The Solar Rotation and its Evolution During Cycle 23

S.G. Korzennik1,2, A. Ell-Darwich1
1 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA
2 Instituto de Astrofísica de Canarias & Universidad de La Laguna, Tenerife

Introduction

We present the most exhaustive and accurate inferences of the internal solar rotation rate and its evolution during solar cycle 23.

The Fit-Matching Method

This method fits individual modes, using an asymmetric profile, and an optimal multi-tapered spectral estimator. It fits simultaneously all $n$ for a given $\ell$ / multiplet, using an iterative scheme to include mode contamination, and a “sanity” rejection.

Key elements of this method:

- Include leakage, and solar multi-tapered spectral estimator, simultaneous fit of individual modes (all $n$ / sanity rejection, and mode contamination (iterative), fit time-series of varying lengths.
- Use improved SNC time-series: $\text{GONG} / \text{sym 64e vs SGK/asym 64e}$ for a given $m$, and GONG pipeline 9 term expansion, or my fit to GONG frequency tables using 9, 18 or 36 terms (left to right).
- Leakage matrix accounts for plate scale and image distortion
- Leakage matrix includes effect of distortion by differential rotation 1 – 6% effect
- Inverse problems are singular, require regularization, – inverse problems are singular, require regularization, – produce an estimate of the solution, $\hat{\mu} = (B \hat{\mu}) / (\text{det}(B))^\dagger$
- $B$ resolution kernels – depend on the input set
- Solar Rotation
- inverse leakage matrix:
- input set is defined by $m$, $\ell$, $\ell_1$;
- temporal changes in the input set affect $B$, hence $\hat{\mu}$

We chose to invert a constant input set to avoid injecting changes of the input sets into inverted rotation profile changes.

The Inversion Method

The inversion methodology is an iterative methodology based on a least-squares regularization (Eff-Darwich & Korzennik, 2007).

• Inverse Theory
• Leakage matrix – closest leaks – $\Delta \omega_{\ell m}, \ell_1 \ell_1$ are rarely resolved
• $\Delta \omega_{\ell m}, \ell_1 \ell_1$ are rarely resolved
• plate scale, image & eigen values distortions, orientation ($\ell_1$)
• accounts for plate scale and image distortion
• distortion by differential rotation 1 – 6% effect
• $B_{\ell m} = B_{\ell m}(t)$
• 3 – 15% effect
• other geometric variations negligible
• very long time-series indicate remaining mismatch for $\ell$-mode
• independent leakage computation
• small differences

The Mean Solar Rotation Rate

Mean Solar Rotation Rate for Cycle 23

The Mean of the rotation rate, as a function of time and latitude, derived from inferences using Clebsch-Gordan coefficients, at four depths ($\ell = 1$, $0.05$, $0.5$, $0.71$; top to bottom) and using either the GONG pipeline 9 term expansion, or my fit to GONG frequency tables using 9, 18 or 36 terms (left to right).

MDI/SPHL & GONG $\omega / R$ vs $t$ - 1.00

Fig. 6: Rotation rate (left) as a function of depth and latitude derived from a solar cycle worth of data. Right: The formal uncertainty of that inversion.

The Attrition Issue

The Attrition Issue

We computed and fitted power spectra derived from time series of varying lengths: from a single 4600-day-long epoch (54 x 72 day or 12.6 year) down to 64 segments each 72-day long.

Other Issues

Other Issues

We present the most exhaustive and accurate inferences of the internal solar rotation rate and its evolution during solar cycle 23.

Fig. 1: A full solar cycle of MDI observations has been analyzed using our state of the art fitting methodology.

Fig. 4: Data and model (top and middle respectively) of the f-mode at $\ell = 251$ & $250$ (left & right resp.). Bottom: difference. Note the mismatch of the peaks at $\ell = 251$.

Conclusions

Conclusions

• Fitting: Issues still remain to be solved.
• Mean rotation
• Very long time-series improved precision, resolution & extent
• Dip at $0.41$, $0.37$, $0.18$, $0.04$
• Rise at branch of cycle
• Evolution
• Easy at the surface, and low latitudes
• No consistent picture yet at base of CZ & difficult below CZ.