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COMMISSION E2 SOLAR ACTIVITY

ACTIVITE SOLAIRE

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TRIENNIAL REPORT 2021–2024

1. Introduction

Commission E2 of the IAU pertains to the observation and study of solar activity. The Sun, our closest stellar laboratory, is being observed intensely but keeps surprising us with its ability to generate more questions than answers, the more we are looking with increasing instrumental and modeling sophistication. As a partially convective star, it generates magnetic fields in the bottom of its convection zone, also known as the tachocline, that buoy and emerge in the solar atmosphere dominating it through the photospheric boundary. The hierarchy of scales and structures seen in the low solar atmosphere is astounding and one can be confident that looking with higher spatial, temporal and spectral resolution will only lead to observations of new structure: from tiny jets (coined jetlets) to spicules, to full-blown jets and coronal mass ejections (CMEs) in terms of eruptions, and from powerful X-ray (and often γ-ray) flares, to micro-, nano- and even pico-events, in terms of electromagnetic bursts. Wave activity in the low solar corona and magnetic reconnection are believed to initiate at kilometer-scales or less, so with the current state-of-the-art on spatial resolution at several tens to $\gtrsim$100 km, we can only anticipate more confounding structure as we refine our observational capabilities.

From this concert of diverse activity in the low solar corona, outward pressure pulses and escaping magnetic structure generate the middle corona and eventually the outer corona and the solar wind modulated by the Parker spiral, that is caused by the solar differential rotation. We have now space missions probing the origins of solar wind and heliospheric transients virtually on the Alfvénic boundary, and the turbulent evolution and corresponding structure observed is unlike anything we have seen so far. For the past 30+ years we have moved from tens of GB to tens of PB of solar observational data and this Big Data landscape dictates ways and methodologies of tackling that extend beyond solar physics as a discipline and call for novel interdisciplinary approaches. It is only fortunate that the observational volume increases in par with our computational capabilities.

All these are happening as another solar maximum, that of Solar Cycle 25, is imminent this year and the next. Beyond colloquial interest, our exponentially expanding dependence on space-based assets and the revamping of human space exploration for the first time since the 1970s, generate a pressing need to understand and ultimately predict the variable space weather. Much of it, in fact, is the impact of solar weather (the outcome of solar activity) on various heliospheric planetary magnetospheres, natural satellites and the deep space. The heliosphere, after all, can be thought of as a driven system of systems. We should keep in mind the transformative effects all these factors have brought to fundamental physics of solar activity, that has become key to real world problems in the 21^{st} century. Our tangible and frail dependence on solar activity is not expected to change in coming years and solar cycles and, in fact, it may well intensify.

2. Activities of IAU Commission E2 during 2021-2024

On top of the IAU General Assembly 2022 and subsequent focus meetings coordinated by Division E with participation from Commission E2, the following activities took place in the time period period 2021 - 2024:

2.1. *IAUS 372: The Era of Multi-Messenger Solar Physics, Busan, Republic of Korea, August 2 - 4 2022*

The Symposium† was organized during the 2022 IAU General Assembly. It aimed to exploit the contemporary ”multi-messenger” scientific approach by combining data from multiple ground- and space-based facilities and observatories including, but not limited to, the Daniel K. Inoue Solar Telescope (DKIST) and the Low-Frequency Array (LOFAR) on the ground, along with the Solar Orbiter and Parker Solar Probe (PSP) space missions.

The Symposium showcased the immense volume and complexity of the combined data sets and the resulting needs for novel methods in data analysis, mining and modeling. A sustained level of cooperation and coordination between facilities and observatories is also necessary, aiming to enhance their joint diagnostic potential.

The Symposium was successful in disseminating to a broad audience both new and anticipated data and results, as well as how to best optimize combined operations and forge synergies and collaborations. It featured about 80 oral and poster presentations and was in hybrid format, with speakers delivering presentations botn in-person and remotely. It further allowed 16 invited talks with speakers affiliated to institutes in Austria, China, Germany, India, Italy, Japan, The Netherlands, The Republic of Korea, Spain, and the United States of America. Gender balance in the invited speakers was 5 (female):11(male).

2.2. *IAUS 370: Winds of Stars and Exoplanets, Busan, Republic of Korea, August 8 - 11 2022*

The Symposium‡ was also organized during the 2022 IAU General Assembly. It aimed to bring together observers and modelers of the solar wind with observers of pristine observations of stellar winds engulfing stellar systems with exoplanets, along with winds from exoplanets themselves.

Besides the key question of magnetism in low-mass stars and how it compares to solar magnetism, the Symposium addressed the critical question of the theoretical differences between fully ionized (stellar) and partly ionized (exoplanet) winds and radiative transfer with metal spectral lines present in the planetary wind acceleration region. The unanticipated complexity of ultra-hot Jupiters was highlighted, and potential synergies between the exoplanetary community and those of low- and high-mass stars were investigated.

The Symposium was novel in its conception and was successful, with discussions and debates that traced the state-of-the-art in the field. It featured 56 oral presentation, both in-person and remote, of which 12 were invited. The invited speakers were affiliated

† `https://nso.edu/iau-symposium-372/`

‡ `https://local.strw.leidenuniv.nl/cms/web/2022/20220801/description.php?wsid=73&clean=1`

with institutes in Chile, The European Union, Japan, the Republic of Korea, Russian Federation and the United States of America. Gender balance in the invited speakers was 4 (female):8(male).

2.3. *IAUS 365: Dynamics of Solar and Stellar Convection Zones and Atmospheres, Yerevan, Armenia, August 21 - 25 2023*

The Symposium† was initially planned for 2021 but it was postponed due to the Covid-19 pandemic and geopolitical adversities. It was initially planned for a venue in the Russian Federation.

