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COSMIC MAGNETIC FIELDS IN THEORY AND EXPERIMENT: THE ROLE OF HARMONIC FORCINGS

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Recent decades have seen great progress in the experimental investigation of fundamental processes that are relevant to geophysical and astrophysical magnetohydrodynamics. After summarizing the results of the most important liquid-metal experiments on the dynamo effect, the magnetorotational instability and Alfvén waves, we sketch some new results concerning helicity oscillations in convection and their synchronization by time-dependent tide-like forces. Closely related to these experimental efforts, we discuss the potential role of harmonic forcings in synchronizing the solar dynamo or triggering reversals of the geodynamo. A special focus lies then on the DRESDYN precession-driven dynamo experiment which is presently in the commissioning phase.

Introduction.

The homogeneous dynamo effect in moving electrically conducting fluids, such as liquid metals or plasmas, is responsible for magnetic-field generation in planets, stars and galaxies. Magnetic fields, in turn, can trigger various types of waves and instabilities in which the Alfvén velocity plays a key role. By virtue of the magnetorotational instability (MRI), they dramatically speed up cosmic structure formation by destabilizing rotational flows in accretion disks that otherwise would be hydrodynamically stable. For a long time, both the dynamo effect and the MRI had been the subject of purely theoretical and numerical research. This situation changed in 1999 when the threshold of magnetic-field self-excitation was crossed in two large-scale liquid-sodium experiments in Riga [1] and Karlsruhe [2]. Later, the VKS dynamo experiment in Cadarache successfully reproduced field reversals and excursions which are of great geophysical interest [3]. Meanwhile, various versions of the MRI have been studied in liquid metal experiments at the Princeton Plasma Physics Laboratory [4, 5] and at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) [6, 7]. Even the more traditional field of Alfvén wave experiments was extended in a liquid-rubidium experiment at the Dresden High Magnetic Field Laboratory (HLD) by reaching the “magic point” of coinciding Alfvén velocity and sound speed, which is thought to play a key role for heating the solar corona [8]. For more details on those developments, we refer to the recent review [9].

1. Recent developments in liquid metal convection.

Rayleigh-Bénard convection is one of the most fundamental paradigms of fluid dynamics, with enormous implications for geo- and astrophysical processes. Heating a fluid layer (with height H and diameter D) at the bottom of a container and cooling it at the top leads to an unstable temperature profile that gives rise to a motion of the fluid, which typically takes on, depending on the aspect ratio $\Gamma = D/H$, the form of flywheel structures [10] or jump rope vortices [11].

In this context, liquid metal experiments are not only suited to investigate the special regime of low-Prandtl-number convection (which applies to the liquid core of the Earth and the convection zone of the Sun), but also to study the effect of magnetic fields. In an impressive 'pub crawl' through the parameter space of rotation and magnetic field, different regimes of magnetoconvection, rotating convection, and rotating magnetoconvection were investigated in much detail [12]. Another effect of the interaction of convection, rotation and magnetic field was first observed experimentally [13] and later explained numerically [14]. Here it was shown that the typical symmetric butterfly structure of azimuthal variant of the MRI (AMRI) can be de-symmetrized by applying a radial temperature gradient, leading to a prevalence of upward or downward traveling AMRI waves.

Recent progress in applying Contactless Inductive Flow Tomography (CIFT) to convection driven flows has not only allowed to safely reconstruct transitions between convection flow modes with different roll numbers [15], but also to follow the helicity oscillations that are connected with sloshing and torsional oscillations [16]. In a closely related experiment [17, 18], helicity synchronization was observed after crossing a certain threshold of a tide-like electromagnetic forcing.

2. A self-consistent synchronization model of the solar dynamo.

Actually, the latter experiment [18] was motivated by ideas about the synchronization of the solar dynamo by tidal forces as exerted by the tidally dominant planets Venus, Earth and Jupiter. While the most recent variant of this theory [19] relies on the triggering of magneto-Rossby waves [20] at the solar tachocline by two-planet spring tides [21], the underlying concept is still related to the synchronization of the flow helicity (and the α-effect connected with it) by tidal forces [22, 24, 37].

