*Transactions IAU, Volume XXXIA*
*Reports on Astronomy 2018-2021*
*Maria Teresa Lago, ed.*

DOI: 00.0000/X000000000000000X

# COMMISSION E2 SOLAR ACTIVITY

*ACTIVITE SOLAIRE*

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## TRIENNIAL REPORT 2018–2021

## 1. Introduction

Solar activity is the business of Commission E2. It originates with the dynamo in the Sun's interior, resulting from a complex interplay of differential rotation, convection and magnetic field, and gives rise to the 22-yr sunspot cycle. Manifestations of activity range in size from coronal holes covering large fractions of the surface, through active regions with their powerful sunspots, coronal mass ejections, coronal loops, flares and nanoflares, network, etc., right down to small magnetic elements at the resolution limits of current instruments, and presumably below.

As we emerge from Cycle 24, the weakest in over a century, we look back at the last three years of low solar activity but high human activity in the field. New space- and ground-based facilities are on the cusp of revolutionizing the discipline. This is a pivotal time in solar activity physics.

## 2. Activities of IAU Commission E2 during 2018-2021

### 2.1. *IAUS 354 Solar and Stellar Magnetic Fields: Origins and Manifestations, Copiapó, Chile, June 30 – July 6, 2019*

This symposium, coordinated by Division E and particularly relevant to Commission E2, attracted over 200 registered participants. Its major focus was on observations and understanding of solar magnetic fields with emphasis on the context provided by other stars. Major themes included: diagnostics of solar and stellar magnetic fields; solar/stellar interior dynamics and dynamos; stellar rotation and magnetism; role of magnetic fields in solar and stellar variability; star-planet relations; formation, structure and dynamics of solar and stellar coronae and winds; mechanisms of flaring and CME activity on the Sun and stars; surface magnetic fields of cool stars; observations of solar eclipses and exoplanetary transits. For the published proceedings see Kosovichev et al. (2020) and enclosed articles.

The meeting coincided with the total solar eclipse of July 2. Participants enjoyed excellent conditions for observing the eclipse from sites to the south of Copiapó.

### 2.2. *IAUS 365 Dynamics of Solar and Stellar Convection Zones and Atmospheres, Moscow, Russia, August 25 – 29 2020*

This symposium has been postponed till August 2021 due to the COVID-19 pandemic.

### 2.3. *IAU General Assembly XXXI, Busan, South Korea, August 16 – 27, 2021*

The triennial General Assembly, including its solar activities of course, has been postponed till August 2022 due to the COVID-19 pandemic.

## 3. New Facilities

The advent of three major solar observational facilities, one ground-based and two in space, will transform our understanding of solar activity for many years to come. With these facilities in place, the Active Sun is hoped to give up many of its secrets.

### 3.1. *Parker Solar Probe*

The Parker Solar Probe (operated by NASA/APL) launched in August 2018 and completed its seventh perihelion (inside 20 $R_\odot$) in January 2021. PSP will eventually dip to 6.9 $R_\odot$ during its last five perihelia in 2024-5. First findings were announced in December 2019, with a major Astrophysical Journal supplement ‘Early Results from Parker Solar Probe: Ushering a New Frontier in Space Exploration’ (Neugebauer 2020, and accompanying articles) presenting around 50 science papers resulting from the mission.

The primary Science Goals are focused on the corona and solar wind and are intrinsically linked to solar activity:

- Trace the flow of energy that heats and accelerates the solar corona and solar wind;
- Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind;
- Explore mechanisms that accelerate and transport energetic particles.

One of the first and most intriguing discoveries made by PSP was the ubiquity of ‘switchbacks’ in the otherwise near-radial magnetic field of the solar wind (Dudok de Wit et al. 2020) that strongly affect the field dynamics and that exhibit different turbulence characteristics than their surrounds.

As well as performing in situ measurements, PSP carries an imaging instrument, WISPR, designed to explore the structure of the solar corona near the Sun.

