

DIVISION E
COMMISSION 10

SOLAR ACTIVITY
ACTIVITÉ SOLAIRE

PRESIDENT
VICE-PRESIDENT
PAST PRESIDENT
ORGANIZING COMMITTEE

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Abstract. After more than half a century of community support related to the science of “solar activity”, IAU’s Commission 10 was formally discontinued in 2015, to be succeeded by C.E2 with the same area of responsibility. On this occasion, we look back at the growth of the scientific disciplines involved around the world over almost a full century. Solar activity and fields of research looking into the related physics of the heliosphere continue to be vibrant and growing, with currently over 2,000 refereed publications appearing per year from over 4,000 unique authors, publishing in dozens of distinct journals and meeting in dozens of workshops and conferences each year. The size of the rapidly growing community and of the observational and computational data volumes, along with the multitude of connections into other branches of astrophysics, pose significant challenges; aspects of these challenges are beginning to be addressed through, among others, the development of new systems of literature reviews, machine-searchable archives for data and publications, and virtual observatories. As customary in these reports, we highlight some of the research topics that have seen particular interest over the most recent triennium, specifically active-region magnetic fields, coronal thermal structure, coronal seismology, flares and eruptions, and the variability of solar activity on long time scales. We close with a collection of developments, discoveries, and surprises that illustrate the range and dynamics of the discipline.

1. Historical context

The IAU was founded in 1919, with the first General Assembly occurring in 1922 in Rome, Italy. The standing commissions that focused on what we nowadays capture under the term “solar physics” evolved over the following decades. A “Commission 10” was instituted by 1922, but under the title of “Solar Radiation”. By 1935 that had been changed to “Sunspots and sunspot numbers”, and by 1952 it had transitioned to “Photospheric phenomena”. In parallel to Commission 10 there were the other solar-oriented Commissions 11 through 15 dealing with subjects such as the solar atmosphere, eclipses, rotation, and spectroscopy (with, as noted in the 1961 report by Commission 10, a “lack of clear demarcation lines among the [three] solar commissions”). It was not until 1961 that “Solar Activity” became the title of Commission 10, lasting until its transition into Commission C.E2 in the overall reorganization of the IAU’s structure in 2015.

Table 1. Overview of Commission 10 leadership and triennial reports (as available in ADS) from 1961 onward, i.e. for the period that C10 operated under the banner of “Solar Activity” or “Activité Solaire”. Reports flagged with an asterisk appear not to be available on line.

Years	President and Vice President	ADS bibcode
1961-1964	Severny, A. B. , Ellison, M. A.	*
1964-1967	Svestka, Z. , Jefferies, J. T.	*
1967-1970	Svestka, Z. , Jefferies, J. T.	1970IAUTA..14...71S
1970-1973	Jefferies, J. T., Kiepenheuer, K. O.	1973IAUTA..15...75J
1973-1976	Kiepenheuer, K. O., Newkirk, G. A.	*
1976-1979	Newkirk, G., Bumba, V.	1979IAUTA..17b..11N
1979-1982	Bumba, V., Tandberg-Hanssen, E.	1982IAUTA..18...55B
1982-1985	Tandberg-Hanssen, E., Pick, M.	1985IAUTA..19...57T
1985-1988	Pick, M., Priest, E. R.	1988IAUTA..20...55P
1988-1991	Priest, E. R., Gaizauskas, V.	1991IAUTA..21...53P
1991-1994	Gaizauskas, V., Engvold, O.	*1994IAUTA..22...53G
1994-1997	Engvold, O., Ai, G.	*1997IAUTA..23..121E
1997-2000	Ai, G., Benz, A. O.	*
2000-2003	Benz, A. O., Melrose, D. B.	*
2003-2006	Melrose, D. B., Klimchuk, J. A.	2007IAUTA..26...75M
2006-2009	Klimchuk, J. A., van Driel-Gesztelyi, L.	2009IAUTA..27...79K
2009-2012	van Driel-Gesztelyi, L. , Schrijver, C. J.	2012IAUTA..28...69V
2012-2015	Schrijver, C. J., Fletcher, L.	(<i>this report</i>)

The scientific discipline focusing on solar activity continued to grow after Commission 10 settled on its final name, seeing among the many activities of its community the launch of a dedicated journal “Solar Physics” in 1967 and a marked advance in access to solar corona and inner heliosphere with the space-based Apollo Telescope Mount on Skylab in 1973. At present, we have ground- and space-based observatories looking at the Sun and innermost heliosphere from different perspectives, in a range of wavelengths, and probing the Sun’s internal dynamics using helioseismology. But although these observatories provide a wealth of information and insight into the workings of our neighboring star, we struggle to provide the research community with a comprehensive view of the phenomena captured under the term “Solar Activity”. That is certainly not a new challenge: for example, in the 1970-1973 report, then President Jefferies of C10 notes that “We believe that the major direction in which priority should be placed to facilitate the understanding of solar activity lies in the provision of space and ground based observatories specifically designed to complement each other’s capabilities.”

The early reports of Commission 10 published in the “Reports on astronomy” could highlight many of the key developments in the field overall. With the rapid growth of the discipline from the 1940s through the 1970s that quickly became impossible. From the middle of the 20th Century onward, severe selections had to be made in order for the task of the writing of a progress report to remain feasible. The need for such major down-selects on what to cover clearly concerned the members of the Organizing Committees of the Commission (the presidents and vice-presidents are listed in Table 1). For example, in the report on the period 1967-1970, the Commission President Zdeňek Svestka apologizes for the “fairly severe” selection made in the Commission’s overview with 32 pages of text as “only about one third of all published papers could have been mentioned in the references”. By 2015, with some 6,000 papers appearing per triennium (as discussed in the next section), simply reading all published papers is too challenging a task. Even with severe selections applied by the Organizing Committee of Commission 10, the 1967-1970 report was still deemed too long: John Jefferies notes in the subsequent report for

1970-1972 that the General Secretary requested that the reports should “concentrate on the more important developments” (which led to 34 pages of text in that cycle). The most recent reports condense the increased number of publications into 10 to 20 pages of text, selecting highlights only in the view of the members of the Organizing Committee.

For this report on 2012-2015 we would face a similarly daunting selection task. Instead, we chose to focus on three aspects of our community: the health of the community itself, new developments in the areas of instrumentation and IT infrastructure, and a discussion of scientific developments based on citations within the community and impressions of the OC members of C10.

