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Problems of magnetic dynamo

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Abstract. In what is famously known as the solar activity cycle, every 11 years a wave from a quasistationary magnetic field propagates in the solar convective zone from the middle latitudes equatorwards, driven by the dynamo jointly produced by differential rotation and mirror-asymmetric convection. Similar processes occur in other celestial bodies and can to some extent be reproduced in the lab environment. This paper reviews the current status of and future trends in the study of the dynamo phenomenon.

Keywords: magnetic fields, dynamo, solar activity

1. Introduction: the dynamo on the Sun and elsewhere

The best known manifestation of the physical process recognized for the magnetic dynamo (hydrodynamic) is the solar activity cycle during which an activity wave propagates every 11 years over the surface of both solar hemispheres from the middle latitudes equatorwards. The wave is identified by various tracers, of which the most widely known is the number of sunspots, apart from other characteristics. This activity wave is generated by a wave from a quasistationary magnetic field propagating beneath the Sun's surface, in its convection zone. Certainly, the propagating magnetic structure gives rise to a weak electric field, but the parameters of the wave themselves, viz. an unusually large period, a spatial scale matching the size of the Sun, a magnetic energy density commensurate with the kinetic energy density of convective movements of the solar plasma, suggest that the phenomenon in question is something other than usual electromagnetic waves. On the other hand, the appearance of the activity wave can hardly be attributed to relativistic or quantum-mechanical processes; in classical physics, only electromagnetic induction can take on the role of a process exciting a magnetic field. In such general terms, researchers came to an understanding of the solar cycle very soon after its magnetic nature was demonstrated in the early 20th century when this process was termed the dynamo, by analogy with the now obsolete name of a car engine part.

Magnetic activity reminiscent in a certain sense of solar activity is known to occur in many celestial bodies, even though it takes essentially different forms there due to peculiar observation conditions or problem geometry. Specifically, the dynamo process is associated with the initiation and evolution of Earth's magnetic field on the geological time scale, as well as the origin of large-scale magnetic fields of spiral galaxies, including the Milky Way.

Little by little, it became clear that the magnetic dynamo is essentially different from the familiar process in the theory of electricity, the difference being due to an unusual parameter called the magnetic Reynolds number, Rm. Indeed, inductive effects in the dynamo process must prevail over dissipation and the ordered estimate of the ratio between the respective terms in Ohm's law in a moving media leads to the condition

$$\mathrm{Rm} = \frac{vl}{\nu_{\mathrm{m}}} \gg 1\,, \tag{1}$$

where v is the characteristic velocity, l is the characteristic dimension of the problem, and ν_{m} is the magnetic diffusion coefficient of the medium.

It was estimated that the huge l is responsible for the value of $\mathrm{Rm} \approx 10^6$ in the solar convective zone, whereas in the interstellar medium Rm can be higher than 10^8. At the same time, under usual lab conditions and in technical devices with moving liquid conductors, Rm is much smaller than unity. The dynamo phenomenon occurs when Rm exceeds a threshold value that depends certainly on the system's geometry. In the best case, described by Yu B Ponomarenko [1] of the

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N V Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences (IZMIRAN) in 1973, the critical value of Rm equals 17. It took almost half a century and targeted efforts of researchers in different countries to reach this critical value in lab experiments and observe self-excitation of the quasistationary magnetic field in the laboratory at the turn of the new millennium. Practically all operating and projected laboratory facilities for the study of the dynamo effect in one way or another make use of Ponomarenko's ideas, while reproduction of dynamo versions more plausible in the astrophysical context under laboratory conditions is still a long way in the future. The development of dynamo research, from astronomical models to dynamo experiments, has been overviewed in recent publication [2] and references cited therein. The present paper deals with the dynamo question insofar as it concerns solar physics.