### 3.2. *Daniel K Inouye Solar Telescope (DKIST)*

DKIST (operated by the US National Solar Observatory, NSO) is a four-meter solar telescope situated on the island of Maui, Hawaii, making it currently the world’s largest. It saw first light in December 2019. DKIST provides unprecedented spatial, temporal and spectral resolution and dynamic range. Spatial resolutions of below 0.1 arcsec with a 5-second integration time in the near-infrared will allow researchers to resolve the fundamental scales of the magnetic solar atmosphere (Tritschler et al. 2016; Rimmele et al. 2020).

The fundamental science questions addressed by DKIST include:

- How are cosmic magnetic fields generated and how are they destroyed?
- What role do cosmic magnetic fields play in the organization of plasma structures and the impulsive releases of energy seen ubiquitously in the universe?
- What are the mechanisms responsible for (Earth-affecting) solar variability?

First-generation instruments available on DKIST include: Visible Broadband Imager (VBI), Visible Spectro-Polarimeter (ViSP), Visible Tunable Filter (VTF), Diffraction-Limited Near-InfraRed Spectro-Polarimeter (DL-NIRSP), and Cryogenic Near-InfraRed Spectro- Polarimeter (Cryo-NIRSP).

### 3.3. *Solar Orbiter*

Solar Orbiter (Müller et al. 2020, operated by ESA/NASA) launched in February 2020. It will take slightly less than 2 years to reach its operational orbit. SO carries ten scientific instruments, both in situ and imaging. It will move within 60 $R_\odot$ on a highly elliptic orbit, with an orbital inclination eventually reaching 24° (33° in the extended mission), enabling unprecedented access to the solar poles that are considered crucial to understanding the Sun's dynamo. In particular, the *Polarimetric and Helioseismic Imager* (PHI) onboard will produce high-cadence intensity and Doppler images suitable for helioseismic probing of the interior, especially near the poles where important clues may reside (Löptien et al. 2014).

The objective of the mission is to perform close-up, high-resolution studies of the Sun and its inner heliosphere, and answer the following questions:

- How and where do the solar wind plasma and magnetic field originate in the corona?
- How do solar transients drive heliospheric variability?
- How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- How does the solar dynamo work and drive connections between the Sun and the heliosphere?

An exciting early discovery of 'campfires' (`https://www.esa.int/Science_Exploration/Space_Science/Solar_Orbiter/Solar_Orbiter_s_first_images_reveal_campfires_on_the_Sun#.YGuPvmenujA.link`) – multitudinous micro-flares that in concert may provide enough heating to supply the corona – was made by the Extreme Ultraviolet Imager (EUI) from Solar Orbiter's first perihelion (about 115 $R_\odot$).

### 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, particular mention should be made of exciting solar results from a variety of radio arrays, including ALMA, LOFAR, MWA, the Jansky VLA, and the Expanded Owens Valley Solar Array. The launch of the massive two-continent Square Kilometer Array (SKA) Observatory in February 2021 also promises important advances when routine science observations begin in the late 2020s.

## 4. Solar Interior and Atmosphere Diagnostics

Our knowledge of the solar interior continues to advance due to the availability of a wealth of continuous data acquired over multiple solar cycles and the use of sophisticated helioseismology and flow-tracing techniques. An exciting development has been the convincing detection of Rossby waves. This is based on work by Löptien et al. (2018) who reported a direct detection of Rossby waves at the surface and in the outer 20 Mm of the convection zone. Both granulation-tracking and ring-diagram analysis were applied on six years of SDO/HMI data to measure horizontal flows. They found waves of radial vorticity propagating along the equator in the retrograde direction in the corotating frame. Dispersion relations are consistent with that of classical sectoral Rossby waves. Further confirmation was provided by Liang et al. (2019) who used time-distance helioseismology to confirm the existence of global-scale equatorial Rossby waves over the last two solar cycles, using 21 years of data from MDI and HMI, for deeper layers (down to 63 Mm).

Efforts are ongoing to measure and characterize the solar meridional circulation, especially the return flow with the question being whether there is a single cell or multiple cells stacked in radius, but the results are inconsistent. Gizon et al. (2020) reports a single cell in each hemisphere which contradicts previous reports of two cells (Chen and Zhao

2017; Zhao et al. 2013). Modeling efforts from multiple research groups are using a variety of flow amplitudes and recovery techniques to determine which meridional flow patterns can confidently be recovered. There is some indication that meridional circulation could change during or between solar cycles.

