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Solar cycle variations in the powers and damping rates of low-degree solar acoustic oscillations

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Abstract

Helioseismology uses the Sun's natural resonant oscillations to study the solar interior. The properties of the solar oscillations are sensitive to the Sun's magnetic activity cycle. Here we examine variations in the powers, damping rates, and energy supply rates of the most prominent acoustic oscillations in unresolved, Sun-as-a-star data, obtained by the Birmingham Solar Oscillations Network (BiSON) during solar cycles 22, 23, and the first half of 24. The variations in the helioseismic parameters are compared to the 10.7 cm flux, a well-known global proxy of solar activity. As expected the oscillations are most heavily damped and the mode powers are at a minimum at solar activity maximum. The 10.7 cm flux was linearly regressed using the fractional variations of damping rates and powers observed during cycle 23. In general, good agreement is found between the damping rates and the 10.7 cm flux. However, the linearly regressed 10.7 cm flux and fractional variation in powers diverge in cycles 22 and 24, indicating that the relationship between the mode powers and the 10.7 cm flux is not consistent from one cycle to the next. The energy supply rate of the oscillations, which is usually approximately constant, also decreases at this time. We have determined that this discrepancy is not because of the first-order bias introduced by an increase in the level of background noise or gaps in the data. Although we cannot categorically rule out an instrumental origin, the divergence observed in cycle 24, when the data were of high quality and the data coverage was over 80%, raises the possibility that the effect may be solar in origin.

Keywords: Sun; Helioseismology; Solar cycle

1. Introduction

Natural resonant oscillations of the Sun and stars can be used to study solar and stellar interiors using helioseismic and asteroseismic techniques. In the Sun the most prominent oscillations are acoustic p modes, so called because the main restoring force is a pressure differential. Properties of the oscillations, such as their frequencies, allow profiles of the solar interior to be constructed. Since p-mode oscillations are stochastically excited and intrinsically damped by the near-surface turbulent convection, observations of the powers and damping rates of the oscillations also provide information on the Sun's internal convection.

It has been known for some time that the frequencies of p modes vary systematically throughout the Sun's 11 yr magnetic activity cycle, with the frequencies being at a maximum when magnetic activity on the Sun is also at a maximum (e.g. Woodard et al., 1985; Elsworth et al., 1990; Pallé et al., 1990). However, they are not the only

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parameter of *p*-mode oscillations that vary with time: damping rates and powers are also observed to depend on the level of solar activity, with damping rates being at their highest and powers being at their lowest at solar maximum (e.g. Jefferies et al., 1990; Chaplin et al., 2000; Komm et al., 2000; Jiménez et al., 2002; Salabert et al., 2007). The exact cause of the variations remains uncertain; for example, active regions are known to affect mode lifetimes and suppress mode powers, but the associated mechanisms are not totally understood (Woods and Cram, 1981; Lites et al., 1982; Brown et al., 1992; Rajaguru et al., 2001; Komm et al., 2002; Howe et al., 2004). Meanwhile Houdek et al. (2001) theorized that during times of high activity magnetic structures have a sufficient enough effect on convection to noticeably alter mode damping rates.

Evidence for activity-cycle variations in mode parameters has been observed in stars other than the Sun (García et al., 2010). However, despite the large amount of high-quality data produced by CoRoT and Kepler the expected evidence for similar cycles in solar-like stars has not been forthcoming. The frequency-lifetime-power relationship observed in solar *p* modes could be crucial for identifying stellar activity cycles. It is therefore important to fully understand the activity cycle variations in mode parameters observed for the Sun.

We present variations in the lifetimes, powers and the energy supply rate of global solar *p* modes throughout cycles 22, 23, and the rising phase of cycle 24. In Section 2 we describe the data and analysis procedures employed in this study. The main results are presented and discussed in Section 3. A summary is provided in Section 4.

