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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 sunspot's emergence latitudes as the solar cycle evolves, which was attributed to the equatorward flow at the base of the convection zone. However, helioseismological studies indicate controversial forms of the flow, and even present poleward flow at the base, which poses a big challenge to the wide-accepted mechanism. So we aim to propose a new mechanism, that is the latitude-dependent radial flux transport.

Keywords. Sun: activity, Sun: magnetic fields, sunspots

1. Introduction

Revealing the mechanism causing the butterfly diagram is essential for the understanding of the solar and stellar dynamo. The mechanism that meridional flow causes the butterfly diagram is well-accepted but faces challenges from helioseismological results (Zhao et al. 2013). So new mechanisms are needed. It was suggested that dynamo wave in the near-surface shear layer and latitudinal pumping are two potential candidates (Guerrero & de Gouveia Dal Pino 2008; Pipin & Kosovichev 2011). However, these candidates all have their limits. So this work aims to propose a new mechanism from a new perspective.

2. New mechanism

2.1. *Model*

We adopt the data-driven FTD model of Jiang et al. (2013) to carry out this work and keep most of the ingredients unchanged except the meridional flow and radial pumping. In this work we consider three typical profiles adopted by literature, whose latitudinal velocities are shown in Figure 1. And we consider two profiles of the radial pumping. One is latitude-independent, which has the same strength at all latitudes. The another one is latitude-dependent, whose strength becomes stronger as the latitudes increase.

2.2. *Simulation results and illustration of the new mechanism*

In this section, we will show that the latitude-dependent radial transport of the poloidal flux causes the equatorward latitudinal migration of the toroidal fields at the base of the convection zone (CZ), under different profiles of meridional flows. The results are shown in Figure 2.

Figure 2(a) shows a poleward migration of the toroidal fields at low latitudes. This migration is only caused by the poleward dynamo wave since there is no flow at the

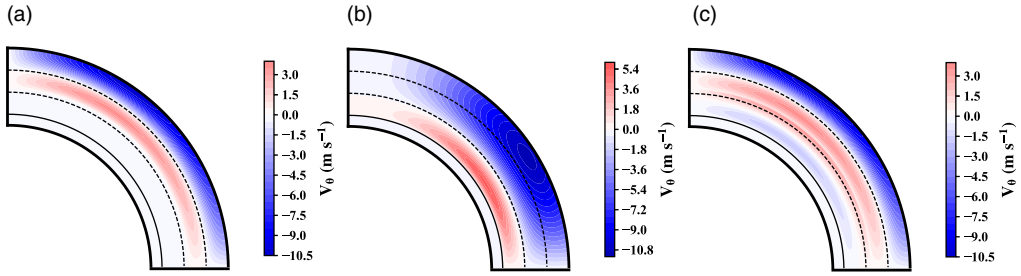

Figure 1. latitudinal velocities of meridional flow profiles used in this work. (a) Shallow single cell. (b) Deep single cell. (c) Double cell.

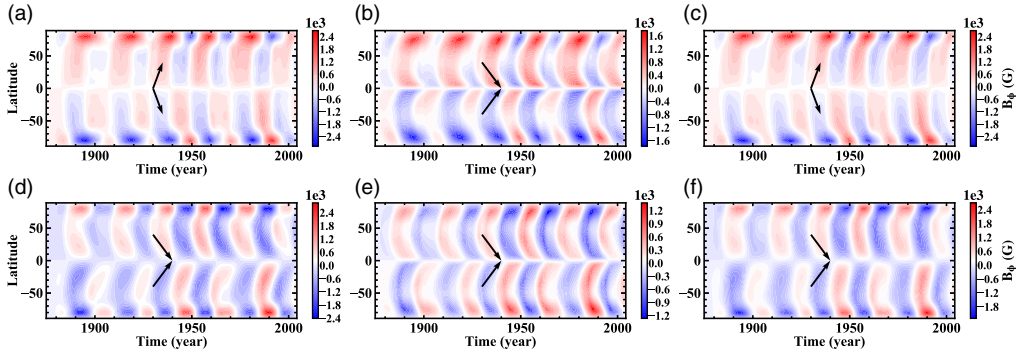

Figure 2. Time-latitude diagrams of the toroidal field at the base of the CZ, r = $0.715R_\odot$. Panels from left to right correspond to the three flow profiles shown in Figure 1. The top (bottom) panels adopt the latitude-independent (latitude-dependent) pumping.

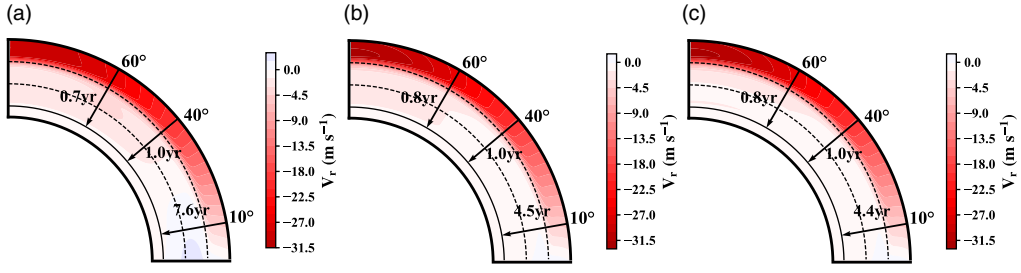

Figure 3. Inward velocity distributions. Three panels correspond to that of Figure 1 with the addition of latitude-dependent inward pumping. The black arrows indicate the transport time of the poloidal fields from the surface to the base of the CZ, at latitudes 10°, 40° and 60°.

base of CZ. Figure 2(b) and (c) show the equatorward and poleward migration of the toroidal field, respectively. Their propagational directions are determined by the flow direction at the base of CZ (see Figure 1). Then we replace the latitude-independent radial pumping by the latitude-dependent radial pumping. The corresponding results are shown in Figure 2(d)-(f) and the toroidal fields all propagate toward the equator. This means that the latitude-dependent radial flux transport is a valid mechanism for the butterfly diagram.

To illustrate how the new mechanism works, we give Figure 3 that shows the velocity distributions of the inward transport of the poloidal field. The poloidal field at higher latitudes is transported inward quicker than that at lower latitudes. Therefore, at the base the toroidal fields generated by the shearing of the poloidal field first build up at about 60° latitudes, and then build up at lower and lower latitudes.

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3. Conclusions

We have proposed a new mechanism for the butterfly diagram. When considering the latitude-dependent radial transport of the poloidal field, the time- and latitude-dependent regeneration of the toroidal field causes the butterfly diagram.

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Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S1743921323000455.

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