RECENT PROGRESS ON G-MODE SEARCH

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ABSTRACT

The Phoebus group is an international collaboration of helioseismologists, its aim being to detect low-frequency solar g modes. Here, we report on recent work, including the development and application of new techniques based on the detection of coincidences in contemporaneous datasets and the asymptotic properties of the g-mode frequencies. The length of the time series available to the community is now more than ten years, and this has reduced significantly the upper detection limits on the g-mode amplitudes. Furthermore, low-degree p modes can now be detected clearly at frequencies below 1000 μHz.

Key words: g modes - SOHO - Sun.

1. INTRODUCTION

At this meeting, we celebrate not only the 10 years of the existence of the SOHO mission but also more than 20 years of g-mode searches. The famous *Catania* meeting of 1983 had several talks claiming g-mode detection (Kotov et al., 1984; Fröhlich and Delache, 1984; Isaak et al., 1984; Scherrer, 1984; Delache, 1984). The detection of g modes was one of the scientific goals of the SOHO spacecraft. The design of this mission was already presented at the *Catania* meeting (Domingo and Wyn-Roberts, 1984). Since the onset of the SOHO programme, there have been several claims of g-mode detection (e.g. Delache and Scherrer, 1983; Thomson et al., 1995), none of which has ever been confirmed.

The Phoebus group was formed in 1997, with the aim of detecting g modes. The group set an upper limit to the g-mode amplitude of 10 mm.s^{-1} at 200 μHz (Appourchaux et al., 2000). The Phoebus group reported its activity at the Big Bear Lake (Appourchaux, 2003), Tenerife (Appourchaux et al., 2001) and Boston meeting (Appourchaux, 1998; Appourchaux et al., 1998). Members of the GOLF team recently joined us at the beginning of 2005. The group is also now supported by the International Space Science Institute[1].

Since the last meeting in Big Bear Lake, there have been new developments in detection techniques, both from work undertaken as part of the Phoebus programme, and from collaborations with the group. In what follows, we begin by discussing techniques developed over the past few years, and illustrate these with results. We then go on to give current upper limits on the g-mode amplitudes, and finally summarize where things stand.

2. G-MODE DETECTION TECHNIQUES.

Appourchaux (2003) noted that any recipe for g-mode detection may be comprised of combinations of the following: *Spectrum estimators*, *Mode masking*, *Statistical testing*, *Patterns*, and *Data combinations*. Each of the 'steps' can be combined to give a different search methodology. For instance *Statistical testing* is required on any *Spectrum Estimators* derived from any *Mode masking*. This is one possible example. One step that must always be included is *Statistical testing*, for it provides an essential safeguard against over-interpretation of the data.

[1]www.issi.unibe.ch/teams/GModes

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Since our last review, a novel technique has been developed by Duvall (2004). It is based on time-distance analysis of p modes, and seeks to uncover and measure flows induced by g modes at the base of the convection zone. This is a very promising technique that uses several of the aforementioned steps, these being spectrum estimators, mode masking, statistical techniques, and patterns. The potential of this technique is yet to be fully realized. Since it aims at observing the g modes deep in the convection zone, this technique might more easily detect greater velocity changes.

Patterns: asymptotic properties. The use of the asymptotic behaviour of the g-mode frequencies (or periods) was pioneered by Delache in 1983, this induced to a claimed detection of g modes (Delache and Scherrer, 1983). This lead other observers to apply the method on their own data (Fröhlich and Delache, 1984). The asymptotic approach is of relevance only to high-order g modes (of frequency below 100 μHz) for which the asymptotic behaviour applies. Unfortunately, the solar noise increases towards lower frequencies, and the mode spacing dramatically decreases; matters are further complicated by the rotational splitting (Fröhlich and Andersen, 1995) which also contributes to the overall pattern. Following discussions in the Phoebus group, we have resumed the work using this technique. As the theoretical mode amplitude increases with increasing frequency (see e.g. Fig.3) the asymptotic frequencies have to be corrected with e.g. the results from the detailed model calculations (Provost et al., 2000). Moreover, the rotational splitting has to be corrected not only for the influence of the coriolis force (Berthomieu et al., 1978), but also for the effect of a possibly rapidly rotating core which has to agree with the results of the p modes in the outer layers of the radiative core. Another crucial point is to derive a statistical test for assessing the significance of the coherence peak found.

