CHAPTER 2.4

VARIABILITY AND EFFECTS BY SOLAR WIND

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1 Average structure of solar wind

A stream of charged particles, called the solar wind, continuously flows from the Sun into the interplanetary space. Solar wind carries with it the magnetic field of the Sun, which is called the interplanetary magnetic field (IMF) or the heliospheric magnetic field, reflecting the fact that the region of space dominated by the Sun via the solar wind and IMF is called the heliosphere (*helios* = Sun in Greek). While the solar wind is flowing radially away from the Sun, the magnetic field is turned to a spiral structure due to the rotation of the Sun, much in the same way as the water running out from a rotating garden hose.

The time of the solar wind to reach the Earth at its typical speed of about 400 km s^{-1} takes about 4 days. While expanding into open space, the solar wind gets diluted, and at the Earth, solar wind is already a very tenuous gas, containing only some of 5–10 particles per cubic centimeter. During this expansion, the solar wind cools down roughly by a factor of ten from the initial temperature of a couple of million degrees of the solar corona. The strength of the IMF also weakens from the Sun to the Earth to about 5 nanoTesla, which is only one in ten thousand when compared to the Earth's magnetic field on the ground. Most of solar wind energy is in the form of kinetic energy related to its anti-solar motion, with smaller contributions in thermal and magnetic energy.

The properties of the solar wind and IMF vary significantly, reflecting the nature of their coronal source. The solar wind can be roughly classified into two groups: the slow solar wind and the fast solar wind. The fast solar wind (faster than about 500 km s^{-1}) originates from large regions of solar corona that are seen as dark when viewed in normal light. Darkness is due to the low density of these regions. These rather empty regions of solar corona are called coronal holes. The low density results from the specific magnetic structure of these regions, which opens directly into space, having no magnetic loops that can contain high densities

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of plasma particles. Obviously, solar wind can better be accelerated to high speeds within the open field lines of large coronal holes. However, the reason to this preference is not yet very well understood and remains a topic of intense research. On the other hand, the slow solar wind originates from the proximity of solar active regions. Since these regions are fairly dense, slow solar wind is also denser than fast solar wind. The magnetic structure of those regions of solar corona emitting slow solar wind is rather complicated, and the field tends to experience non-radial expansion. The speed difference also affects the winding of the IMF spiral, which is more tight for slow solar wind.

The properties of the solar wind and IMF are continuously changing, from very short time scales below one second to intermediate scales of several hours to one solar rotation (about 27 days), and to long time scales of a solar cycle (about 10–11 years) up to a century and even beyond. The short time scale variations mainly develop during the interplanetary space, while the intermediate scales mainly reflect the momentary distribution of solar active regions on solar surface, and the longer time scales reflect the changes in solar dynamo during the solar cycle and longer. The daily averaged values of solar wind speed vary roughly by a factor of five from about 200 to 1000 km s^{-1}. All other solar wind parameters vary even more, especially the solar wind density and the IMF strength, which can vary by two orders of magnitude, reaching their highest values in interplanetary shocks.

2 Solar wind transients

On top of the average solar wind, various temporary phenomena and processes can significantly modify the properties of the solar wind. One can divide these phenomena in two groups: those that have their origin in the Sun and those that develop during the solar wind flow in the interplanetary space. Of the latter, the most important phenomena are the corotating interaction regions (CIR), which are interplanetary shocks that form as a result of the collision of fast and slow solar wind streams. When the fast solar wind stream attains the preceding slow solar wind, it cannot overtake it because the magnetic fields of these two regions strongly oppose mutual mixing. So, instead of a smooth change of solar wind parameters, the two regions form sharp boundaries over which the solar wind parameters vary dramatically. Since the two different solar wind streams often have opposite magnetic polarities, the CIR also typically includes an IMF sector boundary.

Since the source regions of IMF of opposite polarity are typically located rather far from each other on solar surface, the time difference between the fast and slow streams is several days, and the CIR is formed only rather far away from the Sun. Indeed, most CIRs develop beyond the Earth's orbit. The term corotating refers to the fact that the CIRs tend to appear repeatedly, once per solar rotation, as if the CIRs would rotate with the Sun. This repeating pattern takes place because the global solar magnetic field structure, which is produced by