To recall, researchers in this country have been traditionally involved in dynamo research. Suffice it to say that dynamo experiments initiated way back in the 1960s by a group based in Riga (then Latvian SSR) were successfully completed, even if in a different country. The decision taken in the 1960s to choose Soviet Latvia as the most suitable place for the development of magnetohydrodynamics created serious problems 30 years later for Russian specialists engaged in this branch of science, problems that were, however, resolved in the course of time. Dynamo experiments at the Institute of Continuous Media Mechanics, Ural Branch of the Russian Academy of Sciences, based in the city of Perm', have now taken their place along with research in Latvia, Germany, France, and the USA.

2. Solar dynamo scenario in the context of current observations

Large Rm values by themselves are insufficient for a magnetic field to be self-excited by the dynamo mechanism. According to the Lenz rule, the magnetic field produced by electromagnetic induction is not added to the existing weak priming field but is subtracted from it. Therefore, the dynamo process must involve at least two coupled circuits, one of which induces a magnetic field in the other and vice versa, the signs of these fields being such that the overall result of inductive effects chosen gives self-excitation.

In the solar dynamo and dynamos of other celestial bodies, the magnetic field in the first circuit has the form of a usual dipole (possibly, a quadrupole), while the field in the second circuit inside the solar convective zone is directed azimuthally. The former field is referred to as poloidal, and the latter as toroidal. A poloidal magnetic field is transformed into a toroidal one during differential rotation of the medium into which the field is frozen. Half a century and efforts of several research teams were needed to find the motion that restores the poloidal magnetic field from the toroidal one. In 1955, the American astronomer E N Parker [3] intuitively derived equations relating the two components of the field for a thin convective shell. It follows from these equations that the solar dynamo system actually has its own frequency, which can be identified with the solar cycle frequency.

Ten years after Parker's article, equations for the evolution of the mean magnetic field in the case of mirror-a symmetric convection (or turbulence) were developed by the eminent German physicist M Steenbeck and his graduate students F Krause and K-H Rädler [4]. Steenbeck had formerly been affiliated with Siemens military projects and afterwards worked for 10 years in Sukhumi, in all probability with V V Migulin, the future director of IZMIRAN, before he took an interest in more academic matters. It was shown that convective flows in rotating bodies are mirror-asymmetric, because the action of the Coriolis force on the vortices either emerging or submerging in a stratified medium results in a different number of left-hand and right-hand rotating vortices in a given hemisphere of the celestial body.

In less than 10 years, specialists came across article [4] printed in places in Gothic fonts in a poorly known German journal and became aware of the formulas derived by the young co-authors of the President of the GDR Academy of Sciences for the estimation of the so-called α-effect just coupling toroidal and poloidal magnetic fields. Their estimates demonstrated that a solar cycle is roughly 10 times shorter than the observed one. This discrepancy has for a long time been regarded as a tragic mismatch between theory and observations, despite the fact that an order of magnitude error in the estimation of a key parameter unknown from experiment is actually a success rather than a failure in studying the process.

In a few years (1972), Ya B Zeldovich explained by an illustrative example of a figure-eight loop the behavior of magnetic lines of force in astrophysical dynamos. First, the magnetic loop stretches to twice its extent (due to differential rotation), then it folds into a figure-eight whose halves overlap by virtue of the α-effect. Clearly, the magnetic flux is doubled in the process. In the spirit of that heroic epoch, Ya B Zeldovich confined himself to disclosing this beautiful idea in a discussion at a scientific conference in Krakow, and it was published later together with his other work (see, e.g., Ref. [5]).

In the next decades, this beautiful but somewhat abstract scheme was supplemented by a variety of astronomical observations and, partly, by experimental lab findings. A comprehensive review of these results are far beyond the scope of the present article, because even a brief characteristic of the methods and current state of helioseismology contributing to the retrieval of differential rotation in the inner parts of the Sun would require a special large review. What follows concerns only recent progress in the observational definition of the α-effect that has until recently been regarded as an infeasible task. It should be borne in mind that we do not associate the α-effect only with its special form considered by Parker but also deal with the form in which mirror asymmetry is related to the magnetic field action (the so-called Babcock–Leighton scheme).