2. Trends in the research community and its publications

As C10 transitions into C.E2 we take the opportunity to review the community’s size and publication activity. For this, we use the tools provided by the Astrophysics Data System (ADS[†]), which enables searches over all the major trade publications in astrophysics in general. We reviewed the number of refereed publications per year going back over a century, and quantified the population of active researchers and their publication productivity.

The study of phenomena related to “solar activity” often involves other aspects of the Sun (such as internal dynamics, dynamo, or surface field patterns) and they are obviously not limited to the Sun but drive phenomena throughout the heliosphere. We therefore do not attempt a separation by research disciplines along the somewhat arbitrary dividing lines between the IAU Commissions in what was Division II and is now Division E[‡], all the more so because of the shifts in focus of the Commissions related to solar physics since their inception after 1919 as noted above. Consequently, we searched ADS for abstracts of refereed publications in the “Astronomy” database, either mentioning the Sun or heliosphere or their synonyms. We filter out at least many of the papers that do not deal with Sun/heliosphere that come into the search results because their abstracts include, for example, a unit like “solar mass”; to do so, we exclude abstracts that contain one or more of the following words or word groups: cluster, dwarf, extrasolar, galaxy, gravitational, ice, kpc, solar system, stellar, binary, sunset, sunrise, eclipse, solar cell, solar occultation, interstellar medium, and supernova. Sampling the returned titles and abstracts suggests that the sample we study is dominated by far by papers that do indeed focus on Sun and heliosphere, while of course also including topics such as climate forcing, the physics of the upper atmospheres of planets, comets in the solar wind, cosmic-ray modulation, and weathering of lunar surface materials.

The ADS searches suggest that the productivity of the world-wide community researching the Sun and heliosphere continues to grow steadily if measured through its publications (Fig. 1). A rapid growth in the number of refereed publications that started after the Second World War continued up to about 1975. After that, the growth slowed drastically, transitioning to a sustained increase that doubles the number of refereed publications on a time scale of approximately 40 years, reaching a total of some 2200 refereed publications by 2014.

Such automated searches enable us to process a lot of information, but it is not readily possible to avoid a distortion of the statistics associated with the author names. For one thing, authors with identical family names and initials for their given names are not differentiated. Also, authors who publish with different spellings or composites of

[†] URL: http://adsabs.harvard.edu/abstract_service.html

[‡] See http://www.iau.org/science/scientific_bodies/divisions/

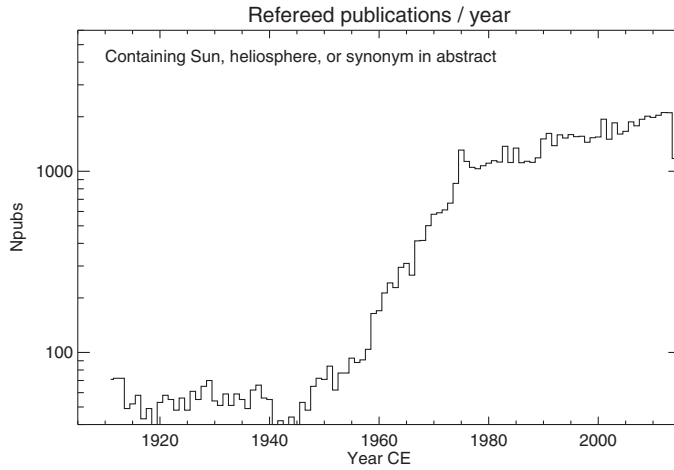


Figure 1. Number of refereed publications per year with abstracts focusing on Sun or heliosphere (as returned by ADS) from 1911 through 2014.

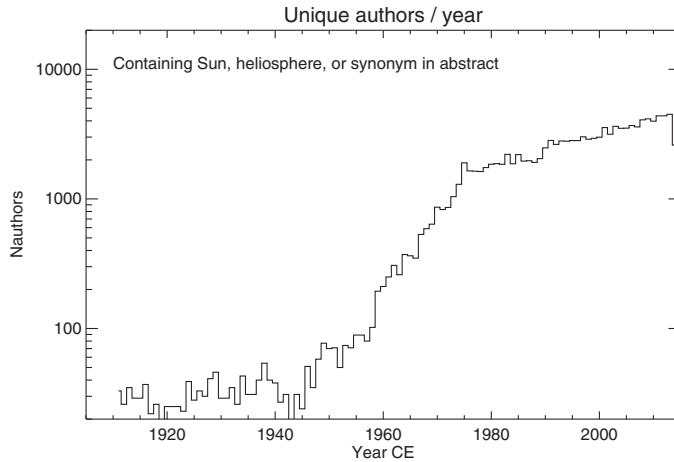


Figure 2. Number of unique authors for each year in publications per year with abstracts focusing on Sun or heliosphere (as returned by ADS) from 1911 through 2014.

their family names (*e.g.* married and maiden names) or their initials will be counted as separate individuals. These effects bias the total number of publications and researchers involved, but we expect their impacts to be limited when we review fractional trends over the years, as we do not expect very substantial changes of the relative impacts of these biases over the years.

The number of unique author names (subject to the above-noted caveat of the way we used the ADS system) contributing to refereed publications shows a trend that roughly mimics that of the number of publications: flat in the first half of the 20th Century with a total population of merely some 40 active researchers globally, then rapidly growing after WW II, and eventually growing exponentially from about 1975 onward up to a total approaching 5,000. This growth rate of $\approx 2.5\%/yr$ is about twice the growth rate of the world's overall population (which averaged at $\approx 1.3\%/yr$ over the same period; Population reference bureau 2013), suggestive of a rather healthy growth in the research discipline of solar and heliospheric sciences and related fields over that of the general population.

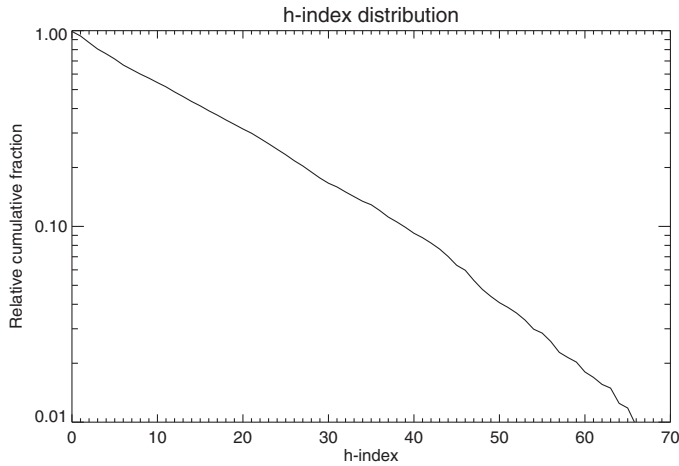


Figure 3. Distribution of H indices for all authors publishing on Sun and heliosphere in 2014, based on ADS citation counts.

