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DIVISION E SOLAR ACTIVITY
COMMISSION 2 *ACTIVITE SOLAIRE*

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TRIENNIAL REPORT 2015-2018

1. Introduction

Commission E2 deals with solar activity on all scales, ranging from the nanoflares that may be implicated in coronal heating, to the largest flares and mass ejections, and includes the origin and dynamics of the large-scale magnetic field that is the foundation of this. This report reviews scientific progress in the domain, over the three-year period from mid 2015- early 2018. This period has seen continued exploitation of space-based missions such as Hinode, IRIS, SDO and STEREO, as well as high-resolution ground-based solar observatories such as the SST and the Goode Solar Telescope. The report is divided into the following sections: the solar cycle and dynamo; the large-scale solar magnetic field; coronal heating; solar flares; particle acceleration; flare forecasting; and solar eruptions. Our report aims to be comprehensive in the topics addressed, though to some extent the topics cover reflect the expertise of the commission members, and many important results are omitted due to limited space.

2. Solar Cycle and Dynamo

Our understanding of the solar cycle and dynamo, which underpins all magnetic activity, is currently in a state of flux. Modelling and simulation are not sufficiently advanced to robustly reproduce the observables (11-year cycles, butterfly diagram, Spörer's Law, Hale's Law, Joy's Law, magnetic helicity, etc.). Specifically, there are more free parameters available in phenomenological models than can be constrained by these observations, and direct numerical simulations are very far from accessing solar-realistic Reynolds numbers. Current issues are reviewed by Charbonneau (2010), Brun et al. (2015), Cameron et al. (2017), and Brun & Browning (2017).

Dominant paradigm: α-Ω dynamo of Babcock-Leighton type? In the wake of the helioseismic determination of the Sun's true differential rotation structure, the ideas of Babcock (1961) and Leighton (1969) were resurrected in the 1990s (Wang & Sheeley 1991; Choudhuri et al. 1995; Durney 1995; Dikpati & Charbonneau 1999). The Babcock-Leighton model specifically describes a surface toroidal-to-poloidal mechanism explicitly involving Joy's Law (active region tilt).

When coupled with a particular appreciation of the role of meridional circulation as a conveyor belt, this forms the family of Flux Transport Dynamo models. If meridional circulation reaches to the tachocline at the base of the convection zone (CZ), differential rotation there is believed to provide the complementary poloidal-to-toroidal part of the story and possibly an additional α-effect (lift and twist). This was perhaps the dominant paradigm a decade ago, and is still under active development. For example, Dikpati et al. (2018) argue that tachocline nonlinear oscillations are linked to "solar seasons" of enhanced CME activity (McIntosh et al. 2015), suggesting that the tachocline may indeed play a role in large scale surface magnetic activity.

What can Convection Zone Simulations Tell Us? In recent years though, the attention of many has shifted from the tachocline to whole-convection-zone dynamos (Brun et al. 2004), or surface-shear-layer-dynamos (Brandenburg 2005), modelled using large-scale simulation made possible by increasing computing power. The details of the models take a wide variety of forms, for example the Anelastic Spherical Harmonic (ASH) code (Brun et al. 2004); a high-order compressible-MHD PENCIL code (Brandenburg & Dobler 2002); and the Reduced Sound Speed Technique (RSST) code (Hotta et al. 2014), and many others. The computational region of the widely-applied ASH code must be truncated well-short of the surface (for example at $0.965\,R_\odot$ in Featherstone & Miesch 2015), but the RSST code can be extended to $0.99\,R_\odot$ (Hotta et al. 2015), making it more suitable for modelling the near-surface shear layer. The RSST code has also been recently applied to the overshoot region at the base of the convection zone for realistic imposed energy flux, predicting that it is extremely thin, around 0.4% of the pressure scale height, and making small-scale dynamo action more efficient.

However, no code has yet been able to self-consistently create a tachocline, suggesting that there remain fundamental shortcomings in the models. Furthermore, predictions of magnetic helicity from simulations appear to be inconsistent with observations (Brandenburg et al. 2017). Nevertheless, dynamo action in the body of the CZ is looking more feasible, though there are many other uncertainties. A brief review may be found in Cameron et al. (2017).

Are current simulations giving a realistic view of deep convection? Time-distance (TD) helioseismic inversion for flows in the deep solar convection zone apparently place very severe bounds on convective velocities (Hanasoge et al. 2012), restricting them to between 20-100 times weaker than theoretical limits in the wavenumber band $\ell < 60$. This seems incompatible with convective energy transport requirements, numerical simulations, and the requirements of a CZ dynamo. On the other hand, Greer et al. (2015), using the ring-diagram technique recover horizontal flow speeds in excess of 120 $\mathrm{m\,s^{-1}}$ between 20 and 30 Mm deep, which is more in line with expectations. The reason for the discrepancy, and therefore the true velocities, is currently unknown.

One suggested explanation for radically reduced convective horizontal velocities of length-scales consistent with $\ell < 60$ is that deep layers may be stirred by entropy rain from the surface that takes the form of strong isolated plumes at depth (Käpylä et al. 2017). These can play a significant role in the convective flux via a non-gradient process called Deardorff flux (Brandenburg 2016).

