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COMMISSION E1 **SOLAR RADIATION AND STRUCTURE**

RADIATION ET STRUCTURE SOLAIRES

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TRIENNIAL REPORT 2021-2024

1. Background

The IAU Commission E1 "Solar Radiation and Structure" (CE1) covers observational and theoretical aspects of the Sun's radiation, structure, and variability under quiet Sun conditions. These differ from the Sun's state established by the impulsive and eruptive processes of the solar plasma covered by the IAU Commission E2 "Solar activity", and by the processes relevant to the impact of the solar variability throughout the heliosphere and star-planet interaction, which are covered by the Commission E3 "Solar Impact Throughout the Heliosphere" and Commission E4 "Impact of Magnetic Activity on Solar and Stellar Environments", respectively. In particular, CE1 focuses on the study and understanding of the solar composition, the interior structure and dynamics, the mechanisms of the solar magnetic cycles, the physics of sunspots and of facular and network regions, the structure and dynamics of the solar atmosphere, the sources of solar irradiance and long-term Sun's variability. CE1 topics include observational and modeling techniques, data analysis methods, coordination of observing campaigns, space and ground-based observations, and synoptic observing programs. In 2021, CE1 had a new President and new Organizing Committee members. It presently consists of 179 members (+7 members from 2022) including 10 junior members (+2 junior members from 2022).

The past triennium marked an important advance for a better knowledge of research topics relevant to CE1. On one hand, it saw the beginning of the science operations by the European Space Agency (ESA) Solar Orbiter (SO) and National Aeronautics and Space Administration (NASA) Parker Solar Probe (PSP) missions, which were launched to get the closest-ever images of the Sun, the first-ever close-up observations of the Sun's polar regions, and the first in-situ measurements of the composition of the solar wind in the solar corona and inner heliosphere. On the other hand, the largest solar telescope in the world, the National Science Foundation's (NSF) 4-m class Daniel K. Inouye Solar Telescope (DKIST), started science operation and gathering of observations of the Sun's surface with unprecedented spatial and spectral resolutions. The data obtained from the SO and PSP offer the fascinating opportunity to get a yet unexplored view of the Sun, our star, while those derived from the DKIST allow researchers to observe the magnetic and plasma processes occurring in the Sun at their characteristic scales. First results and novel knowledge from the operation of the above new infrastructures have just been published in the literature and are a premise for a transformative progress on the current understanding of the Sun's structure and processes. Besides, the continued operation and revamp of other facilities, as e.g. the Interface Region Imaging Spectrograph (IRIS), Solar Dynamics Observatory (SDO) and HINODE satellites in space, and the ground-based Atacama Large Millimeter Array (ALMA) in the Atacama Desert, THEMIS telescope (0.9 m) on Tenerife, Swedish Solar Telescope (SST, 1 m) on La Palma, New Vacuum Solar Telescope (NVST, 1 m) at Fuxian Lake, GREGOR telescope (1.5 m) on Tenerife, Goode Solar Telescope (GST, 1.6 m) at Big Bear Lake, and Global Oscillations Network Group (GONG) and Birmingham Solar Oscillations Network (BiSON), offered valuable new data relevant to the science covered by CE1. The past triennium also saw the launch of a few new missions of interest to CE1, e.g. the Aditya and ASO-S satellites by the Indian Space Research Organisation (ISRO) and Chinese Academy of Sciences (CAS), respectively.

In addition to the advancements in the observations, noteworthy progress has also been made in the large-scale hydro-dynamic (HD) and magneto-hydro-dynamic (MHD) modeling of the dynamics of the convection zone, dynamos, and differential rotation with e.g. the PENCIL, R2D2, ASH, and RAMSES codes, and of the upper convection zone and atmosphere, with e.g. the MURaM, SolarBox, MANCHA3D, and Bifrost simulations, as well as in the application of machine learning techniques to the aims of accurate image classification and segmentation, and data inversion. Besides, new codes were developed for the inversion and processing of solar spectro-polarimetric data, e.g. the DeSIRe, Bayesian Stokes inversions, and SSRED codes. Finally, several new databases of solar observations have been publicly released. These include results from coordinated observing campaigns involving space- and ground-based telescopes, e.g. the IRIS, SST, and ALMA telescopes, and the GREGOR Infrared Spectrograph (GRIS) and Interferometric BIdimensional Spectropolarimeter (IBIS) instruments, as well as time series of 3D snapshots from the radiative MHD modelling.

It is worth noting that the above list of achievements is not complete but just an indication of the developments on the topics of CE1 interest during the last triennium.

2. Research Highlights

Investigations of the solar structure are focused on four primary directions: 1) diagnostics of the internal structure of the Sun by helioseismology and tests of the standard evolutionary models, 2) helioseismic studies and numerical simulations, and modeling of the internal dynamics of the Sun, 3) investigations of MHD processes in the solar interior, including the solar dynamo and emerging magnetic fields, and formation of sunspots and active regions, and 4) observations and numerical modelling of the solar atmosphere. The key role in the recent advances of our understanding of the solar internal structure is due to the uninterrupted helioseismic and magnetic field observations by the ground-based networks Global Oscillations Network Group (GONG, since 1995) and Birmingham Solar Oscillations Network (BiSON, since 1976), and from space by Michelson Doppler Imager (MDI), VIRGO and GOLF of Solar and Heliospheric Observatory (SoHO, since 1996), and the Helioseismic and Magnetic Imager (HMI) instruments on Solar Dynamics Observatory (SDO, since 2011), as well as the development of 3D MHD numerical simulations on modern supercomputer systems. On the other hand, recent progress of our knowledge of the solar atmosphere mostly derives from observations acquired by several ground-based telescopes, e.g. the ones listed above, and by the HMI and Atmospheric Imaging Assembly (AIA) on the SDO and Interface Region Imaging Spectrograph (IRIS, since 2013) in space, as well as from numerical investigations with 3D MHD models. Focusing on the solar radiation, the investigations aim: 1) to characterize the total solar irradiance (TSI) and spectral solar irradiance (SSI), 2) to understand the physical sources of their variations, and 3) to estimate their evolution in the past and near future. Recent advances of these research areas are due to the continuation of solar irradiance measurements in space and the development of irradiance models. Indeed, the TSI and UltraViolet (UV) SSI have been regularly monitored from space since the late 1970s, while measurements of SSI at other spectral bands are more sparse and still rather uncertain. Coming from a number of different instruments operated in space, and being characterized by small intrinsic variations, TSI and SSI measurements require hard analyses and challenging cross-calibrations. As a consequence e.g. several composite records of TSI and SSI variations, as well as several reference spectra, have been created. Different models have also been developed to understand the irradiance variations measured over the satellite period, as well as to extend the records of solar irradiance back in time and predict the evolution of the Sun's radiation in the future. All of the developed models employ as input either direct observations or proxies of solar dark (sunspots and pores) and bright (faculae/plages and network) magnetic regions emerging into the Sun's atmosphere.

