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Solar Dynamo and Magnetic Self-Organization

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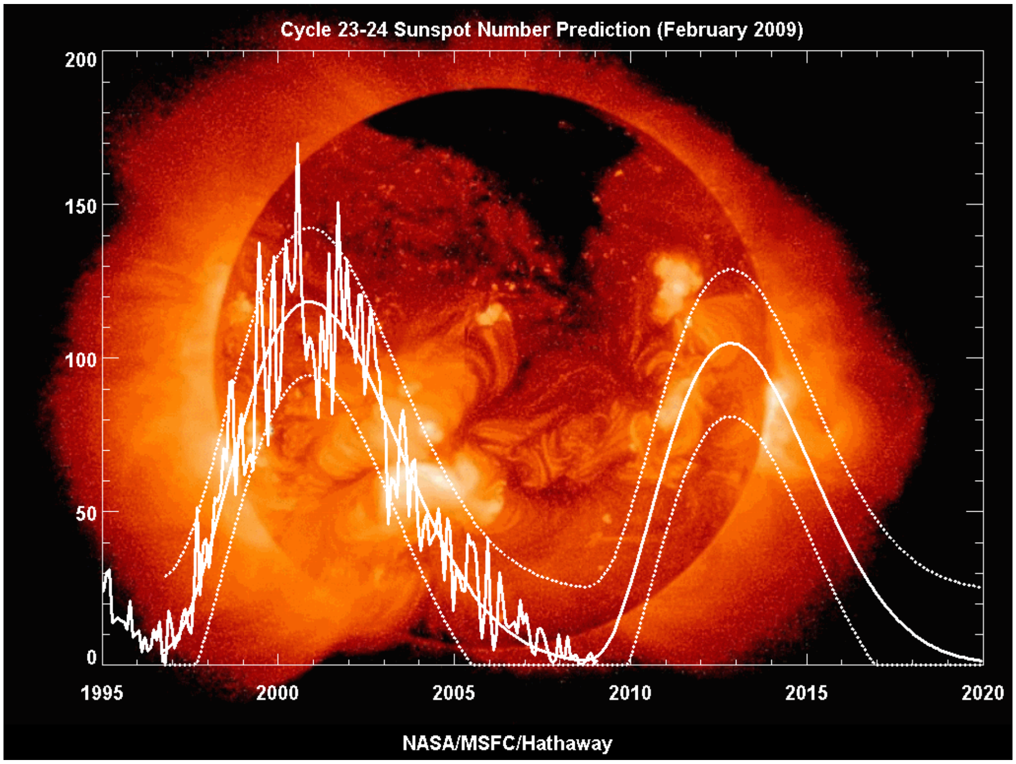

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1 Overview

It is well established that magnetic fields exist in astronomical objects of all scales, in planets, stars, galaxies and clusters of galaxies. Magnetic fields play a crucial role in star formation, solar and stellar activity, pulsars, magnetars, accretion disks, formation and stability jets, origin of cosmic rays, and stability of galactic disks. It is generally accepted that cosmic magnetic fields are produced by dynamo processes operating on various scales. In these processes the magnetic field is maintained against Ohmic dissipation by turbulent motions, and despite the turbulent nature it shows remarkable self-organization properties, forming sunspots and starspots, magnetic loop structures, magnetic spiral arms etc. These phenomena show striking similarity suggesting that the basic physical mechanisms are essentially the same.

The Sun is our Rosetta stone when it comes to magnetic-field studies in the entire Universe. The solar magnetism is studied in great details, from global fields of the interior by helioseismology, to the smallest resolved and even unresolved scales by new large ground-based telescopes (SST, GREGOR, BBSO NST) and from space (SOHO, RHESSI, STEREO, Hinode, and SDO (scheduled for launch in 2009). In addition, significant progress has been made in realistic numerical MHD simulations. This progress in observations and modeling provides a good basis for solving the problem of the solar dynamo and formation of self-organized magnetic structures during the next decade. This will have tremendous impact in many fields of astrophysics.

However, this new science opportunity requires focused coordinated efforts in observations, modeling and theory. This opportunity can be realized with relatively modest investments, mostly, for supporting the projects that already exist or are under development. The Sun is the only object that can be observed to the level of details sufficient for investigation of the basic physical processes in a magnetized astrophysical plasma. These processes are a cornerstone of modern astrophysics.