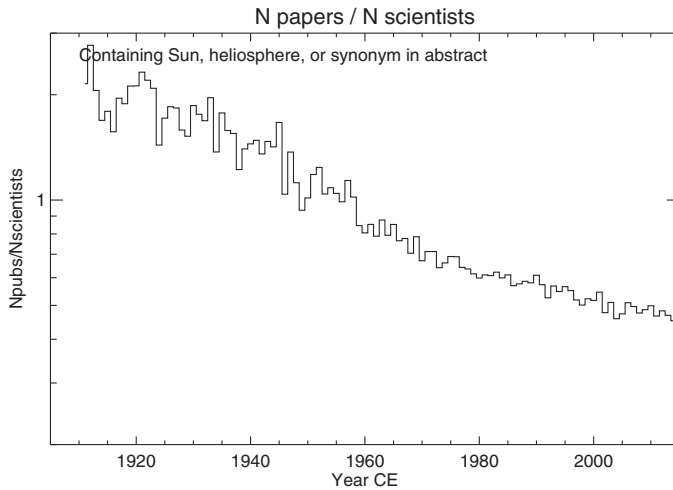


Figure 4. Number of refereed publications per author with abstracts focusing on Sun or heliosphere (as returned by ADS) from 1911 through 2014.

Many of the authors in the population publishing in the refereed literature are in the field only for a short time, or publish only infrequently as team members on, for example, instrument and facility papers. If we look for the population of authors who have worked in the field of solar-heliospheric sciences long enough to have contributed several papers that have been cited a few times, we can use the so-called H index. That index is computed by ranking all refereed publications by an author in decreasing order of the number of citations, and then looking for the rank in that list where rank and number of citations equal. The downward-cumulative H index distribution for authors publishing on Sun and heliosphere in 2014 (based on citations in ADS, and using refereed as well as unrefereed publications) is shown in Fig. 3.

For the present purpose of selecting researchers with a few years of activity in the field, we take a rather arbitrary H -index threshold of 5, i.e., looking for authors with at least 5 refereed publications on their record that have each been cited at least 5 times. Fig. 3 shows that this includes about two thirds of all publishing authors in 2014.

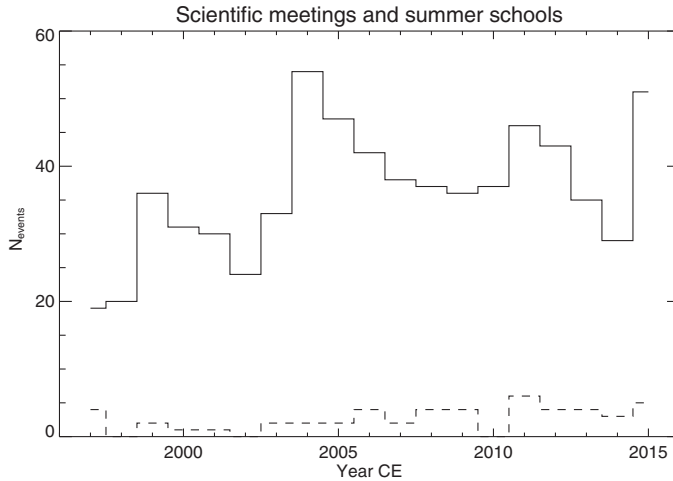


Figure 5. Number international scientific meetings (solid) and summer schools (dashed) from 1997 through 2014 (from the SOHO web site: <http://sohowww.nascom.nasa.gov/community/>).

Table 2. IAU meetings related to solar activity in the triennium 2012-2014.

2014	IAUS305 Polarimetry: the Sun to stars and stellar environments
2013	IAUS302 Magnetic fields throughout stellar evolution
2013	IAUS300 Nature of prominences and their role in space weather
2012	IAUS294 Solar and astrophysical dynamos and magnetic activity

The number of publications per year grows somewhat slower than the population of contributing authors, so that the number of publications per author shows a steady decrease over the past century, trending to just under half a refereed publication per year per author (see Fig. 4). That average value is subject to a large range for the population: some authors may not publish for years in a row, while others may exceed a dozen in particularly productive years, for example as members of sizable teams working with new instrumentation.

The community exchanges information efficiently at scientific meetings. Fig. 5 shows that the number of such events tends to increase over the years, with marked fluctuations from year to year, averaging around 40 meetings per year over the past decade. The Symposia supported by the IAU through Commission 10 in the last three years are listed in Table 2. Summer schools in which new generations of researchers are given broader or deeper views into the community’s activities appear to grow slowly in frequency, trending towards about five events per year (dashed line in Fig. 5).

Although the scientific community working on “solar activity” appears healthy and growing, there is a clear need to improve how we communicate the excitement about our science to the general public: for example, only 8 in the most recent 400 press releases and news articles listed by the AAS[†] were related to some aspect of solar activity.

3. Trends in observational capabilities

The observational infrastructure enabling the study of solar physics has seen dramatic advances over the past five years. Among these, we highlight a few:

[†] <http://aas.org/astronomy-in-the-news>, accessed on 2015/09/03.

In 2009, the two STEREO spacecraft (launched into Earth-trailing and Earth-leading orbits in 2006; Kaiser *et al.* 2008) passed the quadrature points relative to the Sun-Earth line. When combined with Earth-perspective viewing, the following years enabled a view of the entire solar surface, for the first time in history showing us the evolution of an entire stellar atmosphere.

The Atmospheric Imaging Assembly (AIA; Lemen *et al.* 2012) on board the Solar Dynamics Observatory (SDO - launched in 2010; Pesnell, Thompson, and Chamberlin 2012) provides uninterrupted observing of the outer atmosphere of the entire Earth-facing side of the Sun at a cadence of 12s and a resolution of close to an arcsecond. Combined with magnetography and helioseismology with the Helioseismic and Magnetic Imager (HMI; Scherrer *et al.* 2012), as well as Sun-as-a-star spectroscopy in the EUV with the EUV Variability Experiment (EVE; Woods *et al.* 2012), this powerful SDO spacecraft sends down well over 1 TB/day. The primary data and higher-level derivatives fill a data archive that now exceeds 7PB and holds over 96% of all data ever taken from space in the domain that focuses on the Sun and the physics of the Sun-Earth connections.

