Open Access Online Journal on Astronomy and Astrophysics

Acta Astrophysica Taurica

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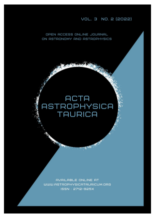

Acta Astrophys. Tau. 3(2), 8–11 (2022)

Some unresolved problems in the solar dynamo

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Submitted on September 27, 2021

ABSTRACT

Contemporary solar dynamo theory is now transiting to the solar activity prediction problems. It looks important however to keep in mind foundations of the solar dynamo theory. This is why we consider here some unresolved problems in these foundations. The problems are important for understanding solar activity as well as activity of stars similar to some extent to the Sun.

Key words: solar activity, solar cycle, stellar activity, stellar cycles, magnetic field generation

1 Introduction

Over the past years, there has been observed a well-distinguishable convergence in the points of view of different researchers, which can be traced in works on the nature of solar magnetic activity. Groups of researchers have quite converging opinions concerning the basic features of the mechanism that causes solar magnetic activity. It seems likely that this branch of science is ready for the development of problems related to the solar cycle activity prediction and to the gradual transition to a more applied look at the relevance of problems. Many other branches of science have already gone through a similar transformation; their experience shows that when transiting from the ascertainment of basic features of a phenomenon to its detailed description in the applied aspect there appears a temptation to stop thinking of the remaining unresolved fundamental problems. Speaking less formally, the colleagues start wondering why people still continue to construct solar dynamo models of various degrees of complexity if there is a possibility to proceed to data assimilation in the most developed models. Apparently, there is a necessity to answer this legitimate question not in general – any problem has some unexplored issues – but more specifically, within the framework of a scientific publication. The format of a paper from the conference report seems adequate in this case.

The proposed paper expresses a personal opinion of the author. Others would make another list of issues to resolve. The formulated opinion is based on numerous discussions with colleagues who somehow expressed their opinion in the form of various remarks in their publications. But selecting these remarks from particular works is a rather difficult task; this paper thus provides only those references that support directly the expressed thoughts.

2 Characteristics of solar magnetic fields on the surface and in the region of dynamo operation

According to the established notions, the solar magnetic field generation by the solar dynamo mechanism occurs not on the solar surface but in its interior. The question as to how deep this region is under the solar surface remains unclear yet. It may be located not (or not just) in the inverse layer of the inner boundary of the convective zone but significantly higher, relatively close to the solar surface. But there are no doubts that the dynamo region is not observed directly from a predominant number of surface tracers of solar activity, which allow us to assess the magnetic field distribution in the solar interior. Experts in solar activity are like blind sages from the well-known parable who describe an elephant by feeling its parts of the body. Naturally, the descriptions of the magnetic field configuration in the solar interior made by the experts in solar dynamo, in optical observations of the solar surface or the solar wind data can vary strongly because each one distinguishes the most important for him features of a phenomenon. The convergence of experts' points of view seems very important but difficult task. Unfortunately, it is hard to rely only on the results of direct numerical simulation. The point is that the characteristic dimensionless numbers that describe the amplitudes of magnetic field generation sources differ greatly from unity, which makes the task of direct numerical simulation to be extremely difficult, whereas our knowledge about the details of motions inside the Sun are very incomplete. The set of solar activity tracers applied to resolve this task needs to be extended. In particular, in this regard it seems promising to study the statistics of sunspot groups that disrupt the rules of solar magnetic field symmetry (see, e.g., Zhukova et al., 2020).