Another advancement in the implementation of helioseismology techniques is the use of multiple measurement schemes, multi-skip time-distance helioseismology and holography, simultaneously to image the Sun's far side and allows far-side monitoring of active regions with higher confidence and better reliability (Zhao et al. 2019). The improved ability to monitor active regions on the far side of the Sun is useful to space weather forecasting and solar wind modeling. On an active region scale, a compact source of sunquakes was detected using acoustic holography (Lindsey et al. 2020) with the surprising result that the source was submerged a thousand kilometers beneath the photosphere of a flaring active region.

Diagnostics of the solar atmosphere come in many forms including inversions, extrapolations, global modeling, etc. This is a very broad topic that cannot be covered comprehensively in a short report, therefore, we only touch on a few recent advances.

The differential emission measure inversions on narrow-band EUV images from the Atmospheric Imaging Assembly (AIA) continue to advance studies of the energetics of the outer atmosphere of the Sun lending insight into coronal heating, flares, CMEs and smaller eruptive phenomenon.

A diagnostic tool for analysis of data from the Interface Region Imaging Spectrograph (IRIS) has been made publicly available and is called IRIS$^2$ (Sainz Dalda et al. 2019). It quickly, using machine and deep learning techniques, provides thermodynamic parameters (temperature, line-of-sight velocity, non-thermal velocities, electron density, etc.) based on non-LTE inversions and a set of representative profiles of the optically thick Mg II h&k lines. The IRIS$^2$ database and tool provides new windows to understanding the chromosphere. Gošić et al. (2021) used the IRIS2 tool in conjunction with IRIS and Swedish Solar Telescope data to show that weak, internetwork magnetic fields with strengths between 450 and 800 G reach the chromosphere and transition regions heights and locally heat the upper solar atmosphere.

IRIS observations were also used to reveal the signature of an abrupt transition in the magnetic reconnection rate from a slow to a fast phase during UV bursts (Guo et al. 2020), which is consistent with models of the plasmoid instability. Reconnection rates are of critical importance in many space plasma environments and there are many unanswered questions about the onset of reconnection rates, so these observations are of broad astrophysical interest.

An impressive effort that combined several diagnostic techniques, including the derivation of electric fields from surface magnetic data and the reconstruction of them into a global electric field to determine the current density in the low corona, was accomplished via the Coronal Global Evolutionary Model (CGEM) (Hoeksema et al. 2020). CGEM used data-driven simulations of the magnetic field in the solar corona to better understand the build-up of magnetic energy that leads to eruptive events. The derived electric fields drive a 3D spherical magnetofrictional (SMF) model and detailed magnetohydrodynamic (MHD) simulation of active regions in the low corona. The CGEM group compared a modeled proxy of emissivity based on the current density to AIA data with good agreement.

A new diagnostic technique to determine coronal magnetic field strengths in active regions was reported (Landi et al. 2020; Si et al. 2020) using a magnetically sensitive Fe X transition. This technique can be applied to existing Hinode EIS data to image the coronal magnetic fields on the disk which will be complementary to the measurements of UCoMP and DKIST at the solar limb.

## 5. Solar Dynamo and Solar Cycle

All solar activity has its roots in the Sun's dynamo. Conversely, our knowledge of the dynamo (such as it is) is based primarily on surface and helioseismic observations of the sunspot cycle and other features that evolve over the 22-year magnetic cycle, such as sunspot latitudes, the butterfly diagram, active region orientations (Joy's Law), surface and subsurface flows, etc. Gross properties, such as convection zone depth, differential rotation profiles, and (near-surface) meridional circulation have also been revealed by seismology and play significant roles in many dynamo theories. Especially in recent years, simulation has come to the fore, principally in the form of toy kinematic dynamo models (Charbonneau 2020), since Direct Numerical Simulation (DNS) on a global scale is unable to achieve realistic solar parameters by many orders of magnitude. It is feasible on a sufficiently local scale though.