Does meridional circulation have multiple cells stacked in radius? There is growing evidence from time-distance helioseismology using HMI data that meridional circulation may consist of multiple cells in radius in the convection zone (Zhao et al. 2013; Zhao 2016). However, this is disputed by Jackiewicz et al. (2015) who apply similar techniques to GONG data, but comment that their derived flows do not conserve mass well. Rajaguru & Antia (2015) also apply TD to HMI data, but with a technique that enforces mass conservation, and find only a single circulation cell with depth. At the moment, this is an open question. A mechanism for generating double-cell patterns is suggested by (Bekki & Yokoyama 2017), assuming Reynolds stresses that transport angular momentum upwards in the lower convection zone and downwards in upper CZ. Simulations using the Anelastic Spherical Harmonic (ASH) code (Featherstone & Miesch 2015) indicate that the Sun may lie close to to the boundary between the one-cell and two-cell parameter regimes. Of course, the question of meridional circulation cell structure is of vital relevance to flux transport dynamo models with their supposed conveyor-belt mechanism (Belucz et al. 2015).

Is data assimilation a way forward? Attempts to fit model parameters using single observed initial conditions to obtain predictions of future behaviour do not recognize the inherently chaotic nature of the Sun's dynamo or the uncertainties in observations. Recently, modern data assimilation techniques such as ensemble Kalman filtering have been employed to estimate the parameters based on sets of data accumulated over a period of time and a simple parametrized model, specifically the flux-transport Babcock-Leighton model, where there is a readily understood relationship between model parameters and observables (Kitiashvili & Kosovichev 2008; Hung et al. 2015; Dikpati et al. 2016, and references therein).

Early results appear to promise more accurate and robust prediction of future behaviour than deterministic approaches, and possibly also more reliable reconstructions of deep meridional circulation (Hung et al. 2015) than are provided by various mutually inconsistent helioseismic results (Zhao et al. 2013; Jackiewicz et al. 2015).

3. The large-scale magnetic field as the foundation of the heliosphere

The partial yet historically unmatched coverage of the Sun's magnetic field, corona, and innermost heliosphere over the past two decades, coupled with advances in computational infrastructure and methods as well as increasing interest in space weather, are helping us to better understand the dynamics of, and processes in, the Sun's outermost atmosphere. It is in that domain where solar flares and eruptions occur, and from where field and wind begin to form the heliosphere with its variable solar-wind conditions that, when enveloping Earth, powers space weather. Understanding of all of these phenomena would clearly benefit from an improved knowledge of the global coronal and inner-heliospheric field for multiple reasons, from which we select three themes to highlight in this brief summary. These three have seen substantial advances in the recent triennial period: the Sun's large-scale magnetic field (1) is instrumental in triggering of many flares and CMEs by long-range interactions, (2) determines the initial path of not only the solar wind but also of CMEs from near the solar surface into the inner heliosphere, and (3) sets the conditions for the interacting slow and fast solar winds in quiescence and for the propagation of CMEs that interact with wind streams into which they propagate.

The large-scale field and flare/CME triggering The mounting evidence that the evolution of the large-scale coronal field influences at least the timing, but likely the very occurrence, of flares and CMEs is behind the first of these three drivers of interest in the large-scale coronal field. For example, Schrijver & Higgins (2015) found evidence that flares and eruptions from an active region are associated with an increase in such activity from distant other regions within hours from such events. Lee et al. (2016) present arguments that long-range magnetic couplings may play a role in the increased frequency of flares and CMEs when the activity belts on the two hemispheres approach each other in the declining phase of the solar cycle through transequatorial connections. In another observation-based study, Fu & Welsch (2016) revealed that the emergence of new active regions leads to an increase in flaring from pre-existing regions well away from the emerging region; they argue that this is caused by the distortion of the peripheral coronal field of regions which influences in turn the stability of the field in the region's interior coronal domain. Combined ground- and space-based observations enable the observational study of such interactions, such as the analysis of sympathetic filament activity in the work by Wang et al. (2016). In the virtual world, global MHD models of eruptions by, for example, Jin et al. (2016) are revealing how sympathetic eruptive events may occur either through direct coupling of field, through field distortions driven by CMEs, or through transient deformations associated with large-scale wave fronts.

Near-Sun propagation in the large-scale field Interest in improved forecasts of geomagnetic storms combined with the unprecedented coverage of the Sun-Earth system powers the interest in the second theme. Not only are the source regions of flares and CMEs being actively studied, but also the propagation of those eruptions that eventually drive space weather. In these studies, it has become clear that knowing the large-scale coronal field, from around erupting active regions to half a dozen solar radii, is important to CME propagation. CMEs often do not move simply radially away from the Sun as has been assumed generally in the past: Möstl et al. (2015) and Wang et al. (2015), for example, report on the deflection of CMEs from a radial propagation by over 40 degrees away from radial.

The origin and drivers of the solar wind The third theme that we selected from among the reasons to study to Sun's large-scale field have to do with the origin and drivers of the solar wind. Whereas the origin of the fast solar wind is firmly tied to large coronal holes through many observational and modeling studies, the origin of the slow solar wind remains under debate. Abbo et al. (2016), Cliver & von Steiger (2017), and Cranmer et al. (2017) review the evidence for the leading scenarios: plasma may be expelled into the heliosphere driven by wave turbulence or by reconnection, while potential source regions range from the quiet-Sun coronal holes to active regions. They review decades of study and conclude there there is mixed evidence for both driver scenarios and several of the source regions, so that the process that dominates the driving of the slow solar wind continues to elude us, or maybe it is telling us that multiple processes are at work in different source regions.