Instrumentation with high spatial or spectral resolution is flown on the JAXA-led Hinode/Solar-B mission (launched in 2006; Kosugi *et al.* 2007) and the NASA Small Explorer IRIS (Interface Region Imaging Spectrograph, launched in 2013; De Pontieu *et al.* 2014b) that offer images with resolutions between 0.1 and 0.3 arcsec, combined with spectroscopy in the visible and ultraviolet. RHESSI (Lin *et al.* 2002), launched in 2002, is continuing to provide unique spectroscopic images of the Sun at high energy.

These space-based instruments provide important access to the domain from photosphere to corona, critically complemented by ground-based telescopes and their instrumentation, as well as by rocket experiments such as Hi-C (Winebarger *et al.* 2014).

In the optical domain, the 1.6 m New Solar Telescope (NST, Goode and Cao 2012) at Big Bear in the U.S.A. and the 1.5-meter German GREGOR solar telescope at Tenerife in Spain (Schmidt *et al.* 2012) have been in regular operation since 2012. The 1-m New Vacuum Solar Telescope (NVST, Liu *et al.* 2014c) at Fuxian Lake in southwest China is also in regular operation recently. CRISP (Crisp Imaging Spectro-polarimeter) at the Swedish 1-m Solar Telescope (SST; van Noort and Rouppe van der Voort 2008) reached 0.13 arcsec spatial resolution and high polarimetric sensitivity aided by post-processing. All these telescopes have capacities close to their diffraction limit due to advanced designs and excellent seeing conditions. We have seen glimpses into very high-resolution ground-based coronal observing as well with, for the first time, synoptic observations of coronal Stokes polarimetry in the near infrared by the Coronal Multichannel Polarimeter (CoMP, Tomczyk *et al.* 2008) telescope.

In the radio domain, the recently commissioned Chinese Spectral Radioheliograph (CSRH; Yan *et al.* 2009; Wang *et al.* 2013) at Mingantu in Inner Mongolia of China (renamed as Mingantu Ultrawide Spectral Radioheliograph-MUSER) is a radioheliograph operating with the widest frequency range ever reached from 400 MHz to 15 GHz, with a high temporal, spatial, and spectral resolution. Recent non-solar dedicated radio arrays such as the Murchison Wide-field Array (MWA, Oberoi *et al.* 2011) and the Low-Frequency Array for Radio astronomy (LOFAR, Mann, Vocks, and Breitling 2011) have obtained spectroscopic solar imaging at metric and lower frequencies. The recently upgraded Karl G. Jansky Very Large Array (EVLA) has provided solar radio dynamic imaging spectroscopy of type III bursts at decimeter wavelengths (Chen *et al.* 2013). Even the millimeter domain and beyond is seeing major advances with the Atacama Millimeter/sub-millimeter Array (ALMA; Bastian *et al.* 2015) observatory coming on line for solar observing as it continues to complete its construction phase.

The observations of tens of thousands of Sun-like stars by the NASA Kepler satellite is offering yet more insights into the physics of the Sun, ranging from an improved understanding of internal structure and dynamics (with asteroseismic techniques) to a view of rare, extremely energetic flares. Kepler data, with ground-based follow-up studies, suggest that solar flares may occur with energies up to several hundred times higher than observed directly in the past half century with space-based instrumentation (Schrijver and Beer 2014).

4. Trends in IT infrastructure for research and data

The volume of information that needs to be processed by solar researchers is increasing rapidly. In terms of data to be analyzed, we have definitely reached the petabyte era. This is true for observational data in the archives of SDO, but also in computer experiments in which single snapshot data dumps of the advanced codes can exceed a TB.

A tendency towards open data policies means that we have ever more access to large volumes and a daunting diversity of data. That complicates finding, processing, and integrating data. Infrastructure support for, for example, the Virtual Solar Observatory (VSO), SolarSoft IDL (SSWIDL), and the Heliophysics Events Knowledgebase and Registry (HEK, HER) are critically important to enable efficient utilization of the growing data diversity and volume. The community lags in strategic thinking about these meta-infrastructure elements, both where current support and future expansion or replacement are concerned. There has also been a recent movement towards open-source data analysis software, with the development of the SunPy solar analysis environment in Python (Mumford *et al.* 2013).

A similar flood of information is found with scientific publications, which exceed 2,000 refereed publications per year (see above). Here, the support infrastructure of ADS is of critical value. The wide diversity of journals in which the works of colleagues are published requires subscription access to many publications, at costs that are increasingly hard to bear for relatively small research groups; here, preprint services such as arXiv and MaxMillennium play significant roles in making the community aware of what is going on. “Living reviews” as offered by the free on-line journal Living Reviews in Solar Physics enable new researchers to understand the context of their work and established researchers in one sub-specialty a quick introduction into adjacent areas by their peers.

Among the difficulties the solar activity community also faces is that many solar and inner-heliospheric events are studied by different groups and published in different journals. Finding studies on a particular solar region of interest is hampered by inconsistent use of the characterizing spatio-temporal coordinates of events which may be found in abstract, main text, tables, appendices, and sometimes only marked in figures that are not machine-readable. The IAU adopted a standard convention for this in 2009 (Leibacher *et al.* 2010) in its SOL standard (short for Solar Object Locator). Its use is encouraged by journal editors including those of Solar Physics, the Astrophysical Journal, and the Journal of Geophysical Research. Broad usage of the SOL standard would enable computer searches of related publications, enabling researchers to put new (meta-)studies in broader contexts.

5. Trends in research directions and key findings

For the highlights touched upon in this report, we opted for two criteria to identify topics of interest. One is to mention specific areas of note in the opinion of the Organizing Committee that may be new developments, are highly specialized yet significant, may

concern new instrumentation or methods, or are otherwise deemed to be developments that may grow to see more activity in terms of publications in the near future.

The other criterion we applied is to be guided towards topics of frequent activity by the community itself by looking at the most cited works. Such a selection does introduce a bias toward the papers published early in the period reviewed, of course, but our purpose is not to identify the most-cited works per se, but rather to find the dominant themes within the set of these works that apparently resonate strongly within the community already within the 3-y window from which they are selected.

We searched for the most-cited refereed publications from ADS with the terms “solar.activity”, “coronal.mass.ejection”, “solar flare”, “solar prominence”, or synonym(s) in their abstracts in the period 2012-2014. Within this set, we identify the following themes (sorted alphabetically): active-region magnetic fields; coronal thermal structure; coronal seismology; solar flares and eruptions; and the Sun-in-time related aspects of long-term solar variability including cosmic-ray modulation. We close with a collection of developments, discoveries, and surprises.

