GOLF: PROBING THE OBSERVED LOW FREQUENCY SPECTRUM WITH A NUMERICAL MODEL.

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ABSTRACT

The averaged power spectrum of the GOLF velocity signal is computed with a 0.2 µHz frequency resolution and compared with a power spectrum of solar g modes created from a standard solar model. There appears to be a significant correlation between the two with a shift of 0.95 µHz; the model giving the higher frequencies.

1. INTRODUCTION

The techniques used for the detection of solar g modes are implicitly based on hypotheses about the damping time and phase stability of the observed oscillations. The usual assumption of a vanishingly small variance of those two parameters leads to an elementary strategy of increasing the time resolution of the power spectrum in order to see the solar modes growing above the background noise. However, this hypothesis is not correct for the lower frequency acoustic modes. For the GOLF measurements, three experimental settings have been used with the Doppler shift measured in the blue or red wings, and the deduced phase of the signal related to g modes is likely not simply shifted by π. Furthermore, a close analysis shows no evidence for a long-term coherent signal growing in the low frequency domain.

We use an alternate approach, searching for stochastically excited modes. A limited time resolution permits the calculation of a series of independent power spectra, or an averaged power spectrum, reducing the energy of random components, from the available long data sequence. This averaged spectrum is then compared to a synthetic template deduced from the numerical results obtained for an evolved model of the Sun, calculated with the CESAM code, Morel et al. (1997). The table of frequency calculated in Provost et al. (2000) for their reference model M1 include the low radial order modes and are extended in low frequency to 80 µHz. The calculation of the rotational splitting assumes a rigid rotation in the radiative zone and the core and a differential rotation in the convective zone, as discussed in Corbard et al. (1997). The value $\Omega = 433$ nHz assumed for the rigid rotation is deduced from the p-mode splitting.

2. THE GOLF DATA SET

The data set used starts on April 10, 1996 and ends on November 18, 2002, corresponding to a change of the GOLF configuration. 2.5 years of additional data are available up to the present (June 2004) but not yet included.

The data were preprocessed, as described in Gelly et al. (2002), in order to produce a normalized radial velocity signal. There is a low frequency limit of 24 µHz.

We then select 44 non-overlapping 50 day long intervals, distributed basically uniformly but taking into account the principal SOHO interruptions. An oversampled power spectrum is calculated for each period. No apodization was used, which might have reduced the noise due to the side lobes arising from the few data discontinuities.

3. THE NUMERICAL SCHEME

The numerical table gives the central frequency and the rotational splitting of a given mode corresponding to the spherical harmonic $n, l, m$. We produce from the table a template spectrum as a set of identical window functions centered on each calculated g-mode frequency, 0.1 µHz wide and of equal amplitude. The value for the tesseral order $m$ of the modes used in the filter follows the mode-visibility rule that $l + m$ be even. As the splitting separation is narrower than the uncertainty margin of the model, an additional selection over $m$ must be made for the first step of analysis, in order to avoid fringes resulting from multiplets, as discussed in Section 4.

For the GOLF data, we calculate the averaged power spectrum for a set of the periods defined in Section 2, or all of them. The mean spectrum is then corrected for the well known low frequency increase, using a polynomial fit.

Finally, we compute a correlation function using a uniform shift of the template from -10 µHz to 10 µHz; a wide range compared to the 3 µHz uncertainty expected from the model calculation.
4. PRELIMINARY RESULTS

This analysis shows a maximum in the cross-correlation for a frequency shift of 0.95 \( \mu \text{Hz} \), for any calculation including the modes of degree \( l = 1 \) to \( l = 3 \). Typical results are shown in Fig.1 and 2.

Figures 3 and 4 show that the correlation peak is approximately reproducible in two calculations using only one of the two independent halves of the data (i.e. 22 of the 44 existing 50 day intervals). We then obtain different cross-correlation patterns but a single common resonance, with the delay already detected. This result increases the likelihood of the detection of a signal related to solar g modes.

The rotational splitting in the template spectrum produces fringes in the cross-correlation when not all of the components exist in the observed data. Conversely, splitting in the observed data also results in fringes if the template does not include the splitting. If the pattern of the observed power spectrum corresponds to the template, all the splitted components of each mode are added in single peaks, giving a maximum energy for the correlation.

Up to now we are in the first case, apparently not all of the theoretically visible modes of tesseroid order \( m \) are detected. So, the value for \( m \) of the modes used in the calculation of the filter is arbitrarily restricted in order to clean up the resulting figure. On the other hand, this strategy may also reduce the number of coincidences, lowering the signal to noise ratio. The optimum filter is not yet known and should obviously depend on the data set used.

Nevertheless the detected signal is weak, as seen in the low signal-to-noise ratio in the correlation of the solar signal with the numerical model.

The comparison of Figures 5 and 6 with Figure 1 gives an example of the results related to the rotational splitting of \( l = 1 \) modes. In Figure 1, the use of the \( m = \pm 1 \) modes cleans up the fringes observed in Figure 5 and 6 for a single value of \( m \). We can then conclude that doublets exist in the GOLF spectrum, with the expected separations.

5. CONCLUSION

This preliminary result is evidence for the detection of a pattern corresponding to the calculated solar g modes in the GOLF low frequency spectrum.

The numerical model gives frequencies higher than the observations; the shift measured in the correlation function is 0.95 \( \mu \text{Hz} \). This result is within the uncertainties of the solar model (related to the uncertainties on metallicity, opacity or nuclear reaction rates), leading to a realistic adjustment of the core.

The result is consistent with a rigid rotation below the convective zone.
Figure 1. Correlation figure for predicted modes for $l = 1 \ m = \pm 1$ and $l = 2 \ m = 0$. Horizontal scale in Hz, arbitrary vertical scale.

Figure 2. Correlation figure for predicted modes for $l = 1 \ m = \pm 1$, $l = 2 \ m = 0$ and $l = 3 \ m = \pm 1$. A single common resonance at 0.95 $\mu$Hz is present in Fig.1 and 2. Horizontal scale in Hz, arbitrary vertical scale.

Figure 3. Correlation figure for $l = 1 \ m = \pm 1$, $l = 2 \ m = 0$ and $l = 3 \ m = \pm 1$. The first half of the GOLF data is used. Horizontal scale in Hz, arbitrary vertical scale.
Figure 4. Correlation figure for $l = 1$ $m = \pm 1$, $l = 2$ $m = 0$ and $l = 3$ $m = \pm 1$. The second half of the GOLF data is used. The resonance at $0.95\mu$Hz already seen Fig.1 and 2 is the only common feature observable in Fig.3 and 4. Horizontal scale in Hz, arbitrary vertical scale.

Figure 5. Correlation figure for predicted modes for $l = 1$ $m = 1$ and $l = 2$ $m = 0$. Horizontal scale in Hz, arbitrary vertical scale.

Figure 6. Correlation figure for predicted modes for $l = 1$ $m = -1$ and $l = 2$ $m = 0$. Horizontal scale in Hz, arbitrary vertical scale.