IL NUOVO CIMENTO **42 C** (2019) 2
DOI 10.1393/ncc/i2019-19002-5

Colloquia: SoHe3 2018

Attracted by the fascinating magnetism of the Sun

G. Nigro
Dipartimento di Fisica, Università della Calabria - P. Bucci 31C, 87036 Rende (CS), Italy

received 28 December 2018

Summary. — The Sun is a quite active star, where still enigmatic phenomena characterize its life. This one is modulated at large scales by a remarkable degree of order (11-yr cycle and other superimposed cycles) even if the regenerating convective source of the whole magnetic activity is characterized by a chaotic and turbulent behavior. Several aspects of the solar magnetic activity are still not completely understood, such as the time-length of cycles, the dependency of the activity on the latitude, the actual role of the tachocline with the exact location of the dynamo regenerating sources. Here the solar dynamo problem is reviewed in the light of recent developments in theories and observations. In particular, global spherical simulations of convective dynamos and numerical experiments on Parker dynamo waves will be discussed. This latter are recently drawing a possible way for an unitary view of both large-scale and small-scale dynamo, contrary to the conventional theory that considers these as complementary approaches of the same problem: the astrophysical magnetism.

1. – Introduction

Since the pioneering Hale's work(1908) [1], we have learned that solar magnetism controls and generates many manifestations of solar activity. Stellar magnetism is more accessible in solar observations than in other cool stars, considering also the incoming Parker Probe and Solar Orbiter missions that will give very valuable informations regarding our star and its activity in very close future. Solar magnetic activity is characterized by wide range of temporal and spacial scales encompassing events like solar flares and coronal mass ejections (CMEs), lasting minutes, to long periods on which the basic 11-yr activity cycle (22-yr magnetic cycle) is modulated.

Solar activity shows a cyclic behavior revealed by the butterfly diagram, where a butterfly sunspot pattern, is repeated every $\sim$11 yr. The cycle is irregular in the period, in amplitude because of long term modulations, in rise speed since strong cycles peak early than weak cycles, with other irregularities regarding the field parity like the not perfect synchrony in polarity switching between the hemispheres, a north-south asymmetry etc.

Along the path of solar magnetism knowledges, we passed through hurdles, like Cowling's antidynamo theorem (1933) then masterfully overcame by Parker (1955) [2], and periods of great dynamism, like after the first observations of subsurface structures provided by helioseismology. This revealed the tachocline, a thin shear layer below the convection zone (CZ), then considered fundamental for solar dynamos. Currently a great impetus is coming out from recent observations extended to other cool stars, revealing that the activity-rotation correlation (proxy for the behavior of the dynamo) is the same for both partly and fully convective stars [3]. This finding suggests that the tachocline, very likely absent in fully convective stars, is not a vital ingredient for solar-like dynamos as it has been thought so far. Moreover, numerical experiments of fully convective stars are showing cycles and other solar features without a tachocline [4].

An other important issue, recently considered [5] concerns the classical approach that proposes large-scale dynamo and small-scale dynamo as complementary theories to study astrophysical dynamos. This enduring approach arises from observing that astrophysical magnetic fields are correlated on spatial and temporal scales far exceeding that of the underlying fluid motions. A typical example is the solar cycle.

In this manuscript, after a brief overview of observational constrains, recent advances in numerical modeling of solar dynamo will be discussed. In fact, although numerical models suffer of several limitations like the not ability to reach the extreme dynamical ranges, which are instead typical in solar and stellar dynamics, they are giving important insights into the nature of the interaction of turbulence, shear flows and magnetic fields, which is fundamental for a complete understanding of solar and stellar magnetic dynamos.

2. – Observational Constrains

The most relevant observations we have are the time series of surface magnetic and velocity fields provided by SDO and SOHO. These allow to study solar magnetic field on time scales from minutes to decades, starting from the 23^{th} cycle. Magnetograms provided by Mount Wilson and Wilcox observatory allow to extent records back to the 21^{st} cycle, though within reduced resolution. Moreover, indirect measurements of cosmogenic radioisotopes allow to extent our knowledge of solar activity back to over 9600 yr.