Early in the 21st century, it was commonly believed that at least the large-scale manifestations of the dynamo, such as active regions, originated in the tachocline, a shear layer between the Sun's radiative core and convective envelope. The tachocline possesses several attractive features for dynamo modellers: it can store strong ($10^5$ G) magnetic field against buoyancy in its lower reaches as it is being amplified by differential rotation; it can host an array of magneto-shear instabilities that may supply the required toroidal-to-poloidal mechanism for a global dynamo (Gilman and Cally 2007); it can potentially explain the preferred sunspot latitudes (Kitchatinov 2020); and, together with detailed models of fluxtube rise to the surface (Fan 2009)†, can potentially explain further details of active region structure. A whole class of dynamo models incorporating the tachocline, the flux-transport dynamos (Dikpati and Gilman 2009 with weak convection zone turbulent diffusivity; Choudhuri et al. 2007 with much higher diffusivities), is based on a conveyor-belt concept relying on Babcock-Leighton poloidal generation at the surface with $\alpha$ and $\Omega$ effects operating in the tachocline, coupled by single-cell-per-hemisphere meridional circulation that circulates magnetic flux between them on a timescale that gives rise to the solar cycle. The high-diffusivity models have shorter memories though, typically less than a solar cycle, and therefore a qualitatively different evolution.

However, despite their easily understandable and compelling essence, Flux Transport Dynamos did not perform particularly well in predicting the very weak Solar Cycle 24 (Petrovay 2020). They are notoriously sensitive to model parameter and data assimilation details, and in any case may not provide much predictive capability due to the apparent existence of a chaotic regime in their solutions (Charbonneau 2007). Fundamentally, there is even doubt from helioseismic inversions that the solar meridional circulation has only one cell in depth through the convection zone (Zhao et al. 2013), though other inversions strongly support the single-cell model (Gizon et al. 2020). A time-varying meridional circulation, perhaps involving a changing number of cells, may produce more solar-like sunspot cycles compared to a fixed circulation pattern (Hung et al. 2017). In any case, the very structure of the Sun's deep meridional circulation is still controversial, leaving doubts about Flux Transport and related tachocline dynamo models.

† Recently, Hotta and Iijima (2020) have used the Reduced Speed of Sound Technique (RSST) to model convection and the rise of a flux tube from the base of the convection zone to surface flux emergence. Although the numerical resolution in the deep convection zone is not yet sufficient to yield a fully consistent simulation throughout, they report that it will be possible with next-generation supercomputers.

It has recently been noticed that bursts of eruptive activity on the Sun show some tendency to cluster in ‘seasons’ that appear, from modelling and observation, to be related to magnetic Rossby waves at the tachocline (Dikpati et al. 2017; Dikpati et al. 2018; Zaqarashvili et al. 2021), and which also show up in the corona in the motion of magnetic bright points (MBP; McIntosh et al. 2017). This has the potential to enhance our predictive capacity, and also to directly probe tachocline instabilities and waves.

However, contrary to the tachocline explanation of dynamo activity, body-of-the-convection-zone dynamos have gained credence in recent years. Stunningly, Wright and Drake (2016) describe four fully convective stars that display solar-like correlations between X-ray emissions and rotation period, indicating that a tachocline is not a *necessary* component of a solar-like dynamo. Current knowledge of magnetism and dynamo action in solar-type stars has been reviewed by Brun and Browning (2017).

This is not to say that mean field dynamos (Jouve et al. 2008) do not also face many difficulties. The recent review of Brandenburg (2018) is very critical of flux-transport models, partly on the basis of the very low turbulent diffusivities, seemingly at odds with mean field theory, required for them to produce solar-like behaviour. However, it also points out a depressing number of failings and uncertainties of body-of-the-convection-zone mean field models, e.g., the role and nature of mean-field and topological pumping; the dependence of the $\alpha$ effect on density and other parameters; inconsistencies in simulated and seismically measured convective velocities; doubts about convective energy transport in deeper layers; an inability to consistently explain the Sun’s internal differential rotation profile and in particular the near-surface shear layer; etc. Overall, it is safe to say the the solar dynamo question is very far from solved.

## 6. Solar Atmospheric Heating

Million degree temperatures have been observed in the corona for decades, but the mechanism of how the upper atmosphere is heated to a 2–3 order-of-magnitude higher temperature than the photosphere is still unresolved. Different mechanisms have been proposed for various regions and physical conditions. Overall, most of the heating mechanisms can be classified into two categories: magnetic reconnection and MHD waves, both associated with magnetic field but in different ways. With the advanced capabilities of modern observational instruments and numerical computations, some progress has been made in recent years.

