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BiSON observations, their application to the rotation of the solar interior and to excitation mechanisms - the advantages of long, continuous time series

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Abstract. The Birmingham Solar Oscillations group runs the so-called BiSON network. As the network has been operational since 1981 we have the great advantage of long, well-filled, historical datasets. These data have been put to many uses of which two are highlighted here. We have recently been able to use 16-month spectra with good fill to measure, unambiguously, the rotational splitting of low-ℓ p-modes at frequencies where, although the modes are very weak, they have line widths which are significantly less than the line splitting. This has lead to the conclusion that the core of the Sun probably rotates slowly, possibly at the same rate as the rest of the radiative interior. The other issue which is addressed is the use of short transforms to follow the evolution of individual modes. The analysis gives strong support to the stochastic excitation mechanism and allows one to measure decay times and other mode parameters directly.

Key words: Sun, Oscillations, Networks, Rotation, Mode excitation

1. BiSON

This network observes the Sun as a star, that is to say, we do not have any spatial resolution. The advantage of this strategy is that the instruments are extremely stable and are sensitive to those modes which penetrate into the deep solar interior. Since the first observations by the Birmingham group in the mid 1970s, BiSON has grown to its current size of six stations distributed around the world (Chaplin et al. 1995b). The first station to be installed in the network (known as Mark I) is at Izana in Tenerife and the

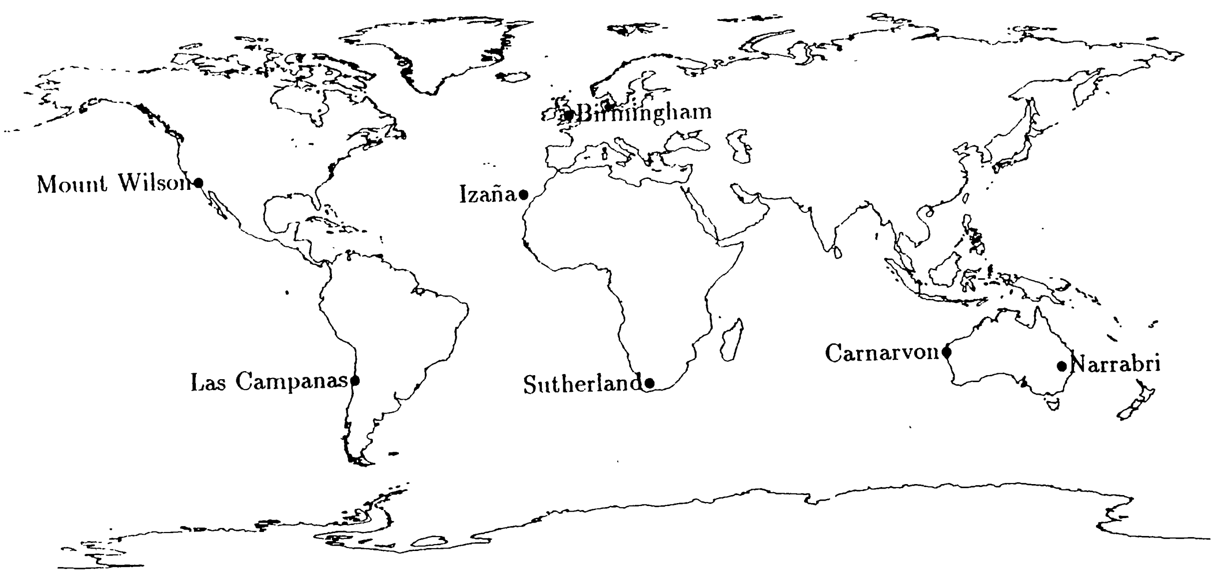

Figure 1. The BiSON network. The web address at which information can be found is http:// bison.ph.bham.ac.uk

latest station is at Narrabri in Eastern Australia. The geographical distribution of the stations and the address of our Web page are shown in figure 1.

The last complete year for which we have statistics on the performance of the network is 1994. In that period we had good data for 78 percent of the time and overlaps for 45 percent of the time. The time series that we derive from the observed solar velocity is Fourier transformed to give estimations of the eigenfrequencies of the Sun. There are always trade-offs in computing such transforms. Short transforms allow one to follow the temporal evolution of the modes but they do not give good frequency resolution nor do they permit the detection of weak modes. As a general indication, one can say that a mode must be detected within one decay time with a signal to noise of at least unity if one is going to detect it at all. Thus for modes in the middle of the p-mode spectrum, the modes must be detected with several days of data but at frequencies below 1.5mHz, there are advantages of using spectra many months long (Chaplin et al. 1995a).

