the size of the shift strongly increases as the mode frequency increases, suggesting that the origin of the shift is predominantly a subsurface phenomenon. In fact, in the Sun’s interior the ratio \(\beta = \frac{\text{gas pressure}}{\text{magnetic pressure}} \gg 1\) and only close to the surface layers the two terms become of comparable strength. As a consequence we observe a shift in the mode frequencies only very close to the subsurface layers and its amplitude varies along the 11 yr solar magnetic activity cycle. It is then important to carry out the same type of investigation over the 2 yr cycle, because if the origin of the shift is due to a mechanism acting at a different depth (such as a second dynamo mechanism close to the subsurface layers), its signature might be revealed by the frequency analysis.

3 Subsurface analysis and latitudinal dependence of the shift

3.1 Localizing the origin of the shift

We consider the central frequency \(\nu_{n,\ell}\) of the \((n,\ell)\) multiplet, representing a global average of the activity through the frequency shift. We investigated the solar cycle changes in \(p\)-mode central frequency averaged over spherical degree \(\ell=0-120\). Fig. 1 compares the solar cycle changes in \(p\)-mode frequency induced by the two periodic components of solar magnetic activity and the 2-year cycle in the two frequency bands. There are several features underlying the magnitude of the shift over the 2 yr cycles:
characterizing all type of solar activity indices is the quasi-periodicities, but the one reaching significant level and characterizing all type of solar activity indices is the quasi-biennial periodicity (QBP). In the attempt to explain the origin of this second cyclic component, several mechanisms have been proposed so far such as a second dynamo mechanism acting in the subsurface layers (Benevolenskaja 1998a, Benevolenskaja 1998b) or the instability of magnetic Rossby waves acting in the tachocline (Zaqarashvili 2010, Zaqarashvili 2011). Unfortunately the debate is still open as no clear mechanism has been identified and supported by observational evidences. We, then, asked ourselves if the QBP is a phenomenon that might be explained in terms of non linear dynamo theory (as it happens for other stars) or instead we need to invoke a further mechanism. To this aim we investigated the properties of the frequency shift over the two periodic components of solar magnetic activity and we found several similarities: i) the observational evidences place the origin of the shift in the subsurface layers, with a sudden enhancement in the size of the shift over the last few hundred kilometers; ii) the magnitude of the shift increases from minimum to maximum of solar activity and towards equatorial latitudes. On the other hand we also found that the signatures of the two cycles differ in the amplitude of the shift as the QBP causes a weaker shift and a slower enhancement in the last few hundred kilometers. Based on this difference some authors speculated that inside the Sun a second dynamo mechanism is acting (Fletcher et al. 2010, Broomhall et al. 2012), but if this is indeed true, we wouldn’t expect the same latitudinal dependence in the size of the shift over the two cycles (Schou et al. 1998). This might suggest the need to take into account different mechanisms to explain the origin of the QBP (Simoniello et al. 2012). To this aim it will be important to complete the investigation with a depth dependence analysis of the shift in the subsurface layers. If this further analysis will not show any difference over the two cycles, then we should start exploring the possibility that the QBP signal might be the result of the beating between different dynamo modes, such as dipole and quadrupole modes. Within this theory, the secondary cycle is shown to have lower amplitude as we observe in the Sun (Brandenburg 1989, Fluri and Beryugina 2004, Sokoloff 2005, Tobías et al. 2005, Moss 2008). Furthermore, there is evidence that a quadrupole-like field was important during the Maunder Minimum and there is also a contemporary evidence that there is still a significant quadrupolar component (Pulkkinen et al. 1999).

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Fig. 2 The temporal evolution of \( p \)-mode frequency shifts at different latitudes (from left to right) over both periodic components of solar magnetic activity cycle (upper panel) and the 2-yr cycle (bottom panel) in low (green) and high (red) frequency bands.