3 Two mechanisms of reconstructing the toroidal magnetic field

The reconstruction process of the toroidal magnetic field from the poloidal one is an important element of the solar dynamo. Since the 1950s, it has become clear that the solar dynamo-machine cannot work without such a reconstruction. It was ascertained that this reconstruction occurs due to the mirror asymmetry of solar convection. This mirror asymmetry can be triggered by the Coriolis force or determined by the Lorentz force that is proportional to the existed magnetic field. The first possibility is associated with the name of Parker, and the second possibility is currently believed to be more important than the first one. Probably, this is it that makes a decisive contribution to reconstructing the toroidal magnetic field. In any case, the effect of the magnetic field is considered to be sufficient for a cycle of solar magnetic activity to occur. But such a formulation of the question does not seem sufficient. A more quantified version of this notion would be preferred. In the simplest case, we would like to know what percent of the reconstruction of the toroidal magnetic field is associated with the second mechanism and what percent – with the first one. Perhaps, such a formulation of the question is inadequate for some reasons (although such a possibility is not supported with any particular researches). In this case, it seems interesting to ascertain the role of both mechanisms in the total operation of the solar dynamo. The paper of Choudhuri, Karak (2012) can be mentioned in this direction, but a more detailed study is required. The contributions of both mechanisms may practically be inseparable, but this conclusion needs a scientific substantiation.

Obviously, this problem can be considered as one of the aspects of the previous problem. However, it seems that this aspect is the closest to elucidation. The apparent difficulties are probably not so much of a conceptual nature as a psychological one.

4 Solar dynamo in a series of stellar dynamos

When constructing solar dynamo models their authors naturally tend to reconstruct solar phenomenology. While organizing stellar activity observations the observers also focus on the well-studied solar magnetic activity. Therefore, it seems that solar activity can to some extent be considered as a typical model of stellar activity, at least for stars of late spectral types. Meanwhile, since the 1990s of the past century, it has been known that at a free game with the amplitudes of magnetic field generation sources, i.e., with differential rotation and mirror asymmetry, many dissimilar magnetic configurations (Jennings, Weiss, 1991) appear in the spherical envelope in dynamo models. In particular, in addition to magnetic configurations of the dipole type, which are characteristic of the Sun, there appear magnetic configurations of the quadrupole symmetry with the zero magnetic dipole moment. To transit from the mode with the excited dipole configuration to the mode with the excited quadrupole configuration, it is sufficient to have a moderate variation in the amplitudes of magnetic field generators. It is hard to believe that among a huge set of stars one cannot find those in which the magnetic configuration is excited, which is drastically different from the solar configuration. Observers regularly note that, for instance, M dwarfs have activity that differs noticeably in some way from solar activity, but they find difficulty to formulate clearly how these differences manifest themselves. An entirely different configuration than that on the Sun is presumably formed on such stars. Meanwhile, the available data on stellar magnetic activity commonly provide no basis for such comparisons. The point is that all available long time series of observations characterize insufficiently the magnetic configurations on stars, whereas the data that characterize them represent, at best, a small set of instantaneous images of a star. The arsenal of astronomy has for about 40 years had instruments that enable maps of spottedness to be constructed, at least for some types of stars. For observations carried out in a small number of spectral lines there are long time series that allow one to distinguish stars with cyclic magnetic activity compared to that of the Sun. This is primarily the famous H–K project organized by O. Wilson. To distinguish stellar cycles with ascertained magnetic field configurations using the mapping of stellar temperature distribution by the method of inverse Doppler images, the long time series are required in hundreds of spectral lines. This represents a potentially resolvable task, but a many-year monitoring of the limited sample of stars using observations at many wavelengths fits badly in the framework of grant science. In modern conditions, it is simpler to be involved in the comprehensive development of observational methods and a list of stars for which there are at least instantaneous data on magnetic field distribution. These data are of great interest but do not lead directly to the solution of the discussed task. It seems that the international astronomical community is able to resolve this organizational problem; therefore, in a few decades our knowledge about the place of solar magnetic activity among different types of stellar magnetic activity should be drastically improved.