Fig. 1 illustrates the present status of our synchronization model. We start with a rather conventional $\alpha-\Omega$-type solar dynamo, with the α-effect being situated in the

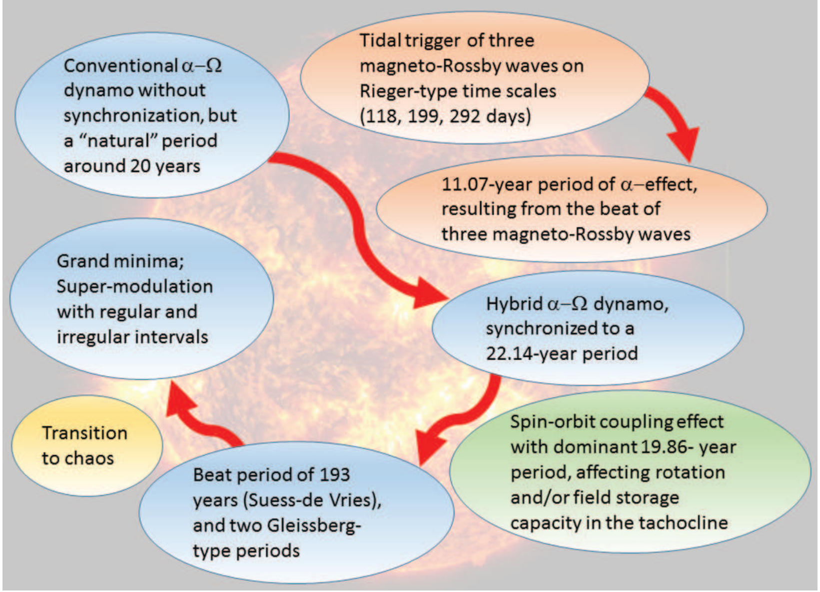

Fig. 1. Scheme illustrating our present understanding of the double-synchronized solar dynamo. A conventional solar dynamo is entrained by an 11.07-yr periodic α-effect in the tachocline that, in turn, results from the beat between three tidally excited magneto-Rossby waves. A second beat period of 193 years results then from the 22.14-yr Hale cycle and the 19.86-yr barycentric motion. For more details, see the main text.

convection zone, while the Ω-effect is concentrated in the tachocline. When adding a meridional circulation with realistic velocity values to it, this model produces a reasonable butterfly diagram of the azimuthal field at the surface, and a Hale cycle period in the range of 20 years. Now we further assume that the two-planet spring tides of the three tidally dominant planets Venus, Earth and Jupiter excite magneto-Rossby waves in the tachocline. The resulting wave periods of 118 days (Venus–Jupiter), 199 days (Earth–Jupiter) and 292 days (Venus–Earth) belong to the so-called Rieger-type periodicities which were indeed observed in various proxies of solar activity [25]. Depending on a (not very well-known) damping parameter, the amplitudes of these waves were shown to lie in the range of 1 to 100 m/s [19, 21]. In view of the notorious weakness of the tidal forces, such wave velocities are indeed remarkable, though not incompatible with a simple energetic consideration that translates the tidal height of less than 1 mm to an equivalent kinetic energy corresponding to a velocity of 1 m/s [26].

Having corroborated the deposition of this dynamo-relevant energy into the magneto-Rossby waves, the question remains how the 22.14-yr Hale cycle may be synchronized by those waves with their much shorter Rieger-type periods. The answer lies with Scafetta's notion of an "orbital invariant inequality" [27], implying that the sum of the three waves includes a beat that is independent of the azimuthal angle. As shown in [19], this leads to a noticeable beat period of 11.07 years even in the axisymmetric part of quadratic functionals of the waves, including the α-effect or any zonal flow.

While the detailed determination of the α-effect of the three waves requires more work on the arguments developed in [28], its amplitude will probably be in the range of dm/s or more, given the amplitude of 1–100 m/s of the underlying waves. Interestingly that range of dm/s corresponds to the estimated amplitude of an 11.07-yr periodic α-effect in the tachocline region which is required for synchronizing (via parametric resonance) the solar dynamo to the Hale period of 22.14 years [24]. Those estimates show that dynamo synchronization by tidal forces is indeed a physically feasible mechanism rather than just an"astrological quest", as still recently argued [29].

