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Solar deep mixing as a proxy of stellar convection and modulation of surface activity

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Abstract

It is shown that the longitudinal variations of solar activity are modulated by the deep turbulent eddies. These vortexes are the result of breaking up of giant convection cells. Therefore, the deep convection could be a noticeable factor in stellar-planetary magnetic interactions.

1. Introduction

Certain relations between exoplanetary magnetic phenomena and interiors of host stars are possible. For example, the deep convection in the star could modulate the emergence of magnetic flux, which may influence the stellar-planetary magnetic interactions. Accurate and precise values of radii and masses of host stars are needed to correctly estimate properties of extrasolar planets. However, the most significant errors in the estimates of stellar properties are caused by uncertainties in stellar convection, quantified in terms of uncertainties in the value of the mixing length parameter [2]. The mixing-length theory (MLT) represents an extreme simplification of the actual physical process of convection. Hence, the physical validity of MLT standard convective cells considered instead of turbulent vortices with wide spectra of diameters and lifetimes must be tested. The Sun is the only star where such detailed analysis can be done. That is why we search for some specific scale in the solar activity pattern, which could be a manifestation of the deep convection.

2. Manifestations of deep mixing

To search for manifestation of deep mixing in the Sun, we analyze the average power spectrum of the longitudinal variations of solar activity. We use the cylindrical synoptic charts of various indexes of solar activity in the photoshere (Fe I, 5250.2 Å, Mount Wilson), transition layer (He II, 304 Å; EIT/SOHO), and corona (Fe IX/X, 171 Å; EIT/SOHO). To maximize visibility of the effects from the interior processes, only the individual spectra of high activity (in the active latitude belts for years 2000-2002) are averaged. The resulting average spectra are shown in Fig. 1. The Kolmogorov's energetic spectrum of turbulence (e.g., [5]) for the energy cascade from maximal vortexes $\lg C_m^2 = C_1^2 - (5/3)\lg m$ is plotted (points) for comparison, where C_m is the amplitude of the harmonic with number m.

One can see in Fig. 1 that the power spectra consist of two parts $0 < \lg m < 0.5$ and $1 < \lg m < 2$ with a quasi-Kolmogorov's inclination. For example, the average spectral index at $10 \leq m < 100$ is -1.62 ± 0.03 (Fig. 1a), -1.60 ± 0.05 (Fig. 1c) and -1.63 ± 0.09 (Fig. 1e). It is close to the Kolmogorov's value of -5/3 or -1.67. This proximity to the prediction of the turbulent theory at $m<100$ is a 'fingerprint' of the deep mixing, because even super-granules correspond to $m>100$.

However, the second parts of the spectra ($1< \lg m< 2$ in Fig. 1) are systematically shifted towards higher power with a factor of 5-8 times relatively to the theoretical curve. Apparently, these patterns represent two turbulent cascades. The first cascade is launched by the global ($m = 1$), equatorial and meridional flows, well known from helioseismic data. The second cascade could be a result of the deep mixing with $m \approx 10$.

Additional argument for the deep mixing pattern in the solar activity is found analyzing the time scale of the harmonic variability (τ_m). We analyzed the amplitude of a harmonic as well as its phase with the same correlation method [1] but using a more extensive experimental material. It was found that τ_m decreases with m increasing in accordance with the Kolmogorov's theory of turbulence:

$$\lg(\tau_m/P_s) = \alpha \lg m + \gamma, \qquad (1)$$

where $\alpha = -0.64 \pm 0.04$ (instead the Kolmogorov's value of -0.67 [5]); $\gamma = 0.42 \pm 0.03$; $P_s = 27.28$ days is the synodic period of the solar rotation.

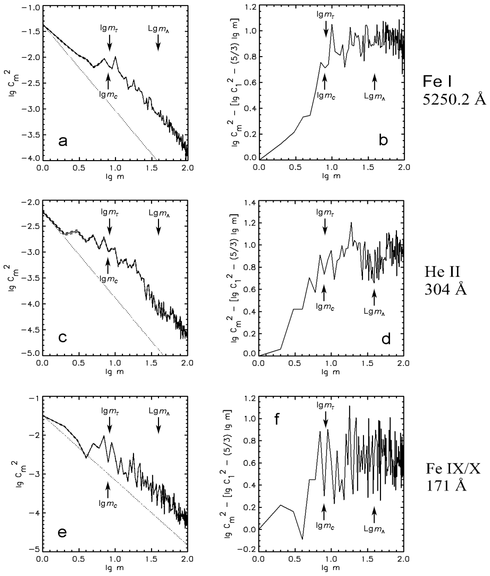

Figure 1: The average power spectrum of the longitudinal variations of solar activity as a function of harmonic number m. The arrow markers are explained in Sect. 3.

3. Convective interpretation

Dibaj and Kaplan [4] have derived theoretically the typical diameter for convection cells in the homogeneous and incompressible liquid: $D \approx 2^{3/2}H$, where H is the depth of convection layer. Taking into account that the depth of the solar convection zone (CZ) is $H = 0.287\, R_s$ [3], where R_s is the solar radius, one can calculate: $D/R_s = 0.812$ rad $=46.5$ deg. The corresponding harmonic number is $m_c = 360^{\circ} R_s/D \approx 8$. This estimate approximates to the found scale of deep mixing ($m \approx 10$).

The regression given by Eq. (1) can be used for the conversion of MLT turnover time τ_{MLT} for the Sun into the corresponding longitude scale m_τ. Calculating the average $\tau_{\mathrm{MLT}} = 18.4 \pm 1.6$ days from the summary of published estimates (1984-2012), we find with Eq. (1) the same $m_\tau = 8$.

Hence, the turbulent cascade of the deep mixing (Fig. 1) starts at the vortex size corresponding to the trans-CZ convective cells with the turnover time about the MLT predictions. This connection between MLT formalism and real features in the Sun would explain the MLT success in stellar modeling.

6. Summary and Conclusions

1. It is shown that the deep convection controls the pattern of large-scale solar activity.

2. Therefore, the solar activity seems a promising tester for the convection models.

3. The deep convection could be the significant factor in stellar-planetary magnetic interactions.

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