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STRUCTURE OF THE SOLAR CORE: INVERSION OF RECENT LOW-DEGREE DATA

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ABSTRACT

The deviations of the property, $u \equiv p/\rho$, in the Sun's interior from a standard solar model have been studied by inverting six different sets of frequencies of low-degree modes, recently obtained from space- and ground-based observations. The results from the IPHIR space experiment, the IRIS network and from the LOI ground-based observations indicate an increase of the deviation δu towards the center, which could be evidence of material redistribution in the solar core. The inversions of the three datasets from the BISON network, corresponding to low, high and mean levels of solar activity, show complicated changes of δu in the core among the datasets, with the average tendency of decreasing towards the center. The reason of the inconsistency between BISON and the other datasets remains unknown. Nevertheless, property u (or the speed of sound) in the central core inferred from each of the datasets is higher than in a solar model with gravitational settling of helium, which is currently the closest to the inversion results.

Keywords: *Sun's interior, oscillations, energy-generating core, solar models, SOHO*

1. INTRODUCTION

The structure of the energy-generating core is determined by inverting data sets that include oscillation frequencies of p-modes of low angular degree, l. The previous studies by Gough, Kosovichev & Toutain (1995) revealed a significant discrepancy between inversions of low-l frequencies obtained by Birmingham Solar Oscillation Network (BISON) group (Elsworth *et al.* 1991, 1994a) and from the Interplanetary Helioseismology by Irradiance (IPHIR) space experiment (Fröhlich & Toutain, 1992). The reason for the difference was unknown, preventing any definite conclusion about the structure of the solar core.

I present inversions of new low-l data sets obtained recently by the International Research to the Interior of the Sun (IRIS) group (Gelly *et al.* 1994), by the Variability of Solar Irradiance and Gravity Oscillations (VIRGO) team (Appourchaux *et al.*, 1994), and by BISON (Elsworth *et al.*, 1994b).

2. DATA

The inverted data are combinations of the frequencies of the low-degree modes, taken from each of the low-degree datasets (Table 1), and 598 frequencies of intermediate-degree modes ($l = 4-140, \nu = 1.5-3.0$ mHz), observed at BBSO in 1988 (Libbrecht *et al.* 1990). We note that except the IPHIR dataset the low-l frequencies were measured during the time intervals different from the time when the BBSO data were obtained. Therefore, the combinations of the data could be, in principle, affected by solar-cycle variations in properties of the surface layers of the Sun. However, Dziembowski *et al.* (1991) and Kosovichev *et al.* (1992) have demonstrated that such variations are eliminated by adding to helioseimic equations (1) a smooth function of frequency alone, $F(\nu_i)$, the behavior expected from incorrect modeling of the outer surface layers of the Sun (e.g. Däppen *et al.*, 1991).

3. INVERSION METHOD AND RESULTS

For the data inversion we use the linearized integral equations (Gough and Kosovichev, 1993) relating the frequency difference between the eigenfrequencies of a solar model (model 1 of Christensen-Dalsgaard *et al.*, 1993) and the corresponding frequencies of the Sun, to deviations of $\delta \ln u$ and δY of solar structure:

$$\frac{\delta\nu_i}{\nu_i} = \int_0^{R_\odot} \left[K_{u,Y}\delta \ln u + K_{Y,u}\delta Y\right] dr + \frac{F(\nu_i)}{E_l(\nu_i)}, \quad (1)$$

where $\delta\nu_i$ is the frequency difference between the eigenfrequency ν_i of a solar model and the corresponding frequency of the Sun, $u \equiv p/\rho$ is the ratio of the pressure to the density, Y is the helium abundance in the convection zone, $R_\odot$ is the radius of the Sun, and $E_l(\nu_i)$ is the mode inertia.

I have used a version of an optimal averaging inversion procedure described by Däppen *et al.* (1991) and Kosovichev (1992).

Table 1: Low-degree frequency datasets

Dataset	Dates of observations	Type of observations
IPHIR	July 14 – December 22, 1988	Uninterrupted observation on spacecraft PHOBOS (Fröhlich & Toutain, 1992)
IRIS	July 1 – September 26, 1992	IRIS Network (Gelly *et al.* 1994)
LOI (VIRGO)	May 2 – October 11, 1994	Ground-based observations with the Luminosity Oscillations Imager (Appourchaux *et al.*, 1994)
BISON-1	1981 – 1994 (low activity intervals)	Mean frequencies from BISON network spectra with the solar 10.7 cm radio flux $<$ 130 Units (Elsworth *et al.*, 1994b)
BISON-2	1981 – 1994 (high activity intervals)	Mean frequencies from BISON network spectra with the solar 10.7 cm radio flux $>$ 130 Units (Elsworth *et al.*, 1994b)
BISON-3	1981 – 1994	Mean frequencies for all BISON spectra corrected to RF=65 Units (Elsworth *et al.*, 1994b)