5.1. *Active-region magnetic fields*

The photospheric magnetic field of active regions forms the foundation of the overlying atmosphere. Its evolution – through emergence, displacement, and submergence of flux – is key to driving eruptive and explosive events in the corona and into the heliosphere. Until recently, generally only line-of-sight magnetic field maps were available for this work (with its routine observations enabling the study of increasingly large samples; one example of a large study is the work by Al-Ghraibah, Boucheron, and McAteer 2015, who analyse the magnetic properties of $\sim 2,000$ active regions looking for signatures likely involved in flaring). Nowadays, regular vector-magnetic determinations from the observed polarization signals are available from sources that include Hinode, SOLIS, and SDO/HMI. The sensitivity of such vector field maps allows the detection of lasting changes in the photospheric field when comparing pre- to post-flare observations (*e.g.* Wang *et al.* 2012). Temporal resolution is so good that coronal events can be tightly bracketed to try to understand the causes of flares and eruptions, as well as the changes in energy and helicity involved; for example, Sun *et al.* (2012) analyze a series of nonlinear force-free field models for the evolution in the energy of an active region around the time of a major eruption.

The increasing availability of vector-magnetic data enables statistical studies on the properties of active regions and their activity heretofore possible only on line-of-sight magnetograms. For example, Bobra and Couvidat (2015) use a data base of vector field maps of over 2,000 active regions to train a machine-learning algorithm to attempt forecasting of large flares. Su *et al.* (2014) review 3,000 vector field maps of some 60 regions to compare estimates of free energy with flare rates. Tiwari *et al.* (2015) analyze a sample of nearly 200 coronal mass ejections to reveal that flux, twist, and proxies for free energy tend to set upper limits to the speed of CMEs emanating from the active regions studied. Otsuji, Sakurai, and Kuzanyan (2015) review hundreds of vector magnetograms of a sample of 80 active regions to study helicity and twist parameters to test for the influence of Coriolis forcing.

One long sought-after goal of flare and CME physics is to use models of the solar atmospheric field to understand why field configurations destabilize and under what conditions destabilization begins and proceeds. In a “meta-analysis” review, Schmieder, Aulanier, and Vršnak (2015) discuss recent developments, including the use of 3D field extrapolations that suggest that topological structures (notably null points and hyperbolic flux

tubes) may be involved in the triggering and generally as tracers of reconnection processes early on.

But even as the availability of vector-magnetic field maps becomes routine, the realization is growing that by themselves they appear insufficient to provide generally adequate lower-boundary conditions to understand the solar atmospheric activity. For example, a group of modelers using a variety of non-linear force-free field algorithms concludes in a series of studies (see, *e.g.* DeRosa *et al.* 2009; Tadesse, Wiegelmann, and MacNeice 2015; DeRosa *et al.* 2015, and references therein) that snapshot vector-magnetic maps do not suffice to obtain a reliable coronal field model with accurate energy or helicity measurements, with effects of instrumental resolution and field of view, as well as the model geometry (cartesian vs. spherical) all compounding the problems. New developments include the use of coronal loop observations to guide non-potential field models either from a single perspective as is possible currently (*e.g.* Malanushenko *et al.* 2014) or by using stereoscopic data from existing or future space-based instrumentation such as STEREO, Solar Orbiter, and SDO (*e.g.* DeRosa *et al.* 2009; Aschwanden, Schrijver, and Malanushenko 2015). Methods to follow the evolution of active-region fields based on data driving are also being developed, using the uninterrupted stream of (vector) magnetograms now available from space-based platforms (*e.g.* Cheung and DeRosa 2012; Fisher *et al.* 2015, based on the MHD-like magnetofrictional approximation), even reaching up to global MHD field models from near the solar surface into the heliosphere (Hayashi *et al.* 2015). Others are developing MHD methods to study CME initiation based on observed surface field evolution (*e.g.* Amari, Canou, and Aly 2014). Fundamental difficulties with these emerging methods include the difficulty in measuring the transverse field in areas of relatively low flux densities, the intrinsic 180-degree ambiguity in the field direction given a magnitude for the transverse component, the need to constrain the electric field to drive the model's evolution, and ultimately the quantitative comparison with solar observables to determine the verisimilitude of the model fields.

Even as our ability to observe and process rapidly growing data volumes on active region fields increases, we remain puzzled by the Sun's atmospheric magnetic field: we have yet to understand how large amounts of energy can sometimes be stored to eventually be explosively converted into flares and CMEs, while in other cases the energy is either not stored or is not explosively released. For a recent review of our understanding of the magnetic field in the solar atmosphere, and the variety of methods used to observe and study it, we refer to Wiegelmann, Thalmann, and Solanki (2014), and references therein.

5.2. *Coronal thermal structure and heating*

The X-ray solar corona is made of complex arrays of magnetic flux tubes anchored on both sides to the photosphere, confining a relatively dense and hot plasma. This optically thin plasma is almost fully ionized, with temperatures above 1 MK, and emitting mostly in the extreme UV to X-rays with intensities proportional to the square of its density. Significant progress was made in studying the physical and morphological features of coronal loops in a series of very successful EUV and X-ray solar missions, since the first observational evidence of the presence of coronal loops provided by rocket missions in the mid-1960s (Giacconi *et al.* 1965).

In recent years, several solar missions were launched and started producing spectacular images and data in different spectral ranges. The high spatial and temporal resolution of these instruments and the complementarity between these data sets, poses new challenges to understand the heating and dynamics of coronal loops. The launch in 2010 of the Solar Dynamics Observatory (SDO, Pesnell, Thompson, and Chamberlin 2012) allows continuous observation of the whole Sun with high temporal and spatial resolution with

AIA, EVE, and HMI. In particular, AIA images span at least 1.3 solar diameters in multiple wavelengths, at about 1 arcsec in spatial resolution and at a cadence of about 10 seconds. Coronal loops observed by AIA have been found to be highly variable and highly structured in space, time, and temperature, challenging the traditional view of these loops as isothermal structures and favoring the case for multi-thermal cross-field temperature distributions. Because the thermal conductivity is severely reduced in the directions perpendicular to the magnetic field, a spatially intermittent heating mechanism might give rise to a multi-threaded structure in the internal structure of loops. One possible example of such an intermittent heating process is MHD turbulence, which is expected to produce fine scale structuring within loops all the way beyond the resolution of current observations (Gómez, Martens, and Golub 1993; van Ballegoijen, Asgari-Targhi, and Berger 2014). A recent study by Brooks, Warren, and Ugarte-Urra (2012) combining spectroscopic data from the EUV Imaging Spectrometer (EIS, Culhane *et al.* 2007) aboard Hinode and SDO/AIA images, shows that most of their loops must be composed of a number of spatially unresolved threads.