The Symposium was devoted to the theoretical and observational aspects of solar and stellar magnetohydrodynamics (MHD) in both global and local scales. Both analytical and modeling works were presented. In particular, the meeting featured presentations on the following topics:

- Solar and stellar convection on different scales.
- Solar and stellar differential rotation and meridional circulation.
- Global dynamo in the Sun and stars, as well as solar-cycle observed patterns and predictions.
- Local and global helioseismology and asteroseismology, probing subsurface structure and dynamics.
- Local processes of magnetic-flux emergence, sunspot and starspot formation.

The meeting was a success with vibrant discussions and debates. It was attended by 107 participants and featured 19 invited speakers from Brazil, China, the European Union, India, Japan, the Russian Federation, and the United States of America. Gender balance in the invited speakers was 5 (female):14(male). The attendees also enjoyed meeting-sponsored sightseeing and visits to local landmarks.

3. New Facilities

3.1. *Advanced Space Solar Observatory (ASO-S)*

The Advanced Space Solar Observatory (ASO-S) was launched on October 8, 2022 and was implemented by the National Chinese Academy of Sciences (CAS). The mission has provided data that have been included in a very recent article collection in Solar Physics, entitled‡ "ASO-S Mission: Inflight Performance and First Results", edited by W. Gan and J. Leibacher. The spacecraft orbits Earth in Sun-synchronous orbit.

The ASO-S mission (named Kuafu-1 in Chinese; Gan et al. 2023) contributes to the community the first Chinese comprehensive solar observatory with the explicit aim to provide observational data for the operational forecasting of solar eruptions (CME's, most notably). The ASO-S science goals are to study and understand the relationship between (a) the solar magnetic field and flares; (b) the solar magnetic field and CMEs; and (c) solar flares and CMEs (e.g., Gan et al. 2019, and references therein). To achieve these goals, the mission features the following objectives:

- Simultaneously acquire non-thermal images of solar flares in hard X-rays and the initiations of CMEs in the Lyα waveband, aiming to understand the relationships between flares and CMEs;
- Simultaneously observe the full-disk vector magnetic field, the energy build-up and release of solar flares, and the initiation of CMEs, in order to establish causality among them;

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† `https://iaus365.sinp.msu.ru/`

‡ `https://link.springer.com/collections/gjgieihdhc`

- Record the response of the solar atmosphere to eruptions, in order to understand the mechanisms of energy release and transport;
- Observe solar eruptions and evolution of the magnetic field, in order to provide clues for forecasting space weather.

Furthermore, the above objectives will be achieved with the following payload: a Full-Disk Vector MagnetoGraph (FMG), a Hard X-Ray Imager (HXI), and a Lyα Solar Telescope (LST).

3.2. *Aditya-L1*

The Aditya-L1 mission of the Indian Space Research Organization (ISRO) was launched on September 2, 2023. The spacecraft is scheduled to implement a halo orbit around L1 and gave its first light via a series of ultraviolet solar images on December 8, 2023†.

Aditya-L1 is India's first solar mission and carries a comprehensive payload of seven instruments. For a detailed presentation of the mission, see Seetha and Megala (2017) and references therein. Its payload, in brief, is the following:

- The Solar Ultraviolet Imaging Telescope (SUIT), aiming to understand the coupling of the solar atmosphere and energy flow from the photosphere to the corona;
- The Variable Emission Line Coronagraph (VELC), aiming to observe the dynamics of the solar corona in visible and infrared channels;
- The Solar Low-Energy X-ray Spectrometer (SoLEXS), aiming to observe and understand the origin of solar flares;
- The High Energy L1 Orbiting X-Ray Spectrometer (HELIOS), with similar objectives and also to understand flare emission and acceleration mechanism of solar energetic particles during flares;
- The Aditya Solar Wind Particle Experiment (ASPEX); aiming to measure and constrain the physical properties of the solar wind;
- The Plasma Analyzer Package for Aditya (PAPA), with similar objectives and also to understand the composition and particle distribution of the solar wind;
- The Aditya Magnetometer Experiment (AME), that will measure and characterize the magnetic field properties of both the nominal solar wind and transient propagating structures, such as CMEs.

Aditya-L1 aspires to continue and enhance the legacy of historic space-based solar observatories, such as ESA's Solar and Heliospheric Observaroty (SOHO) and NASA's Solar Dynamics Observatory (SDO). Contrary to these missions, however, Aditya-L1 is explicitly intended to provide transformative information and knowledge of the initiation of near-Earth space weather.

3.3. *PROBA-3*

ESA's PROBA-3 mission‡ is planned for launch imminently, in September 2024. This is a particularly important solar mission that will showcase, for the first time, the benefits of precision flying in solar physics. It will feature ASPIICS (Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun), an effective 144-meter solar coronagraph on two spacecraft; the first acting as an occulter and the second hosting the telescope. The occulter being much further away from the primary mirror than in conventional coronagraphs, the community expects that observations of the corona will commence virtually immediately beyond the solar limbs without appreciable distortion, helping to identify and observe the actual sources of solar structures with an impact to the

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† `https://www.isro.gov.in/Aditya_L1_SUIT.html`

‡ `https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Proba_Missions/Proba-3_Mission3`

heliosphere and wind, from eruptive transients (e.g., CMEs) to long-lasting phenomena, much as streamers and others.

Although PROBA-3, the third mission of ESA's PROBA (Project for On-Board Autonomy) series, is a technology demonstration mission, its performance is expected to pave new ways for solar observations and other space exploration missions (Shestov et al. 2021). It remains to be seen how its results will compare to coronagraph observations from SOHO/LASCO, STEREO/COR2, Solar Orbiter/METIS or even heliospheric imagers onboard Parker Solar Probe and Solar Orbiter, but the community is very keen to be working with the ASPIICS data.