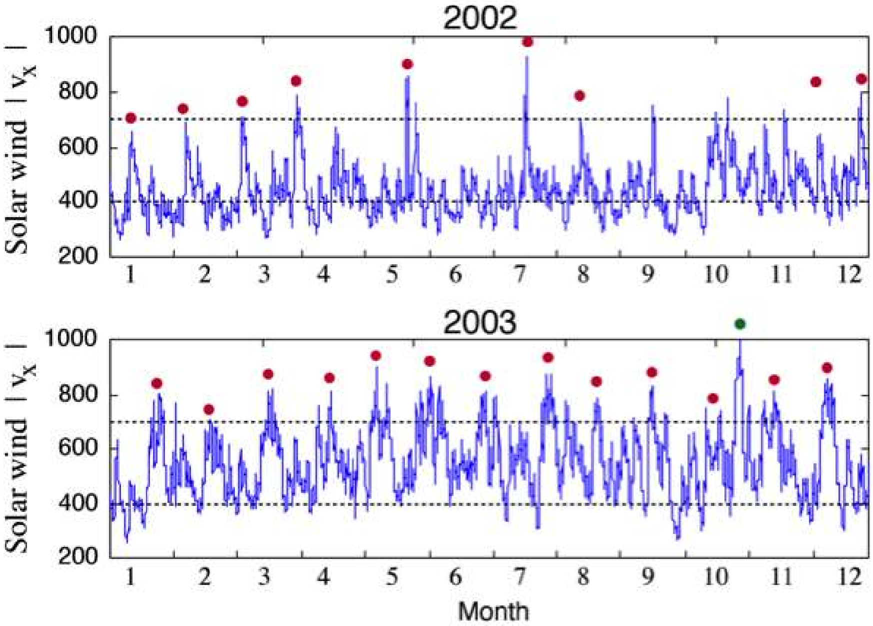

Fig. 1. Periodic high-speed streams from the solar coronal holes in 2002 and 2003. The same solar source region emits fast solar wind towards the Earth repeatedly at the 27-day rotation period of the Sun.

coronal holes and active regions, tends to remain roughly similar during several solar rotations. Figure 1 shows the repetition of high-speed solar wind streams at 27-day intervals during most of the years 2002 and 2003. CIRs are typically found to hit the Earth in the declining phase of the solar cycle, when the polar coronal holes are expanding and have an asymmetric structure in solar longitude. They often have an extension from the pole towards the equator, which can emit fast solar wind at low solar latitudes, thus reaching the Earth. When the production of new flux stops at the end of the cycle, the polar coronal holes become more symmetric and the high-speed streams become again more rare at the Earth. During sunspot maxima, there are active regions all over the solar surface, thus no large coronal holes exist.

The solar originated transients include, in particular, interplanetary coronal mass ejections (ICME) and solar flares. Solar flares can accelerate a fair amount of solar particles to very high energies, forming a burst of solar energetic particles (SEP), also called solar cosmic rays. However, the number of SEPs is rather small and, because of their high energy, they do not behave similarly as the solar wind particles. Therefore flares do not contribute much to the properties of the solar wind, and we will not discuss flares or SEPs in more details here.

Coronal mass ejections are large coronal loops with a huge amount of solar material, which burst into space typically during a few hours. These particles have roughly the same energy as solar wind particles, so they can become part of solar wind in the interplanetary space. Moreover, the ICMEs include so many particles that they can dominate over the background solar wind and thus determine its properties. ICMEs can be faster or slower than the ambient solar wind but, during the interplanetary travel, the ICME speed tends to approach closer to the speed of the backgound wind. Very fast and strong ICMEs, however, do exist and can reach the Earth even in less than one day, as during the famous Carrington storm in 1859.

Since the ICMEs are large loops of magnetic field, which can pertain their structure even in the interplanetary space, the magnetic field observed at the Earth's orbit during ICME passage can be very differently oriented than the background IMF structure. A typical core of a ICME is a magnetic cloud, a dense magnetic flux tube, where the field lines are twisted and tied to the Sun on one or both legs. Note also that fast ICMEs produce a leading shock ahead of them, which is followed by a sheath region of very turbulent field and solar wind until the ICME core arrives. Since ICMEs are related to sunspots and the appearance of new flux tubes on solar surface, they tend to maximise around the sunspot maximum.

3 Solar wind and the Earth

Solar wind affects the Earth's magnetic field, compressing the field on solar side and forming a comet-like tail in the nightside. Solar wind sustains a complicated and extremely variable system of electric fields and currents in this magnetic cavity, the Earth's magnetosphere, and in the ionosphere. The electric fields also accelerate magnetospheric particles (which partly come from the solar wind) and make some of them precipitate into the atmosphere. Overall, there is 10^{13} W power in the solar wind, of which about 10–20% is used to maintain the shape and basic convection of the magnetosphere. Accordingly, the solar wind power is much smaller than, e.g., the power of solar electromagnetic radiation, whereby its possible climatic effects were originally assumed to be minor.

