TEMPORAL VARIATIONS IN THE SOLAR RADIUS?

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ABSTRACT

Solar f-mode frequencies have been used to determine the solar radius. Temporal variations in these frequencies can be used to study temporal variations in the solar radius. Using MDI data for the last 8 years we examine whether there has been any observable change in the solar radius since the beginning of the current solar cycle.

Key words: Sun: Radius; Sun: Oscillations.

1. INTRODUCTION

Temporal variations in the solar radius has been a controversial topic, as direct measurements of the solar radius have given conflicting results (e.g., Laclare et al. 1996; Emilio et al. 2000). The reported temporal variations in the solar radius ranges from 0 to 700 km. Schou et al. (1997) and Antia (1998) have demonstrated that the frequencies of f-modes can be used to estimate the solar radius to a high accuracy. Thus it should be possible to use these frequencies to study possible temporal variations in the solar radius. However, f-mode frequencies have also given conflicting results (Dziembowski et al. 1998, 2000, 2001; Antia et al. 2000) with reported variations between 0 to 5 km. Using more extensive data sets from GONG and MDI, Antia et al. (2001) found no evidence for any variation in the solar radius. They also found that a significant component in f-mode frequency variation is oscillatory with a period of 1 year, which is most likely an artifact of the orbital period. Antia (2003) found that the apparent decrease in solar radius inferred by Dziembowski et al. (2001) could be due to systematic errors in MDI instrument introduced during recovery of SOHO satellite in early 1999.

It can be easily shown that if the solar radius varies by even 1 km over the solar cycle, the rate of resulting release or absorption of gravitational energy would be larger than the solar luminosity. Thus we can rule out a homologous expansion of the Sun. Any possible variation in the solar radius must be confined to the outermost layers of the Sun. In this work we wish to reexamine the issue of solar radius variations using 8 years of MDI data.

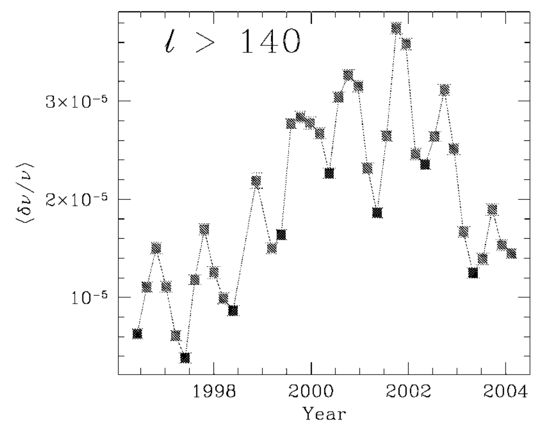

Figure 1. The mean relative frequency difference for each data set is plotted as a function of time. Blue points denote the sets at an interval of 360 days.

2. RESULTS

We have used 38 data sets from MDI (Schou 1999), each covering a period of 72 days starting from 1996 May 1 and ending on 2004 March 19. For each data set we take the frequency differences with respect to a solar model with radius $R_\odot = 695.78$ Mm (Antia 1998). Fig. 1 shows the mean frequency difference for all f-modes with $\ell > 140$ as a function of time as inferred from these data sets.

Following Dziembowski et al. (2001) we express the change in f-mode frequencies as

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

where ν_ℓ is the frequency of the f-mode of degree ℓ, ΔR is the change in radius while $\Delta\gamma$ measures the contribution from surface term and I_ℓ is the mode inertia. Fre-

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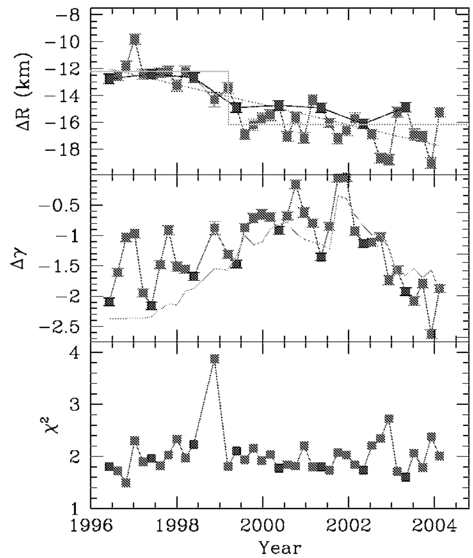

