Introduction

Global helioseismic measurements over a substantial fraction of the solar cycle now allow us to make inferences about the depth and latitude profile of the migrating zonal flow pattern known as the torsional oscillation. However, such results need to be interpreted with some care, as the resolution of the inversions is finite and deteriorates with depth.

Dynamo models can make predictions about the evolution of these flows. In this poster, we take the predictions of such a model, and subject it to a forward calculation and inversion procedure to find what the inversion results would look like if this model represented the true behavior of the Sun. This helps us assess the sensitivity of our techniques to subtle features of the torsional oscillation pattern.

The Observed Pattern

The plots below show radius-time slices through the inferred rotation rate (in nHz) at selected latitudes, after subtraction of a temporal mean at each latitude, for GONG RLS (top), MDI RLS (middle) and MDI OLA (bottom). The inversion techniques are those used by Howe et al. (2000).

Description of the Model

We couple an axisymmetric mean-field Reynolds-stress approach for the differential rotation and meridional circulation with the axisymmetric dynamo equations. This provides a model that allows the study of the back-reaction of the mean-field Lorentz force of the dynamo-generated field on differential rotation and meridional circulation. The assumptions used are:

- Theory of differential rotation:
  - Parameterized Reynolds-stress angular-momentum transport as source term for differential rotation.
  - Meridional circulation driven self-consistently by Coriolis force resulting from differential rotation.
  - Differential rotation in thermal balance: pole about 5K hotter than equator (this avoids the Taylor-Proudman state with $\Omega$ contours parallel to cylinders)
  - Equator-pole temperature difference originates in the subadiabatic tachocline and spreads into convection zone due to turbulent thermal conductivity

- Dynamo theory:
  - Axisymmetric flux-transport dynamo equations with Babcock-Leighton surface $\alpha$ effect and tachocline $\alpha$ effect
  - Feedback of mean field Lorentz force on differential rotation and meridional flow

The model predictions exist only below 0.95 $R_\odot$, so for the purposes of this exercise the flow pattern was extrapolated to the surface.

Simulating Inversions

In linear inversions, the objective is to find a weighted combination of the observables that gives the best estimate of the quantity being measured at each location. The definition of ‘best estimate’ is dependent on the chosen tradeoff between localization and noise. Once this choice has been made, the weights and the formal errors of the inversion depend only on the selection of the input data and their uncertainties – the models. In our case, the observables are rotational splitting coefficients and the quantity of interest is the local rotation rate. These combinations correspond to locally weighted averages over the true rotation profile, plus a noise contribution. Given an assumed profile, we can then reproduce what the inversion result would be in the absence of noise if the assumed profile were true, and also use Monte-Carlo techniques to generate simulated noise for the inversion result. This procedure is equivalent to calculating the rotational splitting coefficients corresponding to the assumed profile, adding noise with variance dictated by the formal errors of real data, and then inverting the coefficients.

Results

The plots below show radius-time slices through the rotation rate, after subtraction of a temporal mean, at selected latitudes for simulated cases corresponding to RLS inversions of a typical GONG modeset (top row), RLS inversions of the MDI modeset (middle) and OLA inversions of the MDI modeset (bottom). The colors (saturated at +/- 3 nHz) show the result of the simulated inversion and the contours, at 0.5 nHz intervals, the original input profile, with solid lines for faster and dashed for slower than average rotation. Two different variations on the input model profiles are illustrated, the second incorporating a thermal component generated at the surface as suggested by Spruit (2003).

In each case, the inversions do a reasonable job of reproducing the features of the input profiles, such as slanting flow bands and flow amplitudes that vary with depth, even in the presence of the noise. The noise-free profiles closely follow the input. Some of the subtleties in the deepest part of the convection zone, below 0.75 $R_\odot$, are captured less well; this is not too surprising given the poor angular resolution at that depth.

Discussion

- The results of this preliminary exercise give us some confidence that the results of global inversions from GONG and MDI data can be used to constrain dynamo models.
- We are also encouraged to believe that the apparent phase shift in the torsional oscillation pattern with depth, seen in the results from GONG and MDI, could well be a real effect.
- On the other hand, neither of the model time series examined is very close to the observed pattern.
- Further experiments could include carrying out a full Monte Carlo simulation with many noise realizations, and attempting to characterize the results with the same diagnostics as used on the real data.

References


Spruit, H. C. 2003, Solar Physics, 213, 1

Acknowledgments

This work utilizes data obtained by the Global Oscillation Network Group (GONG) project, managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. This work was supported in part by NASA grants S-92698-F and NAG5-11703 to the National Solar Observatory, and NAG5-13261 to Stanford University.

This work utilizes data obtained by the Global Oscillation Network Group (GONG) project, managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. This work was supported in part by NASA grants S-92698-F and NAG5-11703 to the National Solar Observatory, and NAG5-13261 to Stanford University.