The most important factor controlling the rate of energy input from the solar wind to the near-Earth space is the IMF orientation. Energy input increases as the IMF becomes increasingly antiparallel (southward IMF) to the equatorial geomagnetic field. Then, large scale merging or reconnection of magnetic field lines can take place, producing important electric fields and accelerating particles effectively. The energy input is enhanced by fast speed and high density of the solar wind, as well as by strong IMF. Moreover, the role of the ultra-low frequency (ULF) waves, also called Alfvén waves, in possibly enhancing the magnetic coupling, is under active study. Alfvén waves, which are more often found in the high-speed stream, may amplify the north-south IMF component and thereby the dayside reconnection electric field.

The charged particles precipitating into the atmosphere collide with the ambient neutral air at heights depending on their energy, the auroral particles at around 100 km and the more energetic particles down to about 50 km. The collisions ionise the atmosphere, thus contributing to the formation of the ionised layer called the ionosphere (which is mainly produced by solar EUV radiation). Most of the kinetic energy of the precipitating particles is converted to the thermal energy of the neutral air. Joule heating dissipates some 10^{15} J of energy during substorms, the majority of the energy available from the solar wind. In addition, the precipitating particles turn on the auroral lights. Most of this energy to all the three forms is dissipated by electrons while ions contribute less.

High-speed solar wind streams and CIRs are known to be particularly effective in accelerating magnetospheric particles. Therefore the declining phase of the solar cycle seems to be the most effective time interval for solar wind-related atmospheric effects, both to the ionised and to neutral air. Interestingly, there is increasing evidence that the high-speed solar wind streams, by accelerating and precipitating charged particles into the atmosphere, can produce significant chemical and dynamical changes in the atmosphere. In particular, they can produce NO_x and HO_x molecules which can descend into the middle atmosphere where they cause massive ozone destruction. This may further cause enhanced meridional circulation, creating a stronger polar vortex and a positive phase of the North Atlantic Oscillation. Indeed, recent studies show that the positive phase of the NAO prevails in the declining phase of the solar cycle and affects the arctic Winter temperatures strongly. These relations and effects are currently under active study.

CHAPTER 2.5

VARIATIONS OF SOLAR ACTIVITY

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1 Introduction

Solar activity is the sum of all phenomena driven by the Sun's magnetic field. These cover a very wide range of features and events and include dark sunspots seen on the solar surface, as well as powerful flares, often emitting energetic particles and high-energy radiation, or coronal mass ejections, eruptions of hot matter (10^4–10^6 K plasma) and magnetic field.

Solar activity varies on all observed timescales: from short term (e.g. when an active region, with its sunspots and associated flares, appears on the solar disk) to long-term, most prominently over the 11-year activity cycle. We are lucky to have had many generations of assiduous solar observers who followed the solar cycle with great care and dedication for over 400 years. This has given us unique insight into how solar activity varies over time. In recent decades, techniques to follow solar activity even further back into the past have been developed that make use of the fact that the ups and downs of the Sun's activity can leave traces on Earth. At the same time, our understanding of what causes the Sun's activity to vary has been steadily improving, although we are still far from gaining a full understanding. Thus, there are still many open questions regarding how well we can predict solar activity.

2 The solar activity cycle and its variations

Roughly every 11 years the strength of solar activity increases, reaching a peak and then decreasing again until a minimum in activity is reached. After this, the cycle starts again. Over such a solar activity cycle (often called a solar cycle, or

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a Schwabe cycle, after its discoverer, Heinrich Schwabe), the atmosphere of the Sun changes dramatically. For example, between activity minimum and maximum the number of sunspots, dark structures on the solar surface with a size of typically a few 10 000 km characterised by a strong magnetic field reaching multiple 1000 Gauss (compared to the Earth's dipole field smaller than 1 Gauss), vastly increases, as does the coverage by plage regions (bright areas associated with a strong magnetic field, which, however, is weaker than that of sunspots), the number of solar flares, which are outbursts of energetic radiation (X-rays, gamma-rays and sometimes high-energy charged particles), and the number of coronal mass ejections. Even the brightness and shape of the whole solar corona changes. Thus, the corona at activity maximum is brighter and hotter and surrounds the whole Sun, just like a crown, from where it gets its name. Importantly, also the total radiative output of the Sun, the so-called solar irradiance, changes over the solar activity cycle, with the Sun being slightly brighter during activity maximum (see Chapter 2.2 of this handbook).

Solar activity in general is driven by the evolution of the Sun's magnetic field. This magnetic field is structured on small scales, but also displays large-scale patterns. The amount of magnetic flux correlates with the level of solar activity, but consecutive cycles display a reversal of the magnetic polarities. For example, if in one cycle bipolar active regions in the northern hemisphere tend to have positive polarity leading the negative polarity, then in the next cycle, the negative polarity leads the positive. The situation is antisymmetric with respect to the solar equator (Figure 1). Thus it takes two activity cycles, i.e., roughly 22 years, for a full magnetic cycle to complete, so that the magnetic polarities return to the original configuration. This ≈22-year cycle is often called the Hale cycle, after George Ellery Hale, who was one of its discoverers.