Figure 2. The estimated variation in the solar radius, ΔR, and the surface term, $\Delta\gamma$ from f-mode frequencies, obtained by fitting frequency difference between a given MDI set and a solar model. The χ^2 per degree of freedom for each set is shown in the lowest panel. In each panel the blue squares are the results for data sets at an interval of 360 days for which the fit is relatively good. The green line in the top panel is a straight line fit to all points, similar to that obtained by Dziembowski et al. (2001). The red line connects all points in upper panel, while the blue line connects the blue points. The heavy cyan line shows a step function fit to all points with discontinuity at 1999.2. The green line in the middle panel shows the radio flux at 10.7 cm plotted on the scale marked on the right axis.

quency differences in each data set are fitted to Eq. (1) to calculate the radius variation ΔR and the surface term $\Delta\gamma$. Fig. 2 shows the results from the fits using all modes with $\ell > 140$. This figure shows the fitted ΔR, $\Delta\gamma$ and the χ^2 per degree of freedom in the resulting fits. It can be seen that all quantities show an oscillatory component with a period of 1 year.

It can be seen that in addition to an oscillatory term with a period of 1 year, the surface term shows an increase with activity level that is well correlated with activity indeces such as the 10.7 cm radio flux. While the radius appears to decrease with time, a closer look reveals that the variation in radius is not continuous, but occurs predominantly around 1999. Unfortunately, this is the period when contact with SOHO was lost. This leads us to wonder whether such a sudden change could be an artifact of change in instrumental characteristics when SOHO was out of contact. A step function with a discontinuity at 1999.2 also fits the radius variation equally well (Antia 2003). To disregard the oscillatory component we can look at fits at an interval of 1 year, shown by blue symbols in the Figs. 1–3. In order to check if there is any correlation between frequency variation and activity index we also show the fitted ΔR and $\Delta\gamma$ plotted against the 10.7 cm radio flux (which is a measure of solar activity) in Fig. 3. Once again it can be seen that points before 1999.2 have slightly higher radius than the points after that date. In the decreasing half of solar cycle, although the activity level has gone below that in 1999.2, the radius has not increased to pre-1999 level. But there could be some delay between ascending and descending branch of the cycle (e.g., Jiménez-Reyes et al. 1998) and we need to wait for the coming activity minimum to come to a definite conclusion.

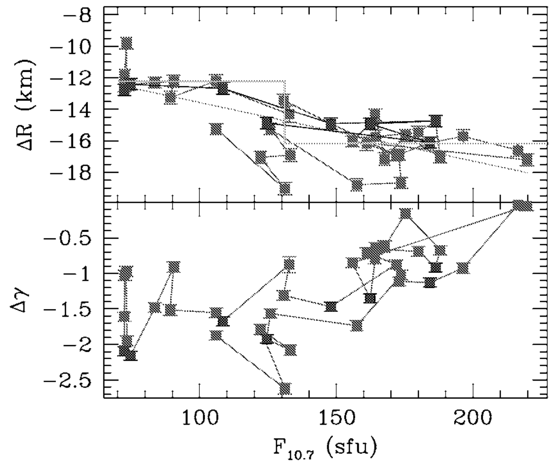

Figure 3. The estimated variation in the solar radius, ΔR, and the surface term, $\Delta\gamma$ from f-mode frequencies, obtained by fitting the f-mode frequency differences, plotted as a function of 10.7 cm radio flux. The convention is the same as that in Fig. 2.

In order to study the robustness of the inferred radius variation, we attempt the fits by restricting the mode set or the data sets and the results are summarised in Table 1. It is clear that the rate of radius variation decreases as the upper limit of ℓ is reduced and further if the data before and after the break in MDI data are fitted separately, the inferred slope is consistent with zero (the first two rows). This tends to further suggest that the apparent variation may be due to some systematic changes introduced in the instrument during recovery of the SOHO satellite. We also list the inferred radius variation in pre-solar maximum and post solar maximum data sets (Rows 3 and 4 of the table). During the ascending period of solar cycle which includes the break in MDI data, the solar radius appears to be decreasing, while in the descending phase the inferred radius variation is consistent with zero, being generally of order of 1σ with its magnitude decreasing with increase in upper limit on ℓ and consequent decrease in errors. The last row of the table lists the total change over the period for which we have data.

