Helioseismic Observations and Modeling of Solar Dynamo

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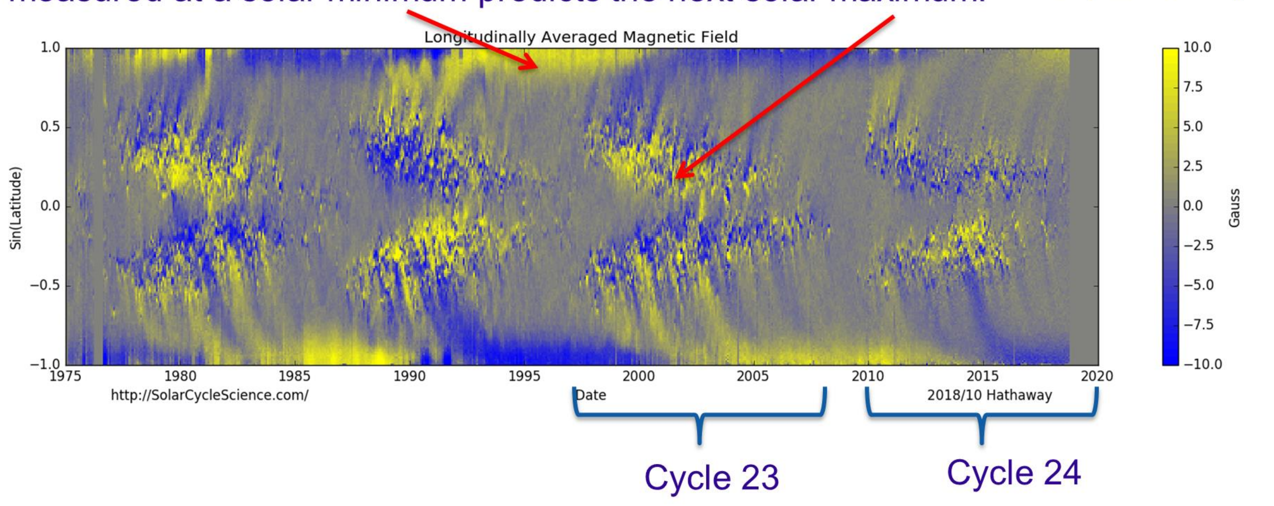
- Helioseismological observations of the internal dynamics of the Sun during the last two solar activity cycles make it possible to trace the development of solar dynamo processes throughout the depth of the convective zone and to link them with models of solar cycles. Observational data obtained from the SoHO (1996-2010) and SDO (2010-2020) spacecraft represent measurements of the internal differential rotation, meridional circulation, and thermodynamic parameters.
- The structure and dynamics of zonal and meridional plasma flows reveal the processes of generation and transfer of magnetic fields inside the Sun. The data analysis shows that active latitudes and regions of a strong polar field on the Sun's surface coincide with regions of deceleration of zonal currents ("torsional oscillations"). The observed structure of zonal flows and their latitudinal and radial migration in deep layers of the convective zone correspond to dynamo waves predicted by dynamo theories and numerical MHD models.
- The data indicate that the development of a new solar cycle begins at about 60 degrees latitude at the base of the convective zone during the maximum of the previous cycle. Then, the process of magnetic field migration to the Sun's surface is divided into two branches: fast (in 1-2 years) migration in the high-latitude zone and slow migration at middle and low latitudes for ~10 years. The subsurface rotational shear layer ("leptocline") plays a key role in the formation of the magnetic "butterfly diagram". Both the zonal flows ("torsional oscillations") and the meridional circulation reveal the 22-year pattern of the "extended" solar cycle, initially discovered from observations of Doppler velocities and the structure of the solar corona.
- A self-consistent MHD model of the solar dynamo developed in the mean-field theory framework is in good qualitative and quantitative agreement with the helioseismic observations. The model shows that the observed variations of the solar dynamics are associated with a magnetic field effect on convective heat transfer and the corresponding modulation of the meridional circulation. The model explains why the solar minimum polar field predicts the next sunspot maximum and points to new possibilities for predicting solar cycles from helioseismological data.