Many manifestations of solar activity have been studied during the space age (i.e., since the 1960s) thanks to modern instruments, in particular those flying in space, which also record radiation at wavelengths that do not reach the ground (such as ultraviolet and X-ray radiation). If we go increasingly further back in time, fewer such records are available, until we are left with just the number of sunspots visible on a given day, scrupulously counted by professional and amateur astronomers starting with Harriot, Galilei, Fabricius and Scheiner around 1610 AD, i.e., basically ever since the first telescopes were available. This so-called sunspot number record reveals (Figure 2):

1. Although the sunspot cycle is remarkably stable, solar activity is not periodic, but cyclic, i.e., the individual cycles have somewhat different lengths (ranging roughly between 9 and 13 years) and often very different amplitudes. Solar cycles are numbered, starting in the middle of the 18th century.

2. The last 400 years have been dominated by cyclic activity, but the activity level has varied a lot with time, implying the additional presence of secular variability. For example, the period 1645–1700 was characterised by an almost total lack of sunspots. This so-called Maunder minimum (named after

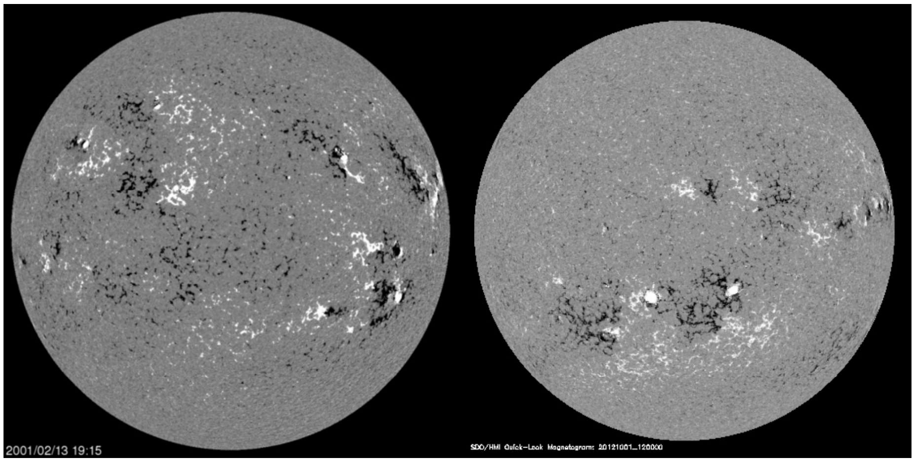

Fig. 1. HALE'S POLARITY LAW. Magnetograms showing the strength and distribution of the photospheric magnetic field (bright shading represent increasingly strong magnetic fields pointing out of the solar surface, dark shading increasingly strong magnetic fields pointing into the solar surface), measured with the SOHO/MDI and SDO/HMI instruments. The magnetogram on the left was measured in February 2001, near the maximum of cycle 23, the magnetogram on the right in October 2012, near the maximum of the current cycle 24. The leading and trailing spots of the nearly east-west (left-right) aligned bipolar structures are of opposite polarities, the pair showing different polarity on each hemisphere at any instant. Between two consecutive sunspot cycle maxima, the polarities on both hemispheres are reversed. Data credit: the SOHO data archive, ESA/NASA.

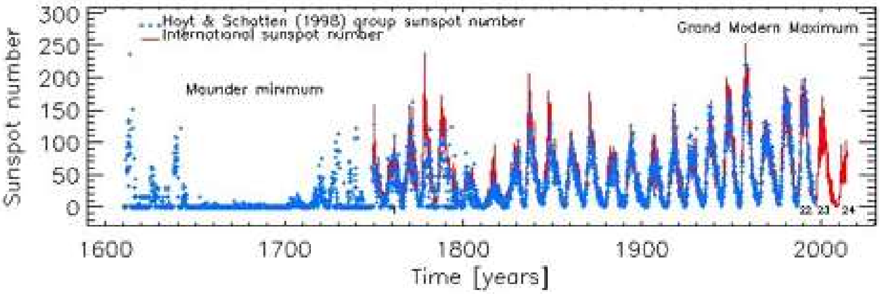

Fig. 2. SUNSPOT CYCLE. Monthly averaged group sunspot number (blue symbols) and the international sunspot number (red line) as function of time during the telescope era showing the 11-year sunspot cycle and its variations. The most notable epochs are the low activity state, Maunder minimum, with hardly any spots, and the current high state, Grand Modern Maximum. The current cycle 24 is the weakest for a century. Data credit: D.V. Hoyt and K.H. Schatten (blue crosses) and WDC-SILSO, Royal Observatory of Belgium, Brussels (red line).