Solar magnetism is generated and sustained by plasma motion, whose observations provide important constrains for dynamo modeling [6]. The interplay of convection and rotation, in the most outer shell of the sun, generates differential rotation (DR) and meridional circulation, which transport magnetic flux and angular momentum in CZ. The helioseismology shows latitudinal shear larger than the radial one, the latter being larger in the tachocline and in the near-surface layer. Time variations of surface DR (torsional oscillations) are revealed as pattern of zonal flow bands migrating towards the equator at low latitudes and poleward at high latitudes. While their sensitivity to the magnetic activity is fairly accepted, their action on magnetic field is less evident since their small amplitude. Finally, meridional motion is measured on solar surface with poleward component, while its subsurface profile is still not very well established [6, 7].

The most important constraints for solar dynamo modeling are related to sunspot eruptions which show well defined roles for emergence latitudes, field parity and a basic cycle with long-time modulations. The butterfly diagram, where sunspots are depicted with their emergence latitudes as the cycle progresses, efficiently summarizes the most relevant sunspots features. In particular it shows the emergence latitudes range, about from $35°$ to $8°$, with equatorial migration, wings overlapping [8] and long term modulations. Moreover, models and simulations need to explain the emergence of sunspots that generally appear in pairs of opposite polarity following Hale's law, with leading spot slightly closer to the equator (Joy's law). Theory has to explain the revealed correlation between polar field, open flux and strength of the next cycle [9] considering also a recent find regarding the correlation of magnetic helicity flux measured on hemispheres during a minimum and the strength of next maximum [10]. This correlation indicates that activity in regions beyond the polar cap is relevant for the progression of solar dynamo. It has been also suggested that the magnetic helicity expulsions by CMEs may play a crucial role in modifying the global topology of coronal magnetic field [11, 12].

3. – Solar Dynamo Modeling

Since the solar magnetic field shows a dual nature both chaotic at small scales and orderly on global scale, it has be supposed the coexistence of two conceptually different dynamos acting on different scales. More precisely, small-scale dynamo, operating in the turbulent upper CZ, generates chaotic magnetic fluctuations evolving on solar surface with little influence by global dynamics. While global dynamo, operating in the bulk of CZ, is responsible of sun activity on global scale with sunspots eruptions manifesting with well defined roles (periodicity, field parity, emergence location and orientation). The current paradigm of large-scale dynamo involves two major components: Ω-effect, describing the generation of toroidal magnetic fields by stretching any existing weak poloidal field via DR, and α-effect, i.e. generation of poloidal magnetic field due to the cumulative action of many small-scale cyclonic turbulent motions in the CZ [2] or/and to the breakup and reconnection of mostly toroidal fields that emerge as active regions (Babcock-Leighton model). There are several dynamo models in the scientific literature [13-15]. Here we limit ourselves to the most recent and important results regarding solar dynamo.

3˙1. *Global models.* – Among global dynamo models, flux transport models are very popular. They acknowledge the Babcock-Leighton model as progenitor, where the meridional circulation is a fundamental ingredient that, being poleward in outer CZ and equator-ward above the core-envelope interface, transports magnetic field as an advection belt. These models produce a magnetic flux behavior suitable to explain the solar surface observations [16]. In spite the important contributions this models are giving, they suffer of some limitations. They are, in fact, kinematic models where the prescribed velocity is not completely probed and they necessarily contain parametrization of different processes.