Among the various lines of evidence published in the triennium covered here we find the work by Zhao et al. (2017a) who note a tendency of solar wind to be slower and of a higher ionization temperature going trough the following series of likely sources: coronal hole, coronal-hole boundary, quiet Sun, quiet-Sun boundary, active region, and helmet streamer. This is in line with work by Brooks et al. (2015), Fazakerley et al. (2016), and Wang (2017) who discuss the evidence that much of the slow solar wind originates from open-field patches and channels that occur at the periphery of active regions, as well as from the edges of large coronal holes from the central regions of which the fast wind originates. These studies rely heavily on being able to map the solar wind as measured near Earth (often based on L1 data) back to the high corona and from there through some model field down to the solar surface. The latter, in particular, requires that we understand how that large-scale field is shaped and how it evolves.

These three themes are among the many that benefit from a better understanding of the Sun's large-scale magnetic activity. The data base formed by SOHO and SDO now provides insight into the evolution of the solar corona over a period extending over more than two decades. Among the many things that can be studied in such a data archive is the evolution of the global corona, among them the characteristic markers formed by coronal holes that form the primary source of the fast solar wind. Lowder et al. (2017) perform such a study revealing latitude-dependent evolution and the disappearance and re-formation of the polar coronal holes that can then be used in comparison with global-coronal and heliospheric field models.

Modeling and extrapolations of the large-scale magnetic field The impossibility of probing the 3D structure of the Sun's large-scale magnetic field makes its study necessarily rest on models that extrapolate the surface magnetic field into the heliosphere. The input to such models is itself of insufficient quality: we do not have the means to reliably quantify currents and stresses that are forced upon the atmospheric field while more than half of the Sun's surface remains inaccessibly to present-day magnetographs. Despite these challenges, some workhorse model assumptions have survived decades of developments, most notable the potential-field source-surface model (PFSS) or variants of it, as well as increasingly MHD models.

The PFSS concept assumes that the large-scale coronal structure is fully relaxed to its lower boundary conditions, regardless of the dynamics of flux transport through emergence, dispersal by flows from granulation to meridional circulation, and subduction in cancellation collisions. Despite that simplifying assumption, it works remarkably well in describing, for example, the evolution of long-lived unipolar regions and patterns in polar and lower-latitude coronal holes. One example of that is found in the study by Golubeva & Mordvinov (2016) who focus on a period in 2014 which exhibited multiple activity complexes (also known as active-region nests).

More powerful computers allow more elaborate schemes of extrapolation, but the main stumbling block for deeper understanding remains the lack of observational coverage of the Sun's surface that drives all models as well as of the coronal and heliosphere where model validations are made. For example, Linker et al. (2017) show that regardless of which lower boundary is used, large-scale coronal field models that map out coronal holes (from which open field should largely originate) show a significant shortfall in predicted heliospheric flux and that forcing sufficient open flux results in model coronal holes that are far larger and more widespread than coronal observations suggest. Despite that shortcoming, the PFSS model remains helpful in describing the large-scale structure, as for example in the analysis by Nandy et al. (2018) in the context of the total solar eclipse that traversed the continental United States on 2017/08/21. They noted that not only did the overall configuration of the coronal during eclipse match the PFSS model state quite well, but that the global field often evolves slowly enough that the large-scale morphology can be maintained for several subsequent rotations, which can provide some guidance to space-weather modelers even in the absence of global solar surface coverage. The shortcomings of PFSS extrapolations based on incomplete solar coverage also become clear when trying to model, for example, the polarity patterns in the solar wind such as measured in the timings of Earth crossings for the polarity changes that define the heliospheric current sheet (see, for example, an analysis by Peng et al. 2017).

Incorporating observational constraints Given the imperfect knowledge and approximating models, multiple groups are exploring ways to tune parameters or to include constraints to improve the match between observation and model. For example, the PFSS model can be tuned by varying the chosen height for the source surface. A modified approach to the simple PFSS model is that of the horizontal current-current sheet-surface model (HCSSS) in which a current sheet is introduced, whose starting height can be adjusted. Arden et al. (2016) argue that the HCCSS model always improves on the PFSS model, by degrees that depend on cycle phase, and that both these models benefit from adjustment of the height of either the open field or the cusp that is the base of the heliospheric current sheet with solar activity. But then, adding a degree of freedom often allows for an improved match between model and observation; that is not an improvement in our understanding, and whether it is an improvement in our knowledge of the state of the field that connects Sun and heliosphere remains unproven.

A new modeling method that was developed in the 3-year period of this overview aims to incorporate observational constraints from coronal images: the algorithm by Jones et al. (2016) and Jones et al. (2017) iteratively minimizes a penalty function that measures deviations between morphological structures that can be compared between visible-light, EUV, or X-ray observations and PFSS model by varying the spherical harmonics that define the field. Another path to improved models is explored by Merkin et al. (2016) who argue that evolving 3D MHD models based on sequences of synoptic magnetic maps offer the promise for a better approximation of the heliospheric field, and by implication also for the global coronal field. A hybrid instantaneous-cum-evolving model for corona and heliosphere was explored by Linker et al. (2016) who use a potential field model for the corona, and then take the top range of that, at heights of 30 solar radii, as time-dependent boundary condition for an evolving MHD model of the solar wind. They claim this provides an improvement at least when modeling the evolution of the quiescent solar wind near Earth.

