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Solar dynamo studies: current stage and perspectives

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Contemporary solar dynamo studies present an explanation for the solar activity cycle driven by the solar dynamo. The explanation considers solar differential rotation as well as mirror asymmetry of convection as main dynamo drivers. Nevertheless, quite a lot of new problems discussed below arise beyond this explanation.

Keywords: Solar activity, solar dynamo, solar cycle

1 Introduction

Solar dynamo studies have made substantial progress in understanding of the physical mechanisms underlying the solar magnetic field properties and evolution on scales of the main solar activity cycle known as the Schwabe (nominal 11-year) or Schwabe–Hale (nominal 22-year) activity cycle, which is an impressive and spectacular phenomenon on the Sun (e.g. Charbonneau, 2014). Now, the general concept concerning the nature of the cycle looks well-appreciated by the community and reasonably stable, and the new perspectives and new challenges for the topic become visible.

The aim of this paper is to present in a short form this new perspective in comparison with the achieved state of affairs. The bibliography is obviously not comprehensive, but gives a minimal set of references required to support the viewpoint presented.

2 Basic explanation for the solar cycle

The basic interpretation of the nature of the solar cycle considers it as an instability which arises in some properly averaged equations for the mean magnetic field. This

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instability is driven by solar differential rotation and mirror-asymmetric solar convection. The interpretation was initially suggested by Parker (1955) and then developed and modified in various directions. With reference to the original paper by Parker (1955), we separate the basic idea from the details which reflect the actual scientific situation for that time rather than for the contemporary stage of scientific development. At that time, it was very important to demonstrate that induction effects in celestial bodies, i.e. dynamo action, can amplify an infinitesimal magnetic field up to arbitrary large values in a reasonably short time. Correspondingly, Parker (1955) considered mirror asymmetry as a hydrodynamic phenomenon and associated it with the Coriolis force action. In fact, the asymmetry can arise from the magnetic force action as well. This is the key issue in the well-known Babcock (1961)–Leighton (1969) scenario which is now considered more realistic for the solar situation. In particular, there is no need to insist that the Sun was burned in a non-magnetized media and magnetic structures including sunspots important for the Babcock–Leighton scheme did not arise in the young Sun. A more balanced view is that sometimes, say, at the end of a Grand solar minimum like the Maunder minimum the Coriolis force becomes more important than the magnetic one (Choudhuri & Karak, 2012).

In 1955, Parker postulated solar dynamo equations based on his physical common sense rather than on some formal mathematical procedure. The procedure was suggested independently by Steenbeck, Krause and Rädler (1966) as mean-field equations and became the basis of the later dynamo studies. Modern numerical tools allow solar dynamo simulations in terms of direct numerical simulations, which is an obvious fundamental achievement, but a physical understanding of a complicated process remains problematic without more simple models.

The dynamo equations can be presented in various forms which are important to reproduce specific details of the cycle and require some bulky algebra which we do not include here (for mathematical details see e.g. Brandenburg et al., 2012). What is important is that the equations even in the simplest form are fourth-order ones rather than the second-order wave equation. If dynamo drivers are strong enough, they contain eigensolution with positive real part (dynamo excitation) and non-vanishing imaginary part (dynamo wave propagation). In a proper parametric range the waves reproduce the Hale polarity law known from the sunspot studies.

It becomes clear that differential rotation and mirror asymmetry are not the only quantities important for the cycle. In particular, the meridional circulation plays an important role (e.g. Belusz et al., 2015).

The further logical and, to some extent, temporal stage of solar dynamo theory was the elaboration of a nonlinear dynamo saturation. Obviously, contemporary solar magnetic fields do not grow exponentially with time. A straightforward idea here is that the growing magnetic energy becomes comparable with kinetic energy of and somehow suppresses the weakest term in the chain of self-excitation, i.e. mirror asymmetry. The point is that the measure of the mirror asymmetry, known as α-effect and measured in the units of convective velocity v, is usually about $\alpha \approx 0.1v$ while the solar rotation velocity is even much larger. Later it becomes clear (e.g. Rogachevskii & Kleeorin, 2024) that the magnetic helicity balance is very important as well. In any case, the main point is that the real part of the dynamo eigenvalue vanishes while the imaginary part survives in the form of a solar cycle.

One more important physical idea is that the α-effect as well as other dynamo

drivers are mean quantities determined by a statistical ensemble of convective cells. The number of cells in the solar convective zone is about 10^4, i.e. substantially lower than the Avogadro number important for kinetic molecular theory of gases. Correspondingly, one has to take into account statistical fluctuations of dynamo drivers (e.g. Moss et al., 2008) in addition to the various nonlinear effects which can appear due to the dynamo suppression.

The above scheme is indeed a basic explanation only. We did not address the very important point: how deep in the convective zone is localized the layer most important for the dynamo action, what is the profile of meridional circulation, how to estimate the dynamo drivers and many other important topics which are significant in various aspects of the theory and interpretation of observations. It looks however plausible that these and many other topics can be successfully incorporated in the basic explanation. Of course, it requires hard theoretical, numerical and observational efforts and is done at different levels for particular problems.