Below, we briefly review some advances in the knowledge of the solar structure and radiation, and mention prospects for future studies.

2.1. *Standard Solar Model*

The state of our current knowledge of the interior structure and evolution of the Sun was reviewed (Christensen-Dalsgaard 2021). Despite various attempts to explain the differences between the standard solar model and helioseismic inferences in the past 30 years by modifying solar composition, opacity tables, element diffusion, and other parameters, the current solar models are still inadequate. The models neglect important evolutionary factors, such as redistribution of angular momentum, magnetic fields, and turbulent dynamics, that could change the composition structure and have significant effects on the structure and dynamics of the Sun. A fundamental part of solar model calculations is the knowledge of the nuclear reaction rates that are now typically determined with 5% accuracy. However, the uncertainties of some nuclear reaction cross-sections are about a factor 2 larger than the uncertainties in the experimental determinations of the Beryllium and Boron neutrino fluxes. Improving the accuracy will allow verification of the effects of elemental diffusion in the solar models (Villante & Serenelli 2021).

Realistic, detailed HD simulations and modelling of the origin and effects of the solar cyclic magnetic activity are expected to provide further insight into the physical processes inside the Sun. However, determining changes in the Sun's internal structure has proved difficult. A recent analysis of the MDI, HMI, and GONG data revealed that the sound speed in the solar convection zone decreases by about 0.002% compared to the sound speed in the layers below it as the Sun becomes more active (Basu 2021).

2.2. *Solar convection*

A review of the mixing-length theory (Joyce & Tayar 2023), a key component of solar modeling, raised concerns about the inability of sophisticated three-dimensional (3D) numerical simulations of solar and stellar convection to predict mixing length parameters that match observational requirements. It is suggested that the progress in the mixing length will be driven observationally through an iterative calibrated mixing-length framework, getting it sufficient to predict stellar properties to an acceptable precision. In this respect, the recent helioseismic data raised doubts about the validity of the fundamental principles of the mixing-length theory. A new study (Proxauf 2021) of the energy spectrum of large-scale convection using correlation tracking and the ring-diagram technique revealed a huge discrepancy for the velocity of large-scale convection in the solar interior with theoretical models (root-mean-square values of roughly 1 and 100 m/s, respectively). This disagreement, the so-called convective conundrum (Gupta et al. 2023; Hotta et al. 2022), is crucial with regard to the current models of the solar convection zone structure. It led to the idea that the convective flux in the stably stratified but convecting layer is carried by a counter-gradient term proportional to the variance of entropy fluctuations referred to as the Deardorff zone (Käpylä 2023).

A spectral analysis of the subsurface flows inferred by the time-distance helioseismology from the HMI data revealed a multi-scale structure of solar convection (Getling & Kosovichev 2022). The horizontal flow scales rapidly increase with depth, from supergranulation to giant-cell values, and indicate the existence of large-scale convective motions in the Near-Surface Shear Layer (NSSL). The results are interpreted in terms of a superposition of differently scaled flows localized in different depth intervals. The total power of convective flows is anti-correlated with the sunspot number variation over the solar activity cycle in shallow subsurface layers and positively correlated at larger depths, which is suggestive of the depth redistribution of the convective flow energy due to the action of magnetic fields. Measurements of the large cellular flows on the Sun made by local correlation tracking of features (supergranules) seen in full-disk Doppler images revealed large cellular flows in the form of vortices with left-handed helicity in the north and right-handed helicity in the south with rms velocities of about 12 $\mathrm{m\,s^{-1}}$ at wavenumber corresponding to the spherical harmonic degree 10. The high-latitude cells form spirals, have lifetimes of several months, rotate differentially with latitude, and drift poleward at speeds approaching $2\,\mathrm{m\,s^{-1}}$ (Hathaway & Upton 2021). The development of a novel helioseismology mode-coupling technique can potentially improve the diagnostics of subsurface convection, large-scale flows, and magnetic fields (Das 2022; Mandal et al. 2021; Mani & Hanasoge 2021; Mani et al. 2022).

2.3. *3D MHD simulations of the solar atmosphere*

3D radiative MHD simulations allow to model stellar atmospheres without any ad hoc parameterisations. Several 3D radiative MHD codes have achieved good quantitative agreement with several observables for the Sun. A comparison (Witzke et al. 2024) between results derived from some simulations and observations of the solar spectral irradiance and intensity limb darkening, and of selected spectral lines, showed that the computed observables agree well with the observations; in particular, the limb darkening of the quiet Sun is reproduced remarkably well.

Detailed numerical models of the chromosphere and corona are required to understand the heating of the solar atmosphere. An accurate treatment of the solar chromosphere is complicated by the effects arising from e.g. non-local thermodynamic equilibrium (non-LTE) radiative transfer and non-equilibrium (NE) treatment of hydrogen ionisation. Over the reference period, the MURaM code was extended to include the physical process required for an accurate simulation of the solar chromosphere (Przybylski et al. 2022), as implemented in the Bifrost code. Indeed, including the necessary physics leads to significant differences in chromospheric structure and dynamics. On the other hand, several comparative studies were performed using observations and results from Bifrost simulations (Krikova et al. 2023; Moe et al. 2024; Pandit et al. 2023), concerning e.g. spectra and continuum brightness temperature maps at mm wavelengths and at other bands.

These studies provided new insights into the physical properties of solar atmosphere, such as its temperature stratification, magnetic structure, and mass density distribution in several observed regions. The capabilities and properties of the MANCHA3D code, which has been employed in many such investigations and it is still expanding, were also thoroughly presented in the literature (Modestov et al. 2024).

2.4. *Differential rotation and meridional circulation*

The mechanism of the solar differential rotation is still not fully understood. While the mean-field theories that separate turbulent and large-scale flows, and introduce a parametric description of non-diffusive angular momentum transport, can qualitatively reproduce the angular velocity inferred from helioseismic measurements (Pipin 2021), including the rotational NSSL (Kitchatinov 2024), the 3D numerical simulations are still far from the observed characteristics. It is understood that the solar-type rotation arises when Coriolis effects are stronger than the buoyant driving of the convection. When buoyancy dominates, the rotation becomes "anti-solar", characterized by rapidly rotating poles and a slow equator. Recent 3D simulations showed that the solar/antisolar transition occurs when the columnar convective structures characteristic of rotating convection attain a diameter roughly equivalent to the shell depth (Camisassa & Featherstone 2022). In addition, the solar-like differential rotation was obtained in 3D MHD simulations with very high numerical resolution, which indicated that the strong magnetic field generated by a small-scale dynamo has a significant impact on thermal convection and may be crucial in the mechanism of the solar differential rotation (Hotta & Kusano 2021). The dynamo-generated magnetic field may also play a key role in the confinement of the tachocline - the rotational shear layer at the bottom of the convection zone (Matilsky et al. 2024, 2022).

