TEMPORAL VARIATIONS OF SOLAR STRUCTURE

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ABSTRACT

We have analysed GONG and MDI data for the past 7 years to determine if there are any changes in solar structure. We fail to find any change in the solar interior. In the process of investigations, we find that there are possible systematic differences between the pre- and post-recovery MDI data for the high degree ($l \gtrsim 120$) modes.

Key words: Sun: oscillations; Sun: interior.

1. INTRODUCTION

That solar oscillations frequencies change with time has been known since the last solar cycle (Libbrecht & Woodard 1990). The change in frequencies is clearly seen in the current solar cycle with high-precision data from both the Global Oscillation Network Group (GONG) and the Michelson Doppler Imager (MDI). The accumulation of data by these two projects over the last seven years enables us to make a detailed study of changes that take place within the Sun as the solar cycle progresses.

We use GONG and MDI data to study how the radial as well as latitudinal dependence of structure changes with time. We also study possible temporal variation in solar radius using the f-mode frequencies. Since any study of time variations pre-supposes that the data do not have time-dependent systematic errors. We check for that in the data.

2. DATA AND TECHNIQUES

We have used data obtained from 108-day observations from GONG (i.e., three GONG months) and 72-day observations from MDI. We use 68 temporally overlapping data sets from GONG starting from 1995 May 7 and ending on 2002 February 22, with a spacing of 36 days between consecutive data sets.

Table 1. Data sets used

Set #	Start Day	10.7 cm Flux[a]
GONG sets		
1–3	May 7, 1995	75.1
10–12	Mar 26, 1996	72.7
24–26	Aug 12, 1997	91.0
34–36	Aug 7, 1998	131.3
63–65	Jun 16, 2001	180.8
66–68	Oct 2, 2001	214.0
MDI sets		
1216	May 1, 1996	72.4
1432	Dec 3, 1996	73.2
1936	Apr 21, 1998	108.5
2224	Feb 2, 1999	130.7
2800	Sep 1, 2000	175.3
2944	Jan 23, 2001	164.4
3160	Aug 27, 2001	219.8

[a] *Units of* $10^{-22} J\ s^{-1}\ m^{-2}\ Hz^{-1}$

The MDI data consists of 30 non-overlapping data sets starting from 1996 May 1 and ending on 2002 August 21 (Schou 1999). In order to keep figures from overcrowding we have not shown results of all data sets in all figures. The ones that are shown are listed in Table 1. In the table, the heading "Start Day" is the beginning of the 108 day observational period for the GONG sets and the 72 day period for the MDI set. Also listed in the table is the average 10.7 cm radio frequency flux over the observing period, which is known to be a good solar activity index.

The radial sound-speed profiles were obtained by SOLA inversions (Pijpers & Thompson 1992, 1994) applied to solar structure inversions (see Rabello-Soares et al. 1999 for details). The latitudinal sound-speed distribution was determined by 2d RLS inversions (Antia et al. 2001a). The position of the CZ base was determined by the method described by Basu & Antia (1977).

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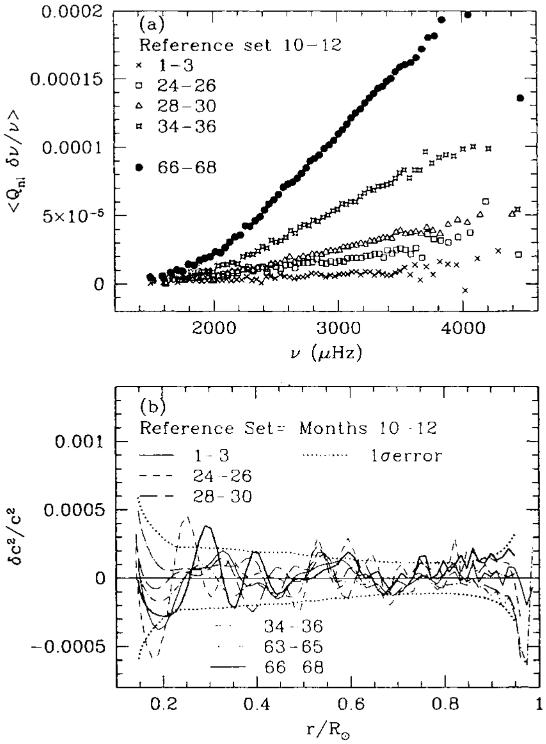