Edward Walter Maunder) was not just an artefact caused by a lack of observations. Many observers looked hard, but could not find spots on the Sun. This indicated the extreme quietness of our star at that time. The other extreme in solar activity was reached in the second half of the 20th century, the modern Grand maximum. Solar cycle 19 was the strongest observed so far. The current cycle with the number 24 is to date the weakest cycle for nearly a century, indicating that the modern Grand maximum is coming to an end.

3 Solar activity on longer time scales

For many purposes, even the 400-year long dataset of telescopically measured sunspot numbers is too short, leaving open, e.g., the question of how typical are the changes in the solar activity level witnessed during the era of the telescope.

Unfortunately, quantitative and regular direct observations of the Sun do not exist for times prior to the 17th century. But luckily there is another method, based on cosmogenic radionuclide proxies, which makes it possible to reconstruct solar activity in the past, before the telescope era. Cosmogenic radionuclides (the most famous being ^{14}C or ^{10}Be) are produced by cosmic rays in the Earth's atmosphere.

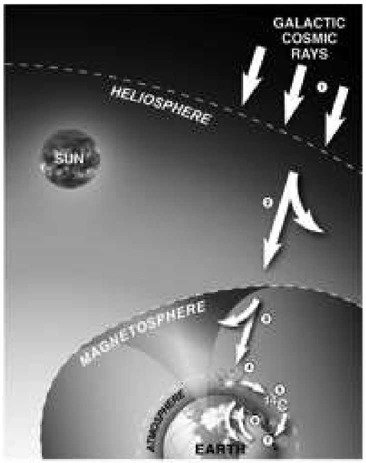

Fig. 3. A SKETCH OF THE MODULATION PROCESS. Artistic view of the link between ^{14}C record and solar activity, not to scale (credit to Dyon, Hulot and Gallet, IPGP). Galactic cosmic rays with roughly constant flux (item 1) enter the heliosphere and are modulated by solar magnetic activity (2) and by the geomagnetic field (3). Cosmic rays cause nuclear collisions in the Earth's atmosphere producing, in particular, radiocarbon ^{14}C (4), which takes part in the global carbon cycle (5) and finally is stored in a tree (6). By measuring ^{14}C in a tree sample dated to the past, one can assess the atmospheric ^{14}C production rate Q at that time. Using a physical model of ^{14}C production combined with an independent model of the past geomagnetic field, the production rate Q can then be converted into information about past solar activity.

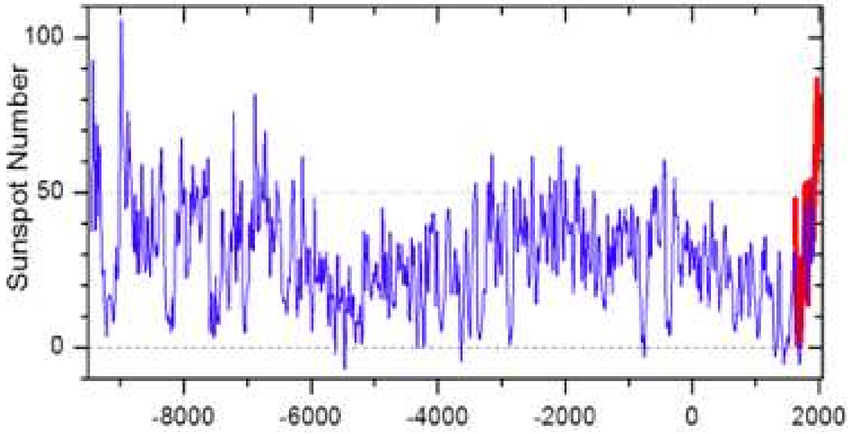

Fig. 4. RECONSTRUCTED SOLAR ACTIVITY. Sunspot number (10-year averages) reconstructed from ^{14}C data since 9500 BC (blue curve) and 10-year averaged group sunspot number (GSN) obtained from telescopic observations since 1610 (red curve). The horizontal dotted line marks the threshold above which we consider the Sun to be exceptionally active.

After production they are stored in natural stratified dateable archives (such as trees, polar ice, corals or lake/marine sediments) and their concentrations can be measured in specialized laboratories. Cosmic rays that produce the nuclides are modulated by solar activity, so that stronger solar activity leads to weaker cosmic ray flux and vice-versa. Thus, by measuring, in a modern laboratory, the concentration of a cosmogenic nuclide in an archive sample, one can reconstruct solar activity at the time when this sample was formed. For example, determining the amount of ^{14}C (a heavier radioactive isotope than normal carbon ^{12}C) in the trunk of a dead tree tells us how strong the cosmic ray flux was at the time that this tree lived (this time can be determined by dendrochronology from the pattern of tree rings). This in turn is related to the strength of solar activity at that time (for a sketch of the modulation process (Figure 3).