Ultimately, the way to certain improvement of our knowledge of the solar and heliospheric fields is through increased observational coverage. Making a case for that, Pevtsov et al. (2016) explored the value of an additional magnetograph perspective, specifically that at the L5 Lagrange point trailing Earth, and thus providing information on what is about to rotate onto the Earth-facing side of the Sun and what has been unobservable for some two weeks. They show, based on a few initial tests, that one can expect significant differences (presumably improvements in an actual implementation) in model fidelity for solar wind plasma properties and the open flux reaching into the heliosphere.

4. Coronal Heating

The heating of the solar atmosphere remains an interesting and open problem in solar astrophysics. Though the surface of the Sun is only 6000 degrees Kelvin, the outer solar atmosphere, or corona, can reach more than one million degrees Kelvin even in quiescent, non-flaring times. The theories for heating the solar corona can be broken down into two categories, heating by dissipation of magnetic stress through magnetic reconnection or heating by dissipation of wave energy (e.g., De Moortel & Browning (2015); Klimchuk (2015)). Unfortunately, these heating mechanisms predict many of the same observational characteristics, such as the pervasive cooling that has been detected Viall & Klimchuk (2017). Despite this difficulty, several encouraging advances have occurred over the past three years.

Heating by wave dissipation Simulations of wave dissipation indicate that the heating would occur frequently and be highly stratified along the effected magnetic field lines (Asgari-Targhi et al. (2015); Downs et al. (2016). Such heating often has no steady solution along the longer field lines, instead the plasma is in a state of thermal nonequilibirum with a long period thermal cycle. There are two observational indicators that this type of heating is occurring. The first is so-called “coronal rain, when cool condensation appear high in the solar atmosphere and slide down the magnetic field. Though coronal rain has been observed and studied for many years, high-resolution observations have allowed for new results on the multi-thermal and multi-stranded nature of coronal rain Antolin et al. (2015). The second observational consequence of wave heating is long period “pulsations of coronal loops in EUV images, meaning that loops repeatedly appear and disappear in narrowband EUV images as they cycle. These long period pulsations have been observed in recent years Auchère et al. (2016); Froment et al. (2017, 2018), confirming the plasma in these structures is in a state of thermal nonequilibrium. These new results have been made possible by long term observations available from the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). The most compelling argument for wave heating has been the recent detection of both coronal rain and long term pulsation with the same cycle time Auchère et al. (2018). These observations are very specific to long term, quasi-steady, highly stratified heating. It is hard to reconcile them with any other heating mechanism other than wave heating.

Heating by magnetic reconnection Likewise, dissipation of magnetic stress via magnetic reconnection is also associated with several "smoking gun observations, including the observation of high temperature (5-10 MK) plasma outside of flaring regions and the presence of nonthermal particles. Both high temperature plasma and nonthermal particles are a natural result of the violent energy release expected of magnetic reconnection and are not expected for wave heating. It is difficult to observe high-temperature plasma with current instrumentation. There have been several recent attempts to constrain high temperature plasma in an active region. Parenti et al. (2017) utilizes observations with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) to determine the relative emission of high temperature in an active region above the limb by observing high temperature spectral lines in the ultraviolet wavelength range. Another measurement was made by Extreme Ultraviolet Normal Incidence Spectrograph (EUNIS-13) sounding rocket instrument Brosius et al. (2014). Both these studies found evidence of Fe XIX in a quiescent active region, indicating the presence of ¿ 5 MK plasma. The Focusing Optics X-ray Solar Imager (FOXSI-2) also found evidence of localized high temperature plasma in the hard x-ray observations Ishikawa et al. (2017). These observations all point to the presence of magnetic reconnection. The impact of nonthermal particles on the chromosphere has also been detected in high-resolution transition region observations made with the Interface Region Imaging Spectrograph (IRIS) as short lived intensity enhancements Testa et al. (2014) that can be used to constrain the heating model.

Advances in numerical models and observations Numerical models of energy release mechanisms and the plasma response continue to develop in parallel and often motivated and challenged by the observations. Over the past three years, several numerical models have been expanded to include a more realistic treatment of plasma and atomic processes, such as departure from thermal equilibrium (e.g., Bjørgen et al. (2018)), partial ionization (e.g, Martínez-Sykora et al. (2017)) and non-equilibrium ionization (e.g., Brooks et al. (2016)). In addition, a simplification of the plasma processes have been used to generate the 0-dimension enthalpy-based thermal evolution of loops (EBTEL) model that has been used to investigate a large parameter space without significant computational requirements (e.g., Viall & Klimchuk (2015); Bian et al. (2018)).

The advances the past three years have been driven by improvements in observations. Continued advances will come from the expansion of current observations to smaller spatial scales, meaning higher spatial resolution; an improvement of temperature coverage, particularly in the 5-10 MK temperature range; and consistent long term observations, such as those provided by AIA. As the observations improve, so must the fidelity of the numerical models to explain and understand the observations.

5. Solar Flares

The flaring lower solar atmosphere Observations with the Interface Region Imaging Spectrometer (IRIS) continue to make significant contributions to our understanding of solar flare energy deposition and the resulting chromospheric dynamics (Brosius & Daw

2015; Graham & Cauzzi 2015; Li et al. 2015c; Polito et al. 2015; Tian et al. 2015; Young et al. 2015), demonstrating beyond doubt the value of high cadence sub-arcsecond UV and EUV spectroscopy in understanding the flare environment. Similarly, as the community gears up for observations with the 4m Daniel K. Inouye Solar Telescope, ground-based flare observations in the optical, for example with the Swedish Solar Telescope, and the Goode Solar Telescope (formerly the New Solar Telescope at Big Bear), are confirming the value of high spatial resolution for flares, since spatial structure in the flaring chromosphere is present on the smallest observable scales - currently around 100 km (e.g. Jing et al. 2016; Kuridze et al. 2017).