The f-mode frequency variation shows an oscillatory component as well as possible discontinuities around the time when contact with SOHO satellite was lost. Thus it is of interest to see if low radial order p-modes also

Table 1. Inferred rate of radius variation over different time periods for different ranges of degree, ℓ.

Time interval	Inferred rate of radius variation (km yr^{-1})			
	$\ell < 140$	$140 < \ell < 200$	$140 < \ell < 250$	$140 < \ell$
1996.4–1998.6	1.97 ± 1.44	-1.60 ± 0.57	-0.29 ± 0.28	-0.11 ± 0.20
1999.2–2004.1	0.56 ± 0.94	0.14 ± 0.16	0.04 ± 0.08	-0.40 ± 0.06
1996.4–2001.8	1.42 ± 0.34	-0.75 ± 0.14	-0.81 ± 0.07	-1.23 ± 0.05
2001.8–2004.1	-1.78 ± 1.09	0.56 ± 0.47	0.52 ± 0.23	0.26 ± 0.17
1996.4–2004.1	0.13 ± 0.20	-0.24 ± 0.08	-0.41 ± 0.04	-0.91 ± 0.03

show such a behaviour. To study the frequency variation in p-modes we take the temporal average of each mode frequency and subtract it from that in each set to get the frequency differences.

Fig. 4 shows the average scaled frequency difference in the frequency range of 1100 μHz to 2300 μHz as a function of time using both MDI and GONG data. These differences are scaled for the mode inertia (Christensen-Dalsgaard & Berthomieu 1991). It is clear that these frequencies also have an oscillatory component, though the non-oscillatory variation is larger and this variation is known to be correlated with activity indices. There is no clear evidence of any discontinuity around 1998.5 in these modes.

Fig. 4 also shows the same frequency difference plotted as a function of the 10.7 cm radio flux, which traces the level of solar activity. It can be seen that for the GONG data the ascending and descending phases of solar cycle fall essentially on the same line, but for MDI there is a small difference. Similar behaviour has been seen earlier in low degree modes from BiSON (Jiménez-Reyes et al. 1998) though it is not clear if the difference is significant. It is possible that some of the difference is due to the break around 1999, as the difference is more pronounced at low activity level between the pre-break and post-break data.

To study possible discontinuities in p-mode frequencies around the time when contact with SOHO satellite was lost we show in Fig. 5 mean frequency difference between two data sets as a function of degree ℓ. This figure shows the mean frequency difference in frequency range 2000–3000 μHz, with respect to a data set around minimum activity in 1996. It can be seen that for the GONG data there is no steep variation with ℓ in the frequency differences, while the MDI data shows steep variation around $\ell = 120$ for all sets taken after the contact with SOHO satellite was resumed in 1999.