Thus the resolution with one half day of data is of order 23μHz which is enough to separate odd and even mode pairs but not to split ℓ=0 from ℓ=2, with 2 months of data the resolution is 0.18 μHz and with 16 months it is 0.02 μHz. These latter two spectra will split the modes and resolve the rotational structure of the modes which is 0.4μHz and greater. The advantage of the longer spectrum comes with the range of modes detected. The difficulty with the clear observation of rotational splitting is that the strong p modes

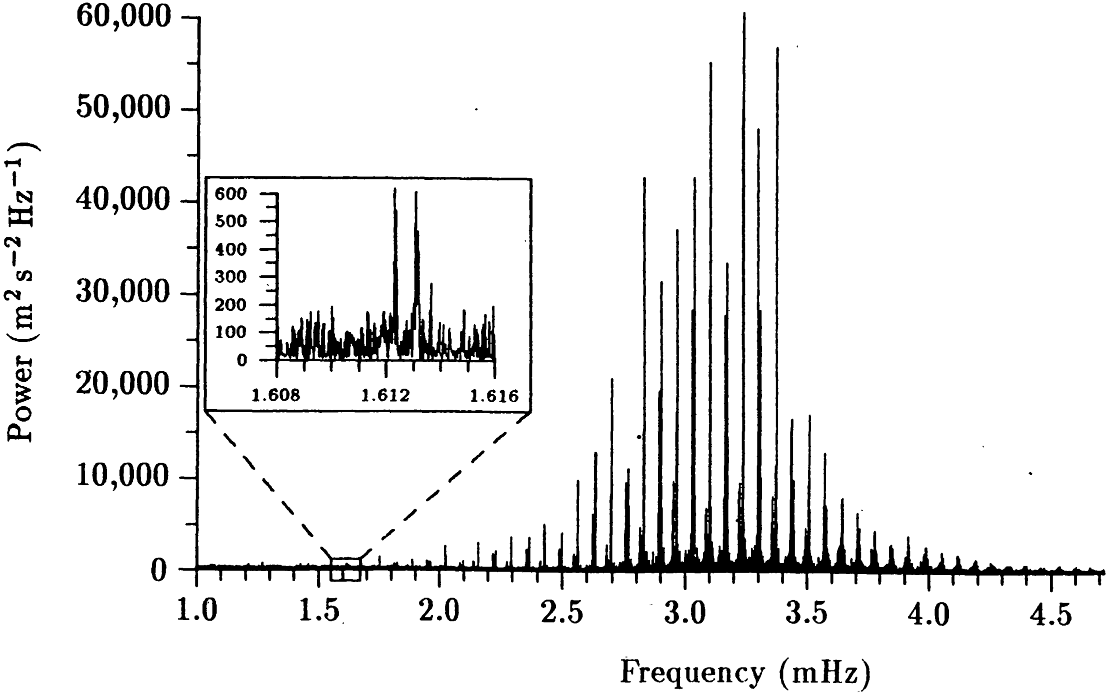

Figure 2. A power spectrum generated using data collected in a 16-month period from May 1 1993 to August 23 1994. The expanded plot displays a region of the spectrum showing the ℓ=1, n=10 mode. The double peak is caused by rotational splitting

have line widths which are at least comparable with the rotational splitting and often larger than it. The splitting is clearest for the modes below 2mHz. As can be seen from the spectrum (figure 2), these modes are weak and require long spectra to detect them.

2. Mode excitation

As we have discussed elsewhere (Elsworth et al. 1995a,c), the use of very many short spectra whose length is less than the life time of the modes concerned allows us to test the predictions of the theory of stochastic excitation. BiSON data and IPHIR (Toutain & Fröhlich 1992) give strong support to the theory (Kumar 1988). However, we see a few more excitations of high amplitude than the theory predicts and the origins of these excursions are not known at this stage. We wish here to test the hypothesis that they are merely artifacts of the low resolution and are beats between unresolved components. There are two approaches to the problem. The first is to inspect the modes themselves and see if the large modes are preferentially seen in the even mode pair which is likely to show the effects of beating more than the odd mode pair will. We find that both even and odd mode pairs show excesses. The second approach is to simulate the data and compare the distribution that one gets for a single mode and for a close pair of modes.

For the real data we have just over 22,000 sets of data coming from half-day transforms and the simulations are run with a similar number of realisations. The distribution of mode strengths obtained in the simulations is very close to the theoretical prediction and does not show the number of excesses seen in the real data. We see one excess which is probably due to beating. Thus, although mode beating does occur, it is not appear to be the principal cause of the excess effects. We have also tested the dataset to see if the excesses are due to insufficient resolution in the time series. Again, reducing the length of the time series used to derive the mode strengths does not remove the excess points.