SOLAR MAGNETIC CYCLES

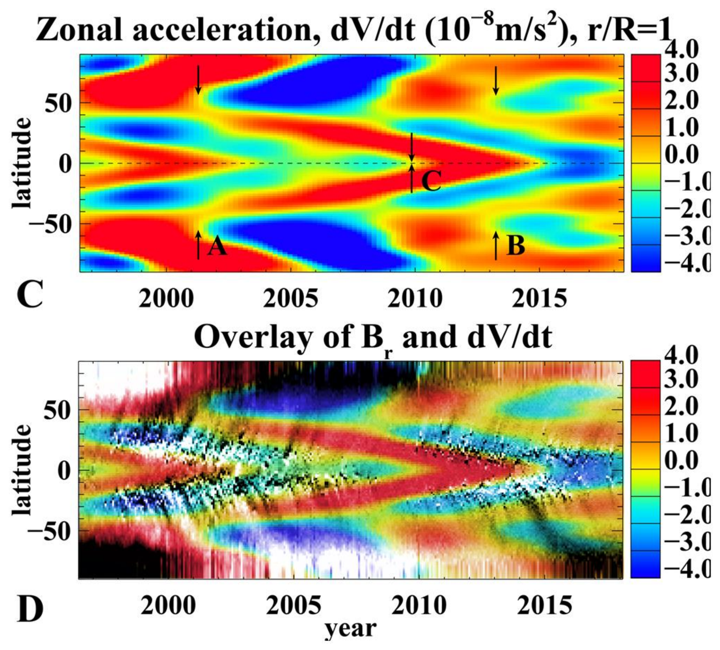
Previously, it was found that the strength of polar magnetic field measured at a solar minimum predicts the next solar maximum.

Our analysis explains why.



New approach: helioseismic measurements of zonal acceleration

- The zonal flow acceleration calculated after applying Gaussian spatial and temporal filters to smooth noise and small-scale variations and reveal large-scale patterns
- Overlay of the zonal acceleration (color image) and the radial magnetic field (gray-scale) reveals that the regions of magnetic field emergence at mid and low latitudes coincide with the zones of flow deceleration.



OBSERVATIONS ARE EXPLAINED BY SELF-CONSISTENT NON-LINEAR MEAN-FIELD DYNAMO MODEL

(PIPIN & KOSOVICHEV, 2019)

Full set of non-linear 2D (axisymmetrical) MHD equations that include:

1. Magnetic field generation by turbulence
2. Magnetic field turbulent diffusion and transport by meridional flows
3. Interaction of rotation with turbulent convection and magnetic fields
4. Generation of meridional flows
5. Effects of magnetic fields and flows on convective heat transport
6. Evolution of magnetic helicity

Model outcome:

1. Differential rotation and variations (torsional oscillations)
2. Meridional circulation and solar-cycle variations
3. Magnetic butterfly diagram and polarity reversals
4. Explains the extended solar cycle

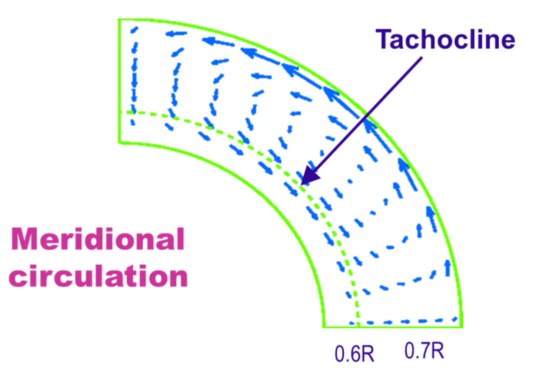
Two paradigms in solar dynamo

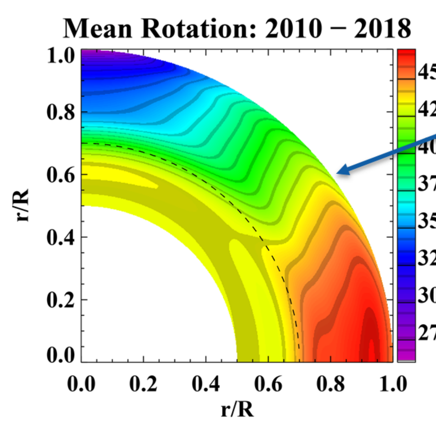
Flux-transport theory

- The dynamo process is controlled by meridional circulation.
- Toroidal magnetic field is generated and stored in the tachocline region. Meridional flow in the tachocline produces the butterfly diagram.

