HELIOSEISMIC DETERMINATION OF THE SOLAR TACHOCLINE THICKNESS

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ABSTRACT

The solar tachocline must necessarily support an Ekman-like circulation, which advects heavy elements that have settled under gravity back into the convection zone, causing an abrupt discontinuity in chemical composition at the base of the tachocline, thereby modifying the hydrostatic stratification. We have calibrated theoretical solar models incorporating the tachocline mixing against the latest seismic data from SOI-MDI, from which we have obtained a value for the tachocline thickness which is substantially more precise than the formal resolving power of the seismic data.

However, the sign of the transport is not correct for reducing shear.

(iii) Lorentz forces associated with a large-scale magnetic field hold the radiative interior rigid, and confine the shear to a thin tachocline (Gough and McIntyre, 1998).

Knowledge of the tachocline thickness provides an important constraint on any dynamical theory. Here we report on a seismological determination of that thickness.

2. METHOD

Existing estimates of the thickness of the solar tachocline are based on inversions of p-mode splitting coefficients to infer the variation of angular velocity, and are limited in accuracy by the low resolution of such inversions.

The tachocline has a weak baroclinic circulation which extends mixing below the base of the convection zone. We measure the thickness of the tachocline through the effect on the sound speed that this extra mixing brings about; the effect is seen as a 'hump' in inversions for the solar sound speed relative to standard solar models (see Figure 2), which we call the tachocline anomaly.

Two kinds of solar model are constructed, one using the standard formulation, including the gravitational settling of helium and heavy elements, the other assuming an additional region of material mixing extending a distance Δ below the base of the convection zone. The mixing length and initial hydrogen abundance are calibrated to give agreement with the present-day solar radius and luminosity at an age of 4.5 × 10⁹y; the heavy-element abundance is not recalibrated. The hydrogen abundance and convective stability parameter, A, are plotted in Fig. 1 as functions of radius, with the dashed line corresponding to the model with the tachocline mixing; Δ is approximately 0.018 R, the value obtained previously (Elliott & Gough, 1998) using a Gaussian approximation to the averaging kernels. The radiative temperature gradient is maintained in the tachocline.

The extra mixing recirculates gravitationally settled...
helium back into the convection zone, thereby increasing the hydrogen abundance just below the base of the convection zone. This increases the sound speed in that region. We adjust $\Delta$ to fit the difference in sound speed between the two models to the tachocline anomaly.

3. RESULTS

We have carried out a new OLA inversion for the solar sound speed with p-mode frequencies from the SOI-MDI instrument, using model S of Christensen-Dalsgaard et al. (1996) as the reference model. This inversion is shown by the circles in Fig. 2, with horizontal bars denoting the widths of the averaging kernels, and vertical bars denoting the standard errors.

We have fitted a quartic polynomial (the continuous curve) through the data points either side of the anomaly, which we regard as representing undetermined deficiencies in either the model construction or the inversion procedure. We then subtract it from the inversion to obtain the tachocline anomaly.

We convolve the difference in sound speed between the two solar models described above with the averaging kernels of the inversion. We then adjust $\Delta$ to fit the tachocline anomaly by least squares. The best fit, which is shown in Fig. 3, is obtained with $\Delta = 0.020 R$. Our ability to reproduce the anomaly gives us reasonable confidence in this value.

In order to obtain the fit illustrated in Figure 3 it was necessary to displace the theoretical curve downwards by $0.015 R$. Thus we infer that the convection zone is deeper than that of the models, a result which is consistent with the previous inference of Elliott & Gough (1998).

We conclude that the base of the convection zone is at $r \approx 0.697 R$, beneath which there is a tachocline of thickness $0.020 R$.

REFERENCES

Christensen-Dalsgaard, J. et al., 1997, Science 272, 1286-1292