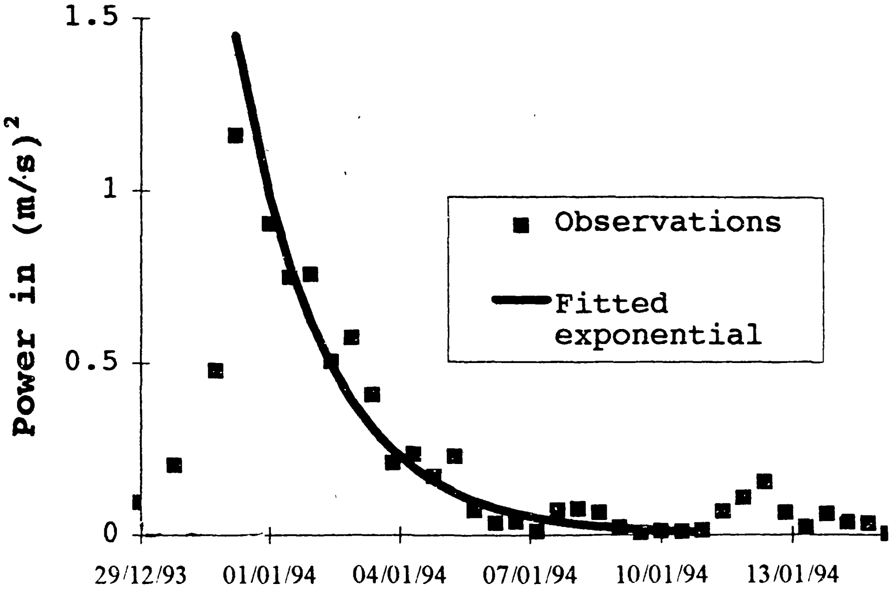

Figure 3. Decay of an ℓ=1 mode at 3.10mHz as a function of time. The data were collected in January 1994

To make these observations requires a well-filled data set with good inherent signal to noise. Redundancy provided by overlaps in the data from different stations is also important in establishing the authenticity of the excess events. The decay of one of these strong modes is shown in figure 3. There is very little evidence for any beat and longer transforms indicate that it is ℓ=1 line that is excited.

3. Rotation

The rest of this paper is devoted to the other example of the advantage that BiSON data afford - namely - long data runs with good fill and good signal to noise. As indicated earlier, we are interested in clearly resolving the rotational structure in the p-mode spectrum. To do this we turn to the lower-frequency part of the spectrum. An analysis (Elsworth et al. 1995d) of many modes (see table 1) from two independent 16-month

Table 1. ℓ- and n values for which rotational splitting measured

ℓ	n	range of frequencies
1	9 to 17	1.473mHz to 2.559mHz
2	9 to 16	1.536mHz to 2.486mHz
3	13 to 21	2.138mHz to 2.676mHz
4*	17 to 21	2.729mHz to 3.272mHz

* see Chaplin et al. 1996

spectra give a mean sidereal splitting of 416±9nHz. This is below the surface rate and indicates that the core of the Sun cannot be rotating faster than the surface.

With reference to figure 2, we see that a 16-month spectrum clearly detects and resolves a rotationally split line at about 1.6mHz. This is an ℓ=1 line and it is split into two components as predicted by theory. Although the width of the components is visible it is much less than the observed splitting of about 0.8μHz. These low-ℓ modes probe the core of the Sun. The inner turning points of the modes are given in detail by solar models but we can make some general statements here. The lower the ℓ-value, the closer to the centre that the mode gets, and the higher the frequency, the closer to the centre. Thus these modes where the line width is low, do not penetrate as close to the centre as do the higher frequency modes analysed by IRIS (Fossat 1996). The inner turning points of the modes we have analysed range from 6 to 18 per cent of the solar radius.

3.1 Analysis of the Data

The method by which the data were analysed is as follows. The data are modelled as lines with lorentzian shape, the number of components predicted by theory and with the relative heights of the components given by Christensen-Dalsgaard (1989). The mode visibility makes the outer components of the split line stronger than the inner components meaning that our results are weighted towards sectoral modes. The statistics of the data are presumed to follow the maximum likelihood distribution. This is an important point worthy of some discussion. It is recognised that the modes themselves appear to be very ragged and the excursions in the amplitude of the mode power are proportional to the power in the modes (Anderson et al. 1990). When the data are fitted to a model, the residual noise can be calculated by dividing the data by the derived model: It is a prediction of maximum likelihood statistics that the distribution of the residual noise should follow a negative exponential curve. This can be tested for the real data and we find that, in general, maximum likelihood statistics are a good representation of the data. Given this, those statistics must be used when fitting the data. If the data are highly smoothed, then Gaussian statistics might be used. If the data are somewhat smoothed then it is hard to know what statistics should be used. Early BiSON analysis (Elsworth et al. 1995b) using smoothed spectra and Gaussian statistics gave a value(440 ± 10nHz) for the rotational splitting which is higher than value given here by about two standard errors. The difference between these two values indicates the range of systematic error possible from employing different analysis techniques. We believe that recent value is more reliable because the use of maximum likelihood statistics is preferred to the use of Gaussian statistics. However, systematic errors at the 10nHz level are not unlikely.

