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COMMISSION E1 SOLAR RADIATION AND STRUCTURE

RAYONNEMENT ET STRUCTURE SOLAIRE

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TRIENNIAL REPORT 2018–2021

1. Overview

The IAU Commission "Solar Radiation and Structure" covers observational and theoretical aspects of the "quiet" Sun radiation, structure, and variability. The primary goals are to investigate and understand the solar composition, the interior structure and dynamics, the mechanism of the solar magnetic cycles, the physics of sunspots, facular, magnetic network, the structure and dynamics of the solar atmosphere, the sources of solar irradiance and long-term variability. The Commission topics include synoptic observing programs, observational, data analysis and modeling techniques, coordination of international observing campaigns, space and ground-based observations.

The range of scientific topics proposed for Commission "Solar Radiation and Structure" is defined as "quiet-Sun" studies to distinguish these from the impulsive solar activity, although there are close interconnections between these two major parts of heliophysics. The IAU Commission has successfully worked for many decades, organizing numerous Symposia, Special Sessions, and Focused Meetings, and coordinating long-term international synoptic observations. With the rapid growth of modern observational facilities and the development of new data analysis and modeling techniques, the role of the Commission increases.

The recent years are marked by tremendous advances in solar observations from the ground and space. These advances include the NASA's Solar Dynamics Observatory for understanding basic mechanisms of the solar interior dynamics, magnetism, irradiance, and variability, the IRIS (Interface Region Imaging Spectrograph) mission for studying the energetics and dynamics of the solar atmosphere; Parker Solar Probe, and Solar Orbiter for studying the structure and composition of the solar wind close to the Sun, as well as the previously launched space solar observatories: SOHO, STEREO, RHESSI and Hinode which continue to operate. Together with ground-based telescopes they provide an unprecedented amount of multi-wavelength data for complex investigations of the structure, dynamics and magnetism of the Sun from the deep interior to the atmosphere and corona. In addition, high-resolution spectro-polarimetric observations of the Sun are obtained with the new-generation large telescopes equipped with adaptive optics: 1.6-m Goode Solar Telescope (GST) and 1.5-m GREGOR telescope. The 1-m optical telescope on balloon observatory SUNRISE had made two successful flights. Two very large 4-m solar telescopes, Daniel K. Inouye Solar Telescope (DKIST) and European Solar Telescope (EST) are being developed.

Substantial progress has been made in developing data analysis, numerical simulations and modeling. This led to the development of 3D global-Sun MHD models that can reproduce the basic features of solar convection, differential rotation, meridional circulation, and magnetic field generation by the turbulent dynamo. However, there are still significant discrepancies between these models and helioseismic inferences, and still there is no robust model of the 22-year magnetic cycles, which could allow us to make predictions of the future solar cycles. These global-Sun studies are supported by the long-term helioseismology, magnetic field and irradiance observations, and are essential for understanding the climate change. Also, a substantial progress is achieved in the 3D radiative MHD modeling the solar magnetoconvection, emerging magnetic flux, sunspots and atmospheric dynamics. These simulations have provided the first realistic models of sunspots, spicules, ubiquitous plasma eruptions and waves in the solar atmosphere. Such modeling coupled with high-resolution spectro-polarimetry has opened new perspectives for our understanding of the small-scale processes and structures – the "building blocks" of solar magnetism.

Among the most remarkable recent advances is the growing realization that the global dynamics and variability of the Sun are coupled to small-scale processes. Investigations of the multi-scale dynamical coupling of the "quiet"-Sun physics will determine the future progress in our understanding of the basic mechanisms of solar magnetism and variability. These investigations require international cooperation and coordination among solar observers, modelers and theorists, and coordination of long-term synoptic observations and high-resolution campaigns. The development of such cooperation and coordination is the primary goal of the Commission.

2. Organizational Activities of IAU Commission E1 during 2018-2021

Commission E1 members actively participated in all major IAU activities, including preparation of proposals for the IAU General Assembly, organization of several IAU Symposia, and numerous educational and research activities to promote astronomy around the world.

In particular, Commission participated in the organization of two IAU Symposia (now postponed for 2021): IAUS 362 "Predictive Power of Computational Astrophysics as a Discovery Tool", and IAUS 365 "Dynamics of Solar and Stellar Convection Zones and Atmospheres". In addition, Commission contributed to proposals for the IAU GA Assembly, including three Symposia "The Era of Multi-Messenger Solar Physics", "Solar and stellar variability: from the interior dynamics to space weather", "The Sun and Solar Twins: Variability, Planetary Systems, Composition", and Focus Meeting: "Subarc second High Resolution Solar Physics."