3.4. *Other Instrumental Highlights*

Further instrumental and observational advances related to solar activity in the last triennium are set out in the Division E report, and will not be repeated in detail here. However, we are compelled to provide the following brief highlights on existing and future ground- and space-based observatories:

In terms of facilities providing observations already, the Daniel K. Inoue Solar Telescope (DKIST) has started releasing data that the community is eagerly awaiting. These are expected to combine ideally with in-situ observations by Parker Solar Probe, in conjunction or not with data from Solar Orbiter. At this time, supporting observations to the PSP mission are provided by the Goode Solar Telescope (GST) at the Big Bear Solar Observatory (BBSO), also in anticipation of data from the PHI magnetograph onboard Solar Orbiter. Furthermore, the US National Solar Obvervatory's (NSO) Synoptic Optical Long-Term Investigations of the Sun (SOLIS) telescope is also expected to complete deployment and commence operations after several years at the BBSO site.

The Daocheng Solar Radio Telescope (DSRT) started its operations in China (Sichuan Province) in mid-2023. This is the largest existing solar radiotelescope array, with 300 dish-shaped antennas in circular formation, with a circumference exceeding 3 km. DSRT data are also anticipated by the international solar physics community, but astrophysics will be also benefited by the facility.

The Square Kilometer Array Observatory (SKAO) is another facility that will immensely boost existing radio observation capabilities brought my facilities such as ALMA, LOFAR, MWA, the Jansky VLA, and EOVSA. The SKAO is an unprecedented, transcontinental Observatory involving locations in Australia, South Africa, and the United Kingdom. Another 13 countries are involved in a global SKAO consortium that involves all continents but Antarctica. The facility's first light is projected no earlier than 2027.

The European Solar Telescope (EST) is Europe's ground-based solar observation megaproject expected to carry the European ground-based solar science forward into the next decades. The main telescope features a 4.2-meter aperture that will observe in optical and infrared wavelengths. The Consortium formed to implement the EST comprises 29 European institutes plus 8 partners from 15 countries. The scientific objectives of the EST pertain squarely to solar atmospheric magnetism and plasma dynamics, stable and eruptive solar magnetic strictures, as well as photosheric, chromospheric, and coronal magnetography. EST's first light is expected no earlier than 2028-2029.

On space-based observatories, NASA is currently building PUNCH (Polarimeter to Unify the Corona and Heliosphere), a Small Explorer (SMEX) mission aiming to understand the origins of solar wind and space weather. Planned launch of PUNCH is in April 2025. In addition, NASA has recently adopted the CMEx (Chromospheric Magnetism Explorer) and ECCCO (EUV CME and Coronal Connectivity Observatory) SMEX missions. CMEx is focusing on chromospheric solar magnetography and how the chromospheric magnetic field connects to the interplanetary magnetic field, while ECCCO aims to understand the middle corona that connects the much better observed low and high solar corona, in an effort to improve understanding of mass and energy flow toward the heliosphere. Meanwhile, JAXA and the National Astronomical Observatories of Japan (NAOJ) are implementing Solar-C, focusing on solar explosive and eruptive dynamics and influence on space weather, particularly in ultraviolet wavelengths. Solar-C has been a provisional name for ”High-sensitivity Solar Ultraviolet Spectroscopic Satellite”, which is now the mission’s official name. Solar-C’s launch is expected in 2028. Finally, ESA is implementing the Vigil mission, namely, the first operational space weather mission that will be based at the L5 Lagrangian point. Vigil data will comprise, at a minimum, a solar magnetograph, an EUV/X-ray imager, a coronagraph and in-situ magnenetometer and plasma sensors. At this point, Vigil’s payload proposals are evaluated. Vigil is expected to launch in the 2030 - 2031 timeframe.

4. Solar Interior and Atmosphere Diagnostics

Recent advancements in solar interior diagnostics, highlight the interplay between sophisticated simulations used to interpret the observational data.

One notable advance involves the ongoing identification and characterization of solar inertial modes. These long-timescale waves, observed as surface radial vorticity, provide valuable insights into the dynamics and structure of the Sun’s convective zone, extending down to the tachocline – a region critical for understanding the solar dynamo. Recent studies by Gizon et al. (2021) utilized extensive observations from both SDO/HMI and GONG to detect quasi-toroidal inertial modes (Rossby modes) at unprecedented azimuthal orders. Further analysis using advanced linear eigenvalue solvers applied to a model of the differentially rotating convection zone (Bekki et al. 2022) pinpointed Rossby modes at mid and high latitudes. However, robust interpretations of these observations remain a challenge due to difficulties in isolating individual modes within the power spectrum (Philidet and Gizon 2023).

Improvements to the helioseismic holography technique have resulted in unprecedented spatial resolution for diagnostics of active regions on the far-side of the Sun (Yang et al. 2023a). For the first time, these far-side images have been corroborated with simultaneous Solar Orbiter Polarimetric and Helioseismic Imager observations of the surface magnetic field on the farside of the Sun, showing that their positions, areas, and mean unsigned magnetic field can be inferred from the far-side helioseismic signal (Yang et al. 2023b).

In light of recent evidence of a passive active region emergence process, and the potential that active regions may be formed within the convection itself rather then in the deeper interior (e.g. Weber et al. 2023), diagnostics to constrain the active region formation process are required. While the observational results are intriguing, the weak signal requires statistical analysis of hundreds of active regions for conclusive detection, presenting a significant challenge for direct simulation testing. In the domain of space weather forecasting, research utilizing machine learning techniques has shown promise in predicting active region emergence (e.g., Dhuri et al. 2020). However, the quest for a robust predictor with practical lead time remains ongoing.

By further refining the interplay between simulations and observations, solar interior diagnostics promises to significantly advance our understanding of the Sun’s interior processes. This understanding has implications for solar and stellar dynamo theory, a deeper understanding of stellar evolution, and practical applications such as potential advances toward space weather forecasting.