A key element of this opportunity is the understanding of interlinks between small-scale turbulent properties of magnetized plasma and large-scale dynamo processes. It has been long assumed that the turbulent properties, such as turbulent diffusivity and helicity, define the large-scale behavior of the magnetized plasma with some simple back-reaction, but recent plasma experiments and theoretical studies showed that the large-scale flows and structures may significantly alter the turbulence, and that this may cause large-scale organization in plasma[1,2]. One striking example is the formation of torsional flows in tokamaks, which led to a new field in plasma physics[3]. Similar interactions between turbulence and large-scale processes are likely to occur in astrophysical plasmas, but, of course, because of the drastically different conditions the laboratory results cannot directly applied in astrophysics.

We would like to draw attention to the unique opportunity of detailed studies the turbulent dynamo and magnetic self-organization phenomena in the conditions of astrophysical plasma, based on recent advances in solar observations, theory and modeling. There is a real opportunity of actually solving the solar dynamo problem during the next decade. This opportunity is based on the following projects:

- the ground-based 4-m Advanced Technology Solar Telescope (ATST) for studying small-scale turbulent processes with the highest possible resolution and also unresolved properties by using advanced spectro-polarimetry methods;
- an out-of-ecliptic space mission, such as the European Solar Orbiter mission, Japanese Solar-

C (Plan A), and NASA's Solar Polar Imager, which are currently under discussion and initial investigations;

- operations and data analysis of the Solar Dynamics Observatory (SDO) mission for the whole solar cycle;
- ground-based synoptic observations at the Mount Wilson Observatory (MWO), Wilcox Solar Observatory (WSO) and the National Solar Observatory (NSO/SOLIS) for studying the long-term behavior of large-scale magnetic fields;
- realistic MHD numerical simulations of the solar turbulence and dynamo at large National Supercomputer Centers.

2 Recent progress and current status

During the last decade helioseismology observations from SOHO and GONG provided us with a detailed knowledge of the internal differential rotation of the Sun and led to the discovery of two rotational shear zones, at the top and bottom of the convection zone[4]. These zones are believed to be important for shaping the solar dynamo[5]. Helioseismology techniques are rapidly progressing. They have provided initial results on subsurface meridional and zonal flows and formation of sunspots and active regions[6–9]. New data from the Solar Dynamics Observatory will allow us to investigate the dynamics of the convection zone and magnetic flux emergence.

The high-resolution observations from the Hinode space mission, Swedish Solar Telescope on La Palma and other large telescopes have provided important details about the interaction between plasma and magnetic fields, and revealed small-scale magnetic structurization[10,11]. New spectro-polarimetry methods based on measurements of scattered polarization provided evidence of "hidden" magnetism of unresolved scales[12]. These studies require large-mirror telescopes, such as the ATST.

In addition, Hinode observations of the Sun's polar region made during the periods of high inclination of the solar equator to the ecliptic (7°) have shown that the polar magnetic field consists of small kilogauss-field structures[13]. This structurization is undoubtedly important for understanding the polar field reversals during the solar cycle.

Rapidly increasing supercomputer facilities have led to significant advances in numerical simulations of the solar dynamo and magnetic structures, including mean-field dynamo models, MHD turbulence, small-scale dynamo, and the sunspot structure[14–21]. Recent realistic numerical simulations of the global dynamics and dynamo of the Sun are extremely promising, but require further advances in modeling of subgrid MHD turbulence, which controls transport of heat, momentum and magnetic flux. This can be achieved by implementing modern turbulence models and comparing with high-resolution observations.

The ground-based long-term synoptic observations of surface magnetic fields and plasma flows play extremely important role for understanding the cyclic behavior of the solar dynamo. Detailed synoptic data from the Mount Wilson, Wilcox and National Solar Observatories obtained for the last three solar cycles have uncovered a fascinating picture of well-organized processes of magnetic flux emergence, transport and polarity reversal, in the apparently chaotic behavior of magnetic field[20]. These synoptic observations definitely play a major role in our quest for understanding the dynamo mechanisms, and must be thoroughly supported.

Thus, the recent advances in observations and theory provide us a solid basis and a new opportunity to substantially advance our understanding of the dynamo processes and magnetic self-organization. From the observational point of view, it is important to use advances of helioseismology to determine the links between the interior dynamics and the surface and coronal phenomena: emergence and evolution of active regions, magnetic flux transport, polar field reversals and magnetic flux dissipation and escape. From the theoretical point, it is necessary to link dynamo models with observed dynamical phenomena, directly related to the magnetic field generation and evolution, such as variations of the differential rotation rate, zonal and meridional flows.