Figure 1. The scaled frequency differences (panel a) between the GONG sets listed in Table 1 and GONG set 10–12. The differences have been plotted after averaging in bins of 25 modes. Only one set of errors has been shown for the sake of clarity. The radio frequency flux for each set is in parentheses. Panel (b) shows the relative sound-speed differences in the Sun at different times as obtained by inverting the GONG frequency differences

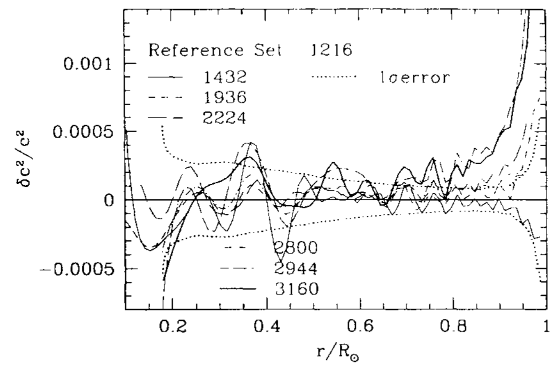

Figure 2. The relative sound-speed differences in the Sun at different times as obtained by inverting the frequency differences between the MDI sets listed in Table 1 and MDI set 1216. The dotted black line is the average 1σ errors.

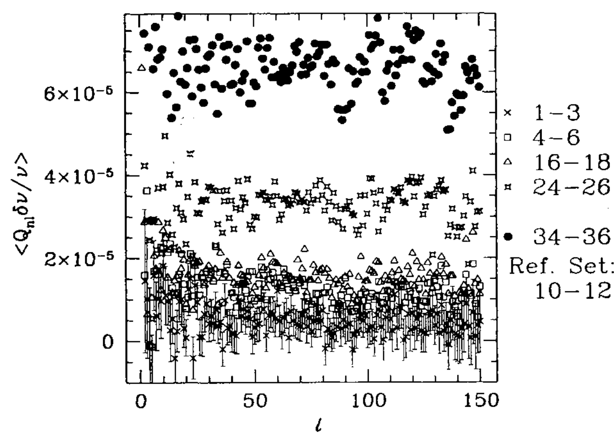

Figure 3. The scaled frequency differences between some GONG sets and GONG set 10–12. Only averaged differences of modes with frequencies in the range 2–3 mHz are shown at each degree.

3. RESULTS

Fig. 1(a) shows the scaled frequency differences between the GONG sets listed in Table 1 and GONG set 10–12. The quantity Q_{nl} is the ratio of the mode inertia of a mode of degree ℓ order n to that of a mode of degree 0 with the same frequency as the mode of degree ℓ order n (Christensen-Dalsgaard & Berthomieu 1991). Since the scaled-differences are just a function of frequency, we plot the scaled frequency differences averaged in bins of 25 modes. A similar result is seen for MDI data. From the figure we see that as the activity level increases, the frequencies increase. The frequency shift is known to be well correlated to solar activity (Howe et al. 1999).

Figs. 1(b) and 2 show the sound-speed differences obtained by inverting the frequency differences between the different GONG and MDI sets respectively. The inversion results are reliable till about $0.965R_\odot$. We do not see any significant, or systematic change in the sound-speed with time in the GONG results. MDI results however show a qualitative difference in the results of sets obtained before SOHO was temporarily out of contact (i.e., sets 1432, 1936) and the other sets that were obtained after contact was resumed. The difference occurs above the CZ base. All the post-recovery sets show a positive c^2 difference with respect to the reference set 1216. The fact that this temporal variation is not seen in the GONG results leads us to believe that there are systematic differences in the pre- and post-recovery MDI data, particularly at the high degree end.