Dynamo-wave theory

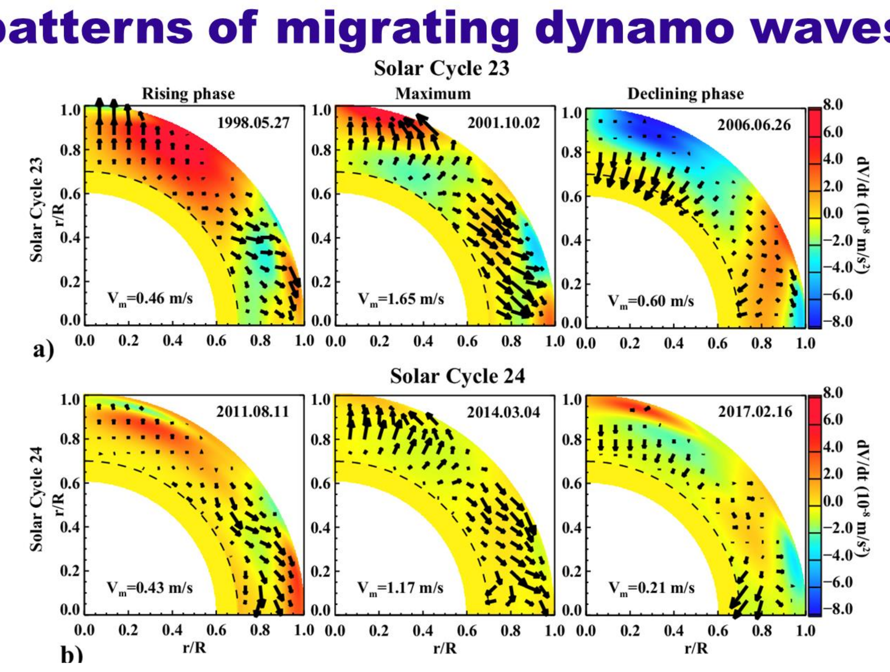
- The butterfly diagram is produced by dynamo waves.
- Theoretical argument: "Dynamo waves propagate along isorotation surfaces" (Parker, 1955; Yoshimura, 1975).





Because of the subsurface shear layer the dynamo wave can propagate towards the equator (Brandenburg 2005; Pipin & Kosovichev, 2011).

Velocity maps of migration of the zonal flow acceleration in the solar convection zone reveal patterns of migrating dynamo waves



MODEL EXPLAINS THE EXTENDED 22-YEAR PATTERN OF THE TORSIONAL OSCILLATIONS

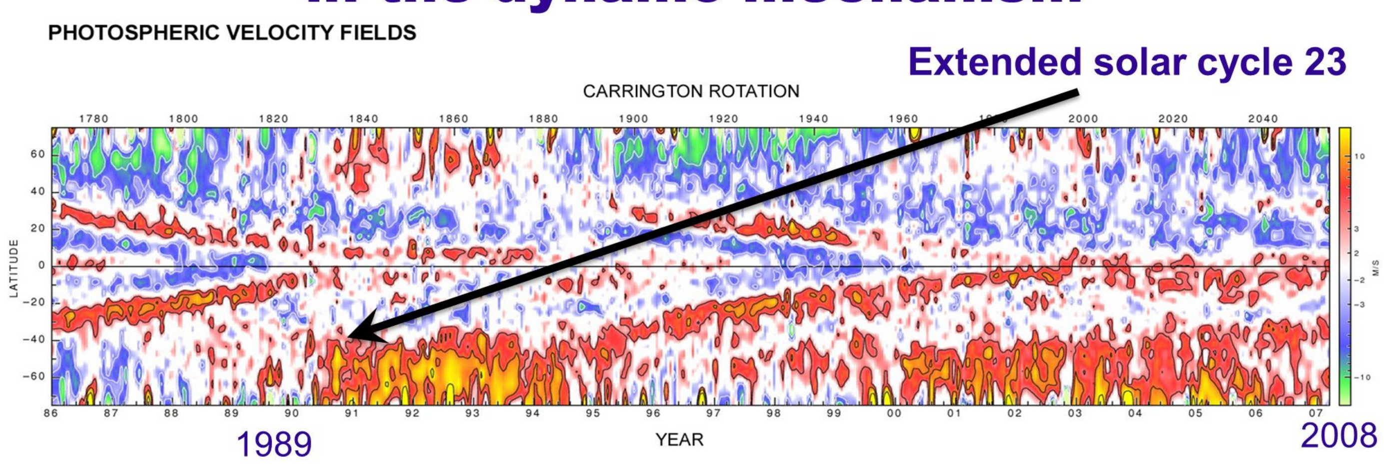
Two necessary conditions for appearance of the extended 22-year pattern of the torsional oscillations.