The NSSL has been in focus of many investigations. This layer is accessible for investigation by the local helioseismology techniques and modeled in great detail by realistic numerical simulations. A study of the radial gradient of the solar rotation rate in the NSSL from about 0.950 solar radii to the solar surface and its variation during Solar Cycles 23 and 24 with ring-diagram analysis applied to GONG and HMI Dopplergrams showed that the average radial gradient is $\partial \log \Omega / \partial \log r = -0.11 \pm 0.01$ at the base of the NSSL, while it is steeper than -1 closer to the surface (Komm 2022). In particular, helioseismology shows that the negative radial gradient of the rotation rate in the NSSL is independent of latitude. The mean-field models explain this property, while global 3D magnetoconvection models do not reproduce this. A possible reason for this discrepancy is a strong meridional flow in the numerical simulations, which prevents the formation of the NSSL outside the equatorial regions (Barekat et al. 2021).

Realistic 3D radiative HD simulations of solar subsurface dynamics revealed the development of a shallow 10 Mm deep substructure of the NSSL, characterized by a strong radial rotational gradient and self-organized meridional flows (Kitiashvili et al. 2023). This shallow layer ('leptocline') is located in the hydrogen ionization zone associated with enhanced anisotropic overshooting-type flows into a less unstable layer between the H and He II ionization zones. A steep rotational velocity gradient was detected in the low photosphere by differential interferometric methods to spectroscopic data obtained with the THEMIS telescope. The rotational radial shear in the low solar photosphere is likely related to the dynamics of the leptocline (Faurobert et al. 2023).

Cyclic variations of the differential rotation observed in the form of migrating zonal flows (so-called torsional oscillations) are of great interest because they reflect the structure and dynamics of the dynamo-generated magnetic fields. A new analysis of observations from the Mount Wilson Observatory showed that the torsional oscillations are well synchronized with cyclic variations of the meridional circulation (Ulrich et al. 2023). Similar conclusions were from the analysis of local helioseismology data (Getling et al. 2021; Komm 2021; Komm et al. 2021). It is intriguing that these observations showed that the variations in the meridional circulation exhibit the well-known 22-year periodicity of the torsional oscillations (so-called "extended solar cycle") and that the variations are observed in the absence of active regions on the surface. While the previously observed inflows into active regions affect the meridional circulation, they cannot explain in full the solar-cycle variations seen in the helioseismic measurements of the meridional circulation (Poulier et al. 2022).

The debates about the deep structure of the meridional circulation, whether it consists of one, two, or more radial circulation cells, still continue. The helioseismic methodology of Fourier Legendre decomposition to 88 months of Dopplergrams obtained by the HMI revealed substantial differences between the meridional circulation in the northern and southern hemispheres and a return (equatorward propagating) flow at a depth of approximately 40 Mm below the photosphere in the northern hemisphere (Braun et al. 2021). However, analysis of the helioseismological sensitivity functions and forward modeling for the current models of the meridional circulation showed that, at the time, it is not possible to distinguish between the single-cell or double-cell meridional circulation and that further careful analysis of systematic uncertainties is required (Fuentes et al. 2024; Stejko et al. 2022, 2021).

2.5. *Rossby waves*

Discovery of Rossby waves by time-distance helioseismology and the mode-coupling technique (Mandal et al. 2021), and their variations with the solar cycle (Waidele et al. 2023) opened new perspectives for modeling and understanding long-term solar dynamics and periodicities of the Sun's magnetic activity. In particular, several theoretical approaches have been developed for studying the spectral properties and excitation mechanisms of the Rossby-type oscillations and waves (Bekki 2022; Bhattacharya & Hanasoge 2023; Fournier et al. 2022; Jain et al. 2023; Triana et al. 2022). While the theoretical investigations are still far from being completed the initial studies showed that the Rossby waves can be excited by the turbulent convection (Philidet & Gizon 2023) and the inverse cascade of kinetic energy of the nearly horizontal motions in supergranules (Dikpati et al. 2022). In addition, the low-order Rossby waves in the tachocline can be excited through the dynamical instability of the latitudinal differential rotation (Dikpati et al. 2021). The interaction of the Rossby waves with magnetic fields is not well understood. Nevertheless, it has been argued that the Rossby waves may play an important role in the Rieger-type periodicities of solar activity (Korsós et al. 2023) and in the longitudinal modulation of the emerging magnetic flux, so-called "active longitudes" (Dikpati et al. 2021; Ruždjak et al. 2023). This topic will be in the focus of further observational and theoretical investigations.

2.6. *Solar dynamo: observations and theories*

Large-scale and small-scale dynamos generating the Sun's magnetic flux are paradigms of fundamental processes in astrophysics. Recent advances from observations, simulations, and simplified models of the solar dynamo were summarized in a topical collection (Schüssler et al. 2023) of 15 comprehensive review papers, which present the state of the art, outline the open questions, and discuss approaches to make further progress in the field. During the last triennium, the development of solar dynamo models continued in three main directions: 1) direct 3D MHD simulations, 2) observationally-guided Babcock-Leighton-type models, and 3) mean-field Parker-type models.

The results of 3D MHD simulations, even performed with the highest possible numerical resolution, are still far from reproducing all the observations. However, these simulations provide important characteristics of e.g. the turbulent magnetic diffusivity, alpha-effect tensor, and other turbulent transport properties (Prabhu et al. 2021; Shimada et al. 2022) that are usually employed in the mean-field models. These simulations showed that while a good agreement between the mean-field and global convective solutions exists, it requires all turbulent effects to be included, even those that have been regarded as unimportant in some basic dynamo models (Warnecke et al. 2021). However, the recently developed Babcock-Leighton (BL) and Parker-type models attempted to include the turbulent effects in great detail (Cameron & Schüssler 2023). For example, a 2D Babcock-Leighton model that included the effect of solar-like differential rotation, one-cell meridional flow, near-surface radial pumping, strong turbulent diffusion, BL-type poloidal source, and nonlinear back-reaction of the magnetic field on its source, reproduced a) the 11 yr cycle period and the 18 yr extended cycle; b) the equatorward propagation of the antisymmetric toroidal field starting from high latitudes; and c) polar field evolution that is consistent with observations (Zhang & Jiang 2022), representing a substantial improvement of the flux-transport theories. Perhaps the most significant advance was in the development of non-kinematic 3D mean-field models, which include the effects of the formation and emergence of magnetic bipolar regions and, thus combine the Babcock-Leighton and Parker's scenarios (Hazra 2021; Pipin 2022, 2023; Pipin & Kosovichev 2024). It is important that the non-kinetic models predict variations of the solar differential rotation (the torsional oscillations) and the meridional circulations, which are observed by helioseismology methods. The comparison of the model predictions with helioseismic observations has provided unambiguous evidence of the existence of dynamo waves traveling from the bottom of the convection zone to the surface during the solar cycles (Mandal et al. 2024).

