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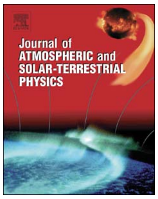

Dynamo theory and perspectives of forecasting solar cycles

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ABSTRACT

Various approaches to forecasting the solar cycle based on solar dynamo models are considered. The importance of separating predictions of catastrophic events such as the Maunder minimum, predictions of general trends in solar activity between Grand minima, and forecasts of the next cycle, based on current knowledge of previous cycles is noted. The role of fluctuations of dynamo drivers for the forecast is emphasized. The polar magnetic field in the current cycle is considered as a natural predictor of the amplitude of the following cycle.

1. Introduction

Prediction of solar cycle is a relatively new branch of solar physics. Various predictions of the current solar cycle was the first one experience of solar physics community in such a forecast (the most best known of these predictions are probably Dikpati and Gilman (2006) and Choudhuri et al. (2007)).

Prediction of the solar cycle is a relatively new branch of solar physics. Attempts to predict the current solar cycle were the first attempts of the solar physics community in such forecasting. Both predictions was based on a dynamo model, more specifically on a flux-transport dynamo model, however they produced quite different results. As a matter of fact, prediction (Choudhuri et al., 2007) appears to be much closer to the actual intensity of the current solar cycle and could be considered as the first successful prediction of this kind. A possible strategy now is to accept this flux transport dynamo model as the basis for future development of prediction studies, to separate prediction studies from the discussion of possible physical mechanisms of stellar dynamo action, to push such discussions in the area of stellar physics, and to focus attention on data assimilation for determination of the governing quantities for the dynamo model. This natural approach is presented in various talks on the meeting and is quite close the personal preferences of the author, and is reflected in the framework of a slightly different dynamo model in Kleeorin et al. (2016).

Solar dynamo studies can be considered to be a natural theoretical background. The point however is that it is difficult to make predictions, and experts in dynamo theory are rather conservative in presenting particular approaches to applying dynamo theory to forecasts. A motivations for the conservative viewpoint is that just one successful prediction among a number of less successful can in principle at least partially considered as a coincident. More deep motivation is that the cycle 24 appears to be substantially different from normal solar cycle known from long-term monitoring of solar activity. In some respects this cycle looks close to unusual cycles referred as, say, Dalton minimum. It is difficult to exclude *a priopri* that a predictor suitable for a normal cycle may be inadequate for an exceptional cycle. Of course, a common sense advice here could be to avoid strong statements and try to predict following the next time learning how to perform the data assimilation. Such programme however is quite difficult in implementation as it requires several decades and postpones any practical for a quite remote future.

At the moment it looks more attractive to consider and compare various approaches that might be applicable to such forecasting based on theory, rather than to advocate any in particular. Such presentations were assumed in the planning of this meeting and it is the aim of this paper.

Presenting this broad aspect of the problem, it is necessary to appreciate that our knowledge about unusual events in solar cyclic activity record such as the Maunder or Dalton minimum are more limited than for the current solar cycle. It is possible (e.g. Choudhuri and Karak, 2012) that the physical mechanisms underlying normal and unusual cycles are different. Observational data of solar cycle activity in remote time epochs are much less definite (cf. e.g. Zolotova and Ponyavin, 2015; Usoskin et al., 2015) than for the current cycle. Again, it is difficult to expect that the attempts to predict Grand minima will be postponed until several more Grand minima have been observed instrumentally. As a result, when presenting available ideas it is not possible to concentrate on data assimilation, and to separate it from discussions concerning basic physical mechanisms of the phe-

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nomena under discussion.

First of all, a proper perspective on the topic is important. The solar cycle is a remarkable example of a natural quasi-periodic process underlain by a rich physics, rather than mere rotation. The cycle length varies slightly from one cycle to another, but the variations are quite moderate and a crude prediction of the year of, say, the next solar minimum seems a quite feasible undertaking. Indeed, the famous International Year of the Quiet Sun (a programme covering the period from January 1, 1964, to December 31, 1965; for an example of many reviews for the results of this programme see e.g. McKenna, 1965) was successfully planned and performed about a half-century ago, and it was indeed implemented at a time near the solar cycle minimum.

The solar cycle as a physical phenomenon is explained by contemporary physics and a corresponding branch of cosmic MHD is known as solar dynamo theory. It would be too much to say that the theory provides the correct cycle length and shape. Naive cycle length estimates give a figure which is one order of magnitude smaller than the actual one. There are several possibilities for reconciling theoretical estimates with the actual length. Each of the options have advantages and shortcomings. Experts need to spend more time and efforts to reach agreement; however the process seems to be converging.

Compare this situation with another example of natural periodicity, say, the economic cycles which are the natural fluctuation of the economy between periods of expansion (growth) and contraction (recession). This definition is taken quite arbitrarily from the internet (see Investopedia). The processes underlying economic cycles were already suggested in the XIXth century and still look reasonable. The practical importance of economic forecasting is clear. The amount of effort and money expended is much larger than in solar cycle studies. Nevertheless a forecast for economic cycles at the level achieved for the solar cycle in the 1960s remains a dream.

