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LATITUDINAL AND TEMPORAL VARIATIONS OF THE TACHOCLINE

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ABSTRACT

Frequency splittings from GONG and MDI data over the last 6 years are used to study the temporal and latitudinal variations in the properties of the tachocline. In particular, we study changes in the position and the width of the tachocline. We find good evidence for latitudinal variations, but only marginal evidence for any temporal variation. The position of the tachocline at high latitudes may be varying slightly with time.

Key words: Sun: oscillations; Sun: rotation; Sun: interior.

1. INTRODUCTION

Inversions of rotational splittings (Thompson et al. 1996; Schou et al. 1998) have demonstrated that the rotation rate changes from being latitudinally dependent within the convection zone to being almost latitudinally independent in the radiative interior in the region close to the base of the convection zone. This transition region has been referred to as the tachocline (Spiegel & Zahn 1992). The exact location and thickness of the tachocline is an important constraint on the theories of angular momentum transport in stellar interiors as well as for solar dynamo models (Rüdiger & Kitchatinov 1996; Gilman & Fox 1997; Canuto 1998). The tachocline is also the region where the solar dynamo is believed to be located and one may expect some temporal variations in this region associated with the solar cycle.

Frequencies of solar oscillations are known to vary with time and this variation is correlated with solar activity (Elsworth et al. 1990; Libbrecht & Woodard 1990). The frequency differences scaled with mode inertia between frequencies at different phases of the solar cycle appear to be a smooth function of frequency indicating that the cause of the frequency changes lies close to the solar surface (Basu & Antia 2000; Basu 2002). However, the solar frequency-splittings reveal changes in the zonal flows as a function of time (Howe et al. 2000a; Antia & Basu 2000), which penetrate up to a depth of $0.1R_\odot$.

In this work we investigate whether the changes in the frequency splittings imply any change in the characteristics of the tachocline as a function of solar activity. In addition to temporal variations, we also investigate how the properties of the tachocline change as a function of latitude.

2. DATA SET AND TECHNIQUES

We have used data sets from GONG and MDI. These sets consist of the mean frequency and the splitting coefficients, $a_j(n,\ell)$, defined by:

$$\nu_{n\ell m} = \nu_{n\ell} + \sum_{j=1}^{j_{\max}} a_j(n,\ell)\,\mathcal{P}_j^{(\ell)}(m), \qquad (1)$$

where $\nu_{n\ell}$ is the mean frequency of the (n,ℓ) multiplet, and $\mathcal{P}_j^{(\ell)}(m)$ are orthogonal polynomials in m (Ritzwoller & Lavely 1991; Schou et al. 1994).

We use GONG data for months 1–60, which cover the period from 1995 May 7 to 2001 April 4. We have generally used the 20 non-overlapping data sets each covering a period of 108 days. The MDI data sets (Schou 1999) consist of 26 non-overlapping data sets each covering a period of 72 days, starting from 1996 May 1 and ending on 2001 November 6.

To determine the properties of the tachocline we use the three techniques described by Antia et al. (1998), which are: (1) a calibration method in which the properties at each latitude are determined by direct comparison with models; (2) a one dimensional (henceforth, 1d) annealing technique in which the parameters defining the tachocline at each latitude are determined by a nonlinear least squares minimization using simulated annealing method; and (3) a two-dimensional (henceforth, 2d) annealing

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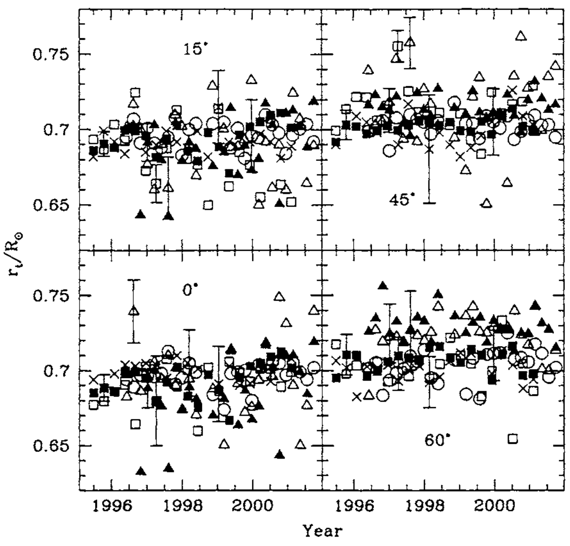