The Commission organized a very successful IAU Symposium "Solar and Stellar Magnetic Fields: Origins and Manifestations", 30 June - 6 July, 2019, Copiapo, Chile. The Symposium brought together solar and stellar astronomers to discuss key problems of solar and stellar magnetic fields, their origin, evolution, structure, atmospheric and coronal effects, as well as their impact on planetary atmospheres. During the Symposium, experts from various fields of solar physics, observers, theorists and modelers, discussed recent advances, exchanged ideas, discussed plans, and developed new collaborations. The Symposium was organized in close cooperation and support of the University of Atacama, other Chilean universities, as well as of local authorities. It was the first international astronomical symposium in Copiapo, and it played a very important educational and public outreach goal.

The Symposium was organized in conjunction with the total solar eclipse in Chile and Argentina. The solar eclipse drew tremendous public attention to astronomy. The SOC and LOC organized public lectures and a special session for the local community. Symposium participants performed scientific observations of the eclipse and presented their initial results at a special open session on the last day of the Symposium. The total solar eclipse provided unique high-resolution images of the low corona, which could not be obtained by any other means. The Symposium included an open public session on solar eclipses and planetary transits. The goal of this session was to discuss how the eclipses and transits provide new information about solar and stellar magnetic fields. The session presented a broad historical overview of solar eclipses, planetary transits, their role in astronomy, as well as a general talk on the habitability of exoplanets. The organized public lectures, discussions, and other activities promoted astronomical education and research in Chile. The Symposium science oral program included 9 sessions, 28 invited reviews, 26 contributed talks, and 39 contributed lightning talks. About 70 contributions were presented at four poster sessions. More than 40 students, mostly from Latin American countries, participated in the Symposium. The broad discussions of solar-stellar magnetism and star-planet relations stimulated new interdisciplinary collaborations and defined the scientific success of the Symposium.

3. Research highlights

During the reported period, substantial progress has been achieved in better understanding the solar total and spectral irradiance, the solar composition, the structure and dynamics of the solar interior, surface, and atmosphere. To illustrate the progress and current trends in observations, data analysis, and theory, we briefly describe some of the advances in the field, published in the past three years. This is by no means a complete review.

3.1. *Solar composition and structure*

In the past years, inferences of the heavy element abundance on the Sun using 3D numerical models of the solar photosphere led to the disagreement between predictions of standard solar models and helioseismic measurements of the solar structure. This disagreement has not been satisfactorily resolved. New attempts to correct the solar model by adding new evolutionary processes and adjusting physical properties showed promising results. In particular, Zhang et al. (2019) found that solar models with convective overshoot, the solar wind, and early mass accretion are consistent with the helioseismic constraints, the solar Li abundance, and observations of solar neutrino fluxes. The results showed that reducing the helium abundance in the solar convection results in an improvement of the sound-speed profile. Yang (2019) constructed rotating solar models with low metal abundances that included enhanced settling and convection overshoot. One of the models with convection reproduced the observed radius of the base of the convection zone (CZ). It is found that the rotational mixing that almost completely compensates the gravitational settling of helium, but only partially the settling of the heavy elements, can explain the observed abundances.

Brooks et al. (2018) suggested that one possible solution is that the photospheric neon abundance, which is deduced indirectly by combining the coronal Ne/O ratio with the photospheric O abundance, is larger than generally accepted. They used daily sampled observations from the EUV Variability Experiment on the Solar Dynamics Observatory to investigate whether the coronal Ne/O abundance ratio changes with the solar cycle when the Sun is viewed as a star and found only a weak dependence on the solar cycle. The deduced value is too low to solve the solar modeling problem. Recent solar wind measurements discussed by Vagnozzi (2019) indicated a high metallicity of the Sun. However, the high abundances of Mg, Si, S, and Fe found in these measurements lead to a higher solar core temperature, and an overproduction of the solar neutrinos. Doschek & Warren (2019) used spatially resolved observations from the Extreme-ultraviolet Imaging Telescope on-board the Hinode spacecraft to examine the spatial variability of elemental abundance in and around active regions. They found that the enrichment of heavy elements with a first ionization potential is limited to bright, active region structures. In quiet Sun regions, the coronal abundances are close to photospheric.

Perhaps, the solar abundance problem can be resolved from measurements of neutrinos emitted by the relatively weak CNO cycle (Gough 2019; Capelo & Lopes 2020). Because C, N, and O constitute the majority of the heavy elements, the heavy element abundance in the solar core is proportional to the neutrino flux. The Borexino Collaboration (2020) has reported the direct observation, with a high statistical significance, of neutrinos produced in the CNO cycle in the Sun. The initial measurements, however, are consistent with both the low- and high metallicity solar models.

3.2. *Solar radiation*

Solar radiation is a dominant source of the Earth's energy balance, variations of which affect the state of the terrestrial atmosphere and space environment. The studies of solar radiations are focused in the following directions: 1) characterization of the total and spectral solar irradiance, 2) investigations of physical sources of irradiance variations, and 3) studies of long-term evolution and forecast.