1. The existence of the 22-year mode in the dynamo wave pattern and the subsequent overlap of magnetic cycles on the solar surface.
2. The magnetic quenching of the eddy thermal conductivity.

This effect results in the cyclic modulation of the thermal wind associated with the mean entropy gradient, and, correspondingly, modulation of the meridional circulation. The variations of the meridional circulation affect the zonal flows, producing the extended cycle pattern.

Without the above two conditions the model can only reproduce the 11-year torsional oscillation pattern that is known from other mean-field and numerical models that can be found in the literature (e.g., Kueker 1996; Pipin 1999; Pipin, 2004; Covas, 2000; Rempel, 2006; Guerrero 2016; Kapyla 2016)

Variations of the differential rotation ("torsional oscillations") provide insight in the dynamo mechanism



Courtesy of Roger Ulrich (http://obs.astro.ucla.edu/torsional.html)

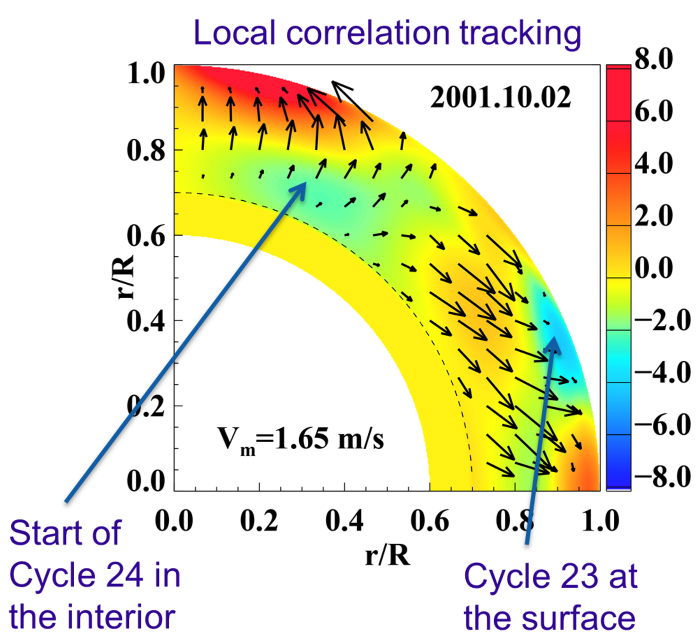
Torsional Oscillations were discovered by Carnegie astronomers Robert Howard and Barry LaBonte using 150-Foot solar telescope data in 1980.

MIGRATION OF DYNAMO WAVES

The dynamo waves originate at the base of the convective zone (in the "solar tachocline") and migrate towards the poles and the equator with a speed of 1-2 m/s.

It reaches the surface near the poles in 1-2 years, but it takes about 10 years to reach the surface at low latitudes where it forms sunspots.

This explains why the polar magnetic field predicts the next sunspot maximum.