Probably more realistic models are global 3D convective dynamo simulations. Several groups have developed magneto-convection models, following the work of Gilman(1983) [17] and Glatzmaier(1985) [18], who found cyclic solutions with anti-solar (*i.e.* poleward) migration of toroidal magnetic flux. Then, numerical models of convective dynamos have been proposed employing different codes: Anelastic Spherical Harmonic (ASH) code [19], Eulag MHD code [20], PENCIL code [21], *etc.* These have shown cycles and the correct toroidal magnetic flux migration. They are validated by an international benchmark [22]. Recent simulations of ASH code with high resolution have shown solar-like rotation. These simulations employ a fixed-background stellar structure, solar mass and luminosity, rotating at 3 times the solar rate [23]. There, the magnetic field dynamics is characterized by wreath structures of magnetic flux. In fact, the toroidal field is organized in almost broad ribbons and tubes, which extend essentially along the toroidal direction. Moreover, the wreaths undergo to a poleward migration at high latitudes and equatorial migration at low latitudes during the cycle as consequence of the DR quenching of the Lorentz force. In addition, thanks to a suitable density stratification and sufficiently low Prandtl numbers (viscosity/diffusivity), some of these simulations have produced grand minima, where the system fails to fully reverse its polarity. The occurrence of these minima is very likely due to an interplay of symmetric and antisymmetric solutions.

Other important results have been achieved using Eulag MHD code [24], making magneto-convection simulations in a spherical shell with solar-like aspect ratio, a background stellar structure with rotation and luminosity ranges including solar values. These simulations reproduce 11-yr cycle, equatorial propagation of large-scale magnetic field, solar-like DR, large-scale axisymmetric magnetic field at the CZ bottom.

These global magnetohydrodynamics (MHD) simulations, even in the limitation due to an insufficient resolution to reliably describe solar dynamo, offer the advantage of not needing to parametrize the influence of rotation and magnetic field on turbulence and convection, albeit they contain parametrization of all processes acting on sub-grid scales.

3˙2. *Local models*. – MHD numerical simulations of dynamo mechanism in local approximation have the advantage to reach higher dynamical ranges than the global models, hence allowing to study with more details the turbulent features concurring in developing a large-scale magnetic field. Within this approach we have investigated the limits of the mean-field dynamo theory (MFDT) [25]. This is a theory of filtered equations, taking the advantage that filtering turns equations with rapidly varying coefficients into equations with smoothed coefficients, the latter being much more easy to solve than the former. Moreover, the filtered equations are free of the antidynamo theorem. According with this procedure, the rapidly fluctuating part of the underlying turbulence is filtered out, and this aspect is relevant, considering that in the astrophysical systems the source of the dynamo lies on small-scale turbulence. Hence, testing the underlying assumption of this theory, namely that the solutions of the filtered equations are equal to the filtered solutions of the full equations, is very important. We made a numerical investigation to address this issue [5]. To establish a relationship between filtered solutions of the full equations and solutions of the filtered equations, hence solution of the MFDT, we solve the full equations and we filter these solutions, where the filter is a spatial average.

Nigro et al [5, 26] solve the full induction equation considering a velocity with a large-scale shear component and a fluctuating part at small scales produced by an overlapping of turbulent helical eddies. This flow have three velocity components, but only depend on two co-ordinates, x and y, say. Because of the invariance in the z-direction, the induction equation is separable with periodic solutions, i.e. $B(x, y, z, t) = b(x, y, t) \exp(ik_z z)$.

The results show that all components, both at large and small scales, of the magnetic field grow with the same growth rate that is determined by the small-scale turbulence. A wave pattern is clear for high shear amplitude s and helicity H, while for low s and H it is difficult to distinguish any wave in the solutions (Fig.1). The transition between a dynamics where solutions show clearly waves and one where waves are not evident is not sharp, *i.e.* it is not possible to actually define an exact threshold. For intermediate s values we can roughly see a pattern resembling waves. These have led to suppose that may exist a wave component even in those solutions where wave pattern is not clearly observed. A likely wave component can be captured by making the (x, y)-Fourier transformation of the magnetic-field x-component, if this is a wave it should be $A_{kx}(y, t) sin(k_z z) + B_{kx}(y, t) cos(k_z z)$ with A_{kx} and B_{kx} lying on a circle during the time for a given y (Fig.2). We find that even in the solutions with low s and H, a wave component exists at large scale (small k_x), but this is not shown in the solutions with the all components, since the wave component is overwhelmed by small-scale turbulence. When s is large enough, turbulence is suppressed by the shear, and the wave component