Significant progress has been achieved in the preparation of the spectral irradiance records for input into atmospheric and climate studies. Harder et al. (2019) constructed an SSI record valid over Solar Cycles 23 and 24 (SC23 and SC24) specifically designed to provide: (1) a daily solar spectrum from SORCE (Solar Radiation and Climate Experiment) observations from 208-2400 nm over the 2003 to 2015 time frame, (2) a wavelength extension of this spectrum out to 10000 nm from daily spectral synthesis from the Solar Radiation Physical Model (SRPM), (3) SRPM gap-filled spectra during the extended SORCE time period (Aug 2013-March 2014) and back to Solar Cycle 23 maximum conditions in 2001 and 2002, (4) analysis of solar images generated by the Precision Solar Photometric Telescope (PSPT) network from the Mauna Loa Solar Observatory (MLSO) and Rome Observatory (OAR). The SOLar SPECtrum (SOLSPEC) instrument of the SOLAR payload on the International Space Station allowed the measurement of solar spectra in the 165 - 3000 nm wavelength range for almost a decade Meftah et al. (2020, 2021). The data are used to develop a new solar spectral irradiance database (SOLAR-v) with the associated uncertainties. This dataset is based on solar UV irradiance observations (165-300 nm) of the SOLAR/SOLSPEC space-based instrument, which provides measurements of the full-disk SSI during solar cycle 24. The NOAA National Centers for Environmental Information (NCEI) Climate Data Record Program established the Solar Irradiance Climate Data Record. Version 2 of the Naval Research Laboratory's solar variability models demonstrated consistency with irradiance observations and specified TSI and SSI for the Solar Irradiance Climate Data Record (Coddington et al. 2019).

Total solar irradiance (TSI) has been monitored from space since 1978, i.e., for about four solar cycles. The measurements show a prominent variability in phase with the solar cycle and fluctuations on timescales shorter than a few days. For getting an insight into the long-term trend of TSI since 1996 and the phase of the solar irradiance variations in the visible part of the spectrum, Chatzistergos et al. (2020) used independent ground-based full-disc photometric observations in Ca II K and continuum from the Rome and San Fernando observatories. It is concluded that the amplitude of the variations in the visible spectrum is below the uncertainties of the processing, which prevents an assessment of the phase of the variations with the solar cycle. Choudhary et al. (2020) investigated the periodic variations of photometric indices on the time scale of solar rotation, using images obtained at the San Fernando Observatory (SFO), and comparing them to the properties of the contemporaneous TSI as measured by the Total Irradiance Monitor (TIM) onboard the SOlar Radiation and Climate Experiment (SORCE) spacecraft. The results suggested that the TSI changes during the solar minimum are caused by the reduced line-blanketing effect of a diffused magnetic field.

The role of the quiet-Sun magnetism in the total and spectral irradiance variations, particularly during the minima of activity, was investigated in several detailed studies. Fontenla & Landi (2018) applied the solar disk image decomposition algorithm (SDIDA) and solar irradiance synthesis algorithm (SISA) methods to ground-based observations from various observatories, which allows for a long-term determination of TSI and SSI. The results demonstrated a significant variable bright network contribution during the cycle maximum and a reduced one at the solar minimum. Such a presence and variability affects both the SSI and TSI. Meunier (2018) analyzed a long time series of Michelson Doppler imaging (MDI) magnetograms jointly with chromospheric emission time series obtained at Sacramento Peak and Kitt Peak observatories to study the variability in the quiet Sun over the solar cycle. The results showed that the magnetic flux covering the solar surface, including in the quiet regions, varies in phase with the solar cycle, suggesting a long-term relationship between the global dynamo and the contribution of all components of solar activity. However, numerical small-scale dynamo simulations Rempel (2020) showed that only a moderate change of the quiet-Sun field strength by 10% would lead to a total solar irradiance variation comparable to the observed solar cycle variation. So, the question about the intrinsic mechanisms of solar irradiance variations is still open.

3.3. *Solar interior dynamics, dynamo and activity cycle*

Recent studies of the internal solar dynamics and the dynamo mechanism are driven by the new observational and modeling capabilities. The weakening global solar activity in the past four cycles raised an intriguing question: whether this trend will continue or be reversed in the upcoming Solar Cycle 25. Various attempts to predict the solar cycle led to a wide range of predictions of the sunspot maximum (Petrovay 2020; Nandy 2021). Most predictions are made using various precursors, among which the most established is the correlation between the strength of the polar magnetic field during the solar minimum and the next sunspot maximum. According to this empirical relationship, the next sunspot maximum will be similar to the previous one. The physical dynamo models driven by active region data (Labonville et al. 2019) and synoptic magnetograms (Kitiashvili 2020) predict a weaker cycle compared to Cycle 24, while an empirical technique based on the Hilbert transform of the 270-year long sunspot number series predicted a substantially stronger cycle (McIntosh et al. 2020).