Note the important role that the clear separation of two types of problems plays in the development of the above scheme, i.e. physical explanation of the solar cycle and theoretical estimation for dynamo drivers. Such separation is usual in laboratory physics. Indeed, the development of a new electric device and the understanding of the mechanism of conductivity in, say, copper are important; however, that is the separate problem. Such separation was not so obvious for astrophysical problems where direct measurements of many physical quantities are problematic. Data assimilation (e.g. Kitiashvili, Kosovichev, 2011) is considered as a reasonable choice now.

One more important point here is that the dynamo studies do not pretend to explain all solar phenomena. In particular, the solar dynamo as a particular physical theory cannot include the full theory of sunspot formation. Indeed, the dynamo is believed to be active within the Earth as well as within the Sun and there is nothing like sunspots at the Earth. Correspondingly, sunspots are not an imminent but accidental property of dynamos.

Experimental verification of theoretical ideas plays quite a limited role in astrophysics. However, many points of the above scheme are supported by laboratory experiments. In particular, the very possibility of dynamo excitation is reproduced in several dynamo experiments (e.g. Verhille et al., 2010) and the periodic oscillations for the dynamo generated magnetic field is now not a theoretical concept, but rather an experimental fact. The α-effect crucial for solar dynamo is also reproduced in laboratory experiments (Stepanov et al., 2006).

Observational verification of the mirror asymmetry in solar magnetic field and convection should also be mentioned here (e.g. Zhang et al., 2010). It confirms that the key solar dynamo driver, namely α-effect is not a theoretical concept but rather a real phenomenon.

An important point is that attention in solar dynamo studies moves from explanation of the known phenomenology to the solar cycle prediction (e.g. Nandy, 2021; Kleeorin et al., 2024).

The very formulation of the commonly accepted basic explanation for solar dynamo effects can be considered as a natural duty of any theoretical study. The point however is that in practice, the elaboration of such a scheme is not so obvious as desirable. In particular, such a scheme is much less developed in contemporary geodynamo studies.

3 Solar dynamo among stellar dynamos

The natural expectation is that stars similar to the Sun should demonstrate cyclic activity similar to the solar one. Of course, this expectation needs an observational verification. Observations confirm that some stars more or less similar to the Sun demonstrate cyclic activity and the cycle lengths are reasonably close to the solar one. A fundamental role in such verification is played by the famous HK project and its following developments (Baliunas et al., 1995; Baum et al., 2022). However, not all the stars involved in such monitoring clearly demonstrate a pronounced cyclic activity while the others demonstrate some activity variations which are not considered as cyclic ones. Of course, various observational problems can make this interpretation shaky, the cycles can be too long to be identified in, say, a 40 year record. However, the percentage of stars with clear cyclic activity remains to be about 20% and the observers do not report that longer observations result in identification of many stars with periods longer than the solar one.

With reference to the dynamo modeling, of course any successful model has a free room in parameter space where the solution remains solar-like. The teams involved in the modeling report various non-solar type behaviors (see for review Shulyak et al., 2015 and references therein). Understandably, the solar-like behavior looks much more attractive rather different activity behaviors and is much better presented in scientific papers.

Moreover, the archive data concerning solar cycle shape just at the end of the Maunder minimum (Ribes & Nesme-Ribes, 1993) present substantially asymmetric sunspot distribution with respect to the solar equator.

Taken together, all this stuff gives a hint that the solar-like shape of stellar activity may not be the only option for the solar-like stars. Moreover, it is difficult to firmly exclude that the contemporary shape of the solar activity is the only option possible for the Sun in the timescale of centuries. Apart from a pure scientific interest, the basic change of the shape of the solar activity may in principle be important in a pragmatic aspect.

The problem deserves a scientific investigation. However, contemporary stellar astronomy obviously underestimates the problem. The main attention in the study of stellar magnetism is concentrated now in the development of Zeeman–Doppler imaging for magnetic stars with kilogauss dipole magnetic fields (e.g. Li et al., 2022). Such stars are obviously interesting, however, they are believed to be something different from the stars similar to the Sun. The cases of magnetic activity comparable with the solar ones are considered to be unimportant and not very attractive for investigation. We stress here that the occurrence of the magnetic stars is estimated as only 10% among the solar-like stars.

A usual idea here is that Zeeman–Doppler imaging is impossible or very time- and effort-consuming for stars with solar-like activity (see, however, Chuti et al., 2025). However, about 3/4 of our knowledge about the shape of solar activity in the past is obtained from indirect temperature data. This kind of observation can be using the Inverse Doppler imaging (Goncharskii et al., 1982) only and are more affordable in practice. Moreover, the investigations with the data from the HK-project show its importance. Simple estimates show that enlargement of the wavelengths involved in observations from 2 as in the HK-project to a dozen could be crucial here.

Of course, a project for several decades is very difficult in the context of the modern grant system. This is a challenge for the astronomy community or even for the intellectual society as a whole.

