A new mechanism for the butterfly diagram of the solar cycle

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Abstract

The butterfly diagram of the solar cycle is the equatorward migration of the emergence latitudes of sunspots as the solar cycle evolves. The equatorward meridional flow at the bottom of the convection zone was believed to be responsible for this migration. However, helioseismological studies indicate controversial forms of the meridional flow, which even present poleward flow at the bottom, dissatisfying the requirements of the butterfly diagram. This motivates us to explore a new mechanism for the butterfly diagram. Here we aim to propose the new mechanism, that is the latitude-dependent radial flux transport.

Current explanations for the butterfly diagram

- Meridional flow, but helioseismological studies show controversial forms of the meridional flow that do not support the solar-like solution with a proper butterfly diagram.
- Dynamo wave in the tachocline. However, dynamo wave poleward propagates based on the Parker-Yoshimura rule, contrary to observations.
- Latitudinal pumping, while there is insufficient evidence for its existence.
- Dynamo wave in the near-surface shear layer, but the toroidal field generated there is hard to store and then form tilt sunspot groups.

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Reference:

[1] Jiang, J., et al., 2013, A&A, 553, A128
[2] Cameron. R, et al., 2010, ApJ, 719, 264

Methods

- Use a data-driven Babcock-Leighton type flux transport dynamo (FTD) model [1], whose source term is constructed from the sunspots records (1874-1981) [2].
- Explore how the latitude-dependent radial flux transport, e.g., the latitude-dependent pumping or meri. flow, affects the migration of the toroidal field

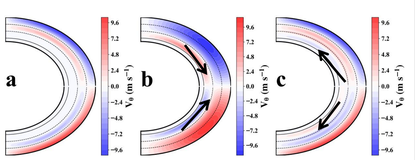


Fig.1 Meridional flows used in the study: (a) shallow single cell; (b) deep single cell; (c) double cell.

- The latitude-dependent radial pumping in the form of cosθ (θ: co-latitude) dominates in the process of radial flux transport, so the higher the latitudes, the faster the radial velocity as shown in Fig.2.

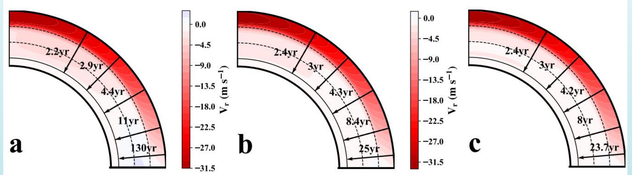


Fig.2 Distributions of radial velocity (red shaded region decoded by color bars) and transport time (black) for 3 flow profiles shown in Fig. 1. Here the latitude-dependent pumping is used.

Results

With the latitude-independent radial pumping

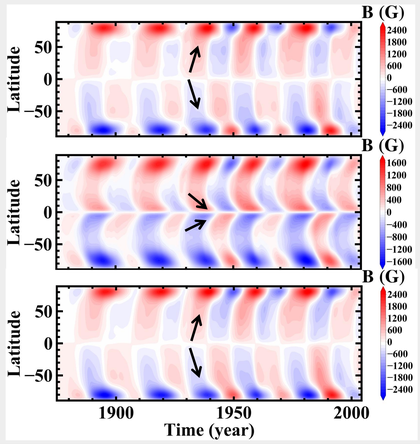
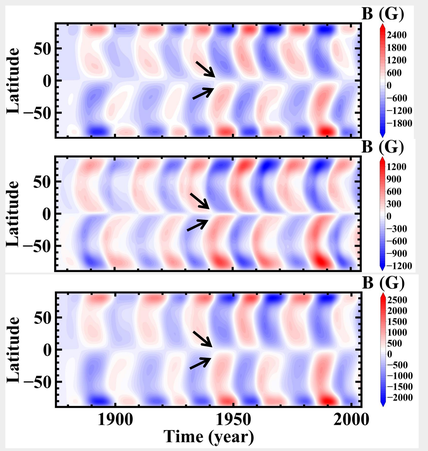


Fig.3 Time-latitude diagrams of the toroidal field at the bottom of the convection zone (CZ). Tope to bottom correpond to the 3 profiles of meridional flows shown in Fig.1.

- When there is no flow at the bottom, the toroidal field at low latitudes poleward propagates, which is caused by the dynamo wave.
- When the meridional flow penetrates toward the bottom, the propagation direction of the toroidal field at low latitudes is determined by the flow direction.

With the latitude-dependent radial pumping

Fig.4 Same as Fig.3, but the latitude-dependent pumping is adopted.



- When the latitude-dependent radial pumping is used, the toroidal fields at low latitudes propagate toward the equator, no matter what form the meridional flow is. → The latitude-dependent radial flux transport provides a mechanism for the butterfly diagram.

Demonstration of the new mechanism

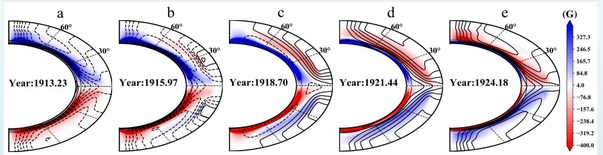


Fig.5 Snapshots of the magnetic fields for the solution shown in Fig.4(a). The simulation period is from 1913 to 1924, covering the whole solar cycle 15.

- In the process of downward transport, the poloidal fields in the bulk of the CZ are sheared by the latitudinal differential rotation to produce the toroidal fields, which are further transported downward to the bottom (see panels (b) - (d)).
- When the poloidal field reaches the bottom of the CZ, the differential rotation there acts on the poloidal field to produce stronger toroidal fields. At higher latitudes, the magnetic fields are transported downward to the bottom earlier than that at lower latitudes (see panels (c) - (e)).
- Therefore, the bottom toroidal fields, partly from the middle of the CZ and partly from the shearing for the poloidal field at the bottom, are regenerated earlier than that at lower latitudes. These toroidal fields also diffuse toward the equator.
- Thus, a butterfly diagram of the toroidal field at the bottom is obtained.

Conclusion

The central point of the new mechanism for the Sun's butterfly diagram is the phase delay of the regeneration of the toroidal field between higher and lower latitudes when the latitude-dependent radial flux transport exists. This mechanism is verified by a data-driven FTD model using different meridional flows, even the poleward flow at the bottom of CZ.