Solar activity reconstructed in this way from cosmogenic nuclides for the last eleven millennia of the Holocene period (Figure 4) demonstrates strong variability, with Grand minima and Grand maxima appearing every now and then. Grand minima (periods of very low activity, like the Maunder minimum in the 17th century) correspond to a very special state of solar activity that occupies about 1/6 of the time. Grand maxima correspond to periods of unusually high activity, as in the second half of the 20th century, and occupy about 1/10 of the time. Present day activity, since 2006, is moderate, comparable to the Sun's state during most of the past 11 000 years, suggesting that the modern Grand maximum is ending.

A thorough analysis of the reconstructed activity suggests that such periods of extreme activity occur irregularly. Although some quasi-periodicities can be found, solar activity contains a significant random component in the long-term variability. Occurrence of Grand minima and maxima cannot be predicted in a deterministic manner, only in a probabilistic sense.

CHAPTER 2.6

UNDERSTANDING SOLAR ACTIVITY

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1 Introduction

While in the interior of the Sun the energy released in nuclear reactions is transported outwards mainly by radiation, in the outer 30% of our star the main energy transport mechanism is convection. This means that the fluid heated from below becomes unstable, rising and sinking bubbles are generated, and they transport heat by their motions (Figure 1). The conditions in the solar convection zone are such that the motions of the bubbles are highly turbulent, which essentially means that the matter in the convection zone is very efficiently mixed and structures at various scales (large and small) occur simultaneously. Being subject to such vigorous stirring, the strong magnetic fields concentrated during the process of the collapse of the molecular cloud leading to the formation of the Sun 4.6 billion years ago, were destroyed on a time scale much shorter than the current age of the Sun. Therefore, to explain the solar magnetic fields observed today, the magnetic field must be actively produced and regenerated by some process.

2 Solar dynamo

Such a process is provided by the inductive effect due to the moving ionised plasma in the convection zone, similar to the electromagnetic induction effect of a current flowing in an electric wire inducing magnetic field around it. The plasma motion has different sources. The first is solar rotation, which has a different angular velocity at different latitudes and also at different depths, which is referred to as differential rotation. The effect of this part of the solar flow field is to wind up any magnetic field oriented poleward (called poloidal magnetic field) into the so-called

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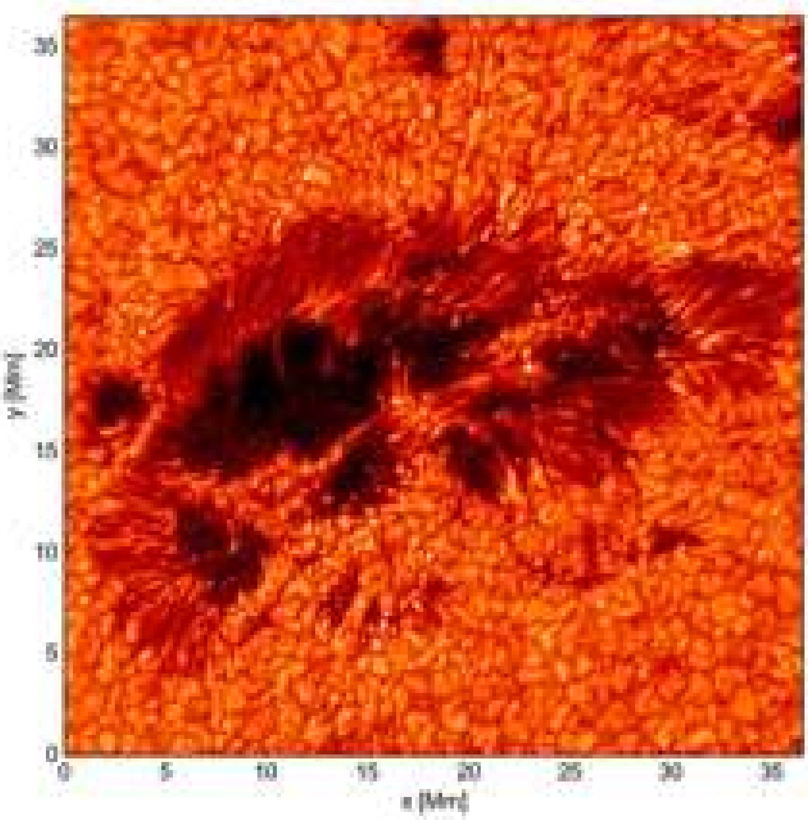

Fig. 1. TURBULENT CONVECTION. Active region observed on June 14, 2013 with the Broad Band imager at the GREGOR telescope at the Teide observatory on Tenerife (Spain). Turbulent convection is seen in the solar photosphere as a granulation pattern, which looks like a huge boiling water kettle: hot rising bubbles (brighter orange regions) are surrounded by cooler, narrow downflows (darker orange patches). In active regions, the strong magnetic field inhibits convection, suppressing the heat transport. Therefore, strongly magnetised regions appear as dark features in the photospheric image. Their sizes usually greatly exceed the typical size of a granule. Image credit: the GREGOR consortium.

toroidal field with field lines oriented along the longitude (see two leftmost panels of Figure 2) at the same time stretching out the field and thereby amplifying it. This process is called the Ω effect.