5. Solar Dynamo and Solar Cycle

A dynamo is an overarching term describing a collection of phenomena that result in the sustenance of large-scale solar magnetic field. In the broadest terms, it represents the conversion of kinetic and internal energy to magnetism and vice-versa. Turbulent convection, differential rotation, meridional circulation and effective diffusivity all play crucial roles in influencing the dynamo. The visible realization of the solar dynamo is the solar cycle, representing periodic variability of large-scale solar magnetic field. Predictions of cycle amplitude, period and the expected timing of the solar maximum are three important parameters space weather (i.e., short term) and space climate (i.e., long-term) predictions. Kinematic solar-dynamo models, which are effective theories of the solar cycle, require as inputs flow systems of differential rotation, meridional circulation and magnetic diffusivity, and more, in order to make predictions. Helioseismology is used to constrain the internal structure of the flows whereas acoustic modes are largely insensitive to the diffusivity. Differential rotation ($\sim$200 m/s), one of the great successes as an outcome of helioseismology research, is well constrained throughout the convection zone. Meridional circulation, whose flow structure is thought to set the 11-year dynamo scale, is still poorly captured at deep layers, i.e., $r < 0.85R_\odot$ despite numerous and significant efforts (for a review, see, e.g., Hanasoge 2022). The weak amplitudes of meridional circulation ($\sim$20 m/s) and the problematic center-to-limb systematic effects are the primary obstacles to a clean inference of this flow. The development of a comprehensive understanding of the center-to-limb bias is central to making further progress in the field. This goal will demand considerable thinking and analysis in the coming years.

An excellent development in the field is the use of solar inertial modes as a means of inferring effective turbulent diffusivity (Gizon, Laurent et al. 2021). The Coriolis force is a primary restoring force for inertial oscillations, meaning that these modes possess frequencies comparable to the rotation rate. Inertial-mode seismology is powerful because it bridges a gap that p-mode heloiseismology cannot address, i.e., it can be used to directly infer diffusivity and the superadiabatic gradient. Weak convective amplitudes, as suggested by Hanasoge et al. (2012), imply correspondingly weak diffusivity, which help in predictions made using kinematic dynamo models (Muñoz-Jaramillo et al. 2009). Hanasoge et al. (2012) took an indirect path to estimate diffusivity, i.e., by applying helioseismology to place upper bounds on convective flow amplitudes $|v|$, subsequently using $|v^2|$ as a proxy for diffusion. Based on measurements of lifetimes of Rossby-like modes, Hanasoge et al. (2012) and Bhattacharya and Hanasoge (2023); Bhattacharya et al. (2023) have obtained low turbulent diffusivities, consistent with the upper bounds placed by Hanasoge et al. (2012). There is general agreement that toroidal magnetic field is stored in the subadiabatically stratified ($r \lesssim 0.7R_\odot$) radiative interior the bulk of the convection zone and buoyantly rises into the convection zone once the field amplitude reaches a critical threshold. This relies on the convection zone being marginally unstable; however, recent analyses by Bekki (2024) of a different branch of inertial modes detected by Hanson et al. (2022) indicate that only the shallowest near-surface layers are likely superadiabatic and that the rest of the interior is subadiabatically (stably) stratified. Although this result bears a great deal of further investigation to be established, the important implication of a mostly convectively stable solar interior is that field could, in principle, be stored in a distributed manner.

Flux emergence can provide important clues about flux storage, the location of the dynamo and release mechanisms. Following the early suggestions (Gilman and Fox 1997) that magnetized Rossby waves in the tachocline trigger the rise of stored flux from stable interior layers, Raphaldini et al. (2023) have attempted to detect these signals in emerged magnetic flux (also see, e.g., Zaqarashvili et al. 2021, for a review). These results are yet to be broadly accepted by the community but provide a tantalizing means to directly image the deep interior from non-seismic surface data (e.g., Strugarek et al. 2023). Recently, Mani et al. (2024), using deep learning, attempted to detect unique signs of flux emergence in surface flows. They found all previously detected flow precursors to be mostly consistent with the variability exhibited by supergranulation. The non-detection of flows, they concluded, is suggestive of surface emergence driven by the effective large-scale action of small-scale turbulent stresses instead of deep-interior dynamics.

6. Solar Atmospheric Activity and Heating

The solar atmospheric temperature rises outward from the chromosphere to the corona, which poses one of the defining – and long-lasting – problems of heliophycics, namely the heating of the solar chromosphere and corona. Even though a complete physical picture of how these environments are heated remains elusive, a consensus in the solar community is that it is the solar magnetic fields that make the solar upper atmosphere much hotter than the photosphere (e.g., Judge 2021; Li et al. 2022). Some progress has been made in recent years with the advances in numerical simulations and observational capabilities, that further advance our understanding.

6.1. *Magnetic reconnection/cancellation heating*

With high resolution observations from both ground-based and space-born instruments and advanced simulation techniques, the role of magnetic reconnection in heating the solar atmosphere has been further understood (Pontin and Priest 2022) and supported by simulations (Upendran et al. 2022; Zou et al. 2023).

Multiline spectropolarimetric observations from the Swedish 1m Solar Telescope (SST) and related data-driven simulations revealed that numerous small-scale heating events in emerging flux regions (EFR) heat both the lower atmosphere and the corona through magnetic cancellation and reconnection (Yadav et al. 2023). Emerging flux regions, when reconnecting with pre-existing magnetic field in the chromosphere or corona, lead to both small- and large-scale events that heat the atmosphere (Moore et al. 2022; Tiwari et al. 2022; Yadav et al. 2023; Rouppe van der Voort et al. 2023). By investigating thermal enhancements in a sunspot light bridge, Louis et al. (2021) found that electric currents produce a chromospheric temperature excess of about 600 – 800K relative to the umbra, providing direct evidence for currents heating of the lower solar chromosphere through Ohmic dissipation.

From the study of bright knots (Zhang et al. 2023) it is argued that half of the energy for heating the chromosphere is supplied by wave dissipation and the other half by magnetic reconnection. Impulsive events were suggested to be a viable heating mechanism in the quiescent corona (Upendran and Tripathi 2021). Meanwhile, after analyzing the long-term observations of the global chromosphere in the Ca II K line and the global corona in the coronal green line, Li et al. (2024) concluded that different parts of the solar corona and chromosphere are heated by different magnetic field-originated mechanisms, indicating that unraveling the heating mystery is best approached through the lens of different categories or classes of magnetic events.