Observational developments have driven significant theoretical work on understanding complicated chromospheric radiation signatures, using radiation hydrodynamic simulations such as RADYN (Allred et al. 2015). This has met with some success: for example details of line profile asymmetries in Hα and Ca II 8542Å can often be well reproduced, showing the complex interplay between chromospheric evolution leading to opacity changes, and velocity structures leading to red- and blue-shifts in both absorption and emission features (Kuridze et al. 2015). Two-component IRIS spectral lines can be well-understood in terms of an optically thick component from a slowly moving but heated region in the flare lower chromosphere, with an optically-thin component, produced by an optically thin downwards-moving condensation, superposed (Kowalski et al. 2017). However, ad hoc modifications to the simulations, such as enhanced turbulence and increased density in the upper chromosphere are required to reproduce some observed line shapes, and it is still often difficult to reproduce the observed ratios of line to continuum intensity (Rubio da Costa et al. 2016). In the majority of current simulations, energy input is by electron beams, and while the close association between hard X-rays and optical flares indicates very strongly the important role of fast electrons in the generation of the flare's main radiation (Kuhar et al. 2016; Lee et al. 2017). In one flare a conduction-driven model seems to be favored observationally (Battaglia et al. 2015), while theoretical modelling of the damping of Alfvén waves in the transition region and chromosphere has also met with some success in explaining upper chromospheric/transition region heating (Reep & Russell 2016) and chromospheric line profiles (Kerr et al. 2016).

The flare corona A well-observed flare on the solar limb, SOL2017-09-10T16:06, captured by the Solar Dynamics Observatory (SDO) and the Extreme ultraviolet Imaging Spectrometer (EIS) on Hinode, provides information on the temperature structure of a flare arcade, and non-thermal broadening and abundance in the overlying (supposed) current sheet (Warren et al. 2018), suggesting turbulence around the current sheet, and sustained late-phase heating in the arcade loops (this event was also observed with great clarity by a new instrument, the Solar Ultraviolet Imager (SUVI) on GOES-16, Seaton & Darnel 2018). The influence of ongoing late phase heating and suppression of thermal conduction is also supported by a study of flare loops with SDO (Zhu et al. 2018). Non-thermal ion distributions in flare coronal loops (as well as footpoints) are strongly suggestive of plasma turbulence - which could play a role in both - were suggested by spectral line profiles reported by Jeffrey et al. (2016), and Kontar et al. (2017) showed that this coronal loop turbulence could play a critical role in the energy transfer from large scales to kinetic scales in solar flares. Sustained turbulence requires a driver, and observations of intensity pulsations during flares at coronal temperatures, as well as consistent with a heated chromospheric source, are now becoming so commonplace (Brosius & Daw 2015; Sun et al. 2015; Li et al. 2015a; Simões et al. 2015) that their role as a large-scale driver of turbulence seems plausible.

Magnetic field evolution during flares Using the topology of the magnetic structures hosting solar flares, and the flare-related changes that take place in this, is a well-established approach to investigating the build-up and release of energy in flares. The last few years has seen work on comparing the morphological appearance, electrical current distribution and time evolution of a category of intrinsically three dimensional, two-ribbon flare events associated with eruption of a twisted magnetic structure called a hyperbolic flux tube and there is strong observational evidence that such structures do exist in large solar flares (Savcheva et al. 2015; Dudík et al. 2016; Zhao et al. 2016). Active region NOAA AR 2192, caused some consternation in that despite being the largest in Cycle 24, and producing numerous X-class and M-class flares, it was 'CME poor'. This was tracked down to the presence of a strong overlying magnetic field, confining the core magnetic flux that, presumably, would otherwise erupt, as also described in Section 7 of this report (Thalmann et al. 2015; Sun et al. 2015; Chen et al. 2015b). Obtaining such information about the magnetic structure reliably will be critical in understanding or predicting the CME-productivity of active regions.

Another aspect of magnetic field evolution in flares is changes in the photospheric and chromospheric fields. The recent availability of a new SDO Helioseismic and Magnetic Imager (HMI) data product of vector fields at 135s temporal resolution in a number of strong flare events has shown very convincingly that flares are accompanied by an increase in the horizontal photospheric field strength close to the active region's polarity inversion line, and a decrease in this quantity in more distant locations (Sun et al. 2017). Changes in the chromospheric magnetic field have also been observed (Kleint 2017) but their spatial and temporal relationship with photospheric field variations are unclear. Convincing evidence has also been found of a transient rotation of the photospheric vector magnetic field, using a spectral line at 1.56μm that is undisturbed by flare effects (Xu et al. 2018). The rotation, co-spatial with Hα flare footpoints, seems consistent with a torsional perturbation of the magnetic field rather than a transient field component associated with a particle beam.

6. Particle Acceleration

The Sun is a powerful generator of energetic charged electrons and ions, some of which escape into the heliosphere. Thus, understanding the origin and properties of energetic particles originating at or near the Sun is crucial to explaining and forecasting space weather. RHESSI, although far beyond its originally-planned mission lifetime, has continued to make major advances in our knowledge of energetic particles in flares. The hard X-ray data from RHESSI is often used in association with other instruments such as SDO or ground-based radio. It has been well known for many years that energetic particles forming a non-thermal tail in the distribution function play a crucial role in solar flares, carrying a large fraction of the released energy. An accurate knowledge of the energy budget in flares, and in particular the proportion of energy in non-thermal ions and electrons, provides essential constraints on particle acceleration. Recent studies of a large dataset of flares (Aschwanden et al. 2016) give a mean value of 0.41 for the ratio of non-thermal electron energy to dissipating magnetic energy, consistent with particle acceleration arising from magnetic reconnection. Turbulence has long been considered as a mechanism for producing energetic particles, through second-order Fermi acceleration.