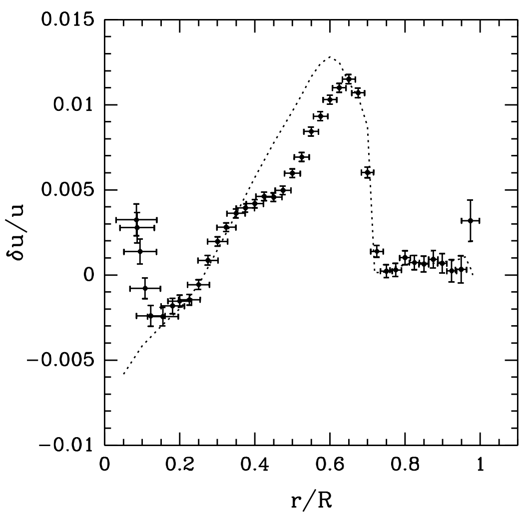

Figure 1: *Inversion of IPHIR + BBSO data: optimally localized averages of the difference $\delta u/u$, where $u \equiv p/\rho$, between the Sun and the reference solar model, inferred from a combination of low-degree mode frequencies from IPHIR and of intermediate-degree mode frequencies from BBSO. The dotted curve shows the difference between a model with gravitational settling of helium and the reference model.*