### *Magnetic Reconnection Heating*

Observations with high spatial resolution (Gošić et al. 2018; Leenaarts et al. 2018) from the Swedish 1-m Solar Telescope (SST) show the chromospheric heating from magnetic flux emergence and internetwork magnetic flux cancellation. However, the latter is estimated to be one order of magnitude smaller than that required to compensate for the radiative losses in the chromosphere. The underestimation of the relevant energy may be due to limitations of present observations. This is shown in Yadav et al. (2020) in which the energy transported by vortex flow in a unipolar solar plage region is calculated with different spatial resolution. Magnetic reconnection at opposite polarities is found to play an important role in heating chromospheric spicules and adjacent corona (Samanta et al. 2019).

The trigger and heating mechanisms of magnetic reconnection in coronal loops are investigated by simulation. Tearing instabilities in current sheets induce magnetic reconnection and magnetic shear therein is considered to be a crucial factor (Leake et al. 2020). Plasma heating through MHD avalanches in coronal loops is simulated in Reid et al. (2020). Their results demonstrate that Ohmic heating is responsible for strong heating events while viscous heating is related to smaller events. For either wave-like drivers or slow stressing motions at the photosphere, energy dissipation is significant in the strongest magnetic field regions and in magnetic separatrix layers, where magnetic reconnection preferentially occurs (Howson et al. 2020a).

Nanoflares produced by ubiquitous magnetic reconnection in the solar corona have been proposed as possible source for corona heating, which is also demonstrated in recent simulation (Kanella and Gudiksen 2018) of small-scale energetic events that reveal the nano-scale events contribute much more heating than do those at pico- or micro-scale. Motivated by the common magnetic flux cancellation observed by balloon-based mission SUNRISE, a nanoflare model with flux cancellation, instead of magnetic braiding and reconnection, is adopted in Syntelis and Priest (2020) to produce a wide range of small-scale phenomena and the details of energy release are investigated in Priest et al. (2018) and Priest and Syntelis (2021). The high instrumental sensitivity of FOXSI and NuSTAR also provides for the first time possible constraints on the nanoflare model at high temperature (Marsh et al. 2018).

For impulsive heating events, the similarity between small-scale chromospheric heating observed by SUNRISE with a spatial resolution of 0.1 arcsec and large-scale flares has been revealed by Smitha et al. (2018). For coronal mass ejections, Reeves et al. (2019) explore plasma heating in the current sheet region from Ohmic dissipation, adiabatic compression and thermal conduction. Ohmic heating is crucial in the early phase of eruption while adiabatic compression becomes prominent in the late phase.

### *MHD Wave Heating*

Chromosphere heating is thought to be related to acoustic and magnetoacoustic waves. In the chromosphere's non-magnetic regions, Kuźma et al. (2019) solve two-fluid equations of ions and neutrals to investigate the energy deposition in acoustic waves by collisions, and find it to be insufficient to balance the known radiative losses. On the other hand, by comparing with chromospheric observations, Abbasvand et al. (2020b) find the energy deposited by acoustic waves can balance radiative losses in the middle chromosphere but not in the upper layers, and the important roles of acoustic wave in quiet regions and also in weak plage regions have been confirmed in Abbasvand et al. (2020a) through non-LTE 1D hydrostatic model and in Murawski et al. (2020) through 3D numerical simulations.