Now we invoke a second beat period to explain also the longer-term solar periodicities known as Suess-de Vries and Gleissberg cycles. The additional period that comes into play at this point is the 19.86-yr period of the Jupiter–Saturn alignments that governs the rosette-shaped motion of the Sun around the barycenter of the solar system. While often dismissed as not relevant for dynamo action due to its "free-fall" character, recent work by Shirley [30, 31] suggests the excitation of an internal motion by virtue of spin-orbit coupling. Indeed, Fig. 4 in [30] shows the resulting motion to have the same $m = 1$ azimuthal dependence as in precession, which is – in view of the arising Poincaré-type force field – not an accident. Admittedly, though, a quantitative determination of the flow directly driven by spin-orbit coupling and any axisymmetric secondary flow emerging from it is still elusive. In a very first attempt, we have incorporated the 19.86-yr forcing into a model parameter that is related to the field-storage capacity in the tachocline, which is known to be very sensitive to any external perturbations. The dynamo spectrum resulting from this enhanced numerical model turned out to be in amazing agreement with that of a 8500-yr stack of sediment data from Lake Lisan (see Fig. 9 in [19]). In particular, both spectra show a sharp peak at the 193-yr beat period, which represents the Suess-de Vries cycle, as well as similar peaks close to 90 and 60 years which are usually identified as Gleissberg cycles.

This remarkable correspondence with climate-related data not only suggests that the chosen parametric inclusion of the 19.86-yr periodic spin-orbit coupling is basically

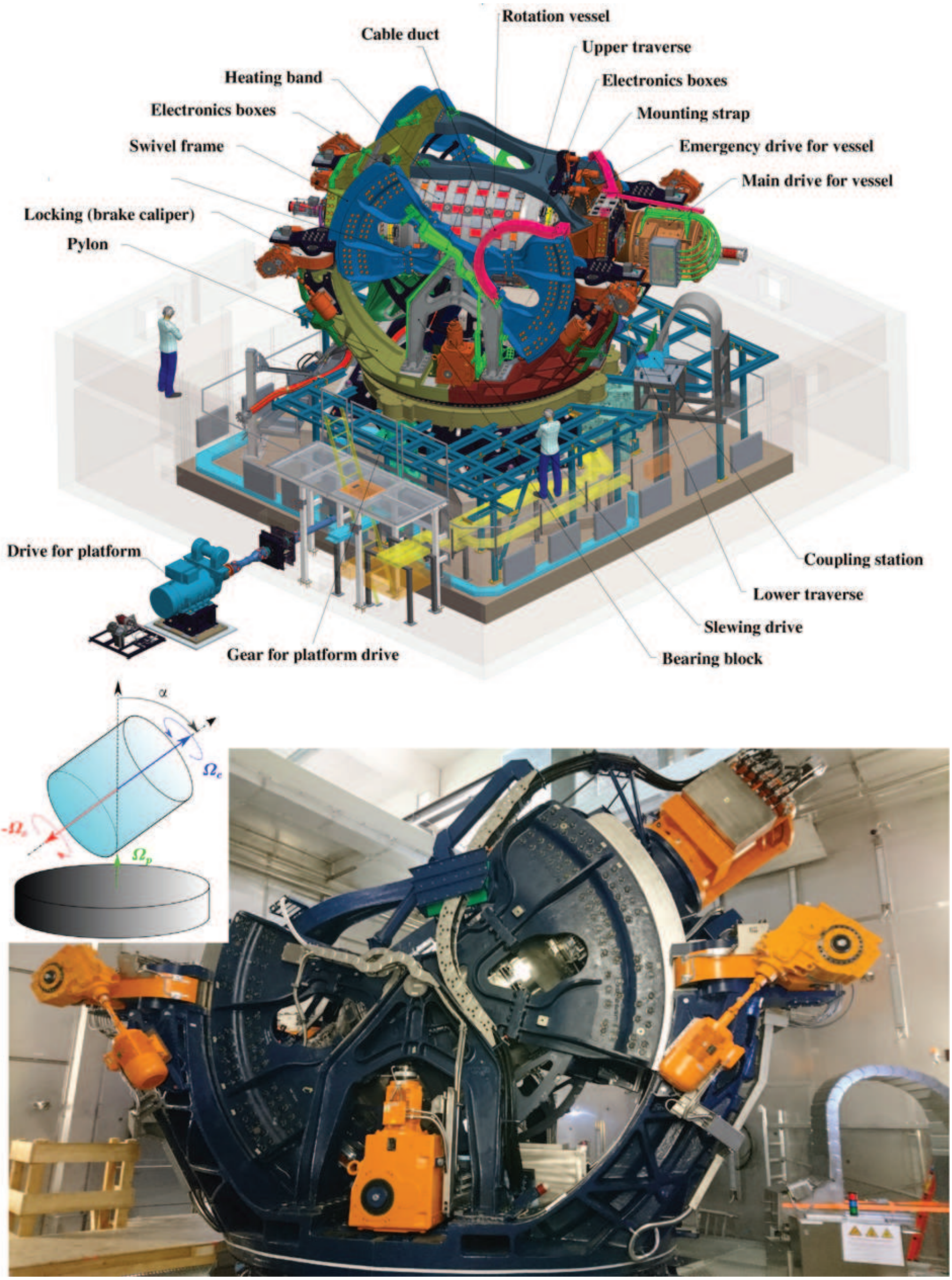

Fig. 2. Drawing of the DRESDYN experiment with main parts indicated (top), and photograph of the facility as of October 2024 (bottom).