Nanoflares occurring via magnetic reconnection in the braided coronal magnetic field have been morphologically shown to be efficient heaters of the solar corona (Bi et al. 2023), while heating of coronal loops by magnetic reconnection was also observationally reported (Li et al. 2023). The newly identified so-called ”campfires” (e.g., Berghmans et al. 2021; Zhukov et al. 2021) observed by the EUI telescope onboard the Solar Orbiter mission were thought to contribute to heating of the solar corona, and interchange reconnection is commonly accepted as the drivers of this phenomenon (Chen et al. 2021; Tripathi et al. 2021).

Tripathi et al. (2021) proposed that interchange reconnection in coronal holes and reconnection between closed-field lines in the quiet Sun can heat the corona and drive the solar wind. A unified model for coronal heating and solar wind generation was proposed by Pontin et al. (2024), while Bale et al. (2023) and Raouafi et al. (2023) explicitly involve the magnetic reconnection, in general, and interchange reconnection, in particular, as the driver of the solar wind. In Pontin et al. (2024), it was proposed that the cancellation of photospheric magnetic flux fragments and the associated magnetic reconnection may provide a substantial energy and mass flux contribution to coronal heating and solar wind generation. Observations from the Solar Orbiter and the Solar Parker Probe provided a lower limit of energy transfer rate, which is useful in refining the turbulence-based modeling of coronal heating and subsequent solar wind acceleration (Telloni et al. 2023).

Numerical simulations have shown that a substantial part of the energy carried by large-amplitude waves can be dissipated in ion-neutral collisions and thus contributes to heating of the chromosphere (Niedziela et al. 2021; Pelekhata et al. 2021; Kumar et al. 2024). In addition, stochastic photospheric convective motions can significantly stress the magnetic field topology of coronal bright points, leading to important Joule and viscous heating above the solar surface (Nóbrega-Siverio et al. 2023).

6.2. *MHD wave/turbulence heating*

MHD waves, mostly the Alfvén and magnetoacoustic waves, are believed to contribute to the heating of the solar atmosphere through damping (Duckenfield et al. 2021; Prasad et al. 2022). A two-dimensional radiative MHD simulation shows that the fast magnetic waves, generated from high-beta fast acoustic waves via mode conversion crossing the equipartition layer, are significant in heating the low-beta chromosphere (Wang et al. 2021).

Studies of magnetoacoustic waves by Niedziela et al. (2021) demonstrated that they can also increase the chromospheric temperature and hence may have some influence on coronal heating (Washinoue et al. 2022). Large-amplitue and impulsively generated two-fluid Alfvén waves (Pelekhata et al. 2021) and magnetoacoustic-gravity waves (Niedziela et al. 2022) were reported to have potential contribution to the heating of the solar chromosphere, cause significant temperature increase and drive plasma outflows in the low corona. Slow magneto-acoustic waves were also demonstrated in simulations to carry enough energy to heat the chromosphere of a solar plage region (Yadav et al. 2021), while Morosin et al. (2022) argued that acoustic wave heating may be responsible for one-third of the energy deposition in the upper chromosphere in plage regions. Other heating mechanisms, such as turbulent Alfvén wave dissipation and ambipolar diffusion, must be responsible for the remaining energy.

Pelekhata et al. (2023) re-examined the two-fluid modeling of Alfvén and magnetoacoustic waves in the partially ionized solar chromosphere and confirmed that the damping of impulsively generated small-amplitude waves negligibly affects the chromosphere temperature while waves generated by large-amplitude pulses significantly increase the chromospheric temperature, indicating that large-amplitude coupled two-fluid Alfvén and magnetoacoustic waves can significantly contribute to the heating of the solar chromosphere.

Multifluid simulations by Evans et al. (2023) demonstrated that the thermal Farley-Buneman instability (TFBI), which can be produced in chromosphere by multifluid model (Dimant et al. 2022), can develop in a meter-scale electrostatic plasma and cause heating.

The authors showed that the TFBI develops in many of the colder chromospheric regions and characterize the resulting wave-driven heating, plasma transport and turbulent motions.

By comparing observations from the Interface Region Imaging Spectrograph (IRIS) and the Interferometric BIdimensional Spectrograph (IBIS) with synthetic observables derived from the 3D radiative magnetohydrodynamic Bifrost solar atmospheric model, Molnar et al. (2023) pointed out that internetwork and enhanced network regions exhibit significantly different wave-propagation properties, and the inferred wave energy fluxes are not sufficient to maintain the solar chromosphere. Similar results have been reported in previous works (Abbasvand et al. 2021; Molnar et al. 2021).

Lim et al. (2023) reported that energy of ubiquitous and more commonly observed transverse oscillations depends on the frequency, i.e., higher energy fluxes are generated from higher-frequency oscillations. The authors argued that high-frequency oscillations could provide the dominant contribution to total coronal heating generated by decayless transverse oscillations.

MHD simulations have suggested that magnetic tornadoes may be a potential mechanism of energy transfer from the photosphere to the corona with less loss in the chromosphere (Kuniyoshi et al. 2023).

7. Solar Energetic Events and Eruptions

7.1. *Flares*

Some fundamental aspects of solar flares have been touched upon earlier in this report, such as magnetic reconnection in the context of atmospheric heating (Section 6.1). Here we focus on new results concerning the conditions that flares occur in and some aspects of plasma dynamics during/after flares, before closing with some comments on improvements in observation planning capabilities most relevant to the study of flare physics.