Figure 1. The mean radial position of the tachocline at a few selected latitudes that are marked in each panel. The crosses and circles show the results from calibration method for GONG and MDI data, the open squares and triangles show the 1d annealing results from GONG and MDI data, while the filled squares and triangles show the results from 2d annealing for GONG and MDI data. For clarity only one representative error-bar is shown for each technique.

technique, where the entire latitude dependence of tachocline is fitted simultaneously, again using simulated annealing. In all techniques the tachocline is represented by a model of the form (cf., Antia et al. 1998),

$$\Omega_{\rm tac} = \frac{\delta\Omega}{1+\exp[(r_t - r)/w]}, \qquad (2)$$

where $\delta\Omega$ is the jump in the rotation rate across the tachocline, w is the half-width of the transition layer, and r_t the radial distance of the mid-point of the transition region. The properties we are interested in are the position and the thickness of the tachocline and the change in rotation rate across the tachocline (i.e., r_t, w and $\delta\Omega$). We study these properties as a function of latitude and time using all the techniques listed above to study the properties of the tachocline.

3. RESULTS

Fig. (1) shows how the position of the tachocline at four different latitudes varies as a function of time. As can be seen from the figure, we find no clear change in the position with time. The results obtained by all three methods are consistent, and none shows any change with time.

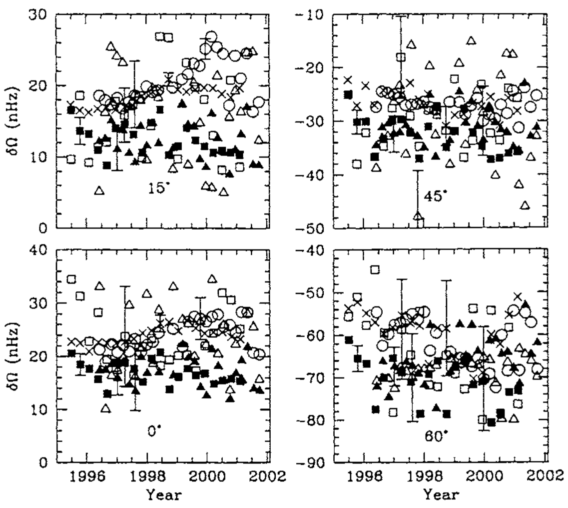

Figure 2. The jump in rotation rate across the tachocline at a few selected latitudes. The different styles of the points have the same meaning as in Fig. 1

Fig. (2) shows the jump in rotation rate across the tachocline at four different latitudes as a function of time. The jump obtained using the calibration technique appears to show an increase with time at low latitudes early in the solar cycle 23. The increase is within error limits, and is not seen in results obtained using other techniques and its significance is not clear.

Fig. (3) shows the half width of the tachocline as a function of time for different latitudes. We cannot infer any time-dependence from the figure.

Howe et al. (2000b) have reported a 1.3 year periodicity in the rotation rate in the tachocline which Antia & Basu (2000) failed to find. Both these works were based on inversion of rotation splittings which is likely to be unreliable in the tachocline region because of applied smoothing. In this work we have tried a forward modelling approach and we fail to find any periodicity in any of the properties of the tachocline.

Table 1. Mean properties of the tachocline at different latitudes

Lat. (°)	$\delta\Omega$ (nHz)	r_t ($R_\odot$)	w ($0.01R_\odot$)
0	21.04 ± 0.27	0.6918 ± 0.0023	0.55 ± 0.12
15	17.59 ± 0.17	0.6908 ± 0.0021	0.69 ± 0.10
45	-30.60 ± 0.39	0.7091 ± 0.0021	1.16 ± 0.12
60	-68.03 ± 0.58	0.7092 ± 0.0027	1.47 ± 0.15

To study latitudinal variations in the properties of the tachocline, we take the temporal average of the tachocline properties obtained from all data sets.