Acceleration in fragmentary reconnecting current sheets Particle acceleration in flares must ultimately be a consequence of the process of magnetic reconnection by which the magnetic energy is released, but many specific mechanisms have been proposed, including shocks, waves, turbulence and acceleration by super-Dreicer electric fields in a reconnecting current sheet. A combination of different processes may operate in reality, and the distinction between different mechanisms is not necessarily clear. For example, recent modelling suggests that particles may be effectively accelerated in fragmented current sheets which arise in the nonlinear stage of kink instability (Pinto et al. 2016), through a process of direct acceleration in reconnecting current sheets but which also resembles turbulence. The synergies for particle acceleration between a turbulent environment and reconnecting current sheets have been further emphasised in recent work (Pisokas et al. 2018). New theoretical tools such a fractional diffusion equations help to develop an understanding of how particles are accelerated in this scenario (Isliker et al. 2017). Particle acceleration in unstable twisted flux ropes is also investigated by Ripperda and co-workers (Ripperda et al. 2017), who consider flux ropes with oppositely-directed currents, which interact and subsequently reconnect through combination of kink and tilt instabilities. This generates substantial numbers of non-thermal ions and electrons. Interacting flux ropes with parallel currents, one of which is kink unstable, have also been recently investigated (Threlfall et al. 2018). This shows particle acceleration in two phases, first within the fragmented current sheets in the kink-unstable flux rope, then both flux ropes fill with energetic particles as they merge through reconnection. This is the first step of a magnetohydrodynamic (MHD) avalanche, which may lead to a burst of heating - and particle acceleration - in multiple twisted magnetic threads (Hood et al. 2016).

Modeling approaches The works mentioned above have utilised test-particles coupled with 3D MHD simulations. This builds on much previous modelling of particle acceleration in flares, which has mainly relied on test particles in more idealised field configurations. Particle-in-cell (PIC) simulations offer a fully self-consistent approach, but have generally been unable to represent the global length-scales of solar flares. However, advances in computing power mean that kinetic modelling of coronal particle acceleration is now realistic. For example Li et al. (2015b) perform PIC simulations of a low-β plasma with strong guide field, and find that, for large enough numerical boxes, power law distributions of non-thermal electrons can be generated. Interestingly, more dissipated magnetic energy is transferred to the ions than the electrons (as sometimes also found in test particle models), highlighting the importance of future observations of ion acceleration.

Acceleration in contracting field The mechanism of collapsing magnetic traps, due to contraction of the large-scale reconnected field lines, is known to accelerate particles but account for the high energies observed in flares (Borissov et al. 2016). A variant on this mechanism, arising originally from PIC simulations of collisionless reconnection (Drake et al. 2006) is that electrons can be accelerated through a first-order Fermi process in contracting magnetic islands in reconnection outflows. It has bene proposed that this mechanism may provide much more efficient electron acceleration in flares than direct electric field acceleration, due to the larger effective volume for acceleration of the contracting islands (Dahlin et al. 2016).

Observables: hard X-rays and microwaves/radio The prediction of observables from models is vital, as particle acceleration processes cannot be directly detected. For example, evidence of particles acceleration in twisted magnetic fields may be provided by hard X-ray signatures (Pinto et al. 2016) and polarisation of microwave emission, generated by gyrosnchrotron emission from non-thermal electrons (Kuznetsov & Kontar 2015; Gordovskyy et al. 2017). The former work shows that care must be taken in interpretation of hard X-rays as indicators of particle acceleration sites, since hard X-rays sources are only predicted at the footpoints and (sometimes) at the looptop - consistent with observations- whilst particles are accelerated throughout the loop volume.

Radio and microwaves provide the most direct evidence for the acceleration and propagation of energy electrons, as they produce both gyrosnchrotron radiation and plasma emission. They can be utilised to identify the locations of electron acceleration, giving important clues to the acceleration process. For example, Carley et al. (2016) use Nancay Radioheliograph images to demonstrate electron acceleration associated with tether-cutting magnetic reconnection during the emergence of a magnetic flux rope. The electron beam is aligned with the spine field line of 3D magnetic null point. This is one instance of an increasing body of observational evidence for reconnecting 3D magnetic null points in solar flares (Sun et al. 2016), and hence in producing energetic particles - confirming earlier theoretical predictions (Dalla & Browning 2005). It is becoming clear that the traditional picture of reconnection in a 2D current sheet is a considerable over-simplification, and in reality much more complex magnetic topologies are involved in particle acceleration.

Theoretical predictions suggest that supersonic reconnection outflows may produce a termination shock, if they impinge on dense underlying loops. Shocks in other astrophysical contexts are known to be effective particle accelerators. Radio observations with the VLA have produced direct evidence of the existence of such a termination shock in a flare, and the associated acceleration of electrons (Chen et al. 2015a). However, the shock may be providing additional acceleration to a population of electrons which already have high energy. Theoretical modelling using test particles also demonstrated the potential role of the braking of plasma jets in particle acceleration (Borissov et al. 2016).