More recently, the sounding rocket mission High-resolution Coronal Imager (Hi-C, Cirtain *et al.* 2013), achieved an unprecedented spatial resolution 0.2 arcsec in EUV images. Winebarger *et al.* (2014) find that the finely structured corona, down to the 0.2" resolution, is concentrated in the moss and in areas of sheared field, where the heating is intense. This result suggests that heating is on smaller spatial scales than AIA and that it could be sporadic. These results are consistent with differential emission measure (DEM) analysis that study the distribution of temperature across loops. Warren, Winebarger, and Brooks (2012) present a systematic study of the differential emission measure distribution in active region cores, using data from EIS and the X-Ray Telescope (XRT) aboard Hinode. Their results suggest that while the hot active region emission might be close to equilibrium, warm active regions may be dominated by evolving million degree loops in the core. More recently, Schmelz *et al.* (2014) used XRT and EIS data as well as images from SDO/AIA, and found that cooler loops tend to have comparatively narrower DEM widths. While the DEM distribution of warm loops could be explained through bundles of threads with different temperatures, cooler loops are consistent with narrow DEMs and perhaps even isothermal plasma. The authors then speculate that warm, multi-thermal, multi-threaded loops might correspond to plasma being heated, while cool loops are composed of threads which have had time to cool to temperatures of about a million degrees, thus resembling a single isothermal loop.

The Interface Region Imaging Spectrograph (IRIS, De Pontieu *et al.* 2014) was launched in 2013, and provides crucial information to understand coronal heating, by tracing the flow of energy and plasma from the chromosphere and transition region up to the corona. IRIS obtains high resolution UV spectra and images with high spatial (0.33 arcsec) and temporal (1 s) resolution. Recent IRIS observations show rather fast variations (20-60 s) of intensity and velocity on spatial scales smaller than 500 km at the foot points of hot coronal loops (Testa *et al.* 2014). These observations were interpreted as the result of heating by electron beams generated in small and impulsive heating events (the so-called coronal nanoflares).

Theoretical models of coronal heating have been traditionally classified into AC or DC, depending on the time scales involved in the driving at the loop foot points: (a) AC or wave models, for which the energy is provided by waves at the Sun's photosphere, with timescales much faster than the time it takes an Alfvén wave to cross the loop; (b) DC or stress models, which assume that energy dissipation takes place by magnetic stresses driven by slow foot point motions (compared to the Alfvén wave crossing time) at the Sun's photosphere. Although these scenarios seem mutually exclusive, two common

factors prevail: (i) the ultimate energy source is the kinetic energy of the sub-photospheric velocity field, (ii) the existence of fine scale structure is essential to speed up the dissipation mechanisms invoked (Gómez 2010). For a coronal heating mechanism to be considered viable, the input energy must be compatible with observed energy losses in active regions, estimated by Withbroe and Noyes (1977) to be $\approx 1 \times 10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$. Welsch (2015) used high-resolution observations of plage magnetic fields made with the Solar Optical Telescope aboard Hinode to estimate the vertical Poynting flux being injected into the corona, obtaining values of about $\approx 5 \times 10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$, which suffices to heat the plasma.

5.3. Coronal seismology

Coronal seismology, like terrestrial seismology and traditional helioseismology, provides a means of probing the background state of the medium through which the waves propagate. Although the corona is not hidden from view like the interiors of Earth and Sun, it is very difficult to directly measure plasma and magnetic properties such as density ρ , magnetic field \mathbf{B} , or transport coefficients. Observations of oscillations in the coronal plasma can potentially provide powerful constraints on these quantities, for example through the Alfvén velocity $\mathbf{B}/\sqrt{\mu\rho}$ (*e.g.*, see the *Living Review* of Nakariakov and Verwichte 2005).

But unlike the solar interior and terrestrial examples where waves are but perturbations on the background state, the coronal seismic waves are crucially important to the energy balance of their host medium. Coronal heating and solar wind acceleration are widely thought to result at least in part from waves (Ofman 2010). An overview of coronal seismology as of 2012 is provided by De Moortel and Nakariakov (2012).

The last 5–8 years have seen an explosion in coronal wave studies due to the advent of new instrumentation, such as the ground-based Coronal Multichannel Polarimeter (CoMP, Tomczyk *et al.* 2008) and the space-based Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). Both have revealed ubiquitous Alfvén-like (*i.e.*, transverse to the magnetic field) coronal oscillations (Tomczyk *et al.* 2007; McIntosh *et al.* 2011, respectively), though the interpretation of their exact natures – Alfvén or kink – is controversial (Van Doorsselaere, Nakariakov, and Verwichte 2008). The term “Alfvénic” is commonly used to encompass both wave types. In either case, the increased resolution of the AIA observations (White and Verwichte 2012) has allowed the detection of sufficient oscillatory power to potentially power both the corona and solar wind (McIntosh *et al.* 2011), though precise mechanisms are not currently known with certainty. The concentration of oscillatory power in the few-minute period band, and in particular at around 5-minutes, strongly suggests a link with the Sun’s internal *p*-mode global oscillations. Consistency in the estimation of Alfvén speed between seismic techniques and magnetic field extrapolation is confirmed by Verwichte *et al.* (2013) using AIA data from a flare-induced coronal loop oscillation.

Time-Distance techniques applied to CoMP observations indicate a preponderance of outward propagating waves over inward propagation, even in closed loop structures, suggesting *in situ* dissipation (or mode conversion) on a timescale comparable to the Alfvén crossing time (Tomczyk and McIntosh 2009).

Disentangling Alfvén and kink waves is addressed in depth by Mathioudakis, Jess, and Erdélyi (2013). In the magnetically structured solar atmosphere, the only true Alfvén wave is torsional, and there is considerable interest in identifying these in observations because of the amount of energy they could potentially contribute to the outer atmosphere. However, being incompressive, Alfvén waves are not seen in intensity, and torsional Alfvén waves are also difficult to detect in Doppler (De Moortel and Pascoe 2012; McIntosh and De Pontieu 2012). Recently though, 0.33-arcsec high-resolution

observations of the chromosphere and transition region (TR) with NASA’s Interface Region Imaging Spectrograph (IRIS), coordinated with the Swedish Solar Telescope, have revealed widespread twisting motions across quiet Sun, coronal holes, and active regions alike that often seem to be associated with heating (De Pontieu *et al.* 2014a). This must presumably extend to the corona as well.