4 Solar activity on the scale of centuries

The timescale of the solar activity cycle as a basic phenomenon in solar dynamo studies is about 22 (11) years. The point is that the cycles demonstrate various modifications on much longer timescales (e.g. Usoskin, 2023). Cycles of the XIXth century are clearly different from the cycles of the XXth century by height, length, and other details. The most pronounced event here is the famous Maunder minimum in the XVIIth to the beginning of the XVIIIth centuries.

It is good luck that observational astronomy already existed in times of the Maunder minimum in forms more or less comparable with its contemporary state. We have to mention here the fruitful role of the King of France Louis XIV who organized *Observatoire de Paris* and made solar observations the main aim of this body. Of course, this project was based on the abilities of the French astronomical school (Ribes & Nesme-Ribes, 1993).

The nature of long-term events in the solar cycle history is much less clear, rather the physical nature of the cycle being considered at the time scales of decade. In particular, it is difficult to insist firmly that the very Maunder minimum is something that happens with the engine driving the cycle rather than with the process of the sunspot formation (see Zolotova & Vokhmyanin, 2023).

The Maunder minimum is far from the only known deviation in the regular sequences of cycles. In particular, the shape and height of the last two cycles are quite different from the cycles of the XXth century. Experts isolate specific events associated with the variations. The Gleissberg cycle with a duration of about a century is well-known here. There are dozens of other events of various nature and timescales and these are suggested later. Some of them including proton events that happened in the Viking times can in principle be associated with some cosmic hazard phenomena (e.g. Usoskin et al., 2023).

The physical nature of the evolution of these long-term solar cycles may be accessible for the ideas of dynamo theory. In particular, random statistical noise in dynamo drivers can, in principle, be responsible for events like the Maunder minimum (Moss et al., 2008). However, it is difficult to insist that it is the only possible explanation. In particular, even planetary effects on the dynamo engine could be helpful here (Stefani et al., 2024).

The time series of telescopic data concerning solar activity occupies four centuries and looks too short to address such problems. A fruitful perspective here seems to be an extension of the time series by isotopic data. Indeed, the time variations in the occurrence of C^{14} and some other isotopes in tree rings, yearly layers in polar ices and some other structures do contain information concerning solar activity variations (see Usoskin, 2023 for review). Historically, the information played a crucial role to convince the astronomical community that the Maunder minimum is the luck of sunspots rather than the luck of observations (Eddy, 1976).

Summarizing, we can expect a new field for fruitful collaboration between solar physics experts and experts in isotopic geochemistry and related scientific fields.

One has to say here again that funding and managing this kind of research is a very nontrivial undertaking. It is very difficult even to keep accessible information, or example to present on the internet all available archive data. It is even more difficult to keep active prolongation of traditional, however crucially important observations of such things as sunspot numbers. We have to conclude here that the efforts of King Louis XIV are not sufficiently continued in modern society.

5 Coexisting with other topics

Note one more time that the solar dynamo is a particular branch of physics and one hardly can expect here some contribution, say, in quantum field theory. There are many more closely related branches of physics and astronomy where an expansion from the solar dynamo is natural and useful. The most obvious case is sunspot formation and evolution. Dynamos do not pretend to provide an explanation for the majority of all relevant ideas, however, some contribution is natural. In particular, sunspots are connected somehow with the mean magnetic field; however, Picard observed one sunspot even in times of the deepest Maunder minimum (Ribes & Nesme-Ribes, 1993).

There are many other cases where knowledge concerning large-scale solar magnetic fields is obviously useful; however, they do not cover the majority of all relevant ideas. For example, a solar flare depends on the mean solar magnetic field; however, solar flares may happen even in times of solar minimum. Almost any phenomenon in solar physics and physics of surrounding space can be given as an example here because the solar cycle modulates almost all such tracers.

Solar cycle modeling isolates the cycle from other phenomena to make the problem affordable. An intention to consider, say, a detailed cycle model with, say, a developed model of solar wind propagation does not look the most reasonable approach. A more attractive way is to separate relevant points from the solar dynamo to be combined with relevant features of solar wind theory. The problem is how to select the relevant features. Of course, particular solar dynamo papers solve the problem in a specific way, but there still exists a rich sample of unclear questions. One can illustrate the statement by various references; however, we restrict citations to just one which is personally important for the author (Maiewski et al., 2022).

Just to mark one more field of research, note that the solar dynamo in its basic form can be considered a mathematical spectral problem for a non-Hermitian operator in a specific functional space. Historically, such problems were more or less related to the development of quantum mechanics. A formal analogy with quantum mechanics is useful in dynamo studies (e.g. Kuzanyan & Sokoloff, 1995) however Hermitian operators in quantum mechanics do not mimic all natural questions for dynamo studies. A contribution from pure mathematics would be useful for further understanding of dynamo problems.

6 Conclusions

We can conclude that the fact that experts in solar dynamo achieved more or less an agreement concerning the nature of the solar cycle does not mean that nothing more should be done. New perspectives for research are clearly visible and demand new contributions.

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