2.7. *Structure and dynamics of sunspots and magnetic regions*

Sunspots, as the most prominent features of solar activity, have been the focal point of numerous research studies over the past three years. In the literature, three main directions of research emerge: 1) high-resolution, high-cadence imaging and subsequent analysis of structure and evolution, 2) comparison with numerical models and 3) continuous investigation of historical archives.

The emergence and evolution of sunspots and active regions remain not entirely understood. Numerical simulations (Manek & Brummell 2021; Manek et al. 2022) have begun revealing certain aspects. It is generally believed that active regions form from flux tubes emerging at the photospheric level from the deeper convection zone. Different types of magnetic regions are formed, with the appearance of δ-spots, characterized by opposite-polarity magnetic fluxes within a single penumbra, being of particular interest. A series of radiative MHD simulations (Kaneko et al. 2022) demonstrated that both δ-type and classic bipolar β-type active regions may form from the same seed magnetic field by introducing differences in the convective flows surrounding the flux tubes. δ-spots were formed by the collision of positive and negative magnetic fluxes. Furthermore, a strong correlation was found between the distribution of the non-potential magnetic field in the photosphere and the position of the downflow plume in the convection zone. This correlation could be observed about a day before the flux emergence, suggesting the potential to predict high free energy regions in the photosphere before observable magnetic flux appears, by detecting the downflow profile in the convection zone. In general, the paradigm of flux emergence and the importance of accompanying processes are shifting from magnetic buoyancy and Coriolis force towards a more passive process, with a seemingly stronger role of convective flows, at least in the upper convection zone (Weber et al. 2023).

It also remains not entirely clear which physical quantity has decisive power over the formation of the stable umbra-penumbra boundary in sunspots. The so-called Jurčák criterion (Jurčák et al. 2015) regarding the value of the vertical component of the magnetic field at the stable umbra-penumbra boundary proved valid for the stable boundary of the small pore as well (Campos Rozo et al. 2023; García-Rivas et al. 2021). A thorough investigation (Schmassmann et al. 2021) of numerically simulated sunspots by the MURaM code showed that the Jurčák criterion is a surface representation of the Gough-Tayler modified convective stability criterion (Gough & Tayler 1966). The work revealed several distinct depth features appearing in the simulated sunspot. On the other hand, the study pointed out that the properties of the magnetic field in the simulated sunspot still differ from those observed on the Sun, showing the need for improvement in the models. The details of transitions from pores to sunspots were studied using high-resolution imaging (Kamlah et al. 2023) and showed that particular flows around pores are conducive to the transition of pores to sunspots. Such claim was also supported by a statistical study (Švanda et al. 2021). Fluting instability may also be helping the formation of the penumbra (Panja et al. 2021).

Analysis of seismic waves and of atmospheric MHD waves offer a great deal of information about the structure and dynamics of the solar atmosphere. The interpretation of the measured propagation properties of helioseismic waves becomes difficult in the presence of a strong magnetic field, even though a particular phase travel-time anisotropy shows some diagnostic potential (Stefan & Kosovichev 2022). In sunspot regions, different types of waves can be excited in response to the external driving action of the surrounding plasma. In addition to low order modes like for instance kink or sausage modes, high order modes can be also excited in strong magnetic concentrations (Albidah et al. 2023), with their properties that largely depend on the shape of the magnetic tube (Stangalini et al. 2022). The spectrum of such modes differs significantly from the Sun's global acoustic oscillations, displaying frequencies other than the usual 3 mHz oscillations. Such resonant waves may show diagnostic potential to investigate the depth structure of sunspots from observations (Jess et al. 2023). In addition, the so-called "umbral flashes" in the sunspot's chromosphere were observed (French et al. 2023) in all details by the most modern solar telescope DKIST. The data allowed the study of details of the long-time known 3-min oscillations and the determination of some fundamental parameters of the wave train. The Mach number was estimated to be around 2, and the propagation speed was around 9 km/s. The propagating flashes perturb the magnetic field by about 50 G and cause about 10% temperature variations. It also was shown that MHD waves take actively part in the plasma fractionation in the chromosphere, through the ponderomotive force associated to Alfvén waves. This eventually results in the observed abundance anomaly in the corona (Baker et al. 2021) known as FIP bias, which can be used to trace the origin of the solar wind.

The understanding of small-scale activity in the solar atmosphere holds paramount importance for advancing our knowledge of solar activity. These small-scale phenomena, often overlooked in favor of more explosive events associated with solar active regions, actually play a critical role in shaping the overall behavior of the Sun. Their widespread occurrence across the solar atmosphere, even during periods of reduced solar activity, underscores their significance as fundamental building blocks of solar processes. Therefore, unraveling the intricacies of small-scale activity is essential for gaining a comprehensive understanding of solar phenomena and their impact on space weather and astrophysical processes. Recent advances in observing and modeling the interaction of convective plasma and small-scale magnetic fields were reviewed (Vargas Domínguez & Utz 2022). In addition, a study investigated the effect of small and large bipolar magnetic regions (BMRs) on the large-scale solar magnetic field by using a surface flux transport (SFTM) model (Hofer et al. 2024). The evolution of the total and open magnetic flux, the polar fields, and the toroidal flux loss since 1874 was simulated and compared to analytical considerations and observational data. The results show that small BMRs may play an important role in the evolution of the solar magnetic field at large spatial scales. Their impact is largest at low solar activity, but it is also substantial during activity maxima, although the actual relative contributions by small and large regions depend on the steepness of their emergence rate distribution. The inclusion of small BMRs in SFTM simulations will allow the secular variability in solar irradiance to be better constrained and the generation of the poloidal field in the Babcock-Leighton dynamo to be better understood.