The rising convective bubbles become twisted by the Coriolis force induced by rotation, and as a sum over all the bubbles, this produces a net effect that results in small loops of magnetic field that have regained their original poleward orientation but with a reversed sign. This is called the α effect (third panel of Figure 2).

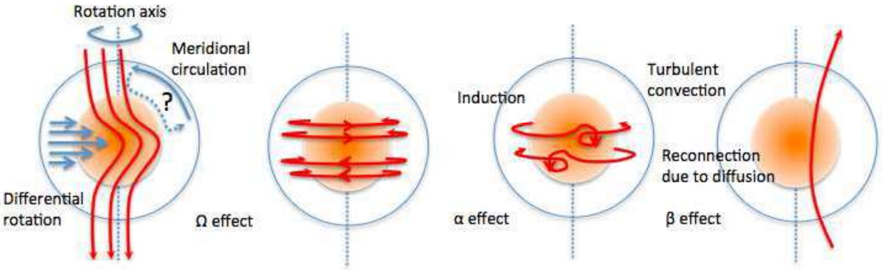

Fig. 2. DYNAMO. Schematic presentation of the dynamo cycle due to the inductive action of large-scale flows and convective turbulence according to the distributed dynamo paradigm. In flux-transport dynamo models, the field generation is localized in the bottom (Ω effect) and surface (α effect) of the convection zone. The single-cell meridional circulation pattern still lacks confirmation, indicated by the question mark in the leftmost image. In the distributed dynamo framework, field generation and destruction by turbulence occur throughout the convection zone.

With the help of the powerful turbulent mixing, called the β effect, the small loops form larger and larger ones, and finally the original, global configuration with a reversed sign is obtained (the rightmost panel of Figure 2). This process is called the hydromagnetic dynamo. One more important component of the solar flow field is meridional circulation, carrying matter and magnetic field between the polar and equatorial regions. This flow field is not a strictly required ingredient for the dynamo process to become operational, but it significantly affects it. Although at present dynamo theory is widely accepted, many details of the solar dynamo process remain uncertain.

The differential rotation profile inside the Sun is known from helioseismic studies, which indicate that most of the winding up occurs in a region localized in the bottom of the convection zone, at the interface between the fixed rotation of the solar radiative zone and the differential rotation of the solar convection zone. Helioseismology also yields information on the meridional circulation profile, although the deep-down circulation pattern is still unknown. There is a poleward directed flow near the surface, but the depth and structure of the return flow are still under debate (see the leftmost panel of Figure 2). The remaining task is to describe the inductive and destructive effects caused by the turbulent convective bubbles. These are not accessible by analytic treatment or laboratory experiments under realistic conditions. Therefore, computer simulations of turbulent convection remain the primary tool for their investigation (Figure 3). Such modelling is also very demanding, and therefore current solar dynamo models still commonly use simple parameterisations of turbulence. The problem with such an approach is that very different types of profiles and magnitudes for the turbulent quantities can satisfactorily reproduce the properties of the 22-year magnetic cycle, such as the butterfly diagram, which represents the time evolution of the surface magnetic