Particle acceleration in nanoflares Whilst emphasis on detection - and modelling - of particle acceleration has tended to focus on large-scale flares, there is now increasing interest in non-thermal particles as a potential signature of nanoflare coronal heating. Hence, the question arises as to whether the physical processes in small flare-like events (microflares and smaller), are essentially the same as in larger flares. New instrumentation is shedding light on this question. for example, the focusing hard X-ray telescope NuSTAR, although not predominantly a solar instrument, has observed several solar microflares (Wright et al. 2017, e.g.). So far, non-thermal emission has not been detected, but the observations place upper bounds on the particle energy spectra which are consistent with larger flares. This is an important area for future research

We are beginning to reach some understanding of the mechanisms for particle acceleration in solar flare, but many open questions remain. Future progress will rely on the development of advanced models, bridging the MHD and kinetic scales, and taking account of the complex, and varied, magnetic field configurations. Advances in instrumentation, including use of current and forthcoming radio facilities, as well as potentially the SMEX FOXSI mission, will also be vital. Observations from forthcoming Parker Solar Probe and Solar Orbiter, with their combinations of remote sensing and unique in situ measurements, may also help to finally resolve this challenging problem.

7. Solar Eruptions

There is a growing consensus that the driving force of a coronal mass ejection is the Lorentz force acting on a bent flux rope or a toroidal current ring. Since the toroidal flux rope is subject to a net Lorentz self force directed outward, an external poloidal field is required for an equilibrium that exerts a force inward. It was known that such an equilibrium configuration becomes unstable to the outward expanding perturbation if the external field decreases rapidly outward (Bateman 1978). Recent studies seem to be consistent with the notion that this torus instability plays a decisive role in the solar eruption (Kliem & Török 2006; Aulanier et al. 2010).

The decrease of the external field is quantified by the decay index $n \equiv -Rd\ln B_{ex}/dR$ where B_{ex} is the strength of the external field and R is the major radius of the toroid. If this value is larger than a critical value, the torus instability operates in the flux rope. From magntohydrodynamic simulations, Zuccarello et al. (2015) concluded that the critical value is not sensitive to either the phtospheric process that produced the flux ropes or the resulting structures of the magnetic flux ropes, and it is in the range $[1.3, 1.5]$. The decay index is expected to increase with height, so it is possible to define a critical height where the decay index becomes equal to the critical value. Wang et al. (2017a) found that the critical height is significantly lower in the eruptive-flare-producing active regions producing eruptive flares than confined-flare-producing active regions. This is a significant result supporting the torus instability as the major cause of the eruption.

Observational evidence for the importance of the torus instability in the eruption was also found in the super active region (AR) 12192 of 2014 October that hosted the largest sunspot group in the last two decades. This super active region produced numerous strong flares, but no coronal mass ejections from the core region during its disk passage. Sun et al. (2015) attributed this behavior to the magnetic conditions that prevent eruptions: the weakly developed core region, the strong overlying field, small flare-related magnetic change. The presence of the strong overlying field was quantified by the small values of the decay index (Chen et al. 2015b; Liu et al. 2016).

In addition, the lack of a well-developed toroidal magnetic flux rope was also indicated in this active region. Zhang et al. (2017) found from EUV imaging observations several sets of flare loops twisted together in this active region and suggested that these complex flare loop structures – which may be interpreted as the lack of a single flux rope – are responsible for confined flares without eruption. From the analysis of the observed photospheric magnetic fields, Liu et al. (2016) found that this active region does not have strong, concentrated current along the flaring neutral line. The existence of a complicated flux tube system was indicated by the nonlinear force-free field modelling of Inoue et al. (2016). From data-driven numerical magnetohydrodynamic (MHD) modeling, Jiang et al. (2016) found that the reconnection that is responsible for the successive strong flares results in a sheared arcade instead of a newly formed flux rope. On the other hand, Chintzoglou et al. (2015) found two pre-eruption magnetic flux ropes in another super active region 11429 of 2012 March that became the seeds of the two CMEs. They suggested that these flux ropes were formed by the confined flares the day before the two CMEs.

The operation of the torus instability in an active region requires the existence of a fully mature flux rope. This is because the flux rope of larger magnetic flux finds its equilibrium at a larger value of R or height, and is put into a condition preferred for the torus instability because the decay index increases with height. Recent studies confirmed the idea that a flux rope is produced or grows through a series of magnetic reconnection events occurring either through flare-producing reconnection in the corona (Chintzoglou et al. 2015; James et al. 2017; Joshi et al. 2017; Priest & Longcope 2017; Wang et al. 2017b) or though flux-cancelling-reconnection in the low atmosphere (Kumar et al. 2015; Zhou et al. 2017; Zhao et al. 2017b).

8. Solar Flare Prediction

Solar flares present one of the three major manifestations of adverse space weather, the other two being coronal mass ejections (CMEs) and solar energetic particle (SEP) events. Flares are known to incur detrimental effects to human life in orbit, or en route to other heliospheric locations in the future. They are also known to cause radio blackouts, giving rise to the so-called R-scale of impacts at NOAA's Space Weather Prediction Center (SWPC†). Recently, Hayes et al. (2017) presented direct evidence for flare-related pulsations in the ionospheric D-region.