Alfvén waves (AW) have long been considered to carry sufficient energy to power the quiet solar corona, but how the energy dissipates has been unresolved. Based on previously proposed mechanisms of dissipation, simulations were carried out of phase mixing (Pagano and De Moortel 2019; Howson et al. 2020b; Pagano et al. 2020). López Ariste and Facchin (2018) include super-oscillations in coronal MHD waves, producing sausage and kink mode transition and ten times higher wave frequencies, producing heating through compressive viscosity. The co-existence of kink and Alfvénic modes turns out to lead to enhanced heating through Kelvin-Helmholtz instability (KHI) (Guo et al. 2019a). Shock and turbulence heating of AW has been compared for different photospheric correlation lengths in Shoda et al. (2018), indicating that turbulence heating is dominant for lengths less than 1 Mm, which corresponds to the spatial scale of granulation. Sakaue and Shibata (2020) show that chomospheric shocks generated by highly nonlinear AW can decrease the wave energy transported into corona. Torsional Alfvénic waves can be dissipated at the chromosphere through Ohmic dissipation and ion-neutral friction, while the energy that can reach the corona is limited (Soler et al. 2019). In the above contexts, gravitationally-stratified (Karampelas et al. 2019) and multi-stranded coronal loop models (Guo et al. 2019b) are recommended when modeling wave heating.

The main obstacle for AW heating of the corona lies in the fact that the ion-cyclotron frequency is much larger than the wave frequency, apparently making ion motion adiabatic to the waves. However, a new neo-adiabatic theory (Escande et al. 2019) shows even a monochromatic spectrum of AW can heat the quiet solar corona due to the breakdown of adiabaticity caused by slowly pulsating separatrices in phase space, which the authors conclude is very efficient.

In polar corona holes, Ultraviolet Coronagraph Spectrometer (UVCS) measurements of the H I Ly$\alpha$ line yield moderate AW amplitudes that show weak dissipation consistent with independently derived proton and electron heating rates (Cranmer 2020).

Besides the above investigations of AWs propagating upward, Reep et al. (2018) studied the AWs that are generated at reconnection sites in the corona and propagate downward to the chromospheric footpoints. The AW is found to dissipate at different locations and at different rates according to the ionization level of the plasma in the coronal loops. The appearance of AW heating is also very different from electron beam heating.

## 7. Coronal Mass Ejections

As a source of disturbances to the solar-terrestrial environment, coronal mass ejections (CMEs) are crucially important, especially in considering the sun-heliosphere connection (Section 9) and space weather forecasting (Section 8). SOHO/LASCO is still observing well, and the SOHO LASCO CME CATALOG† (Yashiro et al. 2004) now lists more than 30,000 CMEs by October 2020, and more than 1,600 events have occurred since 2018, when solar activity has been relatively quiet. The characteristics of CMEs in Solar Cycle 24 based on SOHO/LASCO are summarized in Gopalswamy et al. (2015, 2020). While we lost communication with STEREO-B in October 2014, STEREO-A still continues to observe CMEs from different directions on the ecliptic plane. In coming years, there will be increased opportunities to follow the propagation of CMEs from many angles in three dimensions using spacecraft such as Solar Orbiter.

Filament eruptions, which are phenomena on the solar surface and are seen in chromospheric lines, have attracted much attention as a cause of CMEs on the solar surface, and research on the relationship between filament eruptions and CMEs is long-standing but still active (e.g., Munro et al. 1979; Hori and Culhane 2002; McCauley et al. 2015). While some filament eruptions are clearly followed by CMEs, others become failed eruptions. Therefore, it is very important and challenging to determine what kind of filament eruption can really become a CME from solar surface phenomena. A statistical study of filament eruptions observed in the H$\alpha$ line by the Solar Dynamics Doppler Imager (SDDI) (Ichimoto et al. 2017) on the SMART telescope at Hida Observatory, Kyoto University, done by Seki et al. (2021), found that the product of the erupting velocity and the filament length is well correlated with CME occurrence. Yashiro et al. (2020) reported a statistical study of prominence eruptions in relation to CMEs by using a catalog of prominence eruptions seen in SDO/AIA 304 Å pass band images.

There have also been rigorous attempts to reproduce the structure of magnetic flux ropes and the process of the eruption that causes CMEs based on numerical simulations (Amari et al. 2018; Fan 2018). In particular, data-constrained and data-driven MHD numerical simulations have been actively performed. For the large X9.3 flare on September 6, 2017, where the structure of the magnetic flux rope in the solar corona was estimated from photospheric magnetograms using the NLFFF model, MHD simulations have successfully reproduced the eruption process (Yang et al. 2017; Inoue et al. 2018). The

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

magnetic field configurations in the pre-eruptive stage of magnetic flux ropes are summarized by Patsourakos et al. (2020). If the magnetic field structure of the flux rope can be estimated more precisely by observing the chromospheric magnetic field (Wang et al. 2020), it will contribute greatly to improving the accuracy of predicting the eruption process.