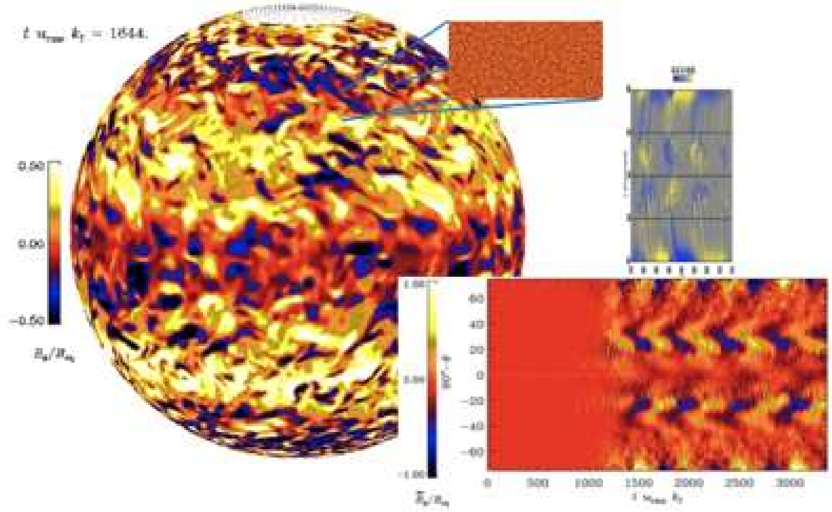

Fig. 3. DNS MODELS. DNS models of turbulent convection have recently reached into parameter regimes in which solar-like oscillatory dynamo solutions emerge. In these models, a large-scale magnetic field, one realization of the azimuthal magnetic field near the surface of the simulation domain shown on the spherical surface, is generated. The much smaller spatial scale of turbulent convection is shown (from another local DNS simulation) in the top right corner. The magnetic field evolves over time similarly to the solar magnetic field (butterfly diagram from the dynamo simulation shown on the lower right corner while the observed magnetic butterfly diagram in the middle). These simulations have been carried out with the PENCIL CODE. Image credit: Petri Käpylä, Maarit Käpylä and Axel Brandenburg (for the simulation pictures) and D. Hathaway/NASA/NSSTC (for the magnetic butterfly diagram).

field as function of time. More information of the unknowns need to be collected to pick up the model best describing the underlying physics, in which task the simulation models play a crucial role.

The presently dominant dynamo paradigm – flux transport or Babcock-Leighton type dynamo models – explains the solar cycle with two localized field generation regions, one being the layer of strong differential rotation near the bottom of the convection zone, and the other a field amplification region near the surface through the release of magnetic flux due to sunspot decay. The two layers are connected in two ways: the wound-up field is transported to the surface from the low-latitude deep layers by buoyant thin flux tubes that become twisted by

Coriolis force, while a counter clockwise conveyor belt of a single-cell meridional circulation pattern brings the generated poleward-oriented magnetic field back to the bottom, first passing through the polar regions. In the majority of these models, turbulence is regarded largely unimportant, which, among other things, implies weak mixing and a "memory" of the magnetic field over several cycles. The competing theory, the distributed dynamo scenario, postulates turbulence important throughout the convection zone, leading to shorter memory and to the fact that the meridional circulation plays a somewhat less crucial role for the results. The flux-transport dynamo models have been developed up to a point, where they have been regarded reliable enough to be used in the prediction of forthcoming solar activity (although with mixed results), whereas distributed dynamos practically lack prediction capability due to the strong turbulent mixing causing too short memory for the dynamo.

The existence of longer-term variations in the solar activity are poorly explained by either of the dynamo paradigms. The general nature of the system of equations describing the solar dynamo naturally favours the existence of chaotic solutions in the highly non-linear regime, where the Sun is inevitably operating. Nevertheless, it is still unclear which are the exact physical mechanism(s) behind the irregular behaviour; among other things, stochastic variations in the turbulent quantities and subtle nonlinear changes in the differential rotation and/or the meridional circulation have been proposed.

3 Can we predict future solar activity?

Reconstructing solar activity in the past is an important area of research and is one of the main sources of constraints on dynamo models describing the origin of solar magnetism and activity. However, for many purposes, it would be even better to predict solar activity into the future.

A few techniques have been applied. Thus, once a cycle has already started, Waldmeier's rule can be used, which says that the more steeply a cycle rises the stronger it will be. This technique can be applied typically 2–3 years into the future. For longer-term predictions, the more successful techniques are similarly empirical and use so-called precursors to determine the strength of the next cycle. A typical precursor is the strength of the magnetic field around the poles of the Sun during the minimum between two activity cycles. The more magnetic flux is present around the poles at activity minimum, the stronger the next solar activity cycle tends to be. Other techniques have typically met with less success.

One such attempt has been the usage of flux-transport dynamo models for long-term prediction of solar activity. Two main data assimilation schemes have been used, one in which the surface source term follows the sunspot number records, and another one where the modelled field is rescaled with the polar dipole field during the minimum. These methods were used to predict the current cycle 24 before it started, with conflicting results: better success was obtained with the polar dipole field method with higher turbulent mixing, while the models based on sunspot data and low turbulent mixing resulted too high activity level. At present, therefore, the prediction capability of dynamo models is still poor, and limited by the fact that the solar cycle is a result of nonlinear processes operating in the chaotic regime.

One limitation of precursor techniques is that they can roughly predict only the next solar cycle, but have little power to predict the strengths of cycles beyond that. Other techniques that claim to be able to predict on a longer term still have to demonstrate if their claims have any validity. Numerous statistical studies indicate that solar activity cannot be predicted longer than one cycle ahead because of the essentially stochastic/chaotic component. This is also supported by the direct numerical simulations of solar convection that consistently yield turbulent diffusion times of the order of the solar cycle length.