Dissipation of Alfvén waves in the solar atmosphere has long been thought to rely largely on the generation of Alfvén turbulence through nonlinear interaction between counter-propagating waves (Cranmer and van Ballegoijen 2005; van Ballegoijen *et al.* 2011). Observations with CoMP showing enhanced high-frequency power near the apex of coronal loops (Liu *et al.* 2014a; De Moortel *et al.* 2014) possibly supports this view.

The presumed acceleration of the solar wind by Alfvén turbulent energy deposition poses the challenge of identifying and explaining counter-propagating Alfvén waves in open magnetic field regions required to produce that turbulence. Morton, Tomczyk, and Pinto (2015) confirm the presence of these counter-propagating waves using CoMP. These observations also provide evidence of a link to the p -mode spectrum, which presumably relies on magnetoacoustic-to-Alfvén mode conversion occurring in the lower atmosphere (Cally and Hansen 2011; Hansen and Cally 2012).

5.4. Flares

5.4.1. The flare’s impact on the lower solar atmosphere

The solar chromosphere is where most of the energy of a solar flare is dissipated and radiated in bright linear structures called flare ribbons, and recent work on this topic has been dominated by observations from IRIS. The high spectral resolution available with IRIS shows complex spectral line profiles in the Si IV transition region line at 1394Å and 1403Å sometimes with two or three time-varying gaussian components within one IRIS spatial pixel (Brannon, Longcope, and Qiu 2015). The hot “coronal” line of Fe XXI (1354Å) on the other hand shows only a single strongly blue-shifted component (Brosius and Daw 2015; Graham and Cauzzi 2015) originating in compact ribbon sources at the beginning of a flare, with no hot “stationary component” present. The presence of this line also demonstrates the high temperatures reached by the chromosphere in flares as deduced from Hinode/EIS observations (Brosius 2013; Graham *et al.* 2013). With EIS, we see 1.5-3 MK redshifts (Young *et al.* 2013) confirming earlier reports, as well as significant non-thermal broadening. This means that the momentum-conserving condensation front that is produced by flare heating and paired with the evaporation flow contains hot plasma. In turn this implies that the condensation front originates relatively high in the chromosphere, otherwise such high temperatures would not be possible in the standard (electron-beam-driven) model of flares. This is somewhat at odds with recent measurements of element abundance (Warren 2014) which look more photospheric than coronal, suggesting that up-flowing evaporated material comes from low down in the chromosphere, below where the normal fractionation by first ionization potential sets in.

Flare optical (or white-light – WL) emission continues to be difficult to observe and difficult to explain. Optical foot points characterized using 3-filter observations with Hinode/SOT (Watanabe *et al.* 2013; Kerr and Fletcher 2014) could be explained by modest temperature increases of the photospheric black body. The other main proposed radiation mechanism is recombination emission, and flare continuum in the near UV (beyond the Balmer edge) observed with IRIS has an intensity consistent with this (Heinzel and Kleint 2014), but the tell-tale Balmer jump has not been seen. Co-spatial hard X-ray (HXR) and white-light flare sources have been observed using RHESSI and SDO/HMI, and require that both emissions are produced a few hundred kilometres above the photosphere (Martínez Oliveros *et al.* 2012; Krucker *et al.* 2015), at a height corresponding

to the temperature minimum region, and beyond the range expected for HXR-emitting electrons arriving from the corona (unless the chromosphere is under-dense compared to expectations). It may be possible to generate optical emission from the temperature minimum region, for example by modest heating due to ion-neutral damping (Russell and Fletcher 2013), but the presence of non-thermal electrons in this plasma is harder to explain. Also indicating the flare’s impact on the dense lower atmosphere, there have been many more reports of “sun quakes” — flare seismic emission (e.g. Alvarado-Gómez *et al.* 2012; Zharkov *et al.* 2013) — but the mechanical driver remains uncertain; there are correspondences with either HXR sources (pressure pulses from electron-beam driven shocks) or magnetic transients (Lorentz forces) in some but not all cases. High-resolution ground-based flare observations using the New Solar Telescope at BBSO show extraordinary fine structure, on a sub-arcsecond scale, in flare ribbons and footprints (Deng *et al.* 2013; Sharykin and Kosovichev 2014), setting the scene for future observations with DKIST.

5.4.2. *Magnetic-field evolution and energetics*

Examination of the changes in photospheric vector field occurring at the flare impulsive phase by Petrie (2012, 2013) using the HMI on SDO suggests strong, permanent and abrupt variations in the vertical component of the Lorentz force at the photosphere consistent with a downward ‘collapse’ of magnetic loops, and changes in the horizontal component mostly parallel to the neutral line in opposite directions on each side, indicating a decrease of shear near the neutral line. The brighter the flare (as expressed in the GOES class), the larger are both the total (area-integrated) change in the magnetic field and the change of Lorentz force (Wang, Liu, and Wang 2012), although Su *et al.* (2014) found that indicators of magnetic non-potentiality (e.g. rotation, shear and helicity changes) are more closely associated with flares — see for example the study of flare-associated rotating sunspots by Vemareddy, Ambastha, and Maurya (2012). In the corona, imaging and spectroscopic observations show compelling evidence for plasma flows suggestive of those expected around a coronal reconnection region (e.g. Tian *et al.* 2014; Su *et al.* 2013).

The growing number of observed flares in archives and the increased coverage of flares in wavelength space and in domains from surface to heliosphere is enabling an improved assessment of energy budgets. For example, Emslie *et al.* (2012) quantify energies of an ensemble of large, eruptive flares to find, among others that it appears that the energy in accelerated particles during the initial phases of the flare suffice to supply the energy eventually radiated in the flare across the spectrum, and that that total energy is statistically just under the bulk kinetic energy in associated coronal mass ejections.

