SOLAR INTERNAL SOUND SPEED AS INFERRED FROM COMBINED BiSON AND LOWL OSCILLATION FREQUENCIES

Sarbani Basu,[1] W. J. Chaplin,[2] J. Christensen-Dalsgaard,[1] Y. Elsworth,[2], G. R. Isaak,[2], R. New,[3] J. Schou,[4] M. J. Thompson[5] & S. Tomczyk[6]

[1] Teoretisk Astrofysik Center, Danmarks Grundforskningsfond, Institut for Fysik og Astronomi, Aarhus, Universitet, DK-8000 Aarhus C, Denmark
[2] School of Physics & Space Research, University of Birmingham, Edgbaston, Birmingham B15 2TT
[3] School of Science & Mathematics, Sheffield Hallam University, Sheffield S1 1WB
[4] Center for Space Physics and Astrophysics, HEPL Annex 201, Stanford University, CA 94305, U.S.A
[5] Astronomy Unit, School of Mathematical Sciences, Queen Mary and Westfield College, Mile End Road, London E1 4NS, U.K.
[6] High Altitude Observatory, NCAR, P.O. Box 3000, Boulder, CO 80307, U.S.A.

ABSTRACT

Recent observations of the Sun with the LOWL instrument have, for the first time, provided a homogeneous set of solar p-mode frequencies from low to intermediate angular degree. Unfortunately, the LOWL data set contains very few of the lowest-degree modes, which are essential for determining the structure of the solar core – in addition, these data have fairly large associated uncertainties. However, observations made by the Birmingham Solar-Oscillations Network (BiSON) in integrated sunlight provide high-accuracy measurements of a large number of low-degree modes. In this paper we demonstrate that the low-degree mode set of the LOWL data can be successfully replaced by the more-accurate BiSON data, provided the observations are contemporaneous for those frequencies where the solar-cycle-induced effects are important. We show that this leads to a factor-of-two decrease in the error on the inverted sound speed in the solar core. We find that the solar sound speed is higher than in solar models for $r < 0.2$ R$_\odot$.

1. MOTIVATION

Meaningful inversions, that provide information over a wide range of solar fractional radii, require a comprehensive mode set (i.e., with measured frequencies from low to high ℓ and n) as input – this often necessitates the combination of data from independent sources. Furthermore, the combined sets may be non-contemporaneous. Any systematic difference between the sets may be interpreted by an inversion as being solar in origin – for example, those resulting from temporal variations in the properties of the p modes over the solar cycle (most obviously, changes in the eigenfrequencies themselves), or differences in observational and analysis techniques.

Here, we address briefly the advantages of combining Doppler velocity data collected contemporaneously by the LOWL instrument (Tomczyk et al. 1995) and the Birmingham Solar-Oscillations Network (Chaplin et al. 1996a). A thorough discussion of the related issues, and a comprehensive dissemination of the results of combining these data can be found in an up-coming publication (Basu et al. 1996b).

2. DATA AND ANALYSIS

The LOWL and BiSON spectrometers employ the same basic physical principles – the use of an atomic standard – to measure the Doppler velocity shift of a solar Fraunhofer line formed by potassium atoms in the near infrared (770 nm). The LOWL instrument spatially resolves the visible solar disc, and is therefore sensitive to oscillation modes of degree up to $\ell = 99$. The BiSON instruments view the unresolved Sun, and are sensitive to modes of $0 \leq \ell \leq 4$. Although limited to the lowest-ℓ modes, the BiSON technique is very stable and provides some of the highest-quality measures of those modes available. The combination of these two data sets should be very powerful given that: they result from observations made on the same line in the solar atmosphere; each are characterized by high intrinsic accuracies; and both were collected at the same epoch.

The LOWL time series used for the analysis covers a 12 month period, beginning 1994 February 26. For reasons of convenience, we have used an 8-month BiSON spectrum within the time span of the LOWL set, generated from data collected between 1994 January 26 and 1994 September 22. In addition, we have fitted frequencies from five 2-month BiSON spectra (which are contemporaneous with the LOWL data) and a single, 32-month BiSON spectrum, the latter generated from data collected between 1992 October and 1995 June (Chaplin et al. 1996b). The modes in the Fourier spectra generated from the LOWL, 8 and 32-month BiSON time series were fitted by minimizing a maximum-likelihood function consistent with the assumed underlying statistical distribution in the frequency domain (e.g., Toutain & Appourchaux 1994). The modes in the 2-month BiSON spectra were first smoothed before fitting to yield pseudo-Gaussian statistics in the frequency domain.

The fitted BiSON frequencies at $\ell = 0$ and 1 were, in general, more accurate than their LOWL counterparts; for $\ell = 2$, the quality of the data were similar; while for $\ell = 3$, the LOWL frequencies were, by and large, better determined. A "best" set of frequencies was derived by merging the available data, giving due and careful consideration to the comparative quality of the frequency determinations in each set.

