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SUPERMODULATION OF THE SOLAR CYCLE

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Abstract. There is evidence from record of cosmogenic radionuclides that the Sun's activity switches between periods of strong modulation with clusters of deep grand minima and periods of weaker modulation. By considering dynamo action driven by three-dimensional rotating anelastic convection in a spherical shell, we demonstrate how interactions between convection, differential rotation and magnetic fields may lead to modulation of the basic cycle of an oscillatory dynamo. For some parameters, Type 1 modulation occurs by the transfer of energy between modes of different symmetries with little change in the overall amplitude; for other parameters, the modulation is of Type 2 where the amplitude is significantly affected (leading to grand minima in activity) without significant changes in symmetry. Most importantly we identify the presence of supermodulation in the solutions where the activity switches chaotically between Type 1 and Type 2 modulation; this is believed to be characteristic of the long term modulation of the solar activity.

Keywords: dynamo, convection, methods: numerical, Sun: magnetic fields, activity

1 Context

The solar dynamo has long been known to oscillate with a mean period of 22 yrs, but it is now established that the amplitude of the solar cycle is strongly modulated on longer time scales (Usoskin 2013). Analysis of the abundances of cosmogenic isotopes ^{10}Be in polar ice and ^{14}C in tree rings reveals the clustering of Maunder like grand minima in the past 11 000 yr, separated by aperiodic intervals of about 200 yr (McCracken et al. 2013).

Mean-field dynamo models have demonstrated that modulation of an oscillatory dynamo may occur through stochastic fluctuations in the underlying transport coefficients (Schmitt et al. 1996; Hazra et al. 2014) or more naturally via nonlinear interactions inherent in the dynamo equations leading to chaotic (though deterministic) modulation (Bushby & Mason 2004). The modulation can then be classified according to the key nonlinear interactions (Tobias 2002). In Type 1 modulation, magnetic modes of different symmetry interact to produce modulation of the basic cycle, with significant changes in the parity of solutions. In Type 2 modulation, a magnetic mode with a given symmetry undergoes modulation via interaction with a large-scale velocity field; here changes in the amplitude of the basic cycle occur with no significant changes in the symmetry of solutions. It has been recently argued that both of these chaotic modulational mechanisms are at play in the solar dynamo, leading to the supermodulation of the solar activity on long time scales (Weiss & Tobias 2016; Beer et al. 2018).

2 Results and conclusion

Motivated by the behaviour of the solar dynamo, we investigate in Raynaud & Tobias (2016) three-dimensional numerical solutions of dynamos driven by anelastic convection in a spherical shell. Our analysis focuses on the equatorial symmetry of the solutions and the nonlinear interactions that lead to modulation of the oscillatory dynamo. We recover Type 1 and Type 2 modulations, as shown in Fig.1(a-d) and Fig. 1(c-f), respectively. Furthermore, we see in Fig. 1(b-e) that the interactions between such modes can lead naturally to a pattern of supermodulation where the system alternates between modulation with little change of symmetry (with clusters of deep minima) and modulation that involves significant changes in symmetry (Arlt & Weiss 2014; Weiss & Tobias 2016). We believe that this is the first demonstration of such an interaction between the two types of modulation leading to supermodulation in the full partial differential equations for convective dynamos.