It has been known for decades that some flares undergo considerable preheating to temperatures ∼10 MK several minutes before the onset of the main hard X-ray emission (Cheng et al. 1985). The sources of these 'hot onsets' have been found to range from 10-15 MK (consistently determined between GOES and RHESSI) irrespective of their subsequent GOES peak magnitude, and their compact sources conjectured as being loop footpoints in the lower atmosphere (Hudson et al. 2021). Additional work combining Solar Orbiter/STIX and SDO/AIA observations of four GOES M-class flares confirmed that each event displayed several compact sources of 10-16 MK with none of them being the standard loop-top thermal source that is observed when nonthermal emission is detected, although an extended bremsstrahlung source at the loop-top cannot be ruled out due to current instrument detection limits (Battaglia et al. 2023). Finally, a statistical study of this phenomenon in 745 flares that were observed during 2010-2011 and covering GOES B- to X-class found that 75% of these events showed GOES-derived onset temperatures >8.6 MK, while 50% showed >10.5 MK (da Silva et al. 2023).

Improved observational coverage of flaring events by spectroscopic instrumentation such as IRIS has resulted in a variety of challenges to our understanding and modelling of plasma dynamics and energy deposition in flares. One such area is that of chromospheric spectral profiles, including the long-known possibility of He I 10830 Å line dimming during flares (Zirin 1980) alongside broad and single-peaked profiles displayed by the Mg II h and k lines (Kerr et al. 2015). Progress has been made in modelling He I 10830 Å flare dimmings where it has been found that nonthermal collisional ionization appears to be necessary, but the tens of seconds over which this is sustained in modelling is still shorter than the several minutes over which it is observed (Kerr et al. 2021). In regards to flare ribbons, IRIS observations have previously shown that centrally-reversed Mg II profiles (i.e., like those seen in the quiet-Sun) can also be found within the leading edge of fast-moving ribbons (Panos et al. 2018). These 'unusual' flare-related profiles are now believed to be a result of gradual nonthermal electron beams with lower fluxes in comparison to the more impulsive and stronger electron beams that generate the 'normal' (and brighter) ribbon emission behind the leading edge (Polito et al. 2023).

Following the energy release and subsequent plasma heating in flares, the manner in which coronal plasma cools and evolves can shed light on the original physical processes of energy deposition and their characteristics. The most visible form of such plasma cooling is that of flare-driven coronal rain (Scullion et al. 2016). Now 3D MHD simulations have been shown capable of producing flare-driven coronal rain in cases where magnetic flux emergence is included (Chen et al. 2022). However, these MHD simulations lack particle acceleration and so their success in reproducing the formation of coronal rain indicates that thermal conduction is key to forming flare-driven coronal rain (Antolin and Froment 2022) – simulations with realistic electron beam heating confirm that the electron beams are significantly less important in producing rain when compared to thermal conduction (Ruan et al. 2021). This interplay between plasma density and thermal effects is also why coronal rain may possibly play a crucial part in the formation of quasi-periodic pulsations during flares (Zimovets et al. 2021).

In a change of focus we conclude with some consideration of pointing selection strategies that scientific planners could employ when seeking to observe flares. The performance that the selection of "which active region is most likely to produce a >M1.0 flare in the next day" was modeled for 2011-2014 by Inglis et al. (2021) through considering active regions' (1) Hale classification of magnetic polarities, (2) McIntosh classification of sunspot structure, and (3) prior flaring history (i.e., the flare index – the sum of all GOES X-ray peak fluxes from a region in the previous 24 hr). It was found that basing active region target selection on the coarsely-categorised Hale classification (albeit supplemented with total number of spots to distinguish regions in the same broad class) resulted in the lowest percentage of flare observations being achieved, with the finer-categorised McIntosh classification leading to a marginally higher percentage, but the greatest return in terms of flare observations was achieved when using the flare index (Inglis et al. 2021). This provides further evidence that the persistence of flaring behaviour means past flaring history is one of the strongest indicators of future flaring activity.

7.2. *Coronal Mass Ejections*

Coronal Mass Ejections (CMEs) are centrally important as a source of disturbances in the solar-terrestrial environment. Both observational and modeling research on CMEs have been steadily promoted. In addition, stellar CMEs are an important factor in considering the habitability of exoplanets, since signs of eruptive events have been observed in stars, as well.

Solar activity has been increasing in Solar Cycle 25 and the number of CMEs has been also increasing. SOHO/LASCO continues to observe well, with over 37,000 CME events listed in the LASCO CME Catalog† (Yashiro et al. 2004) by November 2023, and over 3,700 events since 2021. Aditya-L1 is approaching the L1 point, and new CME observations are expected to be made with the onboard coronagraph (VELC). In addition, by using the Solar Orbiter and the Parker Solar Probe (PSP) observations, we enhance our capabilities for studying both in-situ and via remote sensing the CME propagation

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† https://cdaw.gsfc.nasa.gov/CME_list/

from multiple angles, as well as the shock structure in CME fronts and the properties of the CME source regions (Zhao et al. 2020; O'Kane et al. 2021; Davies et al. 2021).

Filament eruptions are often associated with CMEs (e.g., Munro et al. 1979; Gopalswamy 2015; Patsourakos et al. 2020; Seki et al. 2021). Therefore, attention has been focused on understanding the initiation and acceleration processes of filament/prominence eruptions in order to understand how CMEs are launched.

Numerical simulations of eruptive processes in flux ropes have also been conducted. In particular, pertinent data-constrained and data-driven MHD simulations are being constructed (Inoue and Bamba 2021). The magnetic field structure of flux ropes in the solar corona has been estimated from the photospheric magnetic field using the nonlinear force freee field (NLFFF) model, and the ejection process has been successfully reproduced by MHD simulations in a manner consistent with coronal observations (Yardley et al. 2021). Moreover, if the magnetic field structure of the flux rope can be estimated more precisely by observing the chromospheric magnetic field (Kawabata et al. 2020) and/or the magnetic field filaments/prominences (Yamasaki et al. 2023), it will greatly contribute to improved accuracy in understadning the ejection process.