MODEL M1: HALF OF THE DYNAMO CYCLE

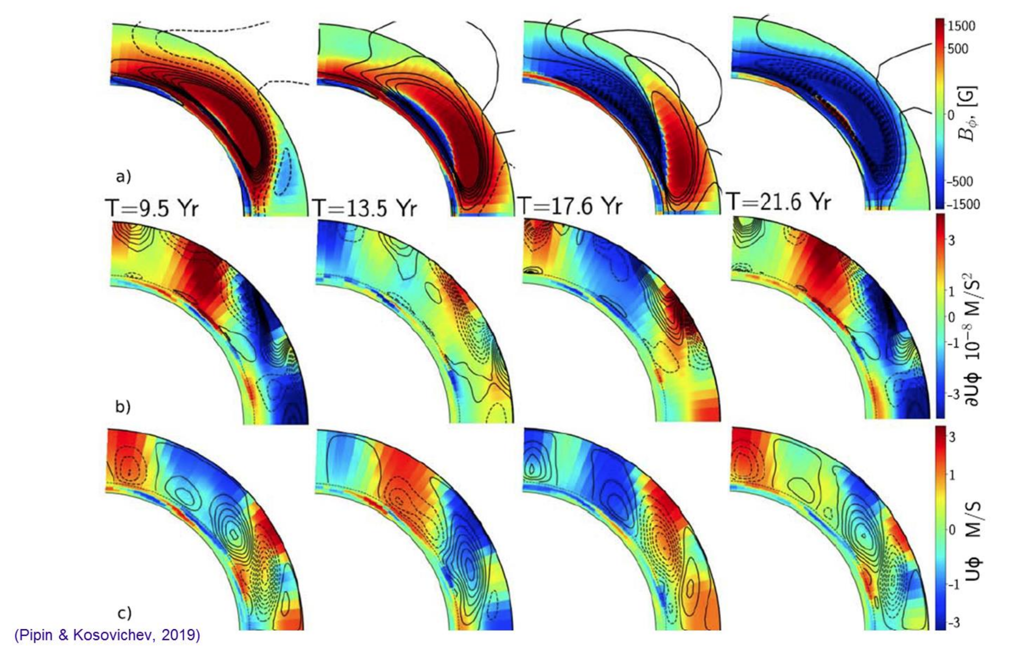


Figure 5: Model M1. Snapshots for half of the dynamo cycle:

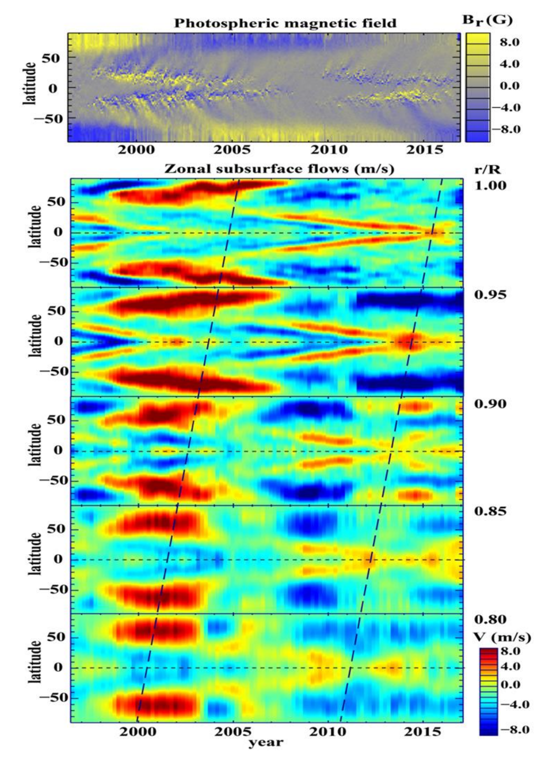
a) the toroidal magnetic field (background image) and streamlines of the poloidal field (contours);

b) variations of the zonal acceleration (background image) and the azimuthal force caused by variations of the meridional circulation, F_U, (contour lines are plotted in the range ±50 m/s^2);

c) variations of the azimuthal velocity and contours show streamlines of the variations of meridional circulation, dashed lines are for the counter clockwise circulation

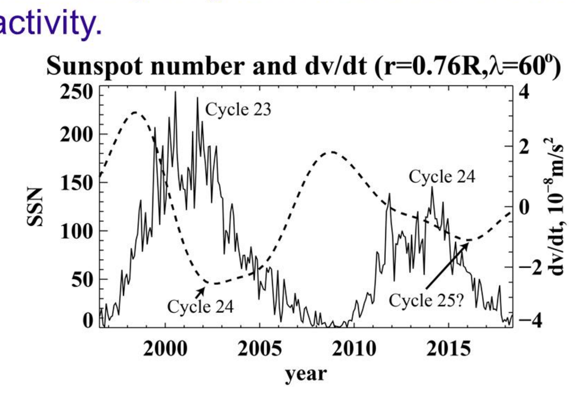
Torsional oscillations at different depth are measured by helioseismology