3 Basic physical questions

3.1 How are heat, momentum and magnetic flux are transported in turbulent magnetized plasma?

The main complication in our understanding of many observed phenomena is due to the fact that the solar and astrophysical plasmas are in strong turbulence state. Turbulence is the major factor determining the heat, momentum and magnetic flux transport. It has been well-established that assessments of the turbulent transport in terms of the traditional (and still widely used) mixing-length theories and order-of-magnitude estimates are insufficient. There is a strong complicated interplay between the turbulence and large-scale plasma flows and magnetic structures. The turbulent transport determines large-scale temporal-spatial characteristics, and, in turn, the turbulent properties strongly depend on the character of large-scale structures and flows. High-resolution solar observations, such as planned for the ATST[22], and realistic MHD modeling[23] can significantly improve our understanding and description of these processes. This requires the development of advanced spectro-polarimetric techniques for observations and of sub-grid MHD turbulence models for modeling.

3.2 How is magnetic field generated and circulated?

In astrophysical objects, dynamo action can exist in plasmas with a seed magnetic field and flow fields. However, sufficient conditions for dynamos are not well-determined. For solar and stellar physics it is particularly important that dynamo processes can result in a cyclic behavior. Mean-field MHD theories of solar and stellar dynamos predict the cyclic behavior, which resembles the observed properties such as the butterfly diagram for sunspot formation zone and polar field polarity reversals. However, our understanding of the underlying physical processes is still schematic.

The standard Parker's $\alpha-\Omega$ mechanism[24] has been applied to the Sun and a wide range of other astrophysical objects, stars, galaxies, interstellar medium. The success of this beautiful theory hinges on the turbulent properties, magnetic and kinetic helicities and diffusivity. However, direct numerical simulations, developed during the past decade, revealed significant limitations, such as the catastrophic helicity quenching, which severely restricts the magnetic field growth[16]. The potential solution is in studying the helicity balance including large-scale circulations and helicity loss through coronal mass ejections[26]. This study requires detailed observations of the solar interior, magnetic field and coronal dynamics over the whole solar cycle. Such observations are planned for the SDO mission scheduled for launch in 2009, but only for a portion of the solar cycle. It is extremely important to extend the operation and data analysis support for this mission. It is particularly important to understand the mechanism of the cyclic polar field reversals revealed in synoptic ground-based observations during the past three sunspot cycles. Because the Sun's axis is almost perpendicular to the ecliptic our knowledge of the polar magnetic field structure and dynamics is very poor. The best opportunity to gain this knowledge can be provided by out-of-ecliptic solar missions, which are currently under discussion and evaluation[25].

3.3 How does magnetic field act on plasma and form self-organized structures?

One of the puzzling features of solar magnetism is the multi-scale spatial and temporal behavior. High-resolution observations reveal that the magnetic field on the Sun's surface is very structured and consists of small, rapidly evolving magnetic elements, the ultimate scale of which is still unresolved. These elements form active regions and sunspots, which seem to emerge randomly. At the same time, the solar magnetic fields show a remarkable degree of organization on the global scale, displaying the 'butterfly' diagram and polarity reversals quite regularly with 11-year cycle. The recent breakthrough in understanding self-organization processes in plasma experiments offer a clue that the mechanism of self-organization is in the interaction between large-scale flows and turbulence. For instance, shearing flows can stretch turbulent eddies and reduce turbulent dissipation and transport in particular directions resulting in localization of flows and magnetic structures. This discovery encourages further development and search for similar mechanisms in astrophysical plasmas where organized self-maintained structures of various scales are common.

4 Major projects

4.1 Advanced Technology Solar Telescope: studying properties of magnetized turbulence and building blocks of solar magnetism

We expect that most of the progress in observational studies of turbulent properties and formation of magnetic structures in the solar plasma will be made in high-resolution observations with large ground-based telescope, such as ATST. These observations require sophisticated instrumentation for high-spectral resolution and multi-wavelength spectro-polarimetry, and also sufficient photon flux for the scattered polarization analysis, necessary for studying unresolved magnetic elements. This type of measurements will make a real breakthrough in our understanding of the nature of the solar magnetism.

