**Abstract**

The helioseismic analysis of torsional oscillations of the Sun, obtained in 1996-2018 from the SOHO and SDO, reveals the spatio-temporal dynamics associated with the dynamo process. The data reveal new relationships between the migrating magnetic field patterns observed in synoptic magnetograms and the dynamics of torsional oscillations near the surface and in the interior. In particular, it is found that the evolution of torsional oscillations in the deep convection zone is ahead of the surface magnetic evolution by several years, and that it is related to the extended solar cycle phenomenon observed in the solar corona.

The data show substantial differences in the torsional oscillation properties between Cycles 23 and 24 indicating on fundamental changes in the dynamo regime, and also reveal initiation of Cycle 25. The helioseismology observations of the torsional oscillations open new perspectives for understanding the global dynamo processes inside the Sun, and for predicting the next solar cycle.

**Motivation**

Helioseismology provides means to probe the structure and dynamics of the solar interior by analyzing oscillation signals observed on the surface. Currently, it is not possible to unambiguously measure subsurface magnetic fields. Thus, the information about the dynamo processes comes from measurements of large-scale subsurface flows. Variations of the flow structure and speed on the scale of 11-year solar cycles are associated with magnetic fields. Therefore, observed flow patterns provide an important clue about the mechanism of solar dynamo.

**Observational data and analysis**

We analyze the rotation rate of the solar interior inferred by inversion of solar oscillation frequencies measured from 1996 to 2018 by Michelson Doppler Imager (MDI) and Helioseismic and Magnetic Imager (HMI). The frequency analysis and inversions are performed using the 72-day times series of full-disk solar Dopplergrams. The total number of measurements of the solar internal rotation is 110.

The rotation rate pattern in the near-surface layers is obtained by subtracting the mean differential rotation and combining the residuals in the time-latitude diagram. The zonal acceleration calculated by differentiating smoothed zonal velocity data shows that the active region zones coincide with the flow deceleration zone (blue color). In the polar regions the deceleration zones correspond to the periods of strong polar magnetic field. This confirms that the torsional oscillations are due to the back reaction of solar magnetic fields, and thus carry the information about the evolution of the internal magnetic field.

**Principal Component Analysis**

Principal component analysis (PCA) converts observational data into a set of linearly uncorrelated orthogonal components called principal components, which are ordered so that the first few retain most of the variance present in the original data. Specifically, we used the Karhunen-Loeve Transform method and the code provided in the IDL Astrophysics Library. The technique allows us to identify the zonal acceleration patterns in the deep convection zone and tachocline. The procedure was to calculate eigenvalues and eigenvectors of the cross-covariance function for the series of zonal acceleration data, and then to reconstruct the data by using the first three principal components which represent most of the variations.

**Time-latitude and time-radius diagrams of the zonal acceleration**

(A) Time-latitude diagrams of the zonal acceleration at four different depth in the convection zone (the corresponding radii: r/R=0.7, 0.8, 0.9, and 1.0 from bottom to top), obtained after applying the Principal Component Analysis. Dashed line with circles marks the end of Solar Cycle 23 at 0.7R and 1.0R.

(B) Time-radius diagrams at four different latitudes: 5°, 15°, 30°, and 60°. Dashed line with circles marks the direction of migration of the low and high-latitude torsional oscillations branches corresponding to Cycle 24.