5 Continuous components of the solar activity spectrum

Let us proceed to more particular problems. The efforts of experts in solar dynamo are traditionally focused on the explanation of the main 11-year (or, taking into account polarity, 22-year) magnetic activity cycle (Schwabe cycle). It should be recalled that the physical idea of this explanation is that in the equations describing the behavior of the solar mean (large-scale) magnetic field in the linear magnetic field approximation there arise a solution the eigenvalue of which is complex and has a positive real part, i.e., a magnetic field growth occurs being accompanied by oscillations. This growth is saturated with time as a result of the inverse effect of the growing magnetic field on the solar matter motion. Because of this, the length of the nominal 11-year cycle and its form somewhat change from cycle to cycle. It is important to note that the Schwabe cycle does not exhaust the entire spectrum of solar magnetic activity. Researchers distinguish various considerably less stable oscillations among which the most well-known is the so-called “quasi-two-year-old”. The very name indicates the difference of this phenomenon from the Schwabe cycle. The recent work of Frick et al. (2020) shows that these oscillations produce a continuous component of the wavelet-spectrum of solar magnetic activity. The obtained wavelet-spectra of solar magnetic activity are very similar to the well-known in optical astronomy continuous spectra on the background of which the pronounced maximum, which corresponds to the 11-year cycle, is clearly distinguished. In such cases in optical astronomy it is said about a spectral line on the background of the continuous spectra. In this case, we deal with a noticeably different frequency range, other equations, but the construction of spectra actually appears to be very similar. We emphasize that it is not about the quasi-two-year-old oscillations cannot exist. It is important that the frequency clearly related to them is not distinguished in a spectrum.

It seems necessary to inscribe somehow the idea of the continuous spectrum into a set of notions about the solar dynamo theory. On the one hand, the continuous spectrum of magnetic field oscillations indeed appears in fairly complex solar dynamo models just as a result of various non-linear effects (Sokoloff et al., 2020). Meanwhile, it is thus natural to interpret the origin of oscillations the period of which is less than the nominal period of the Schwabe cycle, but it is not obvious that one can explain more long-period oscillations of the Gleissberg cycle type (about 100 years). Moreover, there are stars (e.g., V833 Tau, Stepanov et al., 2020) for which the wavelet-analysis detects the presence of a continuous spectrum but shows no distinguished frequency that could be considered an analogue of the Schwabe cycle. Sure, we can insist on the pragmatic point of view – if the numerical simulation reproduces some phenomenon, then this is sufficient for its description. However, it seems preferable to develop the basic representations of the solar dynamo in such a way that they would principally include a description of the continuous component of the solar activity spectrum. One of the possible ways of appearance of the continuous spectrum is the picture of numerous bifurcations suggested by Charbonneau et al. (2005), which occur when the solar dynamo intensity increases. This explanation is analogous to the well-known Landau's scenario of transiting to turbulence and implies a description of the studied phenomenon using a great number of degrees of freedom. Now, the ideas associated with the notion about a strange attractor, which allow one to be restricted to the description in the framework of a small number of degrees of freedom, are considered preferable in the theory of turbulence. Something similar can possibly occur in the solar dynamo.

6 Long-term history of the solar cycle

Instrumental data on solar activity observations on the basis of sunspots are available for approximately all the time of existence of telescopes, i.e., for about 400 years. Of course, for decades the standards and quality of observations have not been constant; thus the available reconstructions of solar activity behavior have naturally been criticized. But one can generally be surprised of the fact that the basic features of these reconstructions prove to be stable. Sunspots can sometimes be observed with the naked eye. There are data on these observations, as well as on observations of other tracers of solar activity (for instance, aurorae), even for a longer time, but the quality of these data is incomparably worse than that of instrumental observations. The temporal resolution of isotope geochemistry depends on the period of isotope circulation, which for C^{14} accounts for a few years. Therefore, the methods of isotopic geochemistry cannot achieve the temporal resolutions of direct observations of spots (day). The temporal resolution is significantly getting worse with increasing age of the analyzed isotopic pattern. It is not easy to substantiate that the observed isotopic variation has not local but planetary nature. Therefore, one can hope that it is associated with variations in solar activity.