In order to test for systematic differences between high-degree frequencies as a function of time, we plot the frequency differences as a function of degree. Since there is a steep frequency dependence of the frequency differences at each degree, we average the differences for modes that have frequencies between 2 and 3 mHz. We use a common mode set for this. The results for GONG and MDI are shown in Figs. 3 and 4. Note that there is no obvi-

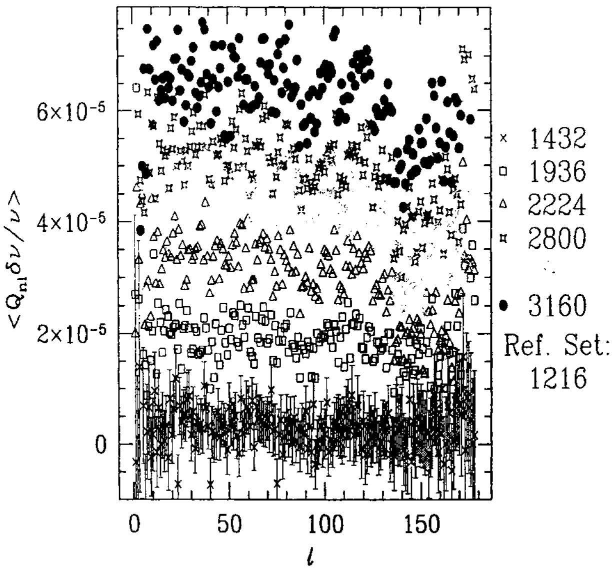

Figure 4. The scaled frequency differences between some MDI sets and MDI set 1216.

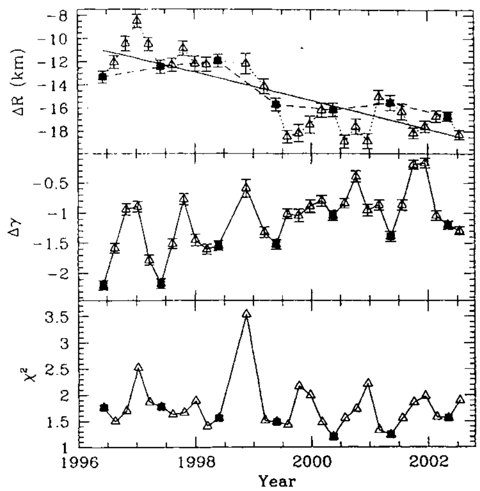

Figure 5. The estimated variation in solar radius, ΔR, and surface term, $\Delta\gamma$ from f-mode frequencies, obtained by fitting Eq. 1 to frequency difference between a given MDI set and a solar model. The χ^2 per degree of freedom for each set is also shown. In each panel the filled squares are the results for data sets at an interval of 360 days for which the fit is relatively good. The solid line in the top panel is a straight line fit to all points, similar to that obtained by Dziembowski et al. (2001).

ous degree dependence in frequency differences in the GONG data. But for the MDI data the pre-recovery differences show no obvious degree dependence, the post-recovery sets do, particularly above $l = 120$ or so. Since the GONG results for data obtained at the same time do not show any such degree dependence this figure supports our hypothesis that there are non-solar systematic differences between pre- and post-recovery data. The sound-speed differences obtained by inverting the differences between the different MDI sets when the mode-set is restricted to modes with $l < 120$ show an absence of any systematic differences between pre- and post-recovery data. The results are similar to the GONG results shown in Fig. 1(b).

Further evidence of systematic errors is obtained when comparing GONG and MDI results of sound-speed asphericity and the f-mode frequency variations. The fundamental or f-mode is a surface gravity mode and its frequency is not very sensitive to solar structure. These frequencies have been employed to determine the solar radius (Schou et al. 1997; Antia 1998). There have been conflicting claims about variation in solar radius, based on temporal variations of the f-mode frequencies. Dziembowski et al. (2001) have claimed that solar radius is decreasing at a rate of 1.5 km/year during the last few years. They express the f-mode frequency variation as

$$\Delta\nu_\ell = -\frac{3}{2}\frac{\Delta R_f}{R}\nu_\ell + \frac{\Delta\gamma_f}{I_\ell} \qquad (1)$$

where ν_ℓ is the frequency of f-mode for a degree ℓ, ΔR_f is inferred change in solar radius. The second term is believed to arise from variation near the solar surface and I_ℓ is the mode inertia.