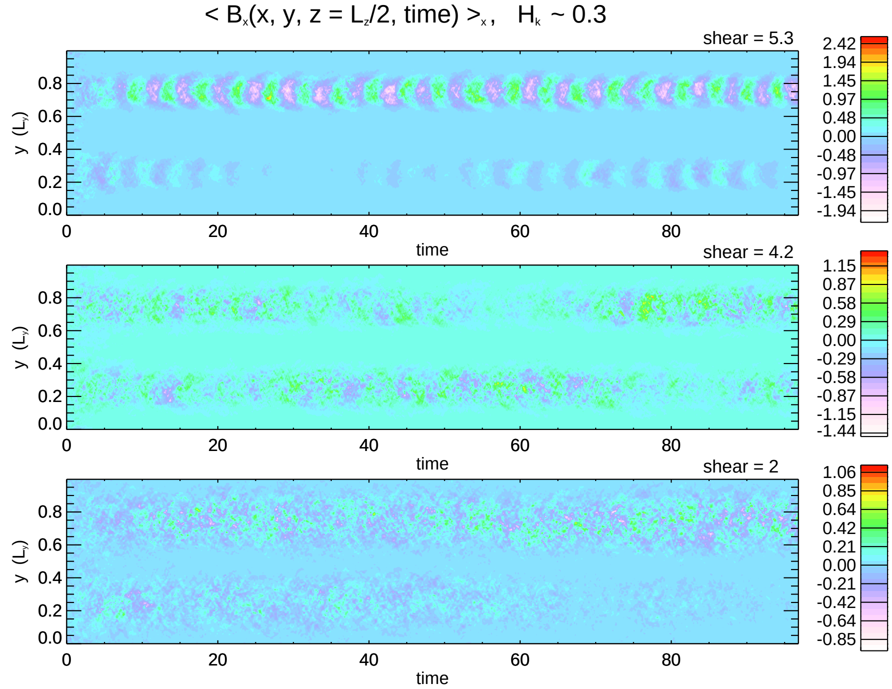

Fig. 1. – For decreasing shear $< B_x(x, y, L_z/2, time >_x$ shows a less evident wave pattern.

is clear. Computing the period of the waves, it turns out to be comparable with the characteristic time of Parker dynamo waves, hence showing the accuracy of the MFDT with regard to this large-scale component. Since all components of the solution have the same growth rate, which is roughly equal to the eddy-turn-over time, the dynamo transition seems to be lead by small-scale turbulence that is instead filtered out in MFDT.

We observe that the phase coherency holding in time is the only valid criterium to discriminate the large-scale dynamo solution, as described by the MFDT and found in our

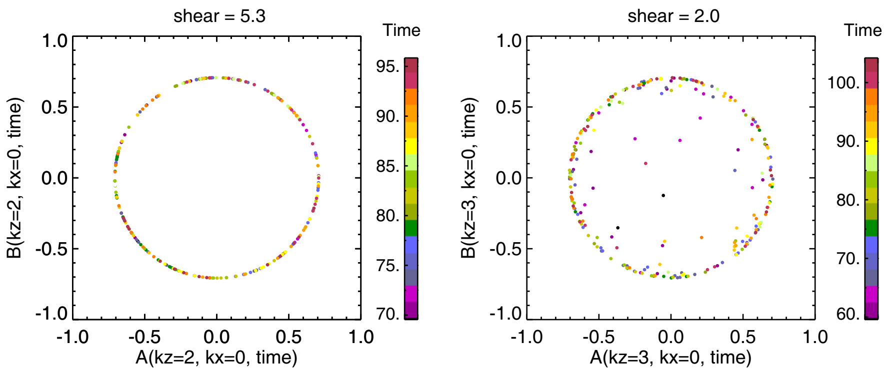

Fig. 2. – Phase diagrams: A_k versus B_k as defined in the text. The large-scale component remains coherent during the time even for the solutions that do not show a clear wave pattern.