Nevertheless, the data of isotopic geochemistry (where, in particular, the term "tracer" penetrates into solar physics) allow one to prolong (Wu et al., 2018) the record of solar activity evolution up to approximately 10 thousand years (from the measurements of abundance of radioactive carbon and beryllium isotopes). The quality of these data is progressively approaching the quality of instrumental observations of sunspots. A gradually formed prospect to study the history of solar activity not during several dozen Schwabe cycles but over several thousand such cycles poses the questions that had not previously gained particular attention, since they seemed outdated. The initial formation of this subject matter is currently under way; therefore, many statements of the questions seem risky and not always adequate. For instance, the prediction of the next solar cycle with not very high accuracy raises no particular difficulty, since the cycle length changes weakly from cycle to cycle. Sure, one can be very much mistaken without including the onset of the new global minimum similar to the Maunder minimum, but as a whole this possibility does not seem particularly relevant. The question as to the extent to which one can predict the time of the onset of cycles in a few hundred years is far less clear. We would like to believe that the deviations in duration of cycles from the nominal 11-year value can be considered as random wanderings; thus, there arises a time limit in predicting the onset of cycles. However, the literature discusses the notion about synchronization of the solar dynamo operation at which some predictions can be made on a longer time interval. Apparently, it is not worth in advance to discard this possibility, and studies of that kind have right to exist.

7 Resonances of activity waves

One more issue from the physics of the solar cycle with difficult history is the issue on the possibility of resonances of dynamo waves. It is historically associated with a great coincidence of the nominal length of the solar cycle with Jupiter's orbital period. It is hard to imagine that this coincidence is really important for the formation of the solar cycle, how such an association can be fulfilled – the distance from the Sun to Jupiter is very large as compared to the distances at which the magnetic field can penetrate, whereas the effects of Jupiter on solar hydrodynamics are not significant. But in the context of studying magnetic activity of stars of close double systems this possibility does not seem unrealistic. Another thing is that it is difficult enough to change significantly the dynamo operation in the stellar interior due to the influence of the companion star (Moss et al., 2002). But the main thing that causes concern and fuels interest in the issue is that the quantitative properties of resonance effects for dynamo waves are poorly studied. The attempts to apply standard notions about the resonance of more usual oscillating systems, which are described by the second-order equations, are in bad agreement with data of the numerical experiment with dynamo equations, which manifest themselves as systems of fourth-order equations (Kalinin, Sokoloff, 2019). These inconsistencies might be omitted, but this seems to be not the best course.

8 Conclusions

We have traced a subjectively selected series of problems in the physics of solar activity – from the problems that seem obviously relevant to far more particular issues that may be important in the course of further development of solar physics and may remain the marginal issues that will be of interest just for a small number of enthusiasts. Most of these issues do not require or are not limited to the construction of detailed models of the solar dynamo in the framework of even more direct numerical simulation. It seems that at the epoch of transiting to the development of methods for predicting behavior of the solar cycle there remain a significant number of interesting problems available for solving by methods of traditional theoretical physics, which does not exclude a reasonable use of computers. It is hard to grasp immense within a report; therefore, such important issues as the presence (or absence) of the memory of dynamo cycles (the problem of synchronization), importance of the stochastic component, magnetic helicity, etc., are beyond the scope of the discussion. Answers to these questions can determine how predictable the stellar cycles are.

The author is grateful to the Theoretical Physics and Mathematics Advancement Foundation “BASIS” (grant 21-1-1-4-1) and the Ministry of Science and Higher Education (agreement 075-15-2019-1621) for financial support of the work.

References

Charbonneau P., St-Jean C., Zacharias P., 2005. Astrophys. J., vol. 619, no. 1, p. 613.
Choudhuri A.R., Karak B.B., 2012. Phys. Rev. Lett., vol. 109, no. 17, id. 171103.
Frick P. et al., 2020. Mon. Not. Roy. Astron. Soc., vol. 491, p. 5572.
Jennings R.L., Weiss N.O., 1991. Mon. Not. Roy. Astron. Soc., vol. 252, pp. 249–260.
Kalinin A., Sokoloff D., 2019. Magnetohydrodynamics, vol. 55, no. 1–2, p. 193.
Moss D. et al., 2002. Astron. Astrophys., vol. 396, p. 885.
Sokoloff D. et al., 2020. Mon. Not. Roy. Astron. Soc., vol. 497, no. 4, p. 4376.
Stepanov R. et al., 2020. Mon. Not. Roy. Astron. Soc., vol. 495, no. 4, p. 3788.
Wu C.J. et al., 2018. Astron. Astrophys., vol. 615, id. A93.
Zhukova A. et al., 2020. Solar Phys., vol. 295, p. 165.