DETECTION OF DYNAMO WAVES INSIDE OF THE SUN

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Torsional oscillations are exhibited by bands of fast and slow zonal flows beneath the visible surface of the Sun, similar to stream jets in the Earth's atmosphere. Analysis of helioseismology data obtained by two NASA missions in 1996-2018 for nearly two solar cycles reveals zones of deceleration of torsional oscillations inside the Sun due to a back reaction of magnetic fields generated by the solar dynamo. Deceleration of the flow originates about 120,000 miles beneath the solar surface at high latitude regions of the solar tachocline. This zonal deceleration migrates through the convection zone revealing patterns of magnetic dynamo waves, analysis of which explains the phenomenon of the 'extended solar cycle' observed in the evolving shape of the solar corona, and why the polar magnetic field strength predicts the solar maxima. The results indicate a further decline of sunspot activity in the next solar cycle.

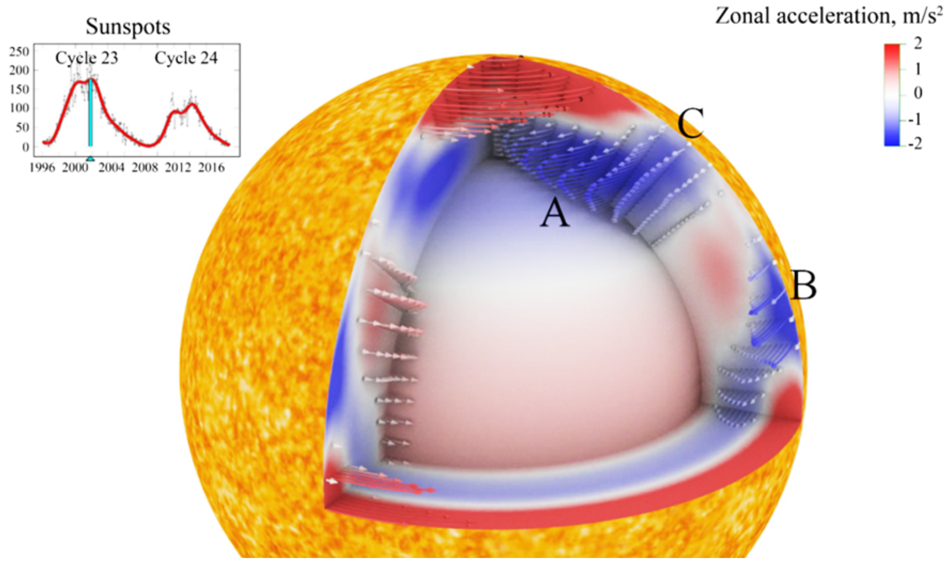

Image of the zonal acceleration pattern beneath the solar surface shows zone of flow acceleration (red) and deceleration (blue). The flow deceleration is caused by the magnetic field. The inner sphere shows the bottom of the convection zone (the solar tachocline). The tachocline region marked with "A" is the primary seat of the solar dynamo, where the magnetic is initially generated. "B" and "C" indicate the polar and equatorial branches of the dynamo wave. When the polar branch reaches the surface it causes polar field reversals, while the equatorial branch, amplified by magnetic field stretching due to differential rotation, leads to formation of sunspots. The insert shows the evolution of the sunspot number during 22 years of helioseismic observations. The image shows a snapshot of the zonal deceleration in 2003 near the maximum of the sunspot number of Solar Cycle 23 (point B), when the generation of magnetic field of the next solar cycle already started in the tachocline (point A). (Visualization by Tim Sandstrom, NASA Ames Research Center).

All manifestations of solar activity, from spectral irradiance variations to solar storms and geomagnetic disturbances, are caused by the magnetic fields generated by a dynamo mechanism operating in the convection zone of the Sun. Despite substantial modeling and simulation efforts, our understanding of how the magnetic field is generated, transported to the surface, and forms the solar activity cycles is very poor. The most prominent feature of the solar cycle is the sunspot 'butterfly' diagram: at the beginning of an 11-year sunspot cycle magnetic sunspot regions emerge at about 30 degrees latitude, after which the sunspot formation zone migrates towards the equator. In addition, during the sunspot maxima the polarity of the global magnetic field in the Sun's polar regions is reversed.

In 1955, Eugene Parker showed that differential rotation and helical turbulence in the solar convection zone can result in dynamo action in the form of migrating dynamo waves that transport magnetic flux from the deep interior to the solar surface, creating the sunspot butterfly diagram. However, in the absence of observational evidence of the dynamo waves, alternative scenarios, called the flux-transport models, were developed. These models suggest that the cyclic evolution of the magnetic field is controlled by meridional circulation which, similarly to a conveyor belt, transports magnetic flux at the bottom of the convection zone from high to low latitudes where it emerges in the form sunspots.

Our new results provide strong evidence of dynamo waves and reveal their migration pattern in a form of two branches: migrating towards the poles and the equator. The polar branch reaches the surface in 1-2 years, while it takes about 8-9 years for the equatorial branch to reach the solar surface and form the sunspot butterfly diagram. Since the polar branch reaches the surface quicker, the strength of the polar magnetic field can help predict the following sunspot maximum. Recent measurements show a significant decrease of zonal deceleration in the tachocline indicating that the upcoming sunspot cycle may be even weaker than the current sunspot cycle. Thus, the long-term trend of the declining magnetic field of the Sun is likely to continue. This can have significant impacts on the state of Earth atmosphere and space weather, and potentially, on climate patterns.

Even though the magnetic field in the convection zone cannot be measured directly, its structure can still be tracked through its effects on large-scale zonal flows that are similar to stream jets, and have been historically called 'torsional oscillations' because of their cyclic variations synchronized with the magnetic activity cycles. Magnetic forces slow down the flows, which can be observed using techniques in helioseismology to measure the deceleration of zonal flows. The flow speed is about 2-4 miles per hour, and is measured in frequency shifts of solar oscillations. The measurements have been performed over the last 22 years by two NASA space missions, Solar and Heliospheric Observatory (1996-2010) and Solar Dynamics Observatory (2010-current). The solar oscillations, which have a characteristic period of 5 minutes, are observed every 45 seconds for an uninterrupted period of 72 days to obtain one measurement of subsurface flows. The amount of data processed for this study at the Joint Science Operations Center at Stanford University is about 5 Petabytes. The flow analysis and visualization were performed at the Supercomputing Division at the NASA Ames Research Center.

Website: http://sun.stanford.edu/~sasha/AAS2019/

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