Given the lack of an early warning window for flare hard X-ray and γ-ray photons, as well as for potentially imminent particle emission, it is meaningful to predict major flares before they are triggered in the Sun. This is traditionally attempted by analyzing the observed photospheric magnetic structure of potential flare hosts, solar active regions. The last three years have seen a significant increase in international activities related to solar flare forecasting, largely spurred by the effort of the science team of the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO) to produce the near-realtime Space Weather HMI Active Region Patch (SHARP) data product (Bobra et al. 2014) and to use it for solar flare forecasting (Bobra & Couvidat 2015). At the same time, two more key developments signaled the future course of flare forecasting: first, the investment of multiple space agencies and other institutional entities on it and, second, an interdisciplinary shift toward big data handling in a machine-learning environment for flare forecasting.

International efforts and co-ordination Flare forecasting attracts more and more interest by international space organizations: besides the longstanding NOAA SWPC non-automated service, Korea's Space Weather Center has been operating the Automatic Solar Synoptic Analyzer (ASSA‡), Australian Bureau of Meteorology features the Flarecast project (Steward et al. 2017), while the Project for Solar-Terrestrial Environment Prediction (PSTEP¶) shows interest in flare forecasting on behalf of the Japanese Space Agency (JAXA). NASA, on the other hand, operates the Community Coordinated Modeling Center (CCMC) which further operates the Flare Scoreboard‖, aiming to collect the results of forecasting efforts worldwide for a future combined assessment of near-realtime predictions. In late 2015, ESA implemented the Athens Effective Solar Flare Forecasting (A-EFFort††) pre-operational service and, since then, it operates the service at the Space Weather Portal of its Space Situational Awareness Programme. The United Kingdom Meteorological Office via its recently established Met Office Space Weather Operation Center (MOSWOC) also operates a semi-automated flare forecast service that has similarities to that of NOAA / SWPC (Murray et al. 2017).

Verification of existing methods The first comprehensive effort to perform a joint performance verification on existing flare forecasting methods and services has been presented by Barnes et al. (2016). This study has shown that (1) no method, out of the 11 tested, clearly outperforms the others and (2) the validation results, particularly the values of strict skill scores such as the Brier Skill Score for probabilistic forecasts and the Appleman skill score for binary (YES / NO) ones are underwhelming, for all methods. Clearly, more work is needed to determine whether a method, or a collection of methods (see, for example, the ensemble forecasting approach of Guerra et al. (2015)) is potentially able to lift the barrier of stochasticity in the flare triggering process. Results such as those of Barnes et al. (2016) have made clear that a new line of support is required to tackle the flare forecasting problem. This support has been offered by a blend of science and technology that relies on big data handling and the application of machine learn-

† Available at `https://www.swpc.noaa.gov/noaa-scales-explanation`

‡ Available at `http://spaceweather.rra.go.kr/models/assa`

¶ See `http://www.pstep.jp/?lang=en`

‖ Available at `https://ccmc.gsfc.nasa.gov/challenges/flare.php`

†† Available at `http://a-effort.academyofathens.gr`

ing methods. Big data serves to secure comprehensive statistics, while machine learning serves to surf the enormous – conventionally infeasible – multi-predictor parameter space in search of the optimal path of predictor combinations.

New initiatives in flare forecasting Efforts to introduce machine learning into flare forecasting have started since the last decade (see, e.g., Li et al. (2008); Song et al. (2009)) and have culminated in the ranking of the SHARP forecast parameters in order of significance, by Bobra & Couvidat (2015). The machine learning initiative in flare (and space weather) forecasting has gained momentum to the extent that a book entitled "Machine Learning for Space Weather" (Editors E. Camporeale, S. Wing & J. Johnson, Elsevier, 2018, in prep.) aims to recount the areas of space weather forecasting where machine learning methods are already at work. In terms of flare prediction, the chapter of Massone et al. (2018 (in prep)) summarizes 21 different machine-learning methods used in the framework of the European Commission Flare Likelihood and Region Eruption Forecasting (FLARECAST) project (Georgoulis et al. 2018).

FLARECAST (distinct from the Flarecast project of the Australian Bureau of Meteorology) has attempted for the first time to collect the entire SDO/HMI SHARP database since its establishment in September 2012 and implement all extractable parameters ever proposed as holding promise for an efficient flare forecasting, including the already available SHARP parameters. The FLARECAST near-realtime online forecast service is scheduled to appear in the first half of 2018. The project has managed to infer more than 100 parameters (predictors) from each SHARP magnetogram and has attempted a ranking whose definitive results will be published in 2018. Preliminary performance verification results from FLARECAST appear in Florios et al. (2018), where the random forest machine learning technique of Breiman (2001) seems to (narrowly) be the method of choice for the tested data subset.

It should not go unnoticed that flare prediction has also motivated more general, integrated forecasting methods aiming to predict flares, CMEs and SEPs in tandem for major solar eruptions. Examples of such methods include the MAG4 (Falconer et al. 2014) and the Forecasting Solar Particle Events and Flares (FORSPEF) tool of Anastasiadis et al. (2017). While this approach is distinct from other approaches that disentangle prediction from detailed information on solar sources (Núñez 2015), it remains to be seen which methodology, if any, will provide a viable resolution for the problem at hand.

Whatever the outcome, a significant part of the solar flare (and space weather, in general) forecasting community now seems compelled to subscribe to interdisciplinary efforts where machine learning plays a central role. Another promising future development would be the operational monitoring of the Sun from multiple vantage points in the inner heliosphere and beyond, including the L1 and L5 Sun-Earth Lagrangian points (Vourlidas 2015; Lavraud et al. 2016; Hapgood & Hapgood 2017).

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