The scientific understanding of the physical mechanism of solar cycles remains elusive. Theoretical studies are focused on two primary ideas: magnetic flux transport driven by the meridional circulation (Babcock-Leighton mechanism) and Parker's theory of dynamo waves driven by helical turbulence and differential rotation. The Babcock-Leighton assumes that the sunspot butterfly diagram observed on the surface is formed by the toroidal magnetic field transported equatorward at the bottom of the convection zone and due to buoyancy emerging on the surface. This scenario led to initial attempts to construct a 3D kinematic Babcock-Leighton solar dynamo model sustained by dynamic magnetic buoyancy and flux transport processes (Kumar et al. 2019). In this type of model, the variability of solar cycles is caused by fluctuations of the tilt of emerging active regions (Kitchatinov et al. 2018). However, due to turbulent magnetic diffusivity, active regions are disconnected from the base of the convection zone. While this improves the evolution of the surface field, the dynamo is unable to sustain itself under such an enhanced diffusivity (Whitbread et al. 2019). Pipin (2018) and Pipin & Kosovichev (2020) developed a fully-dynamical MHD mean-field dynamo model, which reproduces the observed cyclic variations of the Sun's global magnetic field as well as the differential rotation and meridional circulation.

Substantial progress has been made in helioseismic measurements of large-scale subsurface flows, in particular, zonal flows (torsional oscillations) and meridional circulation, thanks to continuous helioseismic observations by the Global Oscillations Network Group (GONG), Michelson Doppler Imager (MDI) on-board the Solar and Heliospheric Observatory (SOHO) and its successor, the Helioseismic and Magnetic Imager (HMI) on-board the Solar Dynamics Observatory (SDO), since 1995, giving us two full solar cycles of observations.

The helioseismic measurements of the deep meridional circulation are still controversial. Lin & Chou (2018) studied solar-cycle variations of the meridional circulation in the convection zone using SOHO/MDI helioseismic data from 1996 to 2010, including two solar minima and one maximum. It was found that, at the minimum, the flow has a three-layer structure: poleward in the upper convection zone, equatorward in the middle convection zone, and poleward again in the lower convection zone and that the flow distribution changes significantly from the minimum to the maximum. The flow speed near the base of the convection zone is found close to zero within the error bar. Contrary, Gizon et al. (2020) concluded that the meridional flow to be a single cell in each hemisphere, carrying plasma toward the equator at the base of the convection zone with a speed of ~ 4 meters per second at 45° latitude. Chen & Zhao (2018) and Rajaguru & Antia (2020) draw attention to the systematic errors in the helioseismic measurements, which do not allow to make a definite conclusion. The forward modeling of Stejko et al. (2021) showed that the current helioseismology techniques may offer important insights about the location of the return flow, however, that it may not be possible to definitively distinguish between profiles of single-cell or double-cell meridional circulation.

By conducting a set of mean-field hydrodynamic simulations, Bekki & Yokoyama (2017) found that double-cell meridional circulation can be achieved along with the solar-like differential rotation when the Reynolds stress transports the angular momentum upward in the lower part and downward in the upper part of the convection zone. Pipin & Kosovichev (2018) further explained that the double-cell circulation structure results from the radial inhomogeneity of the Coriolis number, which depends on the convective turnover time. When this effect is taken into account, the solar differential rotation and the double-cell meridional circulation are reproduced by the mean-field model.

Komm et al. (2018) studied the solar-cycle variation of subsurface flows from the surface to a depth of 16 Mm using the ring-diagram analysis and found the fast zonal and meridional flow that appear 2-3 years before the magnetic pattern. Basu & Antia (2019) studied variations of solar rotation in Cycles 23 and 24, and found significant temporal variation in the change of the rotation rate across the tachocline and substantial difference in these variations between these two cycles. Analysis of global helioseismology data obtained in 1996-2018 performed by Kosovichev & Pipin (2019)revealed zones of deceleration of the zonal flows torsional oscillations inside the Sun due to dynamo-generated magnetic field. The zonal deceleration originates near the bottom of the convection zone at high latitudes and migrates to the surface, revealing patterns of magnetic dynamo waves predicted by Parker's dynamo theory. The observational results are in good agreement with the mean-field dynamo models (Pipin & Kosovichev 2019, 2020), which explained the pattern of the solar torsional oscillations, observed as the propagation of zonal variations of the angular velocity from high to low latitudes during the 'extended' 22yr solar cycle. The extended solar phenomenon is explained as a combined effect of overlap of subsequent magnetic cycles and magnetic quenching of the convective heat transport. The model also explained the extended solar-cycle variations of the meridional circulation observed by helioseismology (Komm et al. 2020; Getling et al. 2021).

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