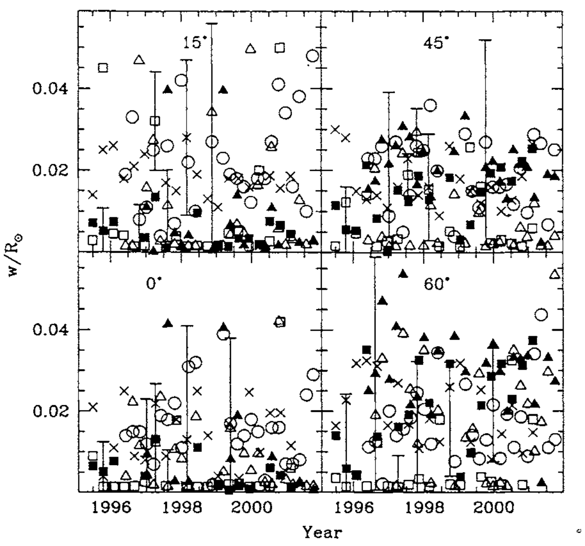

Figure 3. The half-width of the tachocline at a few selected latitudes. The different styles of the points have the same meaning as in Fig. 1

Furthermore, we take the weighted average over all six measurements at each latitude and the results are shown in Table 1. There is clearly a systematic variation in the position of tachocline with latitude while the variation in thickness is not clear.

From Table 1, it appears that there is little difference between depth and thickness of tachocline between latitudes of 0° and 15° and between latitudes of 45° and 60°. In between these two ranges, at a latitude of about 30°, the rotation rate is a slowly varying function of radius and thus this latitude divides the tachocline into two parts, one at low latitude where the rotation rate increases with increasing radial distance and another at high latitude where the rotation rate decreases with increasing radial distance. From Table 1, it appears that these two parts of tachocline are distinct with different depths and thicknesses, while there is very little variation with latitude within each part.

In order to test this hypothesis we have done 2d fits using simulated annealing to a tachocline of form given by Eq. (2) with

$$r_t = \begin{cases} r_{t0} & \text{if } \theta < \theta_0 \\ r_{t0} + \delta r_t & \text{if } \theta \geq \theta_0 \end{cases} \qquad (3)$$

$$w = \begin{cases} w_0 & \text{if } \theta < \theta_0 \\ w_0 + \delta w & \text{if } \theta \geq \theta_0 \end{cases} \qquad (4)$$

where θ is the latitude and $\theta_0 = 30°$ is the point where there is assumed to be a discontinuity with respect to θ. Thus instead of a continuous function for the position r_t and half-thickness w, we use a step function with discontinuity at $\theta = \theta_0$.

Fits to the discontinuous form show a larger variation in parameters compared to fits to the continuous form. For the GONG data sets, the χ^2 per degree of freedom in general comes out to be marginally lower than that for the continuous case (cf., Fig. 4). It can be seen that for GONG set the difference increases gradually with time and the fits to the discontinuous function are in general better. The fits to MDI data do not confirm this behaviour.

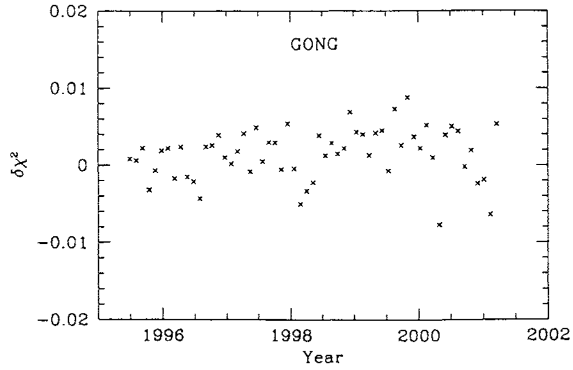

Figure 4. The difference in χ^2 per degree of freedom between 2d fits to the continuous functions and those to functions with discontinuity in latitude.