correct, it also reaffirms the existence of the *primary* synchronization to the 22.14-yr Hale cycle. Indeed, a beat period of $193 = 22.14 \times 19.86/(22.14 - 19.86)$ years would have no chance to emerge if the underlying 22.14-yr period were not phase-stable in the first place. In this sense, the presented double-synchronization model appears to be highly self-consistent.

More remains to be said about the concept of supermodulation [32], i.e. the switching between regular intervals of the solar cycle and grand minima, which might yet be influenced by another planetary beat period of 2318 years, knows as the Bray–Hallstatt cycle [27]. Interestingly, a similar interplay of chaos and regularity had been discussed in terms of stochastic resonance related to the reversal statistics of the geodynamo for which the 95-kyr Milankovic cycle of Earth's orbit excentricity seems to play a decisive role [33–35].

3. The DRESDYN precession dynamo experiment.

Primarily, it was the potential role of the Milankovic cycles for influencing the geodynamo [36] that had stimulated the set-up of the DRESDYN precession experiment. Among other astronomical forcings, such as libration (with the azimuthal wavenumber $m = 0$) or tides ($m = 2$), we have chosen precession ($m = 1$), mainly with view on the corresponding 26-kyr Milankovic cycle. As mentioned above, this choice is lent further support now by the similarity of the Poincaré-type forcings resulting from precession, on the one hand, and from spin-orbit coupling, on the other hand. In this sense, DRESDYN might also be helpful in understanding some effects of the 95-kyr excentricity cycle of the Earth's orbit, or of the 19.86-yr cycle of the Sun's barycentric motion, on the respective dynamos.

In relation to the pioneering dynamo experiments in Riga, Karlsruhe and Cadarche, the DRESDYN experiment (Fig. 2) is also intended to realize dynamo action in a truly homogeneous fluid that is solely driven by external forcing [37, 38], without using any internal impellers, guiding blades, or magnetic materials [39].

Its central rotation vessel encases a cylindrical sodium volume of 2 m in diameter and 2 m high. We plan to reach a vessel rotation rate of 10 Hz (to obtain a magnetic Reynolds number $\mathrm{Rm} = 700$) and a precession rate of 1 Hz to cover the laminar, the fully turbulent, and the transition state in between them, which is the most "dynamo-prone" one [40]. This motion of the vessel, which is driven by a motor with a maximum electric power of 1.2×10^6 Watt, results in a total gyroscopic torque of up to 8×10^6 Nm and an acceleration of 400 g at the rim. Therefore, the entire machine is, in several respects, at the edge of technical feasibility. Careful design and much optimization was required to ensure that the mechanical strains nowhere exceed the limitations of the material. On January 17, 2024, the vessel was inserted into the frame. A very first double-rotation experiment, still without any liquid, was carried out in June 2024, and a vessel rotation of 1.7 Hz was achieved on September 5, 2024. The next steps of the commissioning include the filling of the vessel with de-ionised water, and then a slow and careful approach towards the highest possible rotation rates of the vessel and turntable. After approval, more systematic runs with varying nutation angles, Reynolds and Poincaré numbers are planned. First sodium experiments are foreseen for late 2025 or 2026. Then it remains to be seen if the predictions of flow structures and dynamo action, as obtained for different nutation angles and Poincaré numbers [40–44], can indeed be experimentally confirmed.

Conclusions.

Motivated by the successes of the pioneering liquid metal experiments on dynamo action, the focus of this paper has shifted to the more complex interplay between convection and magnetic fields (without or with rotation), and on the potential role of harmonic forcings on dynamos, with special focus on the various cycles of the solar dynamo. More details on the double-synchronization theory, which was only delineated here, can be found in a series of recent papers [19, 21, 24].

While some smaller-scale experiments have already shed light on specific phenomena, such as reversals of the flow helicity and its synchronization by external forces, the upcoming DRESDYN experiment is poised to show dynamo action in a flow that is exclusively driven by precession.

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