The heart of the issue is that all three velocity field components must be known before and above everything else to enable the observational definition of the α-effect, i.e., the degree of mirror asymmetry of the problem. In astronomy, however, the velocity usually estimated from the Doppler effect gives only the line-of-sight component. In the next approximation, the degree of mirror asymmetry related to the magnetic field itself needs to be known. It already simplifies the problem, since the magnetic field is frequently measured based on the Zeeman effect, which can give all three field components. True, they must be differentiated, which poses a nontrivial task, but a viable method for the purpose was proposed by Seehafer [6].

During the past 30 years, several research teams have observed the so-called current helicity determining the magnetic field contribution of the α-effect in the active regions of the Sun. These observations are of interest for the solar dynamo question if they cover a large part of the cycle or, better yet, the entire solar cycle. The necessary information was obtained by astronomers of the Huairou Solar Observing Station near Beijing. It should be emphasized that dynamo-related specialists of IZMIRAN supported by the Russian Foundation for Basic Research (RFBR) actively participated in the treatment and interpretation of the data collected by their Chinese colleagues. Their meticulous, laborious work made it possible to reconstruct the latitudinal and temporal evolution of current helicity [7] that fits fairly well into the modern dynamo concept. It is noteworthy that researchers concerned with solar dynamo simulation did not care to theoretically describe what latitudinal and temporal distributions should be expected in the framework of the simplest solar dynamo models. No wonder that they were surprised to discover rather intricate but regular distribution patterns consistent with the above findings [8].

It took some time to understand that the data on the regular distribution of the tilt angles of magnetic bipolar structures associated with groups of sunspots (so-called Joy's law) are sufficient to come to a definitive conclusions [9]. Namely, it proved possible to construct latitudinal–temporal diagrams for the entire variation range of the α-coefficient [10]; moreover, helioseismological techniques were adapted for the estimation of the contribution to the α-effect from the velocity field [11]. At approximately the same time, researchers learnt to measure the α-effect in MHD lab experiments with liquid metals [12]. Bearing in mind the paramount importance of this effect in the context of the dynamo problem, it deserves to be comprehensively studied. Generally speaking, this research area still remains obscure, but prospects have now opened up for practical investigations into what formerly seemed beyond reach.

3. Archival data and stellar analogies

No matter how strange it may seem, increasingly more new data are coming from astronomical archives (see, e.g., book [13]). The fact is that soon after Galileo Galilei began to employ the telescope in his astronomical surveys in 1611, observation of sunspots became a favorite pursuit among both scientists and amateurs. In a few decades, the Paris Observatory was established, initially focusing on monitoring the solar activity. An important contribution to the organization of this work was made by King Louis XIV. Indeed, his keen interest in these observations ensured their continuation over a rather long time, even though the net result proved negative. It was the period of a deep, prolonged recession of solar activity, later called the Maunder minimum after the English astronomer of the early 20th century. At the time of E W Maunder, this minimum was a matter of bold conjectures. Later on, its existence was confirmed by the isotopic method, taking advantage of the fact that solar activity affects the dynamics of certain isotopes on Earth. However, the solar activity in the period of the Maunder minimum was completely reconstructed based on archival data only in the last decade of the 20th century.

The investigation of archival materials continues and has revealed some unusual episodes in the solar cycle recorded during the period of instrumental observations of the Sun. These episodes have different scenarios and are of special interest in light of nonstandard patterns of the current activity cycle. The data on isotope dynamics give evidence of earlier activity minima resembling the Maunder minimum They suggest systematic deviations from the normal cycle and demonstrate that the solar dynamo's operation cannot be reduced to self-oscillations of the magnetic field.