In recent years, interest in superflares as an important factor toward determining the habitability of exoplanets has been growing. Stellar superflares may be accompanied by substantially larger CMEs than those observed in the Sun, and such super-CMEs are considered to greatly affect any exoplanets around the host stars (e.g., Airapetian et al. 2020; Cliver et al. 2022). Maehara et al. (2021) and Inoue et al. (2023) analyzed Hα spectra of stellar flares and found blueshifted excess emissions, which might be arising from prominence eruptions. Veronig et al. (2021) reported coronal dimmings in Extreme Ultraviolet and X-ray wavelengths from Proxima Centauri, signifying the potential launch of CMEs. The speeds exceed even the escape velocity of the target star in several stellar CME studies. We expect to see many more reports of eruptions associated with similar stellar flares and CMEs in the future (Argiroffi et al. 2019). And the elucidation of stellar CMEs will undoubtedly benefit from the knowledge gathered for solar CME cases, in the framework of the Sun-as-a-star theme (Namekata et al. 2021; Otsu et al. 2022; Otsu and Asai 2024) that is gathering substantial momentum in recent years.

8. Predicting the solar activity

8.1. *Short-term prediction: the solar end of space weather*

We are currently witnessing a major surge of works aiming to forecast the solar activity, particularly the solar energetic events that are more relevant to changes in space weather conditions. These events are flares, CMEs and solar energetic particle (SEP) events. The urgency for reliable and, most importantly, validated prediction methods is self-evident, given an armada of existing and new missions for space exploration and, most importantly, the revamping of crewed missions to the Moon and beyond (Creech et al. 2022).

In the 2020s, papers featuring "space weather" in their abstract and dealing with aspects of the problem amount to multiple thousand every year, around an order of magnitude higher than early in the previous decade. This exponentially increasing trend is not expected to be curbed, as a potentially transformative development of recent decades has quickly grasped with the intricacies of space weather forecasting: artificial intelligence (AI) and its machine learning (ML) and deep learning (DL) variants (Camporeale et al. 2018; McGranaghan et al. 2021; Bobra et al. 2021). AI methodologies are applied *en masse* in our times; however, their benefits are yet to be fully realized. There are a number of reasons for this including, but not limited to, strong or extreme class imbalance of solar energetic events (major SEP events at a given heliospheric location, for example, are rare or extremely rare), a variable climatological background modulated by the evolving solar cycle, parameter-space challenges with employing timeseries for forecasting, issues with appropriate training, testing and validation, etc. For detailed discussions on prediction challenges, see Campi et al. (2019); Camporeale (2019); Leka et al. (2019); Ahmadzadeh et al. (2021) and references therein.

Another key realization is that, to have any hope of effectively predicting the intense space weather†, we must focus on the solar sources of energetic events, namely the hosting active regions, flares, and CMEs that may be originating from them. In this respect, space weather effectively becomes *solar* weather. An initiative coined the International Space Weather Action Teams (ISWAT) has reached deep into the heliophysics community aiming toward a set of review (and, potentially, roadmap) papers aiming to assess the progress achieved and future expectations since a landmark paper by Schrijver et al. (2015). As far as solar activity is concerned, this grassroots effort has resulted in three papers on forecasting, namely, solar energetic events in general (Georgoulis et al. 2024), CMEs (Temmer et al. 2023), and SEP events (Whitman et al. 2023). The latter two reviews include both methods investigating solar sources and methods dealing with prediction from inner-heliospheric precursor signals. In addition, the review on CMEs involves heliospheric propagation and the arrival time problem, whereas the review on energetic events, in general, discusses only prediction methods applicable prior to the events' onset.

The main results of the review by Georgoulis et al. (2024) and numerous references therein, that largely reflect the community's understanding of the state of the problem, are that (a) published ML methods have already outnumbered conventional statistical methods on solar flare prediction, but not yet in the prediction of CMEs and SEPs (although, it may well be a matter of time before this, too, happens); (b) precise and reproducible method comparison is largely infeasible at the moment; (c) the overall performance of independent methods leaves a lot to be desired; and (d) besides the methods' shortcoming and caveats that are exacerbated by the above-mentioned challenges, crucial observations beyond the Sun-Earth line and the ecliptic are missing. Having such data in place, that would require missions at L5, L4 or constellation mission concepts, would greatly help sophisticated methodologies to cope with the complexity of the problem and allow them to boost their performance. Fortunately, some developments are expected in the mid-to-long term future, by means of the ESA's Vigil mission to L5 (Palomba and Luntama 2022) as well as mission concepts for joint spacecraft at L4 and L5 (Bemporad 2021) and constellation concepts (Raouafi et al. 2023).

To effectively compare between different prediction methods, moreover, two key elements are needed: benchmark data sets, that are well curated, statistically significant event/no-event samples accompanied by appropriate metadata for training, testing and validation, and effective performance verification / validation metrics. One, in fact, envisions infrastructures that will have fixed benchmark data and validation methodologies and the only variable will be the prediction methods themselves. In this way, different methods, AI or otherwise, will be trained, tested, and validated on the exact same conditions and in a reproducible manner. Except from a few cases on flare prediction, or some individual team efforts (see, for example Jiao et al. 2020; Cinto et al. 2020; Cicogna et al. 2021), we are not at this point yet. Fortunately, however, there are currently several recent, readily available and highly curated benchmark data sets on solar flares

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† That is, excluding the contribution and effects of galactic cosmic rays.

(Angryk et al. 2020; Georgoulis et al. 2021), CMEs (Rodriguez et al. 2022; Ji and Aydin 2022), SEP events (Rotti et al. 2022), and even magnetic polarity inversion lines in the photosphere (Ji et al. 2023). All these very comprehensive data are barely exploited, and one expects measurable advances in understanding and predictive capabilities when they are placed to work systematically with different methodologies.

