Rotation-rate variations at the tachocline: an update

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Abstract. After 15 years of GONG and MDI observations of the solar interior rotation, we revisit the issue of variations in the rotation rate near the base of the convection zone. The 1.3-year period seen in the first few years of the observations disappeared after 2000 and has still not returned. On the other hand, the agreement between GONG and MDI observations suggests that variations seen in this region have some solar origin, whether a true rotation-rate change or possibly mere stochastic variation; we present a numerical experiment supporting this contention.

1. Introduction

The region of strong rotational shear at the base of the solar convection zone, known as the tachocline, plays an important role in many models of the dynamo that drives solar activity. The report [1] of apparently periodic variations in the rotation rate at this location, with a period of approximately 1.3 years, therefore attracted considerable attention. Other workers [2] did not reproduce the finding. The periodicity was not seen in observations after the solar maximum [3]. With new cycle 24 finally underway, it seems worthwhile to provide an update on these observations.

2. Data and Analysis

The data consist of 145 sets of medium-degree rotational splittings from overlapping 108-day periods of GONG observations and 69 sets of rotational splitting coefficients from non-overlapping 72-day periods of MDI [4] observations, together covering the period from May 1995 to May 2010. From each data set, two-dimensional rotation profiles were inferred using both regularized least-squares [RLS] and optimally localized average [OLA] inversions, as in our earlier work [1]. A temporal mean at each location was subtracted from each set of inversions to yield the rotation residuals.
3. Results

In Figure 1 we show the rotation-rate residuals at the equator for the two instruments and the two inversion methods, for the depths of 0.72 \( R_\odot \) and 0.63 \( R_\odot \).

We quantify the power in the residuals as a function of frequency by fitting sine waves. In Figure 2 we show the results of this fitting for different subsets of the observation period, for GONG RLS inversions at 0.72 \( R_\odot \) at the equator. Though the 1.3-year signal is quite clear in the first five years of observations, its significance decreases as more data are included, and it is entirely absent when the last 10 years of observations are analyzed alone.

Even though the 1.3-year signal appears only in the early years of the data set, the variation of the 0.72 \( R_\odot \) equatorial rotation rate in MDI and GONG looks remarkably similar during the whole period. We quantify this by interpolating both data sets to a common time base and examining the correlation between them, as seen in Figure 3. The correlation coefficients obtained for RLS and OLA inversions are 0.69 and 0.48 respectively. In the next section we will examine the significance of these correlations for the RLS case.

3.1. Numerical simulation

How significant are these correlations? To test this for the RLS case, we generated simulated inversions by integrating artificial rotation profiles over the averaging kernels for the (0.72 \( R_\odot \), 0°) location. For 1000 realizations of noise distributed according to the formal errors of the real input data, the noise was propagated through to the synthetic inversion profiles via the inversion coefficients [5]. The noise realizations for GONG and MDI were independent. We then examined the correlation between the synthetic GONG and MDI time series, again interpolated to the common time base. Two cases were considered; one in which the artificial profile contains only
Figure 2. The amplitude of sine-wave fits to the GONG RLS residuals at 0.72\(R_\odot\), 0° as a function of frequency, for periods 1995–2000 (a), 1995–2005 (b), 1995–2010 (c), and 2000–2010 (d).

Figure 3. Scatter plots of the interpolated rotation-rate residuals for RLS (a) and OLA (b) inversions of GONG and MDI observations at the (0.72\(R_\odot\), 0°) location.

an emulation of the torsional oscillation signal at all latitudes and at radii down to 0.72\(R_\odot\), and one in which a 1.3-year oscillation, coherent over the region 0.7 \(\leq r/R_\odot \leq 0.8\) and latitudes up to 30°, was also included. Figure 4 shows how the distribution of correlation coefficients changes as the amplitude of the input signal increases. Note that the amplitude of the observed torsional oscillation signal is about 1 nHz. We would expect the correlation to increase as the signal rises above the noise, but it does not seem to be feasible to reach the observed correlation with the torsional oscillation signal alone at realistic levels; the shorter-period signal (1.3 years in this test) increases the correlation more rapidly. However, this test is not designed to exclude the possibility that the fluctuations in the rotation rate arise from the stochastic nature of the modes.
Figure 4. Distribution of MDI–GONG correlation coefficients for RLS rotation residuals at $0.72R_\odot, 0^\circ$, for 1000 realizations of artificial data with only the torsional oscillation signal (a) and with an extra 1.3-year sinusoidal signal (b). The strength of the periodic signal in the artificial data varies along the $y$ axis. The vertical white line in each panel indicates the correlation coefficient from the observations.

4. Discussion
The 1.3-year signal at the base of the convection zone disappeared after 2000 and so far has not returned. The level of correlation between GONG and MDI observations (at least for RLS inversions) does suggest that the variations seen here at least have some solar origin common to the GONG and MDI observations, and is consistent with the presence of a short-period signal at the base of the convection zone. It will be interesting to see what happens in the new cycle, with HMI observations superseding MDI.

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