A continuous effort was put into the investigation of historical archives to assess the long-term evolution of sunspot numbers (sunspot number and group-sunspot number), used as a measure of the strength of solar activity. Historical synoptic observations of the Sun are stored in several archives in the form of hand-plotted charts and tables of values. These documents are still only partly available in digital format. Recent digitization and investigation of several such archives allowed to derive new data on e.g. the group-sunspot number, individual sunspot number, and sunspot positions observed over several time intervals (Bhattacharya et al. 2021; Carrasco et al. 2022, 2021; Ermolli et al. 2023; Hayakawa et al. 2023a, 2024, 2022, 2023b; Vokhmyanin et al. 2021). This research activity follows up on the recent effort to review all sunspot observations and revise the representative composite (Clette et al. 2023). During the reference period significant progress has been made on the database side, while more work is needed to bring the various proposed reconstruction methods of sunspot numbers series closer to maturity. New versions of the series suitable for comparison with solar-activity proxies such as 10.7-cm radio flux or magnetospheric disturbances will be made available to the community in 2024. Meanwhile, a new daily group-sunspot number series was also developed (Velasco Herrera et al. 2024).

Sunspots and active regions are driven by the magnetic field. Two global quantities are particularly important for many purposes, the Sun's total and open magnetic flux, which can be computed from sunspot number records using models. Such sunspot-driven models, however, do not take into account the presence of magnetic flux during grand minima, such as the Maunder minimum. A major update of a widely used simple model was presented (Krivova et al. 2021), which takes into account the observation that the distribution of all magnetic features on the Sun follows a single power law. The exponent of the power law changes over the solar cycle. This allows for the emergence of small-scale magnetic flux even when no sunspots have been present for multiple decades and leads to non-zero total and open magnetic flux also in the deepest grand minima, such as the Maunder minimum, thus overcoming a major shortcoming of the earlier models. The results of the updated model compare well with the available observations and reconstructions of the solar total and open magnetic flux. This opens up the possibility of improved reconstructions of the sunspot number from time series of the cosmogenic isotope production rate.

On the other hand, the solar activity was reconstructed over the past millennium by starting with the ^{14}C production rate determined from the so far most precise measurements of radiocarbon content in tree rings. This reconstruction of solar activity covers the period 971-1900 (85 individual cycles), in the form of annual (pseudo) sunspot numbers, along with its uncertainties (Usoskin et al. 2021). This more than doubles the number of solar cycles known from direct solar observations. The lengths and strengths of well-defined cycles outside grand minima resulted to be consistent with those obtained from the direct sunspot observations after 1750. Solar activity was found to be in a deep grand minimum when the activity is mostly below the sunspot formation threshold for about 250 years.

Studies and reconstructions of past solar activity require data on all magnetic regions on the surface of the Sun (i.e. on dark sunspots as well as bright faculae-plage and network). Such data are also important for understanding the magnetic activity and variability of the Sun and Sun-like stars. A study investigated the relationship between plage areas and sunspot records (areas and numbers) since 1892 (Chatzistergos et al. 2022a), by using the plage areas derived from 38 consistently processed Ca II K archives as well as the plage area composite based on these archives. The relationship between plage and sunspot areas, and the one between the plage areas and the sunspot number, resulted to be well represented by power-law functions. The studied relationships also depend on the bandwidth of analysed Ca II K observations and on the solar cycle strength.

2.8. *Prediction of the solar cycles*

Solar Cycle 25 (SC25) started in December 2019 and is peaking around the time of writing. The 13-month smoothed value of the international sunspot number (S_n) lingered in the range 123 to 125 for 5 consecutive months up to August 2023, suggesting that the cycle is already peaking. While a higher secondary peak may still ensue, experience with previous cycles makes it unlikely that the overall peak will exceed this by more than 25, i.e. the cycle will peak between 125 and 150, more likely in the lower half of this range. This expectation is in agreement with the forecasts of Sunspot Index and Long-term Solar Observations (SILSO) at Royal Observatory of Belgium (Clette et al. 2024; SILSO World Data Center 2024) and is further corroborated by the fact that, in contrast to the last few cycles, the rise of activity displayed no phase delay between the hemispheres.

SC25 will thus be significantly weaker than average and only mildly stronger than the previous cycle, which peaked at $S_n = 116$. This provides further vindication for the precursor methods of solar cycle forecasting, already considered the most reliable (Nandy 2021). Standard precursors are measures or proxies of the solar magnetic field around the time of minimum; most notably, the Sun's axial dipole moment. Recently significant effort was invested in studies aiming to extend this limited temporal range, finding earlier precursors or "precursors of the precursor". This gave a major impetus to the development of model-based forecasting techniques (Bhowmik et al. 2023) as predicting the precursor values requires computing the evolution of the Sun's large-scale global field, either in SFTM simulations (Yeates et al. 2023) or complete dynamo models (Karak 2023).

In comparative studies of the predictive skill of the solar dipole moment in various dynamo models and for various proxies of the dipole moment in empirical data, it has been found that dipole moment values or their proxies may be used for prediction as early as 4 years after polar reversal (Kumar et al. 2021) or, considering the rate of change of the dipole moment around reversal, even at earlier times (Biswas et al. 2023; Jaswal et al. 2024). In addition, dynamo models designed to follow intercycle variations have now identified latitude quenching as a new nonlinear feedback mechanism regulating solar cycle amplitudes, besides the tilt quenching mechanism known earlier (Talafha et al. 2022). Among the stochastic effects impacting solar cycle modulation, rogue active regions have received further attention (Norton et al. 2023; Pal et al. 2023; Wang et al. 2021).

The spectacular development in the field of artificial intelligence and machine learning (AI/ML) has not left the field of solar cycle prediction unaffected. Most of the attempts made to forecast solar cycles by ML methods have been limited to the analysis of a single time series (usually, S_n), limiting their potential. However, in the rising phase of an ongoing cycle, satisfactory results may be achieved also with this approach due to the Waldmeier effect (Bizzarri et al. 2022; Espuña Fontcuberta et al. 2023; Prasad et al. 2023).