Another technique based also on the asymptotic properties of the g modes comprises of computation of the Fourier transform of the power spectrum, and subsequent searches for regular patterns in period. This technique is explained in more detail by García *et al.*(these proceedings). In both cases, it is the use of combined information from many modes, and the patterns they give rise to in the spectrum, that decreases limits on the amplitude threshold required for detection. However, this 'mode averaged' information does impose some restrictions for inference made on the core structure. In short, detection on a mode-by-mode basis (i.e., of individual multiplets) is more desirable. Nevertheless, these pattern methods will provide invaluable input for the mode-by-mode searches.

Patterns: rotational splitting. Appourchaux et al. (2000) made use of the pattern created by the rotational splitting to detect low-frequency p modes: the so-called *collapsogramme* method. Figure 1 shows the result for low-frequency p modes for two different imaging tachometers. It is important to point out that modes below 1000 μHz were not undetectable 5 years ago. The collapsogramme can also be adapted for the full-disc, 'Sun-as-a-star' instruments producing a single power spectrum: in this case it is called an *overlapogramme*. A similar approach has been used by García et al. (2001) for the GOLF data. Multiplet search methods have also been developed by Chaplin et al. (2002) and by Turck-Chièze et al. (2004), which demonstrate that the detection limit can be lowered by searching for a pattern of closely separated 'spikes' (rotationally split compared), as opposed to individual spikes.

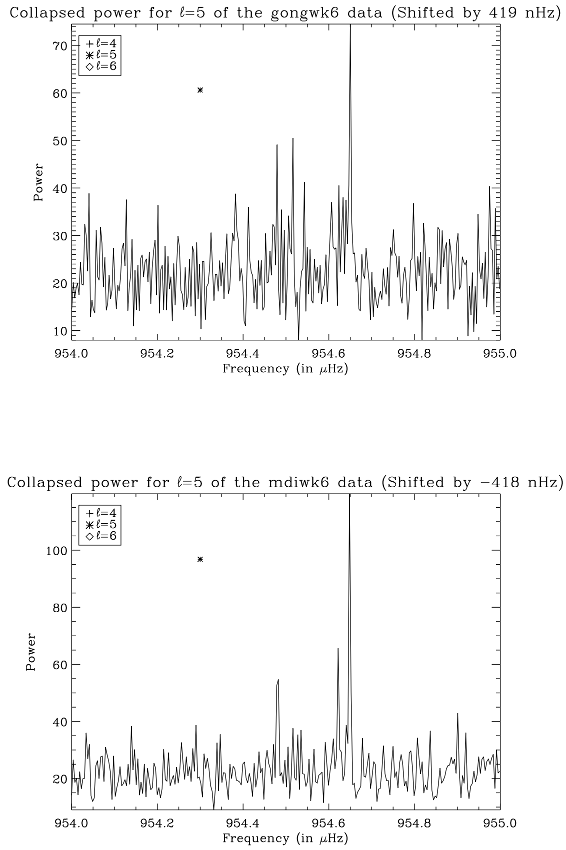

Figure 1. Collapsogramme obtained for the GONG data (top) and MDI data (bottom) with an assumed rotational splitting of 419 and 418 nHz*, respectively. Both are almost 10 years of data for l=5 mode. The star indicates the theoretical location of the* $l = 5, n = 4$ *mode.*

Data combination. George Isaak always advocated use of coincidence techniques (of the type applied in, for example, nuclear physics). This seminal idea has been used in Fig. 2 to derive the 1-σ detection level using a contemporaneous 3071-day combination of GOLF and BiSON data. Proper allowance must be made for the presence of common background noise from the solar granulation. This gives rise to important modifications to the probability thresholds.