We have to conclude that solar cycles are remarkably stable compared to other natural cyclic processes. This stability enables crude predictions to be made for the time of forthcoming minimum, but however may make better predictions of cycle amplitude and other cycle properties more difficult. The issue here is that a link between the properties and the cycle governing parameters is neither very pronounced nor clear.

Contemporary scientific opinion considers the example of solar cycle forecast discussed above (i.e. the interval between maxima or minima) as an achieved milestone and now looks for something further. In order to make corresponding studies specific, it seems important to formulate the aims of the forecast in an explicit form.

It looks natural to suggest three aims for the forecast. It is interesting and important to predict possible catastrophic events such Grand minima (e.g. the Maunder minimum) which are known from archival astronomical observation and isotopic data. Another possibility could be the prediction of general trends of solar cyclic activity between Grand minima. For example, activity cycles at the end of XXth century look stronger than those in the XIXth century and it would be interesting and valuable to forecast similar trends that might occur in the future. One further option is prediction of the forthcoming solar cycle based on information that is available from several previous and current cycles. The aims suggested above might be compared with the distinction between prediction of climatic trends and weather forecasting in geophysics. We consider all three options separately. We note however that Mordvinov and Kramynin (2010) argues that intersections between the various goals of the forecasting can occur.

2. Towards prediction Grand minima and Grand maxima

In some sense, the prediction of Grand minima seems the preferable goal for physical theory. The event to be predicted is considered as being well defined, rather than a result of tiny correlations in the physical parameters of the dynamo. Solar dynamo models that can reproduce something similar to Grand minima have been known for quite a long time, starting from, say, the model of Brandenburg et al. (1989, 1989). The observations available are adequate to discriminate between at least some of such dynamo models. In particular, isotopic data tell us that Grand minima epochs occur aperiodically, and that the sequence of the Grand minima epochs for the last 11,000 years (Solanki et al., 2004) appear chaotic while Grand minima in some dynamo models (e.g. Brandenburg et al., 1989, 1989) occur periodically. Perhaps, it would be more accurate to reformulate the prediction problem for this case as estimating the probability of occurrence of Grand minima. However, it can hardly be expected that everybody will follow this common sense recommendation!.

It looks attractive to base predictions of forthcoming Grand minima on a minimal solar dynamo model that contain only the dynamo drivers that are absolutely essential for solar dynamo action. The logic underlying such an approach is as follows. We certainly do not know all the details of contemporary solar hydrodynamics that are important for dynamo action and we know almost nothing concerning possible peculiarities of the solar hydrodynamics during the Maunder minimum (Ribes and Nesme-Ribes, 1993) collected observational hints that solar differential rotation might be peculiar just before and during the Maunder minimum). We can however hope that such pronounced events as Grand minima are independent of small details and consider only basic effects.

The basic scheme of solar dynamo action originates from the fundamental paper (Parker, 1955) and is as follows. Differential rotation of solar convective zone produces toroidal magnetic field from poloidal (for clarity we consider here axisymmetric large-scale magnetic field.) This process looks clear and straightforward. We know the contemporary solar differential rotation from helioseismological data (see for a short review e.g. Kosovichev, 2010). We can agree that some details of this rotation might be different in the Grand minimum epoch, however it appears not very probable because the kinetic energy of the solar rotation is much larger than the magnetic energy. Differential rotation working alone is however unable to support the solar magnetic field against dissipation. A mirror-asymmetric effect which restores poloidal magnetic field from toroidal is also needed. The physical nature of this effect remains a matter for discussion. Parker (1955) associated it with the action of the Coriolis force in the stratified solar medium. In this context the effect is known as the α-effect. Another scheme originating in Babcock (1961) and Leighton (1964) associates it with the action of the magnetic force. This distinction is not crucial for our analysis and we will use the term α-effect without particular specification of its nature. In both cases the α-effect is small in comparison with the effect of differential rotation. A natural assumption is that it is α which varies from one cycle to another. A further possibility here is variation of meridional circulation which may be also very important factor in the formation of the solar cycle (Dikpati and Gilman, 2001); however let us consider here the simplest case.

An important point here is that α is a mean quantity taken over an ensemble of convective vortices in the solar convective zone. E.g. for the Parker scheme, it is proportional to the excess of the number density of right-handed vortices over the left-handed. The number N of convective vortexes is quite large (a plausible estimate (Moss et al., 2013) is $N \approx 10^4$, at least for orientation). However this is much smaller that usual size of ensembles in traditional statistical physics (where N is usually related to the Avogadro number $A = 6 \times 10^{23}$). Correspondingly, the statistical noise level expected for dynamo drivers should be of order $N^{-1/2} \approx 10^{-2}$. Such noise should contribute to all mean quantities important for the dynamo, say, in differential rotation. However numerical experiments with simple dynamo models show that such a noisy contribution to the differential rotation is not very important. The point however is that the other dynamo driver, α, is weak. α has dimensions of velocity and a standard estimate is $\alpha \approx 0.1$ v where v is the rms velocity of convection. Fluctuations of about 1% in v mean fluctuations of about 10% in α and such a noise level is more than sufficient to produce from time to time events similar to the Grand