The reconstruction of the history of solar activity has little in common with the usual work of a physicist or astronomer — it implies the interpretation and criticism of historical records as is more common in the humanities.

The most straightforward explanation of the Maunder minimum and other peculiar features of the solar cycle is based on the fact that the governing parameters of the cycle are some averaged quantities calculated based on the relatively small ensemble of convection cells. Some of these parameters (first and foremost the α-coefficient) are rather small; therefore, statistical fluctuations may seriously disrupt operation of the solar dynamo [14, 15].

That the activity cycle is not an intrinsic feature of the Sun alone is confirmed in the first place by observations of temporal variations of the integral stellar stream in certain specially selected spectral lines. The well-known American astronomer O C Wilson followed up these changes in more than one hundred stars for a few decades [16]. The results of this monitoring confirm the existence of stellar cycles comparable with the solar one in many stars resembling the Sun. An incidental result of this study is the demonstration of the difficulty of long-term monitoring in the framework of projects supported by scientific grants. The French astronomers of Louis XIV's reign did not encounter such financial problems — their support was guaranteed by the king's initiative. Specialists concerned with the interpretation of observations did their best to extract as much physical information as possible from the data obtained. In certain cases, they managed to construct latitudinal and temporal activity diagrams [17]. Nevertheless, integral data are of limited value.

It is noteworthy that mapping temperature distributions for individual stars has become possible since the 1980s, despite the fact that these stars are invisible to telescopes. The mapping is realized by solving the inverse problem for a certain integral equation describing the formation of spectral lines in the stars by varying the temperature over their surfaces [18]. This technique, exemplifying a very impressive achievement of Russian science, is now known as inverse Doppler imaging. Up to now, many observatories all over the world have made use of computer codes based on program packages copied from perfocards developed in the USSR at the turn of the 1980s for the then very imperfect domestically produced computers.

It could be expected that the inverse Doppler imaging method used during the past 30 years would yield a wealth of data on the activity wave structure in different types of stars. Unfortunately, this method allows latitudinal–temporal diagrams to be constructed only in very rare cases [19] (see the interpretation of these diagrams in the framework of the dynamo theory in paper [20]). Monitoring the stellar activity with the help of this method thus far remains an unresolved problem.

4. Direct numerical simulation of the dynamo

Computer resources and software packages have made possible direct simulation of the dynamo question over the last 20 years without distinguishing equations for large-scale variables of the problem. Such simulation has been first described in Ref. [21] for the geodynamo problems probably because we know less about the hydrodynamics of Earth's outer liquid core than we do about flows in the interior of the solar convective zone. As possibilities for direct numerical simulation are gradually extended, it can be realized at increasingly more realistic values of the governing parameters. At present, several scientific teams in different countries are concerned with direct numerical simulation of the geodynamo; they include M Yu Reshetnyak's group at the O Yu Shmidt Institute of Physics of the Earth and IZMIRAN's team [22]. At the same time, the description of the solar dynamo in the framework of mean-field models is becoming increasingly sophisticated and realistic (see, e.g., paper [23]).

The possibility of scientifically sound forecasting of the solar cycle is becoming a reality. The duration of the cycle is comparable with the active lifetime of specialists engaged in its investigation. The number of sunspots does not give the sign of the magnetic field; therefore, the nominal 11-year cycle corresponds to a 22-year physical cycle. This means that the solution to this ambitious problem will take at least as much time as the lifespan of the entire generation of researchers concerned.

It should be noted that the efforts of geodynamo researchers are largely focused on the methods of direct numerical simulation, i.e., an extremely complicated problem suggesting that the magnetic forces can markedly rearrange flows in Earth's liquid core. Of course, the search for relatively simple (see, e.g., paper [24]) scalings in this field also remains an attractive, if hard-to-reach even goal.

The advantages of direct numerical simulations for solving such problems are obvious. Therefore, it is opportune to mention conceptual difficulties that have emerged in the past 20 years. It turns out that direct numerical simulation is a subject matter of experimental physics to a much greater extent than theoretical physics. In particular, it readily answers the question "what happens?", but does not give a direct answer to the question "why does it happen?"