The report of a stellar flare-coronal mass ejection event (Argiroffi et al. 2019) was startling. We can expect many more reports of similar stellar flare-related ejection events and signs of stellar CMEs in the future, and many solar physics findings and knowledge will surely be used to elucidate stellar CMEs.

## 8. Solar Weather Forecasting

What we collectively refer to as 'Space Weather', that can adversely affect space conditions in the entire heliosphere for relatively brief intervals of the order hours or days, is long known to have two sources: the Sun and solar activity, primarily, and the galaxy and its cosmic rays, to a lesser degree. The lower end of the so-called 'stormy' space weather does not necessarily require eruptive solar activity (i.e., major flares followed by fast CMEs capable of forming heliospheric shocks and accelerating solar energetic particles [SEPs] to relativistic speeds) but can rely on high-speed solar wind streams generated by conspicuous coronal holes at geoeffective longitudes (e.g., Hofmeister et al. 2018). However, major space weather disturbances and subsequent geomagnetic storms are triggered by eruptive activity exclusive to solar active regions. The forecasting of flares, CMEs, and SEP events has, therefore, become a topic of intense focus and has been categorized as a real-world problem. Insufficient solutions can have calamitous consequences for our space-based technological assets and human life in orbit and beyond (Eastwood et al. 2017).

Forecasting of solar flares kicked off some 35 years ago, with observations of particular magnetic features of flaring active regions and the Zurich and McIntosh classification of sunspot groups. In recent years it has become clear that, in spite of statistically substantial data and the plethora of devised prediction methods, we have made important strides but are far from declaring that the forecasting problem has been solved (Barnes et al. 2016). Perhaps this is due to the lack of magnetic field information above the photosphere (Korsós et al. 2020) or the intrinsic stochasticity of the flare triggering process (Campi et al. 2019). Flare forecasting has recently seen community-wide efforts devised to comparatively evaluate the day-to-day performance of numerous operational flare forecasting methods (Leka et al. 2019a,b; Park et al. 2020), with a key conclusion being that there is no clear winner method so far. Comparative performance verification relies on a toolbox of skill scores and statistics metrics that the community has borrowed mainly from terrestrial weather forecasting (Crown 2012; Murray et al. 2017).

As flares are all but electromagnetic radiation, there is no other way to forecast them than before they are actually detected. For CMEs, however, much focus continues to be on the forecasting of arrival times of their interplanetary counterparts (ICMEs) at geospace (Riley et al. 2018; Verbeke et al. 2019) following their detection near the Sun. This exercise has resulted in absolute forecast errors of the order $\gtrsim 10$ hours on average, with somewhat better performance reaching up to absolute errors $\gtrsim 6$ hours when a triangulation is achieved by using data from the STEREO mission (Paouris et al. 2021). The predicted geoeffectiveness of CMEs relies mainly on magnetohydrodynamical (MHD) modeling (Palmerio et al. 2017; Scolini et al. 2018), although there have been some recent efforts to tackle the problem using fundamental physical properties and attributes of heliospheric magnetic fields and plasmas (Patsourakos and Georgoulis 2017; Vourlidas et al. 2019).

Likewise, for SEP event (proton, mainly) forecasting the majority of efforts relied on nowcast eruptions, either in the Sun (e.g., Núñez et al. 2019, and references therein) or in heliospheric precursor signatures of their propagation (e.g., Posner and Strauss 2020, and references therein). In recent years, however, one sees efforts to correlate statistically significant datasets of eruptions in the Sun with SEP attributes (Papaioannou et al. 2016; Kahler and Ling 2017; Aminalragia-Giamini et al. 2020) with an aim to forecast SEP occurrence all the way from Sun to Earth (Falconer et al. 2014; Anastasiadis et al. 2017; Laurenza et al. 2018; Kahler and Ling 2018). Comprehensive overviews of SEP analysis and forecasting efforts can be found in Malandraki and Crosby (2018). A systematic comparison of SEP forecasting efforts has yet to be accomplished; however, one expects skill scores and statistical metrics to be rather low, given that SEP events are the spear's tip of stormy space weather and its scarcest manifestation at the same time. For this purpose, NASA's Community Coordinated Modeling Center (CCMC) has recently instituted the SEP Scoreboard facility (`https://ccmc.gsfc.nasa.gov/challenges/sep.php`), similarly to CCMC's flare and CME scoreboards.

