Helioseismic Observations of Torsional Oscillations Inside the Sun and Their Potential for Predicting Solar Cycles

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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.

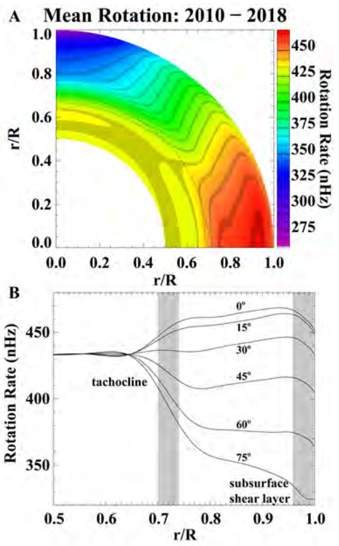
In particular, it is found that the evolution of torsional oscillations in the deep convection zone is ahead of the surface magnetic evolution by several years, and that it is related to the extended solar cycle phenomenon previously observed in the solar corona.

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

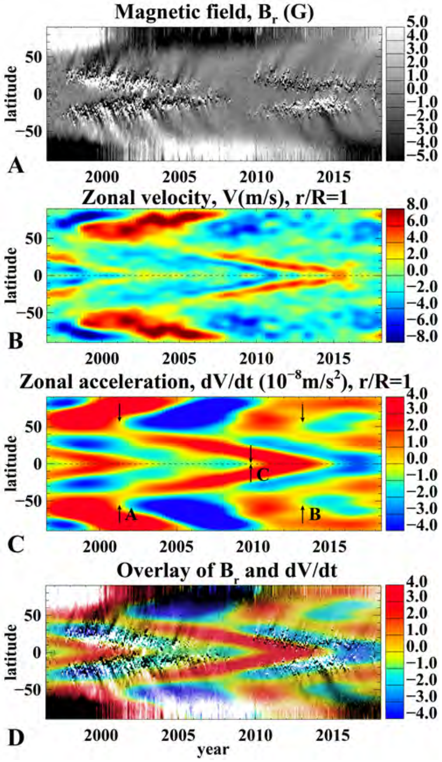
Helioseismology provides means to probe the structure and dynamics of the solar interior by analyzing oscillation signals observed on the surface. Currently, it is not possible to unambiguously measure subsurface magnetic fields. Thus, the information about the dynamo processes comes from measurements 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, the observed flow patterns provide an important clue about the mechanism of solar dynamo.



(A) The mean solar rotation rate profile obtained from the SDO/HMI data. Dashed line indicates the bottom of the convection zone.

(B) The mean rotation rate as a function of radius at different latitudes. The gray intervals indicate the tachocline and the subsurface shear layer.

Magnetic field and torsional oscillations in the near-surface layers



(A) The magnetic butterfly diagram showing the evolution of the radial component of magnetic field during the last two solar cycles as a function of time and latitude.

(B) The zonal flow velocity near the solar surface as a function of latitude an time.

(C) The zonal flow acceleration calculated after applying Gaussian spatial and temporal filters to isolate large-scale patterns. Arrows A and B indicate the start of extended Cycles 24 and 25, Arrow C marks the of extended Cycle 23.

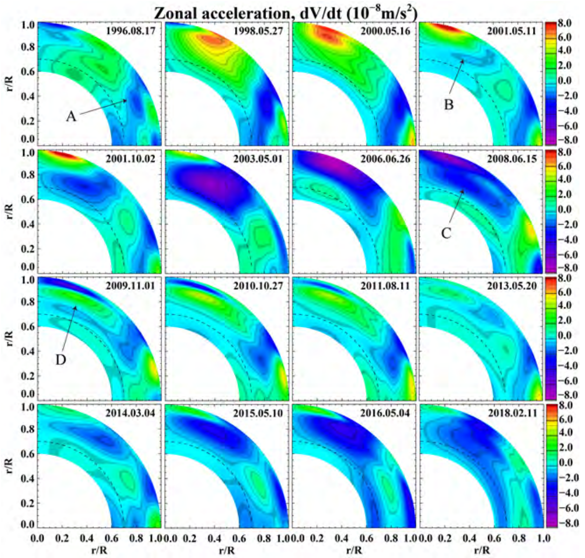
(D) Overlay of the zonal acceleration (color image) and the radial magnetic field (gray-scale) revels that the regions of magnetic field emergence at mid and low latitudes coincide with the zones of flow deceleration.