simulations at large scale, from the rest of the solution, which remains incoherent during the time. For such a reason one possible definition of the large-scale dynamo is one that considers this coherence in time at large-scale, rather then one that relies only on the large spatial-scale concept alone. After all, performing Fourier transformations of the MHD equations describing dynamo systems, it turns out that each Fourier mode is coupled with all the other ones. This makes in principle difficult the validity of the spectral non-locality assumption considered in the scale-separation, which is the cornerstone of the MFDT. Finally, last but not least, solar observations reveal magnetic structures on multiple scales and often the strongest fields have been found on small-scale structures.

Considering the difficulty to infer observational constrains of subsurface magnetic fields, models and simulations are fundamental to understand how the dynamo mechanism actually works to produce the solar magnetic field we see. They are giving important contributions, but many problems are still open. We do not know what set the period of solar basic cycle and the source of its modulations, why sunspots emerge only below about 40 degrees, how actually they are generated considering, in particular, that any 3D MHD dynamo simulation fails to produce self-consistently sunspots. Hopefully, in the next future we will answer at some of these questions, thanks also to incoming space missions, but still many efforts are needed.

* * *

G. Nigro is grateful to A.S. Brun, F. Cattaneo, S.M. Tobias, A. Bonanno and F. Malara for very valuable suggestions regarding this contribution.

REFERENCES

[1] Hale G.E., *Astrophysical Journal*, **28** (1908) 315
[2] Parker E.N., *Astrophys. J.*, **122** (1955) 293
[3] Wright N.J. and Drake J.J., *Nature*, **535** (2016) 526
[4] Yadav R.K., *et al., The Astrophysical Journal Letters*, **833** (2016) L28
[5] Nigro G., *et al., Monthly Notices of the Royal Astronomical Society*, **464** (2017) L119
[6] Howe R., *Living Rev. Solar Phys.*, **6** (2009) 1
[7] Liang Z.C., *et al., Astronomy* and *Astrophysics*, **619** (2018) A99
[8] Simoniello R., *et al., The Astrophysical Journal*, **828** (2016) 41
[9] Wang, Y.M. and Sheeley Jr N.R., *Astrophys. J. Lett.*, **694** (2009) L11
[10] Hawkes G. and Berger M.A., *Solar Physics*, **293** (2018) 109
[11] Brandenburg A.,*Plasma Physics and Controlled Fusion*, **51** (2009) 12
[12] Romano P., *et al., Astronomy* and *Astrophysics*, **582** (2015) A55
[13] Charbonneau P., *Living Reviews in Solar Physics*, **7** (2010) 3
[14] Cameron R.H., Dikpati M., Brandenburg A., *Space Science Reviews*, **210** (2017) 367
[15] Brun A.S.,
et al, Space Science Reviews, **196** (2015) 303
[16] Jiang J., *et al, Space Science Reviews*, **186** (2014) 491
[17] Gilman P. A., *Astrophysical Journal Supplement Series*, **53** (1983) 243
[18] Glatzmaier, G. A., *Astrophysical Journal*, **291** (1985) 300
[19] Brun A.S., Miesch M.S., Toomre J., *Astrophysical Journal*, **614** (2004) 1073
[20] Ghizaru M., Charbonneau P, Smolarkiewicz P, *Astrophys. J. Lett.*, **715** (2010) 133
[21] Käpylä P.J., *et al., Astrophys. J.*, **778** (2013) 41
[22] Jones C.A., *et al, Icarus*, **216** (2011) 120
[23] Augustson K., Brun A.S., Miesch M., Toomre J., *Astrophys. J.*, **809** (2015) 149
[24] Strugarek A., *et al., Science*, **357** (2017) 185
[25] Steenbeck M., *et al., Zeitschrift Naturforschung Teil A*, **21** (1966) 369
[26] Pongkitiwanichakul P., Nigro G., Cattaneo F, Tobias S., *ApJ*, **825** (2016) 23