2. Data and analysis

The Birmingham Solar Oscillations Network (BiSON; Davies et al., 2014) has been making spatially unresolved (Sun-as-a-star) observations of the Sun for more than 30 yrs. However, the early data have relatively poor coverage and so here we use data that extend from January 1st 1985 until March 26th 2014. This allows us to compare two and a half solar cycles, making BiSON unique in helioseismic terms as the longest running helioseismic observatory. We have used the most recent data release from BiSON, which were produced using new procedures that improved the signal-to-noise ratio of the oscillations (Davies et al., 2014).

Although Sun-as-a-star (unresolved) helioseismic observations, such as those made by BiSON, are only sensitive to modes with the largest horizontal scales (low degree, or low-*l*) a rich spectrum of oscillations still exists. In this study we concentrate on modes with $l = 0$, 1, and 2 as these modes have the largest amplitudes in the BiSON data. We only consider modes in the frequency range $2400 \leqslant \nu_{n,l} \leqslant 3500\,\mu\text{Hz}$. These are the most prominent modes of oscillation, which means that parameters of the modes can be obtained accurately and precisely. These are also the modes that experience the largest variation in mode damping as the Sun's magnetic activity varies from maximum to minimum (e.g. Komm et al., 2000). Finally, this range includes 8 modes from each *l* (24 modes in total that correspond to different radial orders, *n*).

Frequency-power spectra of the data were fitted using a Maximum Likelihood Estimation technique (Fletcher et al., 2009), where the asymmetric profile of Nigam and Kosovichev (1998) was used. The width of the fitted profile, $\Delta_{n,l}$, is then proportional to the damping rate of the oscillations. while the power, *P*, is commonly defined as

$$P_{n,l} = 0.5\pi H_{n,l}\Delta_{n,l}, \tag{1}$$

where *H* is the height of the fitted profile. We note that Eq. 1 gives the power of a symmetric peak. We neglect the asymmetries since the asymmetric approximation of Nigam and Kosovichev (1998) is only valid in the vicinity of the mode and the integral of the profile tends to infinity. Since the asymmetries are small (Jiménez-Reyes et al., 2007), Eq. 1 is a good approximation; however, large errors in the asymmetries could affect the determined powers. This is discussed further in Section 3. The uncertainties associated with $\Delta_{n,l}$ and $H_{n,l}$ are those obtained from the fitting procedure. However, $\Delta_{n,l}$ and $H_{n,l}$ are highly anti-correlated and this must be taken into account when determining the uncertainty associated with $P_{n,l}$. We do so in the manner described by Chaplin et al. (2000).

The energy of the oscillations, $E_{n,l} \propto M_{n,l}P_{n,l}$, where $M_{n,l}$ is a measure of the interior mass affected by the oscillation as given by Christensen-Dalsgaard and Berthomieu (1991). The rate at which energy is supplied to the oscillations, $\mathrm{d}E_{n,l}/\mathrm{d}t \equiv \dot{E}_{n,l}$, is proportional to the product of $\Delta_{n,l}$ and $E_{n,l}$ (see Chaplin et al. (2000), for details).

In order to study solar cycle variations in the helioseismic parameters a compromise must be struck. The data series need to be of sufficient length in time to obtain a good enough resolution in the power spectrum to allow the parameters of the oscillations to be obtained accurately and precisely; however, if the data series are too long one loses sensitivity to solar cycle variations. Therefore, we have used a running sequence of 365 d spectra that overlap by 273.75 d. The frequency-power spectrum of each subset of data was fitted independently, producing 114 sets of mode parameters.

We begin by creating a "reference" set of line widths, powers, and energy supply rates. These are constructed by determining the weighted mean line widths, powers and energy supply rates across all 365 d subsets observed after 1993, as this data has a higher fill and lower noise than preceding subsets (see below). The mean line width ($\overline{\Delta_{n,l}}$), power ($\overline{P_{n,l}}$), and energy supply rate ($\overline{\dot{E}_{n,l}}$) are determined individually for each mode (n, l). Since the mode parameters we are considering are dependent on the