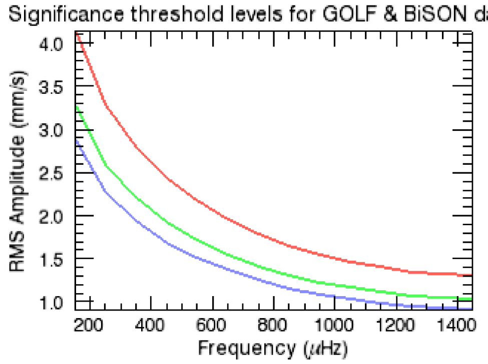

Figure 2. Threshold levels for a 1% probability that anything detected over a range of $100\ \mu\mathrm{Hz}$ *is noise for single peak (red), multiplet (green) and for two peaks in consecutive bins (blue). The levels are specific to GOLF and BiSON data as they depend on the amount of common noise, which will vary between spectra.*

3. ON THE UPPER LIMIT TO G-MODE AMPLITUDE

The canonical upper limit of 10 mm.s^{-1}, given by the Phoebus group in Appourchaux et al. (2000), has since been lowered, as a result of the collection of more data and the application of new analysis techniques (Gabriel et al., 2002).

Effect of time. As mentioned earlier by Appourchaux (1998), limits on the amplitude threshold for detection improve as $\sqrt{T}/\sqrt{\log(T)}$ (as opposed to $\sqrt{T}$). For a singlet, it can be derived that the upper limit at 200 μHz is:

$$v_{\rm up} = 4.3\sqrt{\frac{10+\log(T)}{T}} \qquad (1)$$

where $v_{\rm up}$ is in mm.s^{-1}, T is the observation time in years. Equation (1) is derived from Appourchaux et al. (2000). The limit for a 100-year timeseries would therefore be about 1.6 mm.s^{-1}, not the 1-mm.s^{-1} given by a simple square-root dependence on time. This discrepancy arises from the fact that the probability limit, at which the threshold is determined, must be kept constant for different T (Appourchaux, 1998). To do otherwise would increase the likelihood of making a false detection. The limit is about 4.8 mm.s^{-1} due to a data set about 10 years long.

Effect of pattern. When searches are made for multiplets, in the manner of Chaplin et al. (2002); Turck-Chièze et al. (2004), or when optimal masks are applied, as was done by Wachter et al. (2003), one can gain even more, and lower the limit given above by a good factor 3.

Figure 3 compares the upper limit to the amplitude to theoretical limits. Time is obviously on our side. According to recent numerical simulations, g modes are likely to be excited by convective plumes (Dintrans et al., 2005) which could modify somewhat the amplitude estimate made by Kumar et al. (1996); derivation of g-mode amplitude to be compared with the work of Andersen (1996) is in progress (Dintrans, private communication). Optimism brings with it the possibility that in the not-too-distant future we might hope to detect mixed modes, which are known to have large amplitudes in the convection zone (implying that they might be easier to detect).

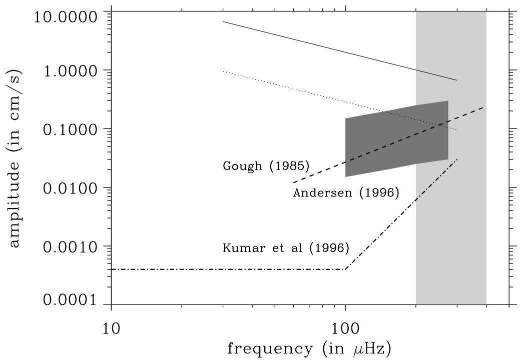

Figure 3. The black thin line is the limit for a singlet derived by Christensen-Dalsgaard (2002) from the upper limit given by Appourchaux et al. (2000) for a 2-year observing time. The dotted is the upper limit for a multiplet for a 10-year observing time scaled as in Eq. (1) assuming an improvement by a factor 3 with respect to a singlet. The thick black dashed and thick black dotted-dashed curves are the simplified version of the theoretical g-mode amplitude for l=1 predicted by Kumar et al. (1996) and Gough (1985), respectively. The dark grey box shows the theoretical range of g-mode amplitude derived for $l = 1$ *from calculation performed by Andersen (1996). The light grey box shows the location of the mixed modes.*

4. CONCLUSION

The future seems to be brighter than ever. The SOHO mission has just been extended to the end of 2009. We are now more optimistic than we could have foreseen several years ago, and believe that at least individual mixed modes may be within reach of detection (given the *highest* theoretical amplitudes, and numerical calculations). One very promising avenue, which is yet to be fully exploited, is the technique pioneered by Duvall (2004), which would aim to detect the g modes below the observable surface using time-distance techniques.

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