We have inverted for the differences between the best-set frequencies and those of a reference model [model 'S' from Christensen-Dalsgaard et al. (1996), presented as model OPAL1 in Basu et al. (1996a)], which was constructed with the OPAL opacities and equation of state, and incorporates settling effects. (For more details, see Basu et al., 1996b.) The data were first subjected to a regularized least-squares (RLS) inversion – those mode frequencies more than 3.5σ from the fit were rejected,

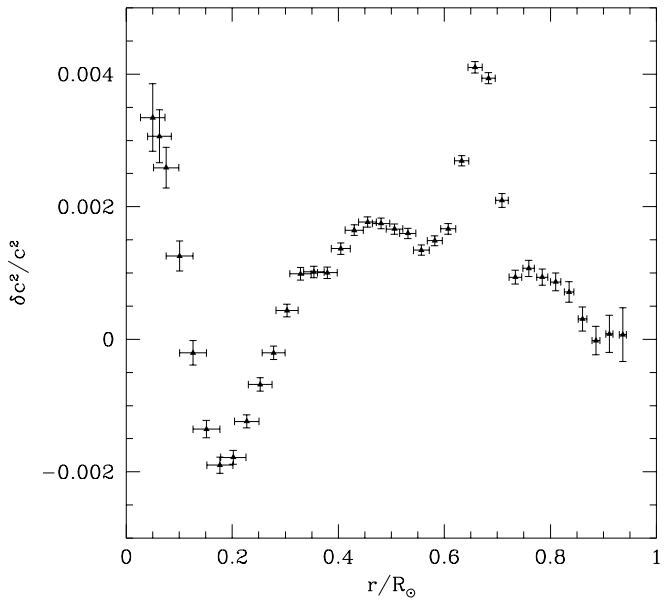

Figure 1: The sound speed inversion results of the "best" set.

and a subtractive optimally localized averaging (SOLA) inversion was then carried out on the resulting data set to yield the final results.

3. RESULTS

The results of inverting for the sound speed with the best mode set are shown in Fig. 1. The introduction of the low-ℓ BiSON data reduces the propagated errors in the vicinity of the core (by more than a factor of two at many target radii) compared with those derived from an inversion on the LOWL data alone. The BiSON-LOWL combination also results in a slight improvement in resolution.

It can be seen from Fig. 1 that the sound speed of the reference model is very close to that of the Sun. The difference is a maximum of 0.5 per cent in squared sound speed and is considerably less in most regions. However, this small discepancy is highly significant, given the size of the data uncertainties and hence the propagated errors in the inversion.

The sound speed difference between the Sun and the reference model has three very-noticeable features – a large positive bump at roughly $0.7R_\odot$, a dip around $0.2R_\odot$ and a rise in the core. The first feature nearly coincides with the base of the solar convection zone, which lies at roughly $0.7R_\odot$. Its presence could be explained by helium settling being too strong in the model in this region. The increase in the helium abundance increases the mean molecular weight of the material at the convection zone base, and hence decreases the sound speed in the model. This might indicate the presence of mixing in this region, a postulate supported by secondary inversions for the helium profile in the Sun (Antia & Chitre 1996). We also note that a mismatch in the depth of the convection zones in the model and Sun (Basu & Antia 1996) could contribute to the feature.

The results in the core are more intriguing. The negative region and the subsequent rise in the solar sound speed can be explained if the variation of the sound speed in the Sun is flatter in this region compared to that in the reference model, and could be due to a less-steep abundance gradient in the Sun. This is a point of contention, since some secondary inversions seem to show that the abundance gradient in the Sun is actually steeper in the region of the dip (Antia & Chitre 1996).

We are indebted to all those concerned with the BiSON and LOWL projects.

REFERENCES

1. Antia H. M. & Chitre S. M., 1996, ApJ, submitted
2. Basu S. & Antia H. M., 1996, MNRAS, submitted
3. Basu S., Christensen-Dalsgaard J., Schou J., Thompson M. J. & Tomczyk S., 1996a, Bull. Astron. Soc. India, 24, 147
4. Basu S., Chaplin W. J., Christensen-Dalsgaard J., Elsworth Y., Isaak G. R., New R., Schou J., Thompson M. J. & Tomczyk S., 1996b, MNRAS, to be submitted
5. Christensen-Dalsgaard J., Däppen W., et al., 1996, Science, 272, 1286
6. Chaplin W. J., Elsworth Y., Howe R., Isaak G. R., McLeod C. P., Miller B. A., van der Raay, H. B., Wheeler S. J. & New R., 1996a, Sol. Phys., 168, 1
7. Chaplin W. J., Elsworth Y., Howe R., Isaak G. R., McLeod C. P., Miller B. A. & New R., 1996b, MNRAS, 282, L15
8. Tomczyk S., Streander K., Card G., Elmore D., Hull H. & Cacciani A., 1995, Sol. Phys., 159, 1
9. Toutain T. & Appourchaux T., 1994, A&A, 289, 649