Fig. 5 summarises the results obtained using such a fit to MDI data sets, where frequency differences with respect to a standard solar model are considered for each of the 30 available MDI data sets. The resulting temporal variation in ΔR and $\Delta\gamma_f$ as well as the χ^2 per degree of freedom for each of the fits are shown in Fig. 5. It appears that there is an oscillatory trend with a period of about one year in all three quantities. This oscillatory trend has been studied by Antia et al. (2001b) and is most likely to be an artifact of data analysis. It is clear from χ^2 values that most of the fits are not good and the assumed form given by Eq. 1 does not fit the observed data. Ignoring the oscillatory trend in the inferred radius variation, which is unlikely to be of solar origin, it appears that most of the variation has occurred between 1998.4 and 1999.4 which is exactly the period when contact with SOHO was lost. This becomes more clear if we look only at the filled squares in the figure which are at intervals of one year and correspond to data sets which give relatively good fits. The variation in solar radius before or after the break in SOHO data is negligible. This is again most likely to be due to systematic variations in instrumental characteristics during recovery of SOHO.

Using the even order splitting coefficients it is possible to infer the latitudinal variation in sound speed (Antia et al. 2001a). Fig. 6 shows $\delta c^2/c^2$ at $r = 0.96R_\odot$ obtained using MDI data. To bring out the temporal variations the temporal average at each latitude has been subtracted from all results. The top panel which shows the results obtained using all modes shows a distinct temporal variation. Before

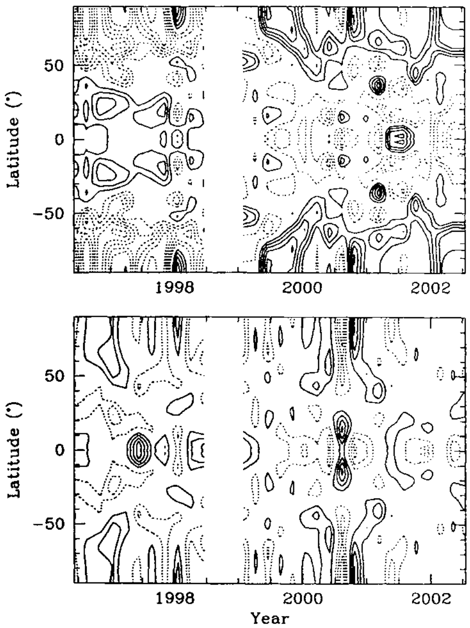

Figure 6. The residual in aspherical component of $\delta c^2/c^2$ at $r = 0.96R_\odot$ obtained using MDI data are shown as a function of time and latitude. The contours are at interval of 2×10^{-5} with solid contours showing positive values and dotted ones showing negative values. The top panel shows the results using all modes, while bottom panel shows the results obtained using only modes with $\ell < 110$.

the gap the asphericity is positive at low latitudes, and negative at high latitudes. This is reversed after the gap. This temporal variation is not seen in GONG data as well as in the bottom panel of Fig. 6 which shows the MDI results when only modes with $\ell < 110$ are used.

Since the solar dynamo is generally believed to be located close to the base of the convection zone, it would be interesting to study temporal variations in this region. No significant temporal variation is found in depth of the convection zone (Basu & Antia 2001).

4. CONCLUSIONS

We find no observable change in the solar sound-speed profile as a function of time. There is a systematic difference between the high-degree modes of the pre- and post-recovery data from MDI. This systematic differences affect the sound speed in the convection zone. This systematic difference also affects the estimate of solar radius and in fact, apart from oscillatory trend with a period of one year, almost all temporal variation in solar radius is found to occur during the time when the contact with SOHO was lost. The aspherical component of sound speed in outer convection zone is also affected by this systematic error resulting in large temporal variation during the gap in data.

There are two alternatives: either the Sun has had some interesting transition during the time when SOHO was not operational or these apparent temporal variations are due to systematic variations in instrumental characteristics during recovery of SOHO satellite. The fact that these variations are not seen in GONG data would tend to suggest that there are indeed some systematic variations in MDI instrument, which should be accounted for before inferring possible temporal variations inside the Sun.

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