In brief, the ultimate objective of forecasting efforts of solar activity is to achieve an effective transition from research to operations (R2O). This can be a first transformative change, but it will be incomplete unless an effective research-to-operations – operations-to-research (R2O – O2R) loop is achieved. The second leg of the loop is learning from operations and return to research in order to update, refine and pursue operations with optimized performance. It is widely accepted that only physics (solar physics, in this case) can help complete the loop. In ML/DL applications, in particular, physical interpretability of the results is key. Promising avenues in this research are efficient ML/DL solvers of partial differential equations (e.g., Chen et al. 2021) in the form of physics-informed neural networks (PINN; Karniadakis et al. 2021) or physics-enhanced deep surrogates (PEDS; Pestourie et al. 2023) that are hopefully able to deal with the MHD and/or kinetic equations governing the solar explosive and eruptive activity. These are all very recent developments, and we have yet to see tangible applications on the prediction of solar energetic events; however, one application to (non-predictive) solar physics is known to be successful (Jarolim et al. 2023).

8.2. *Long-term prediction: space climate*

Space climate pertains to long-term effects due to solar activity, at timescales of the solar cycle and more. While this does not seemingly have the tangible effect a short-term prediction has, it is arguably our only hope to understand how the solar dynamo works at long scales. Importantly, as well, long-term studies of the solar activity help us better understand extreme solar events of the past, in the form of 'black swans' or 'dragon kings', namely, outlier extreme but understood and outlier not understood, events, respectively (Cliver et al. 2022; Usoskin et al. 2023, and numerous references therein). Space climate also aims to understand the century- and millennium-scale progression of the solar cycle, including grand activity mimina that continue to be a mystery to this day (Usoskin 2023, and references therein). Heliospheric modulation is an immediate outcome of this behavior (Väisänen et al. 2023). This area of research also includes methodologies that are not met in other areas of heliophysics, including ice-core, tree-ring and cosmogenic isotope studies (Gao et al. 2022; Koldobskiy et al. 2023; Penza et al. 2022).

Central around this line of research is the sunspot cycle and resulting total (and spectral) solar irradiance. Work on re-calibrating archived sunspot numbers is actively underway (Clette et al. 2023). Besides the improved accuracy these efforts will offer in future works, they will be instrumental toward another activity of strong interest, namely the prediction of the strength and timing of future sunspot cycles. This undoubtedly remains a challenging task, reflecting the challenges still faced toward understanding the drivers of the solar dynamo. Challenges may be attributed to the lack of meaningful observational constraints (e.g. Norton et al. 2023). There are diverse approaches to solar cycle prediction that include, but are not limited to, empirical relationships, time-series analysis, AI/ML methods and physics-based magnetic field evolution models such as surface flux transport and dynamo models (Petrovay 2020; Nandy 2021; Karak 2023). Among these techniques, the most successful solar-cycle predictions are generally achieved through a data-driven, physics-based model approach. Currently, solar cycle 25 is ongoing. A comparative analysis of predictions for solar cycles 24 and 25 shows that diverse techniques have continued to diverge in their predictions across these cycles. On the contrary, physics-based predictions for solar cycle 25 appear to converge, indicating a weak-to-moderate cycle, somewhat similar to, or slightly stronger than, the previous solar cycle 24 Nandy (2021). The most widely accepted metric of solar cycle "strength" is the sunspot number, as mentioned above. Physics-based forecasting models serve two purposes: successful implementation makes them important tools for generating prior knowledge of solar activity. On the other hand, they serve as stringent tests for the underlying mechanisms and assumptions driving physical models. These also reinforce the idea that flux transport is a useful tool for modelling solar cycles and supports the Babcock-Leighton solar dynamo mechanism as the primary driver of solar-cycle variability (Bhowmik et al. 2023). Therefore, the actual strength and timing of the peak of solar cycle 25 is anticipated with great interest because it is expected to place important constraints for solar dynamo theories.

9. Sun-Heliosphere Connection

The heliosphere continues to serve as an exceptional laboratory and locally accessible means for studying and testing phenomena shared across multiple branches of solar physics, space physics, high-energy physics, and laboratory physics. While early Voyager missions initially defined its boundaries, subsequent exploration by missions such as PSP, Solar Probe, and various planetary spacecraft have transformed the heliosphere into a viable laboratory setting. Commission E2 members prioritize identifying in-situ features in the solar wind and tracing their origins back to solar phenomena and origins. This endeavor demands a meticulous blend of remote sensing data, numerical modeling and in-situ observations, a combination seldom found beyond Heliophysics. Notably, the discovery of switchbacks (Squire et al. 2020; Mozer et al. 2021), an unforeseen in-situ phenomenon by the Parker Solar Probe shortly after its launch, exemplifies the challenges scientists face. Addressing such puzzles necessitates the kind of multinational cooperation advocated by Commission E2.

In recent years, Parker Solar Probe (Fox et al. 2016; Raouafi et al. 2023) and Solar Orbiter Müller et al. (2020) have revolutionized our understanding of the inner heliosphere and the Sun-Heliosphere connection. More are expected in the near-to-mid term by ASO-S, Aditya-L1, and Solar-C, among other, smaller missions. As the solar wind, with its varied speeds, moves through the heliosphere, the faster wind caches up and overtakes the slower wind, leading to the formation of multiple, intricate, co-rotating regions where these streams interact. These regions, comprising compressed plasma, take on the shape of a roughly Archimedean spiral due to the solar differential rotation, sweeping past celestial bodies orbiting the Sun, whether natural like planets or human-made spacecraft. While the effects of this phenomenon at a distance of 1 AU have been understood for decades, its impact elsewhere in the solar system has really only been measured with in-situ measurements in the last few years. Indeed, one of the primary objectives of the Parker Solar Probe mission was to measure plasma parameters within these structures, from a few solar radii out to 1 AU. Beyond this distance, the scientific community still relies on missions with a focus on planetary science to fill gaps in our understanding. Modeling the propagation of solar transients, such as interplanetary CME (ICME) flux ropes and corotating interaction regions (CIRs) in such a complex 3D space remains a challenging endeavor (Hajra 2021; Shen et al. 2022; Temmer et al. 2023). Furthermore, beyond the planetary realm, the study of how solar plasma interacts with cosmic rays—whether by blocking, receiving, or modulating these high-energy phenomena—continues to bridge the disciplines of plasma physics, solar physics, and astrophysics (Hill et al. 2020).

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