We can apply other tests to the data. We have averaged the values obtained for all the modes together even though different modes probe different parts of the Sun. If we could detect a variation in the splitting with the turning point of the mode then we could directly infer from BiSON data the variation in the rotation rate with depth. We therefore fit the splittings to the inner turning point of the modes. Before the fit can be made, the errors in the data point must be estimated. There are two routes to this: we can use the formal errors from the fitting or we can determine the error from the scatter of the data points. We have tried both alternatives. If the formal errors are used then we do see a small slope (i.e. variation of splitting with turning point) but the goodness of fit is poor. Increasing the order of fit does not improve the fit and the more probable conclusion is that we have under estimated the errors. Errors can be derived from the scatter in the data by dividing up the data set by ℓ-value and then finding the standard deviation of the subset. If we use this value in the fit, we find no statistically significant slope and the quality of the fit is high.

We therefore believe that the formal errors from fitting individual modes can be underestimates of the true scatter in the data. It is possible that the assumptions of the model used are not correct; the mode amplitudes may, with the length of spectra used, not be symmetric about the mean frequency. It should be noted in passing that the accuracy of the determination of the mean frequency of the mode improves with reducing frequency as predicted by theory (Libbrecht 1992, Elsworth et al. 1994). Taking the complete set of estimates for the rotational splitting one can look at the distribution to see if the mean is being pulled for any reason. Figure 4 shows that the distribution is quite consistent with a normal distribution of the values about the stated mean.

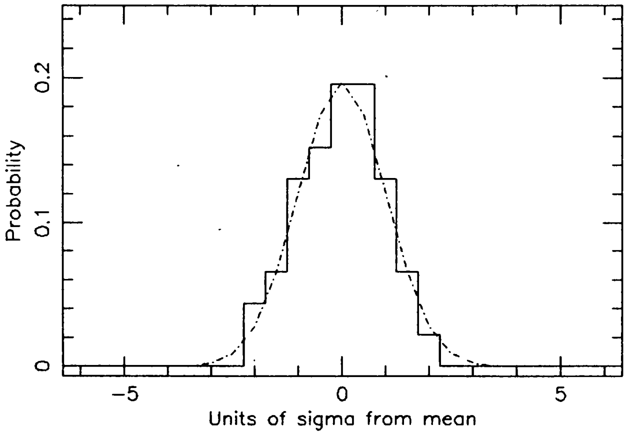

Figure 4. Distribution of the values for the sidereal rotation splitting about the mean value. The data, represented by the solid line, are binned. A normal distribution given by the mean and standard error in the data is plotted as a dotted line. As can be seen, the data are consistent with the assumed distribution.

The value for the rotational splitting measured from the BiSON data can be compared with other values presented at this meeting. The IRIS value at 451 ± 9nHz is 2.5 sigma above the BiSON value. It was obtained using different analysis techniques, using spectra with different statistics, a somewhat different range of modes, and using data gathered at a different time in the solar cycle. The different values are therefore interesting but the difference may resolve itself given time.

3.2 Interpretation of the Data

From the BiSON data on their own, given that we have yet to detect a variation in the splitting between different modes, we cannot determine how the rotation rate varies with solar radius. To use our data to constrain the possible rotation rates in the core, we have to use higher-ℓ data. For our recent publication in Nature we used the analysis of Goode & Dziembowski (1993) on Big Bear data for the rotation of the outer 50 percent of the Sun. We then constructed a range of models for the interior rotation rate that would be consistent with both sets of data. This led us to the conclusion that the centre of the Sun may be rotating slowly, and is certainly not rotating very fast by comparison with the outer regions. These conclusions are consistent with the data presented by LOWL (Tomczyk & Schou 1996) in these proceedings and are not inconsistent with their earlier analysis of 6 months of data (Tomczyk et al. 1995) which showed large error bars at the centre, but no rise in the mean value.

4. Conclusions

Over more than a Solar cycle, the Birmingham group, led by George Isaak have been collecting data on Solar oscillations. What we have presented here is a subset of the many observations published by the group. We have tried to show that long, continuous data sets allow one to probe the Sun in a variety of areas of interest. The most recent analyses, which show the rotation rate of the core of the Sun to be slow, yet again point to the power of solar oscillation to probe stellar interiors.

Acknowledgements

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