2.9. *Composition*

The chemical composition of the Sun is a fundamental problem of astronomy and a reference for studying a broad range of cosmic objects. Newly derived abundances for C, N, and O based on a 3D non-LTE analysis of permitted and forbidden atomic lines, as well as 3D LTE calculations for a total of 879 molecular transitions of CH, C_2, CO, NH, CN, and OH confirmed the relatively low solar abundances of C, N, and O. The revised photospheric metal mass fraction is only slightly higher than the previous value, mainly due to the revised Ne abundance from solar wind measurements: $X = 0.7438 \pm 0.0054$, $Y = 0.2423 \pm 0.0054$, $Z = 0.0139 \pm 0.0006$, and $Z/X = 0.0187 \pm 0.0009$. Thus, the discrepancy between helioseismology and solar models with the revised solar composition remains intact (Asplund et al. 2021). However, the helioseismic inversions of the adiabatic exponent in the H and He ionization zones favored such low metalicity composition (Buldgen et al. 2024). The debate on solar composition led to numerous publications discussing potential issues with solar opacities and other parameters of the standard evolutionary models. However, the solar problem is also linked to the physical formulation of solar evolutionary models and not to chemical composition alone, which is still not satisfactory and requires a significant revision (Buldgen et al. 2023). In an attempt to reproduce spectroscopic and helioseismic constraints, the evolution of the Sun was simulated from the protostellar phase to the present age. It was found that planet formation processes leave a small imprint in the solar core, enhancing metallicity by up to 5%, which is insufficient for improving the agreement with helioseismic observations, but this effect can be tested by neutrino experiments (Kunitomo & Guillot 2021).

2.10. *Irradiance measurements*

During the reference period, the TSI composites by the Royal Meteorological Institute of Belgium (RMIB) and Physikalisch-Meteorologisches Observatorium Davos (PMOD), and the one based on the data by the ACRIM (Active Cavity Radiometer Irradiance Monitor) and by other experiments were revised and updated by using different methods (Dewitte et al. 2022; Montillet et al. 2022; Scafetta 2023; Schmutz 2021). The RMIB composite shows a decrease between the minima in 1996 and 2009, and then a slight increase towards the minimum in 2019, in contrast to the other composite that shows a steady weak decrease in TSI from the minimum in 1986 to the most recent ones in 2009 and 2019. All these changes are, however, statistically insignificant being in the range of the uncertainty of available measurements. On the other hand, the ACRIM composite shows a marginally increasing TSI between 1986 and 2019, which however has been shown to be most likely an artefact (Amdur & Huybers 2023; Chatzistergos 2024).

A new solar irradiance reference spectrum representative of solar minimum conditions between Solar Cycles 24 and 25 was obtained (Coddington et al. 2021) from measurements of the Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) onboard the International Space Station (ISS). This new reference spectrum spans 202-2730 nm at 0.01 to about 0.001 nm spectral resolution with uncertainties of 0.3% between 460 and 2365 nm and 1.3% at wavelengths outside that range. A major difference between the new spectrum and previous reference data, e.g. the Whole Heliosphere Interval (WHI) Reference Spectra and SOLar SPECtrum (SOLSPEC) ATLAS-1 spectra, is a distinct spectral shape, with the TSIS-1 spectrum showing an irradiance that is 1%- 5% higher in the visible band and 1%–2% lower in the near IR wavelength range (between 1000 and 2000 nm), after normalization to the same value of the TSI. The new reference spectrum was also extended (Coddington et al. 2023) to span 0.202-2.730 μm and to encompass more than 97% of the energy in the TSI.

Early results of the SSI measurements by the NASA's Total and Spectral Solar Irradiance Sensor (TSIS-1) Spectral Irradiance Monitor (SIM) covering the first 5 years of operations were presented (Richard et al. 2024). This time-period includes the descending phase of Solar Cycle 24, the last solar minimum, and the ascending phase of Solar Cycle 25. The TSIS-1 SIM SSI spectrum shows lower IR irradiance (up to 6% at 2400 nm) and small visible increases (0.5%) from previous reference solar spectra. Initial comparisons to two SSI models entering Earth's climate studies offered opportunities to validate the model details both for short-term (solar rotation) spectral variability and, for the first time, the longer-term (near half solar cycle) spectral variability across the solar spectrum from the UV to infrared (IR) bands. Besides, a reanalysis of the TSI and SSI measurements recorded from 2003 to 2020 by the Solar Radiation and Climate Experiment (SORCE) in light of the new data collected from 2018 to 2020 with the TSIS-1 allowed to reconcile the results from the two experiments (Harder et al. 2022).

2.11. *Irradiance models*

Observations of solar irradiance by the SORCE and Ozone Monitoring Instrument (OMI) satellites from 2003 to 2020, acquired with 0.1 nm spectral resolution at wavelengths from 115 to 310 nm and 0.5 nm spectral resolution at wavelengths from 260 to 500 nm, were used to construct a new model of solar UV irradiance variability (Lean et al. 2022). This model better resolves irradiance variability in specific emission and absorption features of atoms and molecules in the Sun's atmosphere. Another study focusing on the Sun-as-a-star variability of the solar Balmer lines suggested that there may be complex, time-dependent relationships between Balmer and other chromospheric indices observed for the Sun and solar-like stars (Criscuoli et al. 2023).

A new method to reconstruct irradiance variations from Ca II K observations in historical and modern archives was developed (Chatzistergos et al. 2021), aiming to reconstruct past solar irradiance variations with an accurate description of the facular contribution and independently of sunspot observations. The method was tested with direct irradiance measurements and existing reconstructions, returning good results also when applied to photographic archives of Ca II K observations. An empirical model was also developed to reconstruct TSI variations over the past 5 centuries (Penza et al. 2022), by separating various temporal components of the irradiance variations with an empirical mode decomposition algorithm and by using the first plage area composite published in the literature (Chatzistergos et al. 2024). This TSI reconstruction lies just at the limit estimated via 3D MHD simulations of the solar atmosphere for the minimum TSI level that can be reached when the Sun becomes extremely quiet, similarly to the state of the so-called grand minima. Another study modeled the Sun's large-scale magnetic field and

TSI since 1700 by combining flux transport simulations with empirical relationships between facular brightening, sunspot darkening, and the total photospheric flux (Wang & Lean 2021). A relatively small insensitivity of the irradiance to changes in the large-scale field found during cycle minima resulted in a minimum-to-minimum increase of annual TSI from 1700 to recent minima a factor of 2-3 smaller than predicted in earlier reconstructions where the relation between facular brightness and field strength was assumed to be independent of cycle phase. The recent efforts to improve long-term irradiance reconstructions and to reduce the existing uncertainty in the magnitude of the long-term solar variability were also reviewed (Chatzistergos et al. 2023b).

A new method was developed (Yeo et al. 2023) to combine unprecedented observations from outside the Sun-Earth line recorded by the Polarimetric and Helioseismic Imager (PHI) on board the SO mission with solar observations recorded from the Earth's perspective and to examine the solar irradiance variability from both perspectives simultaneously. This study will be beneficial for the reconstruction of solar irradiance variability as seen from outside the ecliptic from data that SO PHI is expected to collect in the future and for the analysis of how the brightness variations of the Sun compare to those of other cool stars having rotation axes randomly inclined.