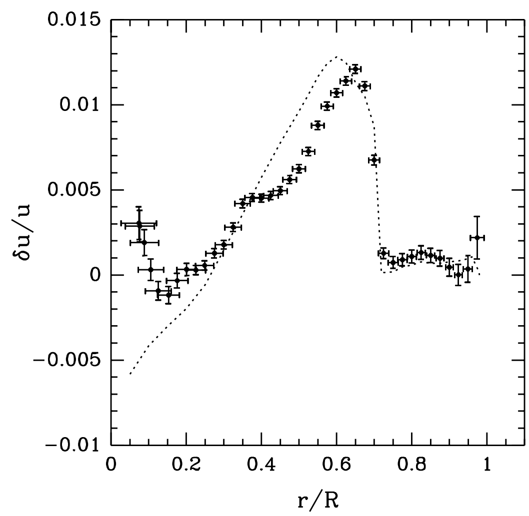

Figure 2: *The same as in Fig. 1 but for IRIS + BBSO data.*

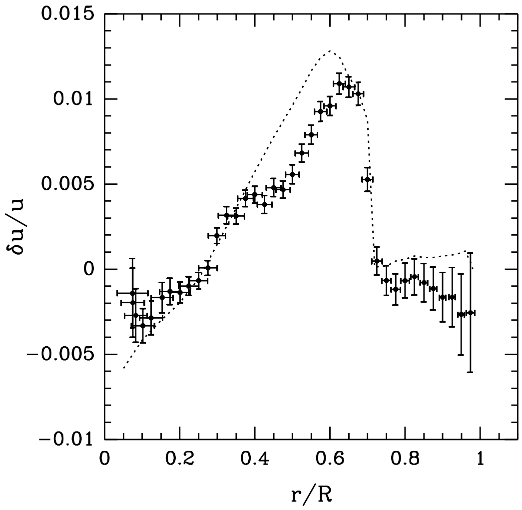

Figure 3: *The same as in Fig. 1 but for LOI + BBSO data.*

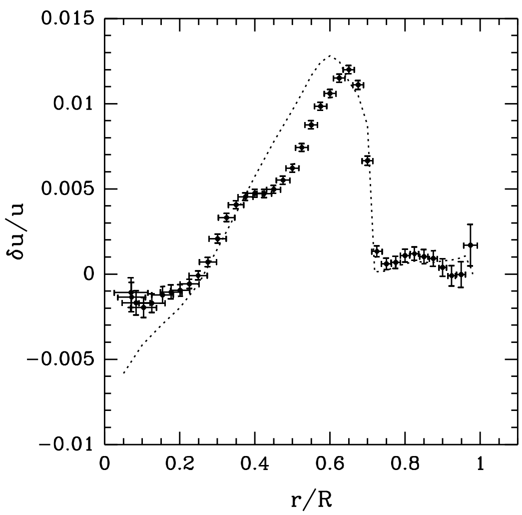

Figure 4: *The same as in Fig. 1 but for BISON-1 + BBSO data.*

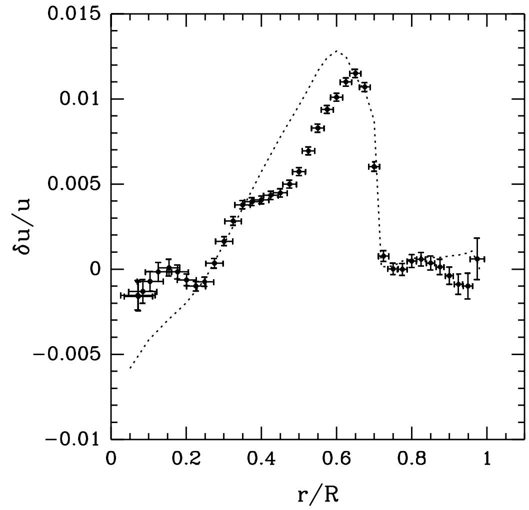

Figure 5: *The same as in Fig. 1 but for BISON-2 + BBSO data.*

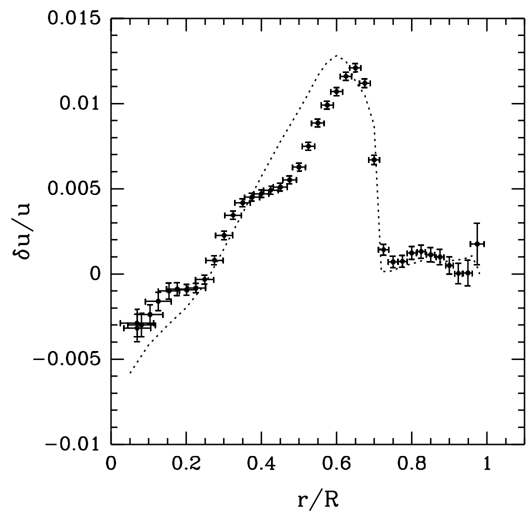

Figure 6: *The same as in Fig. 1 but for BISON-3 + BBSO data.*

Figures 1–5 show optimally localized averages of the difference $\delta u/u$ between the Sun and the solar model, obtained from the different datasets. The horizontal bars represent the resolution lengths (widths of the averaging kernels); the vertical bars represent standard errors. The dotted curve is the corresponding differences between model 2 of Christensen-Dalsgaard *et al.* (1993), which has helium settling against diffusion in the absence of turbulent mixing, and the reference.

The main differences among the inversions are in the central region ($r < 0.25R_{\odot}$), the structure of which is determined from low-degree modes. The inversions of both IPHIR and IRIS data show a sharp increase of $\delta u/u$ towards the center (Figs 1 and 2). The tendency of increasing is also visible in the inversion of LOI data (Fig. 3), but it is much less pronounced. This could be explained by lesser precision of LOI measurements, and by the lack of $l = 0$ modes in the dataset. The BI-

SON measurements for the intervals of low solar activity (BISON-1) reveal a mild increase of $\delta u/u$ in the center (Fig. 4). However, the high-activity data, BISON-2, show the opposite behavior (Fig. 5). It is interesting that the inversion of the of the mean frequencies (BISON-3) corrected to an average level of solar activity indicates even a sharper decrease of $\delta u/u$ (Fig. 6), which is inconsistent with the average of the inversions of BISON-1 and BISON-2 data. If the solar-cycle variations in the central region were real then one would expect the inversion of BISON-3 to be an average of the inversions of BISON-1 and BISON-2. Since it seems not to be the case, it is likely that the variations reflect inconsistencies either in the BISON datasets or in the inversion procedure. Certainly, the inconsistencies have to be resolved in order to make any definite conclusions about the deviation of the structure of the solar core from that of the model. Nevertheless, it is interesting to note that in all the inversions (Figs 1 – 6) the quantity u in the core is higher than in the model with gravitational settling of helium (shown by the dotted curve in the figures), which outside the core describes the solar structure better than the standard model.

4. CONCLUSION

It has been found that the inversions of both IRIS and LOI data are generally consistent with the previous inversion of the IPHIR data, which indicated a sharp increase towards the solar center of the deviation of property $u \equiv p/\rho$ (or the squared sound speed) from a standard solar model. However, the sound speed in the solar core inferred from the new BISON data shows significant variations among subsets of the data, corresponding to different levels of solar activity, and is inconsistent with the inversions of the other three low-l data sets. It is anticipated that new low-degree data from VIRGO and GOLF will resolve the controversy.

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