Fig. 5 shows some of the properties of the tachocline obtained from GONG data sets, by fitting the functions with discontinuity in latitude. It is clear that the fitted value of r_t and δr_t are anticorrelated and as a result there is a lot of scatter in both these parameters. As a result, it is difficult to detect possible temporal variation in these parameters. However, the scatter is much less in $r_t + \delta r_t$, which is the position of tachocline at high latitudes. It can be seen that this quantity shows a steady increase with time, which may look contrary to what is seen in Fig. 1. For comparison the average of all three measurements at 15° and 60° latitude from Fig. 1 are also shown in Fig. 5. It can be seen that even the earlier results have some tendency of increase in the position of tachocline at 60° latitude for both GONG and MDI data and there may be a maximum around 1999, which happens to be the same time when polar rotation rate near the surface has a minimum (Antia & Basu 2001). The increase in $r_t + \delta r_t$ is by about $0.004R_\odot$ which is well within the errorbars and hence its significance is not clear.

4. CONCLUSIONS

We find no significant temporal variation in the position or the width of the tachocline, nor is there any variation in the change in the rotation rate across the tachocline. We do not see any evidence of any short period oscillations in any property of the tachocline.

The position of the tachocline shows a significant variation with latitude, and the tachocline is found to be prolate, with a difference of $(0.017 \pm 0.003)R_\odot$

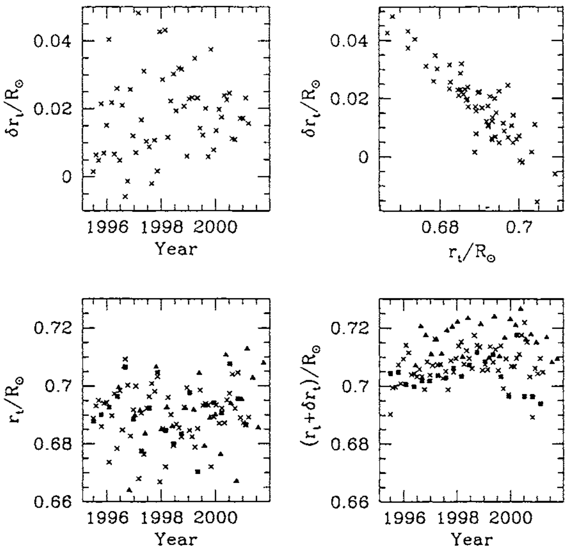

Figure 5. The tachocline position as obtained from 2d fits to a function with discontinuity in θ. For comparison average results at each point from Fig. 1 with GONG (green points) and MDI (blue points) are also shown in the lower panels. In the lower left panel these results are for 15° latitude, while those in lower right panel are for latitude of 60°. The errorbars are not shown in this figure as they are rather large. The size of typical errorbar can be seen from Fig. 1.

in position between the equator and a latitude of 60°, which is consistent with results obtained by Charbonneau et al. (1999). The variation in half-thickness by $(0.009 \pm 0.002)R_\odot$ is less clear as there is large scatter in thickness obtained from various techniques and at various times. It is not clear if the latitudinal variation is a continuous function of latitude, as is assumed in 2D annealing technique. Results in Table 1 suggest that the tachocline may actually be composed of two parts, one at lower latitude where $\delta\Omega > 0$ and the other at higher latitudes where $\delta\Omega < 0$. These two parts may have different locations and thickness, but there may be no significant latitudinal variation within each part. The fits of GONG and MDI data to a function with discontinuity in θ give contradictory results about the position and width of the tachocline. GONG data favour discontinuity, but MDI data do not confirm this behaviour. Clearly, more work is required to check if there is indeed a latitudinal discontinuity in tachocline properties.

Results of fits to functions with discontinuity in latitude, as well as the averaged results from Fig. 1 show a very small temporal variation in the position of the tachocline at high latitudes. The radial distance of tachocline at high latitude appears to have a maximum around 1999 and the variation is probably by about $0.004R_\odot$, which is well within the errorbars. Thus the significance of variation is not clear, but only the high latitude part of tachocline appears to show this variation.

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