The recent advances in observing and modeling irradiance variations of the Sun and Sun-like stars were summarized in a topical collection of studies (Kopp & Shapiro 2021) that emphasise the links between surface magnetic fields and the resulting solar and stellar variability. Significant work has also started for the preparation of new and improved TSI and SSI records for input into Earth's atmospheric and climate studies of the next phases of the Coupled Model Intercomparison Project (CMIP) (Funke et al. 2024) and of the Paleoclimate Model Intercomparison Project (PMIP). These records are expected to become the reference data for further investigations of the solar radiation.

2.12. *Synoptic Observations and Databases*

Full-disc observations of the Sun in the Ca II K line provide one of the longest collections of solar data. Indeed, solar observations in the Ca II K line started in 1892. By now, Ca II K observations from over 40 different sites allow an almost complete daily coverage of the last century. Besides, Ca II K images provide direct information on plage and network regions on the Sun and, through their connection to solar surface magnetic field, offer an excellent opportunity to study solar magnetism over more than a century. A review (Chatzistergos et al. 2022b) provided an overview of the currently known Ca II K archives and sources of the inhomogeneity in the data. The same review also summarized the processing techniques applied to Ca II K images, and highlighted the main results derived with such data. Among these are e.g. estimates of the variability of the solar irradiance derived from Ca II K based models and creation of the first composite of plage areas recently, updated to cover the period 1892-2023 (Chatzistergos et al. 2024). Another study utilized newly calibrated multidecadal Ca II K observations (1907-2007) from the Kodaikanal Solar Observatory, and Ca II K data from Rome, Meudon, and Mount Wilson observatories, to investigate the differential rotation of the solar chromosphere using the technique of image cross-correlation (Mishra et al. 2024). The chromospheric plages exhibit an equatorial rotation rate 1.59% faster than the photosphere when compared with the differential rotation rate measured using sunspots and also a smaller latitudinal gradient compared to the same.

Full-disc observations of the Sun in the Hα line have also been performed at various sites since the second half of the 19th century, with regular photographic data having started at the beginning of the 20th century. These observations provide information about the solar chromosphere too, and in particular, about the filaments. This makes them important for studies of solar magnetism. Accurate information about filaments from historical and modern full-disc Hα observations was obtained (Chatzistergos et al. 2023a), by consistently processing observations from 15 Hα archives spanning 1909-2022. Filament areas, similarly to plage areas in Ca II K data, resulted to be affected by the bandwidth of the observation. The composite butterfly diagram derived from cross calibration of results obtained from the different archives very distinctly shows the common features of filament evolution, that is, the poleward migration as well as a decrease in the mean latitude of filaments as the cycle progresses. During activity maxima, filaments resulted to cover about 1% of the solar surface on average. The change in the amplitude of cycles in filament areas was found to be weaker than in sunspot and plage areas. A deep learning method that provides reliable extractions of filaments from Hα filtergrams was also developed (Diercke et al. 2024) and tested on images from the GONG, Kanzelhöhe, and ChroTel telescopes. Another study explored the imaging Hα excess and deficit as tracers of solar activity and compared them to other established indicators (Diercke et al. 2022). It also investigated whether the active region coverage fraction or the changing Hα excess in the active regions dominates temporal variability in solar Hα observations. The studied quantities resulted to follow the behavior of the solar activity over the course of the cycle. However, a direct relationship between the mean intensity of the Hα excess regions and the area coverage fraction was not found. This would have an impact on the modeling of stellar active regions, where the area coverage fraction and the intensity of Hα emitting regions are required to accurately represent chromospheres of solar-like stars.

During the past triennium, the instrumentation and methods employed to acquire a few multi-band synoptic observations that entered the investigations presented above were carefully described in the literature (Barve et al. 2021; Ermolli et al. 2022a; Malherbe 2023; Pötzi et al. 2021; Romano et al. 2022). In the same period, the IBIS data Archive (IBIS-A), which stores data acquired with the Interferometric BIdimensional Spectropolarimeter (IBIS) from 2003 to 2019 was released (Ermolli et al. 2022b) for public data access, as it was the Science Data Center that stores the observations acquired with the GREGOR Infrared Spectrograph (GRIS) from 2014 to 2021, the Laser Absolute Reference Spectrograph (LARS) from 2016 to 2018, and the ChroTel Telescope from 2012 to 2020. These archives include raw and calibrated observations, as well as science-ready data. Application of Artificial Intelligence (AI) methods to synoptic observational data from various databases and results from numerical simulations, showed the transformative potential of Deep Leaning approaches for robust automatic detections of solar regions in real-time images, image domain transformations for instrument inter-calibrations, image super-resolution and image quality assessment, magnetic field extrapolations (Dos Santos et al. 2021; Jarolim et al. 2024a,b, 2021).

3. Publications

CE1 has publications on a wide range of topics. For the period 2021-2024 the ADS database includes several hundreds of referred publications on topics relevant to CE1, distributed in the following concepts of the Unified Astronomy Thesaurus: Sun oscillations 222, Sun magnetic fields 732, Sun atmosphere 331, Sun helioseismology 110, Sun interior 81, Sun photosphere 256, Sun chromosphere 344, Sun xrays gamma rays 53, Sun rotation 77, Sun transition region 106, Sun abundances 85, Sun fundamental parameters

23, Sun granulation 46, Sun quiet-Sun 8. These numbers provide an outlook of the work in the various subfields from 1st January 2021 to 25th March 2024.

In the reference period, the following review papers were also published:

- Magnetic fields in the solar convection zone by Fan, Living Reviews in Solar Physics, 2021;
- Solar structure and evolution by Christensen-Dalsgaard, Living Reviews in Solar Physics, 2021;
- A New View of the Solar Interface Region from the Interface Region Imaging Spectrograph (IRIS), by De Pontieu et al., Solar Physics, 2021;
- Critical Science Plan for the Daniel K. Inouye Solar Telescope (DKIST), by Rast et al., Solar Physics, 2021;
- Irradiance Variations of the Sun and Sun-Like Stars – Overview of Topical Collection, by Kopp and Shapiro, Solar Physics, 2021;
- Progress in Solar Cycle Predictions: Sunspot Cycles 24–25 in Perspective, by Nandy, Solar Physics, 2021;
- Surface and interior meridional circulation in the Sun by Hanasoge, Living Reviews in Solar Physics, 2022;
- Interaction of convective plasma and small-scale magnetic fields in the lower solar atmosphere, by Vargas Domínguez & Utz, Reviews of Modern Plasma Physics, 2022;
- Amplitudes of Solar Gravity Modes: A Review, by K. Belkacem et al., Solar Physics, 2022;
- Defining the Middle Corona, by West et al., Solar Physics, 2023;
- Polar Photospheric Magnetic Field Evolution and Global Flux Transport, by Petrie, Solar Physics, 2023;
- Solar and Stellar Dynamos: a New Era, Editorial to the Topical Collection, by Schüssler et al., Space Sci. Rev. 2023;
- Dynamics of the Tachocline, by Strugarek et al., Space Sci. Rev. 2023;
- Dynamics of Large-Scale Solar Flows, by Hotta et al., Space Sci. Rev. 2023;
- Scaling and Evolution of Stellar Magnetic Activity, by Isik et al., Space Sci. Rev. 2023;
- Understanding Active Region Origins and Emergence on the Sun and Other Cool Stars, by Weber et al., Space Sci. Rev. 2023;
- Solar Cycle Observations, by Norton et al., Space Sci. Rev. 2023;
- Observationally Guided Models for the Solar Dynamo and the Role of the Surface Field, by Cameron and Schüssler, Space Sci. Rev. 2023;
- Simulations of Solar and Stellar Dynamos and Their Theoretical Interpretation, by Käpylä et al., Space Sci. Rev. 2023;
- Turbulent Processes and Mean-Field Dynamo, by Brandenburg et al., Space Sci. Rev. 2023;
- Stellar Activity Cycles, by Jeffers et al., Space Sci. Rev. 2023;
- Physical Models for Solar Cycle Predictions, by Bhowmik et al., Space Sci. Rev. 2023;
- Mean Field Models of Flux Transport Dynamo and Meridional Circulation in the Sun and Stars, by Hazra et al., Space Sci. Rev. 2023;
- Small-Scale Dynamos: From Idealized Models to Solar and Stellar Applications, by Rempel et al., Space Sci. Rev. 2023;
- Evolution of Solar and Stellar Dynamo Theory, by Charbonneau and Sokoloff, Space Sci. Rev. 2023;
- Surface Flux Transport on the Sun, by Yeates et al., Space Sci. Rev. 2023;

- Long-Term Modulation of Solar Cycles, by Biswas et al., Space Sci. Rev. 2023;
- Models for the long-term variations of solar activity by Karak, Living Reviews in Solar Physics, 2023;
- Waves in the lower solar atmosphere: the dawn of next-generation solar telescopes, by Jess et al., Living Reviews in Solar Physics, 2023.

4. Meetings and Training Schools

In 2021-2024, several scientific meetings relevant to CE1 took place, including the ones described in the following non-exhaustive list:

- January,28-February 4, 2021, 43rd COSPAR Scientific Assembly;
- March 1-4, 2021, IIA-50 Advances in Observation and Modelling of Solar Magnetism and Variability, virtual meeting;
- March 2-4, 2021, Cool Stars 20.5 - virtually cool, virtual meeting;
- April 6-9, 2021, Solar Orbiter School: the multi-instruments space mission to the Sun, in Les Houches, France;
- June 1-4, 2021, 4th NCSP DKIST Data Training Workshop: An Introduction to Chromospheric Diagnostics, virtual meeting;
- June, 14-18, 2021, Parker Solar Probe Conference;
- September, 6-10, 2021, 16th European Solar Physics Meeting;
- October, 25-28, 2021, HINODE-14/IRIS-11 Meeting;
- December 1-3, 2021, FASR2021: Solar Physics with a Next Generation Solar Radio Facility, virtual meeting;
- April 11-15, 2022, International School of Space Science: The different spatio-temporal scales of the solar magnetism, in L'Aquila, Italy;
- May 16-22, 2022, 2022 Sun-Climate Symposium: Improved Climate-Record Reconstructions from Solar Variability and Earth System Observations, in Madison, WI, USA;
- June 27-28, 2022, EAS 2022: S10 Upcoming missions and recent advances to better understand our Sun, in Valencia, Spain;
- August 2-5, 2022, IAU Symposium 372: The Era of Multi-Messenger Solar Physics, in Busan, Republic of Korea (hybrid meeting);
- August 7-10, 2022, Advances in Solar MHD Numerical Simulations in the Era of High-Resolution Observations, in Eastbourne, UK;
- August 22 - September 2, 2022, Summer School on Solar Spectropolarimetry and Diagnostic Techniques, in Boulder, CO, USA;
- September 5-9, 2022, SOLARNET Summer School Solar corona - complex research from ground-based and space, in Tatranská Lomnica, Slovakia;
- September 19-22, 2022, HINODE-15/IRIS-12 Meeting, in Prague, Czech Republic;
- September 19-22, 2022, Space Climate 8, in Krakow, Poland;
- October 24 - November 10, School of Solar and Stellar Magnetism and Activity, in Bogota, Colombia;
- November 28 - December 2, 2022, Modelling, observing, and understanding flows and magnetic fields in the Earth's core and in the Sun , in Cambridge, UK;
- May 8-12, 2023, SOLARNET II: The Many Scales of the Magnetic Sun, in Potsdam, Germany;
- June 20-23, 2023, Solar Physics High Energy Research (SPHERE) workshop, in College Park, MD, USA;
- June 25-30, 2023, SOLARNET Summer School: Solar atmospheric dynamics - From waves to instabilities and jets, in Gyula, Hungary;

- July 3-7, 2023, CESRA Workshop 2023: Radio emission from the Sun to the Earth, University of Hertfordshire, Hatfield, UK;
- August 21-25, 2023, IAU Symposium 365: Dynamics of Solar and Stellar Convection Zones and Atmospheres, in Yerevan, Armenia;
- September 11-15, 2023, SOLARNET Congress: Sun in Science and Society, in Venice Mestre, Italy.

The above meetings attracted several hundreds of scientists each. CE1 members actively participated in the organization and attendance at the above events, and at other national and international meetings.

5. Closing Remarks

In 2021-2024, developments at a few new major infrastructures for solar and heliophysics research, continuation, revamp, and launch of several other facilities available to the CE1 community, and progress in the theoretical studies and 3D MHD modelling of the solar plasma have opened to the provision of new data and novel knowledge. Section 2 highlights key advancements and accomplishments made by the CE1 community over the last triennium, without being a complete and exhaustive review. However, these achievements also reveal areas where our knowledge of the solar interior and radiation is currently lacking. Together with the data collected by the facilities and modeling techniques available to the CE1 community, these are a premise for a progress on our understanding of the solar dynamo and dynamics, and of the sources and characteristics of the solar variability in the years to come.

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