A more specific difficulty is associated with the post-processing problem. Results of direct numerical simulation in the form of an enormous table of figures, e.g., characterizing magnetic field distribution, is rarely of immediate scientific interest. It is necessary to extract from this huge volume of sometimes logically disordered information a relatively small amount of data of real interest for analysis. It turns out that construction of such quantities from the results of direct numerical simulation often presents a more difficult conceptual and computational problem than the initial modeling [25]. (See paper [26] highlighting post-processing problems associated with the calculation of the α-effect from the results of direct simulation).

5. Dynamo waves from the standpoint of theoretical physics

Dynamo waves along with other manifestations of the dynamo mechanism are worth studying as objects of theoretical and possibly experimental physics outside of the special astronomical context. In this regard, it would be interesting to draw a formal analogy between probability waves of quantum mechanics and dynamo waves and to use methods and notions of quantum mechanics, first of all the quasiclassical approximation, to study the dynamo waves. As is known, everything new is actually well-forgotten old: the quasiclassical approximation arose in quantum mechanics from the generalization of the short-wavelength approximation in the theory of versatile waves in liquids.

In the framework of this approach, it is possible to write down the dispersion relation for dynamo waves in the solar convective zone [27]. The dispersion relation, or in more mathematized language, the Hamilton–Jacobi equation, even in the simplest case is a fourth-order algebraic equation for a wave pulse with complex coefficients, including the eigenfrequency γ as a parameter that is certainly also a complex quantity. The real part of γ gives the growth rate proper, and the imaginary one the rotation frequency of the solar cycle. Naturally, the pulse of the dynamo wave is complex, too. It reflects the physical fact that the propagation of a dynamo wave is inseparable from its generation. An acoustic or electromagnetic wave can be excited in a special device to study its propagation, regardless of the excitation mode. In contrast, a dynamo wave rapidly decays in an exponential mode outside the dynamo operation region. Moreover, the wave amplitude in such a region varies appreciably from one point to another. As a result, many familiar phenomena of wave physics manifest themselves in a very unusual form, e.g., resonance, which is the first to attract attention in studies of conventional oscillations and waves. However, the phenomenon of resonance results, according to the differential equation theory, from the coincidence of two or more frequencies, rather than from a concrete form of the equation. Certainly, the resonance occurs in the dynamo phenomenon too, but it is difficult to distinguish it from more striking changes associated with variations of dynamo parameters [28].

The fourth-order dispersion relation naturally has four roots, the values of which vary in a definite manner over the latitude of the convection zone. Joining two of them at the latitude of a highest generation intensity gives γ. In this case, the maximum wave amplitude is markedly shifted from the magnetic field generation maximum, which means in terms of the quantum-mechanical analogy that a quantum particle in the ground state is located somewhere at the wall of the potential well far from its bottom. The sign of the real part of the pulse in the main frequency range and in the case of a proper sign of the governing dynamo parameters ensures, as observations show, wave propagation from the middle latitudes to the equator. However, the direction of propagation at high latitudes changes, and the wave travels toward the pole. This phenomenon has been confirmed by observations [29].

In more complicated dynamo models, the order of the dispersion equation increases [30] and patterns of dynamo wave propagation become even more intricate [31]. For example, standing dynamo waves [32] and standing activity waves [33] may appear.

The relationship between quantum mechanics and dynamo theory has one more aspect; namely, the α-effect is related to the helicities of flows and magnetic fields. In conventional physics, helicity does not play a leading role; at the same time, it is one of the most important quantities in neutrino physics and weak interaction physics. In this respect, the concepts of microworld physics and astrophysics are brought together, and the phenomenon of spatial parity nonconservation in the microworld is manifested in terms of the dynamo theory as the α-effect [34].

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