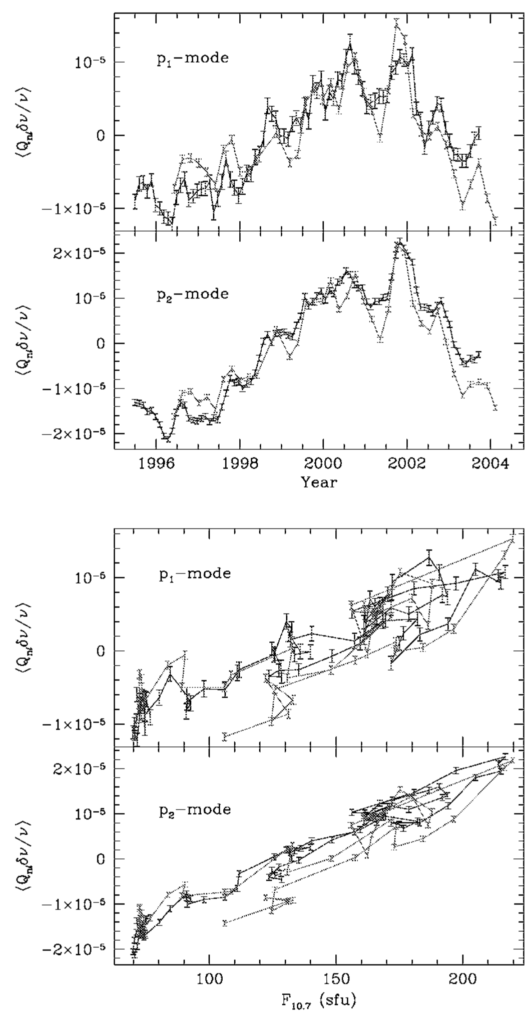

Figure 4. The mean scaled relative frequency difference in p_1 and p_2-modes as for the GONG (red lines) and MDI (blue lines) data. The top panel shows the differences as a function of time, while the lower panel shows the same as a function of 10.7 cm radio flux.

3. CONCLUSIONS

There is no clear evidence to suggest that the solar radius is varying with time. Data of different degree ranges suggest different changes, which may imply that the change is not real. The situation should become clearer as we get

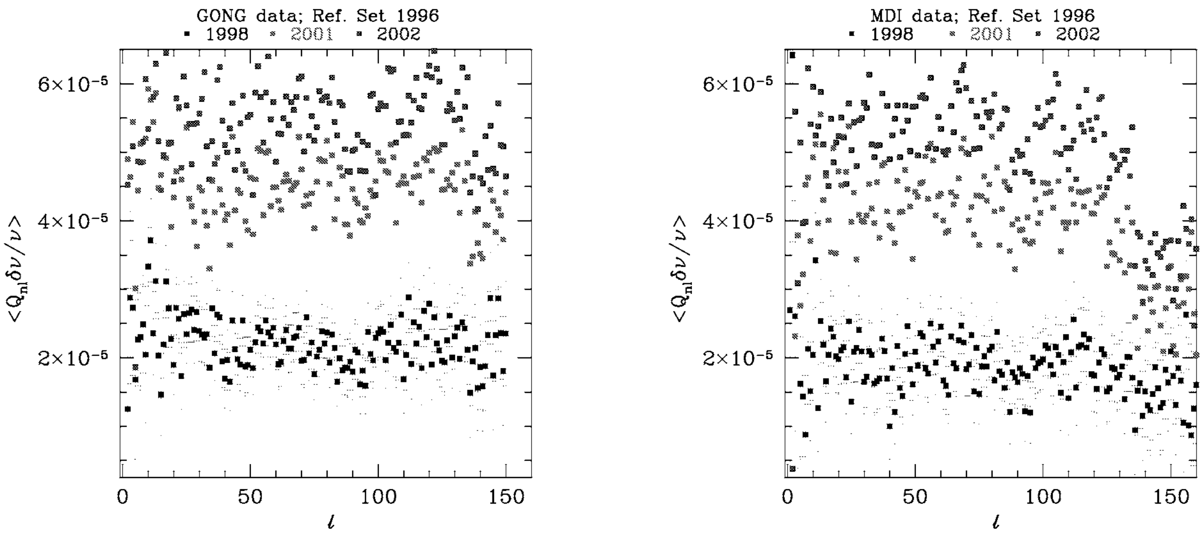

Figure 5. The mean frequency difference in p-modes as a function of degree ℓ. All modes in frequency range 2000–3000 μHz are used in computing the differences with respect to a data set in 1996 around the activity minimum. The left panel shows the results with GONG data, while the right panel shows those using MDI data.

more data on the descending phase of the current solar cycle. The apparent decrease in the solar radius inferred by Dziembowski et al. (2001) could be due to possible variation in the instrument during recovery of SOHO satellite, which introduces an apparent decrease in the solar radius around 1999. Discounting the decrease around 1999, we can put an upper limit of about 1 km on possible radius variation during solar cycle.

The frequency differences for p-modes when plotted as a function of degree, ℓ, show a discontinuity around $\ell = 120$ for MDI data sets taken after the contact with SOHO satellite was resumed. This could be the manifestation of the same effect that causes apparent decrease in solar radius. The f-mode frequencies for $\ell < 120$ are not determined reliably enough to be able to see this effect.

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