Let us now highlight two recent trends in forecasting the solar end of space weather, namely, the establishment of so-called benchmark datasets and the nearly explosive use of artificial intelligence (i.e, machine and deep learning) methods for these purposes. Benchmark datasets rely on and draw from longstanding flare, CME and SEP catalogues, serving as testbeds for the performance verification of different (artificial intelligence or not) methods on the exact same conditions. They present a way to navigate through the Big Data landscape created by the multi-parametric, voluminous and often multi-spacecraft metadata used for the prediction of solar events. Benchmark datasets for flare prediction stem from Barnes et al. (2016); Leka et al. (2019a); Angryk et al. (2020); Georgoulis et al. (2021), while for SEP prediction from Dierckxsens et al. (2015); Papaioannou et al. (2016); Paassilta et al. (2017); Bruno et al. (2018) and others. These datasets can also be combined to enhance the predictive capability of the tested methods (Murray et al. 2018; Kontogiannis et al. 2019). One may expect significant developments from such synergistic, confluent approaches in the future.

Machine learning methods are now applied to flare, CME and SEP prediction, again starting from flares (e.g., Bobra and Couvidat 2015; Florios et al. 2018) and proceeding to more complex applications. Deep learning methods have also been applied to solar flare prediction (Nishizuka et al. 2018), although to this day it is not clear whether deep learning is fully applicable to this problem due to the lack of sufficiently large samples for data-starved deep neural networks (see, for example Goodfellow et al. 2016). Regardless, in spite of numerous applications of machine and deep learning exposed in detail in the reference text of Camporeale et al. (2018), there is vivid discussion on the fundamental framework that such methods should adhere to (e.g., Cinto et al. 2020). Clearly, the landscape on machine and deep learning applications to solar (and space) weather forecasting is rapidly evolving, if not still shifting, in the face of serious challenges, so one should defer potentially important conclusions for the future.

## 9. Sun-Heliosphere Connection

The Heliosphere presents a unique laboratory – available and reachable – where those facets common to solar physics, space physics, high energy physics and laboratory physics can be studied and tested. The early successes of the Voyagers missions defined (and continue to redefine) the boundaries of this volume, but with the new explorations of PSP, Solar Probe, and multiple planetary missions, we can now consider the heliosphere a laboratory space. In this light, identifying in-situ features in the solar wind, and successfully tracking the cause-and-effect back to the solar features has been a priority among the members of Commission E2. This requires a detailed combination of remote sensing data, numerical modelling, and in-situ data, a combination that is rare outside of Heliophysics. The switchbacks, identified as an unexpected in-situ feature shortly after launch of the Parker Solar Probe, is one of these first conundrums that vexed scientists, requiring the type of multi-instructional, multinational cooperation that Commission E2 promotes.

As the multi-speed solar wind propagates through the heliosphere, the fast wind catches up with the slow wind, creating a complex, corotating set of stream interacting regions (Richardson 2018). These regions of compressed plasma form into a roughly Archimedean spiral that sweeps past any object that may orbit the Sun (be that natural such as a planet or man-made such as a spacecraft). Although the effects of this at 1 AU have been well known for decades, the effect elsewhere in the solar system are only now presenting themselves in in-situ measurement. Indeed the measurements of plasma parameters inside these structures from a few solar radii out to 1 AU is one of the key mission goals of the Parker Solar Probe. Beyond 1 AU, the community relies on missions with planetary science focus to fill in the gaps in our knowledge. The propagation of a magnetic flux rope through such a complex 3D space remains a highly illusive topic of numerical modelling. Beyond the realm of the planets, the study of how solar plasma interacts with cosmic rays, either blocking, receiving, or modulating these high energy phenomena, continues to cross the subject divides of plasma physics, solar physics and astrophysics.

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Ayumi Asai, Hui Li, James McAteer, Aimee Norton *organizing committee members*

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