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 torsional oscillation 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.

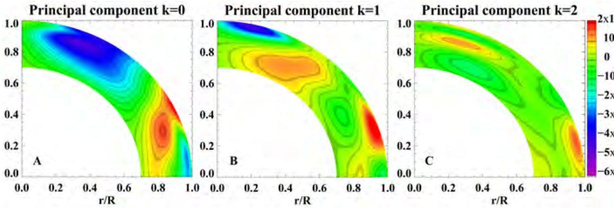
Evolution of the zonal flow acceleration, dV/dt, in the solar convection zone in 1996-2018.

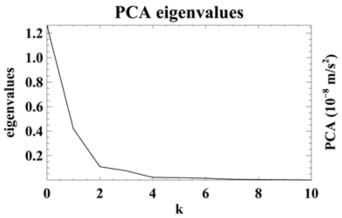


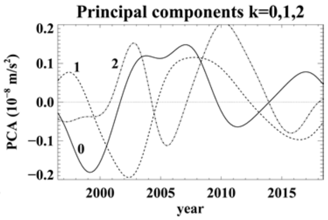
Arrow A indicates the migrating low-latitude branch of the zonal deceleration.
Arrow B indicates the start of Cycle 24 in the tachocline.
Arrow C indicates the start of the downward migration at high latitudes.
Arrow D indicates transition from deceleration to acceleration at high latitudes.

Principal Component Analysis

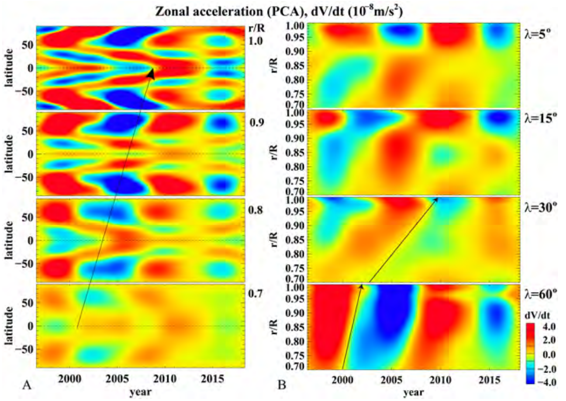
Principal component analysis (PCA) converts observational data into a set of linearly uncorrelated orthogonal components called principal components, which are ordered so that the first few retain most of the variation present in the original data. Specifically, we used the Karhunen-Loeve Transform method 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 eigenfunctions 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.







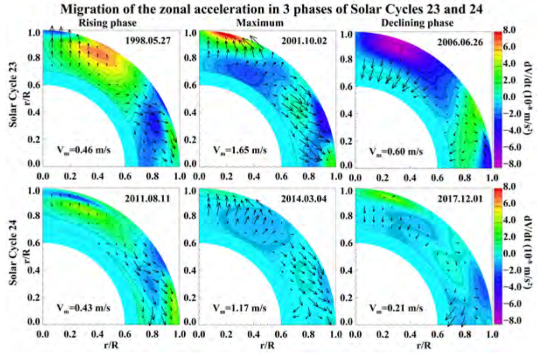
Time-latitude and time-radius diagrams of the zonal acceleration



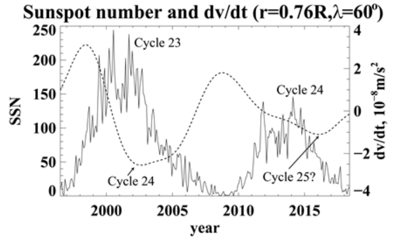
(A) Time-latitude diagrams of the zonal acceleration at four different depth in the convection zone (the corresponding radii: r/R=0.7, 0.8, 0.9, and 1.0 from bottom to top), obtained after applying the Principal Component Analysis. Inclined line with arrows marks the end of Solar Cycle 23 at 0.7R and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

(B) Time-radius diagrams at four different latitudes: 5°, 15°, 30°, and 60°. Inclined lines with arrows the direction of migration of the low and high-latitude torsional oscillation branches corresponding to Cycle 24.

Velocity patterns of migration of zonal acceleration



Velocity maps of migration of the zonal acceleration at different phases of the solar cycles, obtained by the correlation tracking analysis



Evolution of the sunspot number (solid curve) and the zonal acceleration (dashed) in the region of initiation of the torsional oscillations, located in the tachocline at 60 degrees latitude.