4.2 Solar Dynamics Observatory: imaging magnetic structures and dynamics inside the Sun

Solar Dynamics Observatory will provide, for the first time, continuous monitoring of the solar interior, surface magnetic fields and coronal structures with a resolution sufficient to investigate the emergence of magnetic flux, formation and decay of sunspots and active regions, their coronal activity, and most importantly, links between these local magnetic structures and global dynamo processes. This mission will provide tremendous amount of data (2TB a day) and has a huge discovery potential. Unfortunately, the budget for this mission is planned only for 3-5 years of operation. For the data analysis only two groups with the annual budget of $700k are organized. This is grossly insufficient. This mission needs more attention and support. In addition, it is very important to modernize the helioseismology network GONG and prepare it for continuing the monitoring of the physical conditions inside the Sun after the end of the SDO mission.

4.3 Out-of-Ecliptic Solar Mission: studying the global field polarity reversals

Two out-of-ecliptic solar missions are being actively studied and have a chance of being developed and launched during the next decade. These are the European Solar Orbiter and the Japanese Solar-C (Plan A) mission. They will provide an important insight into the structure of polar magnetic fields and the mechanism of polarity reversals. The polar fields are largely unipolar, and it was believed that the polarity reversals result from a diffusion or circulation process of magnetic flux transport from the low-latitude zone where the flux emergences. However, recent high-resolution observations from Hinode showed that the polar fields are highly structured, and, while the mean polar field is only a few Gauss, the field in these elements is very strong[13]. This discovery challenges the flux transport models, and opens a new opportunity of studying the relationships between the structurization and global field reversals. The out-of-ecliptic missions will also improve our knowledge of the large-scale convection, differential rotation and meridional circulation, which are the key ingredients of dynamo models.

4.4 Synoptic Magnetographic Observations: investigating long-term behavior of the solar dynamo

Most of our current knowledge about the solar dynamo has come from the synoptic observations of magnetic fields and Doppler velocities on the solar surface carried out during the past three cycles. These observations have revealed the general picture of the Sun's magnetic structure and dynamics, spatial-temporal magnetic organization in the form of long-living complexes of activity, migrating zonal shearing flows associated with flux emergence zones. These observations also provide data necessary for predicting future sunspot cycles. This global picture needs to be integrated with the detailed helioseismic data anticipated from SDO and numerical models. Thus, it is extremely important to continue these observations. In the current era of space missions and fast publications these long-term observational projects are often undervaluated. However, the characteristic period of the Sun's magnetic cycles is 22 years. Thus, for solving the dynamo problem it is very important to maintain the current synoptic observations, at least, at three observatories, MWO, WSO and NSO/SOLIS, keeping their unique features and calibrations. Otherwise, we will loose track of the solar magnetic cycles.

4.5 Realistic Numerical Simulations: modeling dynamo and magnetic self-organization

Our physical understanding of the complex turbulent MHD phenomena comes mostly from numerical simulations. The modern simulation codes include all essential physics from first principles and are very powerful and efficiently run on parallel supercomputers. Of course, small turbulent dissipation scales are not resolved. Their modeling requires developing subgrid turbulence models, particularly, for the MHD case. The subgrid models are usually tested by using simplified simulations of fully resolved turbulence. However, there is an opportunity of developing a synergy between the modeling and the high-resolution ATST observations, and actually test and calibrate the turbulence models for realistic astrophysical conditions (as is done in engineering fluid mechanics through the use of laboratory experiments). During the next decade the numerical simulations will focus on modeling the entire dynamo process without mean-field assumptions[15], and together with the ATST, SDO and synoptic observations and analyses they will substantially advance the understanding of the solar dynamo problem. The simulations are also capable of providing a more detailed knowledge of the formation of self-organized magnetic structures in the solar plasma. The recent initial attempts to model the entire filamentary sunspot structure are quite encouraging[21].

5 Summary

The recent progress in helioseismic and spectro-polarimetric observations and realistic MHD simulations provides an opportunity of substantially advancing our understanding of the physical mechanisms of magnetic field generation and formation of magnetic structures on the Sun. This opportunity is based on the following main components: Advanced Technology Solar Telescope, Solar Dynamics Observatory, an out-of-ecliptic solar mission, ground-based synoptic observations, and MHD simulations. The realization of this opportunity will be beneficial for many fields of astrophysics, involving magnetic phenomena.

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