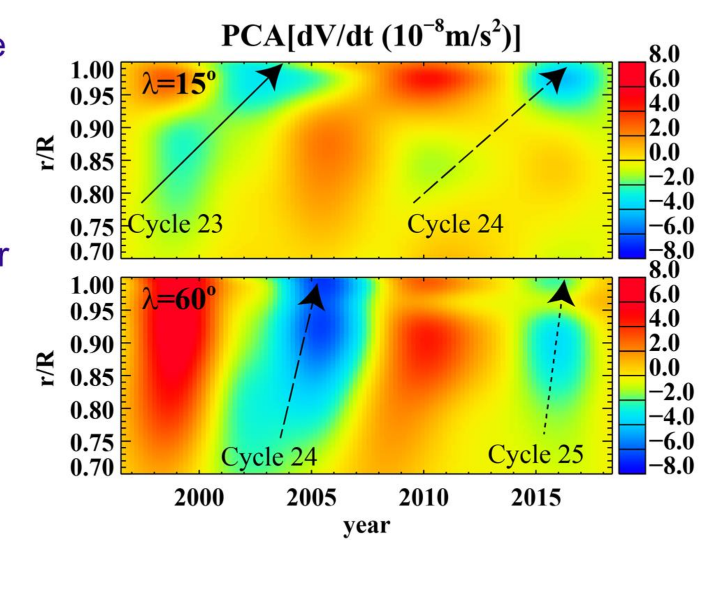
- Comparison of the magnetic butterfly diagram with the corresponding maps of the zonal flows (torsional oscillations) at five different depth in the convection zone during Cycles 23 and 24.
- Inclined dashed lines illustrate an apparent migration of the flow pattern with radius. They are drawn through the points where the accelerated equatorial branch crosses the equator (around the solar maxima).
- The polar branch (red structure at high latitudes) that was very prominent at the surface in Cycle 23 is missing in Cycle 24. However, it is detected beneath the surface at 0.9R (Howe et al, 2018).



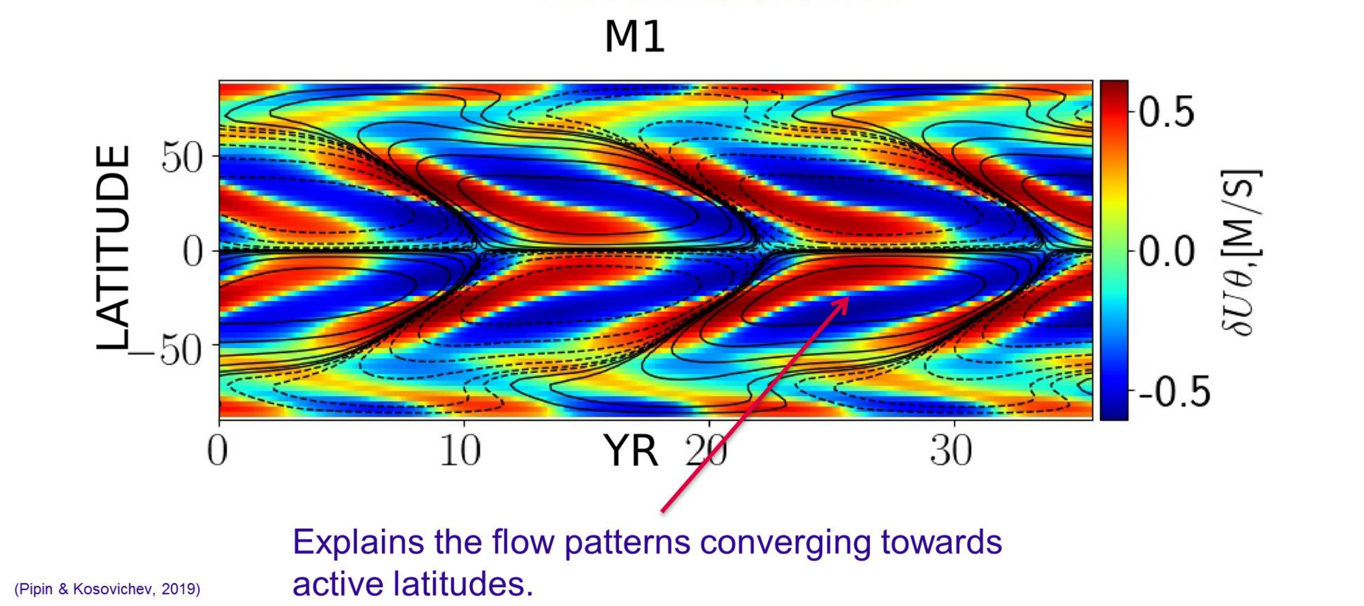
NEXT SOLAR CYCLE

- In the solar interior we already see the signal associated with the next sunspot maximum (Cycle 25).
- It appears that it will be even weaker than the current cycle, indicating on continuing long-term decrease of solar activity.





MODEL M1: VARIATIONS OF MERIDIONAL CIRCULATION



Explains the flow patterns converging towards active latitudes.