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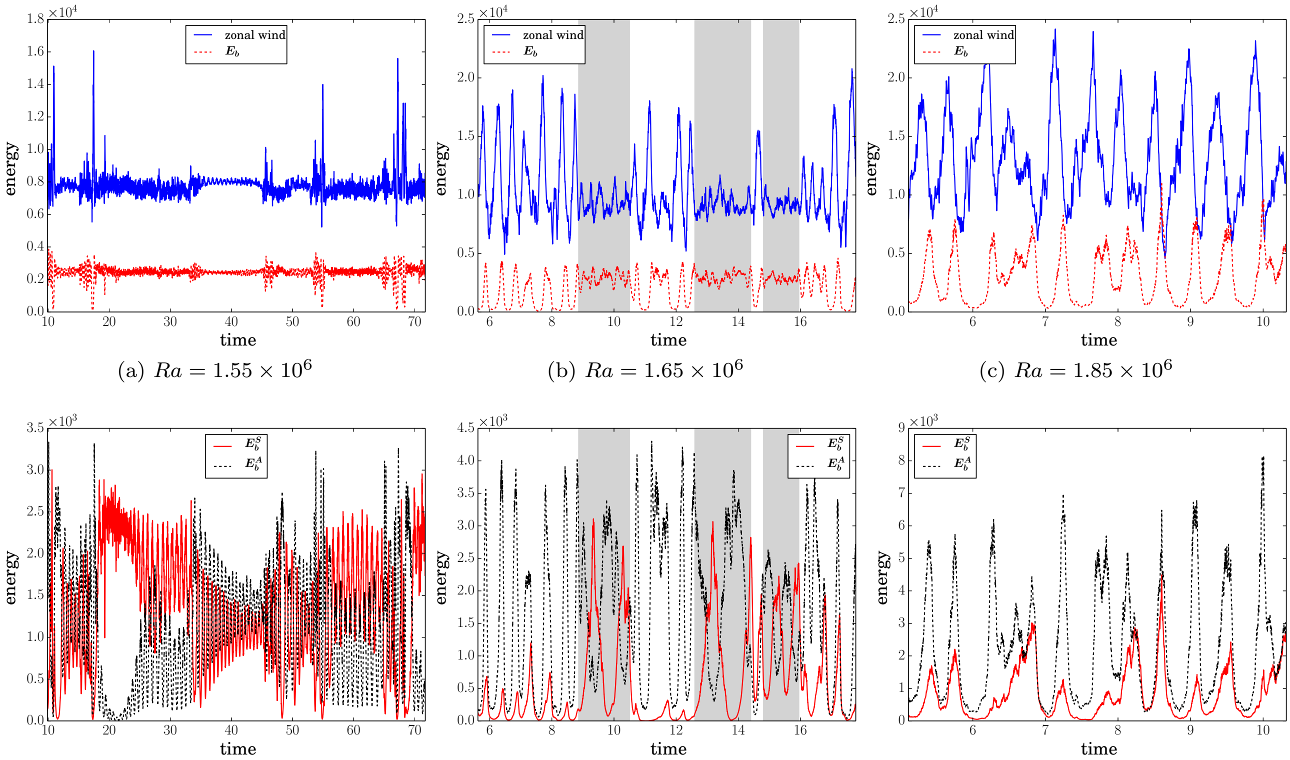

(a) $Ra = 1.55 \times 10^6$ (b) $Ra = 1.65 \times 10^6$ (c) $Ra = 1.85 \times 10^6$

(d) $Ra = 1.55 \times 10^6$ (e) $Ra = 1.65 \times 10^6$ (f) $Ra = 1.85 \times 10^6$

Fig. 1: (a–c) Time series (magnetic time scale) of zonal wind energy (blue) and total magnetic energy (red). (d–f) Time series of equatorially symmetric magnetic energy (red) and equatorially antisymmetric magnetic energy (black). Shaded regions in subfigures (b) and (e) highlight the occurrences of Type 1 modulation.

Although these simulations are far away from being realistic and hence do not have any predictive power, one can draw an interesting parallel when comparing their temporal dynamics to the indirect evidences we have of the modulation of solar activity over the last 10 000 yr. On the one hand, in presence of supermodulation, the magnetic field dynamics is characterised by a hierarchy of time scales between the $\mathcal{O}(0.1)$ dynamo wave period, the $\mathcal{O}(1)$ amplitude modulation time scale and its supermodulation which becomes clear on a $\mathcal{O}(10)$ time scale. On the other hand, observational constraints tend to support that the 11 yr Schwabe cycle is only marginally affected by low frequency modulation processes, while the 208 yr de Vries cycle characteristic of grand minima events is modulated by the 2300 yr Hallstatt cycle which can be associated with chaotic transitions to intervals devoid of any grand minimum (Usoskin et al. 2016; Beer et al. 2018).

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