5.4.3. *Particle acceleration and transport*

The central problem in solar flare theory remains the acceleration of the non-thermal electrons required to explain observed chromospheric HXR sources. Observations with RHESSI and SDO show that coronal electron acceleration can be very efficient; Krucker and Battaglia (2014) find that essentially all electrons in a coronal source of density a few times 10^9 cm^{-3} are energized to above around 10 keV. Kappa distributions, which are found to be a better fit than a standard thermal plus non-thermal distribution in coronal HXR sources (Oka *et al.* 2015), are shown to arise naturally in an acceleration region when there is a balance between diffusive acceleration and collisions, in the absence of significant escape from the acceleration region (Bian *et al.* 2014). In the electron-beam model of a flare, electrons must of course escape the corona to produce the chromospheric HXR sources, and the number flux requirements have always been somewhat

problematic. This may be alleviated if electrons are boosted by wave-particle interactions in the corona; a quasi-linear simulation of coronal electron propagation shows that wave-particle interaction with the high phase-velocity Langmuir waves generated by density inhomogeneities can accelerate beam electrons to higher energies, reducing the requirement on electron flux at energies of a few tens of keV by up to a factor ten (Hannah, Kontar, and Reid 2013). Varady *et al.* (2014) study a model in which electrons are re-accelerated in the chromosphere, concluding that this also reduces demands on putative electron beam fluxes (however requirements on the flare chromosphere energy source, not directly addressed in this model, remain the same). Chromospheric (re-) acceleration models may also produce electron angular distributions which are more isotropic, consistent with the angular distributions inferred from inversion of RHESSI mean electron flux spectra, accounting for photospheric X-ray albedo, by Dickson and Kontar (2013). A completely different view by Melrose and Wheatland (2014) is that the electron energization in flares takes place in a parallel electric field that develops close to or in the chromosphere, in a region of anomalous resistivity, if energy is transported Alfvénically — specifically by inertial Alfvén waves. However, the orthodoxy remains that energy transport is by electron beams, and this is now being tested against observations using beam-driven radiation hydrodynamics codes, the output of which can be compared with, for example, IRIS (Rubio da Costa *et al.* 2015) and EVE and AIA data (Kennedy *et al.* 2015), so far with mixed success.

5.5. Coronal mass ejections

The understanding of the initiation and evolution of coronal mass ejections (CMEs) has tremendously profited from the combination of coronagraphic observations with high cadence imaging in the EUV together with the multi-perspective view provided by the STEREO mission, as well as from increasingly sophisticated MHD and thermodynamic modeling (for reviews see Webb and Howard 2012; Aulanier 2014). Magnetic flux ropes play a key role in the physics of CMEs. But there is a long debate whether flux ropes are pre-existing or formed during the eruption. Patsourakos, Vourlidas, and Stenborg (2013) observed the formation of a flux rope during a confined flare in high-cadence SDO/AIA EUV imagery. Within hours after its formation, the flux rope became unstable and erupted resulting in a CME/flare event. For other CMEs, for example those associated with quiescent prominence-cavity systems, a variety of observations indicate a pre-existing flux rope which may erupt bodily as a CME (see e.g. Figure 12 of Gibson 2015). Vourlidas *et al.* (2013) synthesized 16 years of coronagraphic and EUV observations with MHD simulations, and found that flux ropes are a common structure in CMEs; in at least 40% a clear flux rope structure could be identified. In addition, they established a new “two-front” morphology consisting of a faint front followed by diffuse emission and the bright CME leading edge. The faint front is suggestive of a wave or shock front driven by the CME.

The high-cadence six-passband SDO/AIA EUV imagery allows to perform differential emission measure (DEM) analysis on solar flares and CMEs to study their multi-thermal dynamics (Hannah and Kontar 2012). It was shown that the CME core region, typically identified as the embedded flux rope, is hot (8 – 10 MK) indicative of magnetic reconnection being involved. In contrast, the CME leading front has temperatures similar to the pre-eruptive corona but of higher densities suggesting that the front is a result of compression of the ambient coronal plasma (Cheng *et al.* 2012a; Hannah and Kontar 2013). The hot flux rope is a key indicator to the physical processes involved in the early acceleration phase of the CME (Fan 2012; Cheng *et al.* 2013).

The environment of CMEs is important for the development of non-radial propagation. Zuccarello *et al.* (2012) report that during solar minimum conditions CMEs originating from high latitudes can be easily deflected toward the heliospheric current sheet, thus eventually becoming geo-effective. Panasenco *et al.* (2013) showed that coronal holes nearby the CME initiation site can cause strong deflections of CMEs.

Modeling of the initiation of CMEs continues to provide insights into the various forces and mechanisms that may be involved: initiation may involve the kink instability (Kumar *et al.* 2012), sunspot rotation, reduction of tension of the overlying field (Török *et al.* 2013), torus instability (Kliem *et al.* 2014), and the breakout process (Karpen, Antiochos, and DeVore 2012; Lynch and Edmondson 2013). Which dominates under which conditions and how commonly these occur remain topics of future work.

5.6. Large-scale EUV waves

Since their discovery by the SOHO/EIT instrument about 15 years ago, there has been a vivid debate about the physical nature of large-scale EUV waves, i.e. whether they are true wave phenomena or propagating disturbances related to the magnetic restructuring due to the erupting CME. In the recent years, there has been tremendous progress in the understanding of these intriguing phenomena thanks to the unprecedented observations available, in particular the high-cadence EUV imagery in six wavelengths bands by SDO/AIA combined with the STEREO multi-point view which allowed for the first time to follow EUV waves in full-Sun maps (Olmedo *et al.* 2012). There seems now relatively broad consensus that large-scale EUV waves are often fast-mode magnetosonic waves (of large amplitude or shocks), driven by the strong lateral expansion of the CME (see reviews by Patsourakos and Vourlidis 2012; Liu and Ofman 2014). A number of detailed case studies revealed that the CME lateral front and the EUV wave appear originally co-spatial. But when the lateral CME expansion slows down, the EUV wave decouples from the driver and then propagates freely, adjusting to the local fast-mode speed of the medium (e.g. Cheng *et al.* 2012b; Olmedo *et al.* 2012). Three-dimensional thermodynamic MHD modeling of well observed EUV waves also supports these findings, showing the outer fast-mode EUV wave front followed by another bright front indicating the CME component (Downs *et al.* 2012). Statistical studies of EUV waves based on SDO/AIA (Nitta *et al.* 2013) and STEREO/EUVI data (Muhr *et al.* 2014) revealed EUV wave speeds that range from close to the fast magnetosonic speed in the quiet corona to values well above, the fastest ones exceeding 1000 km s^{-1} . Muhr *et al.* (2014) showed that at least half of the EUV waves under study show significant deceleration, and a distinct anti-correlation between the starting speed and the deceleration, providing further evidence for a freely propagating fast-mode wave. The association rate of EUV waves with type II bursts, which are indicative of shock waves in the solar corona, may be as high as 50% (Nitta *et al.* 2013). Detailed case studies provided a number of further characteristics suggestive of the wave nature, such as reflection and refraction of EUV waves at coronal holes and active regions, transmission into coronal holes as well as the initiation of secondary waves by the arrival of the wave at structures of high Alfvén speed (Li *et al.* 2012; Olmedo *et al.* 2012; Shen and Liu 2012; Kienreich *et al.* 2013) and for one case, Long *et al.* (2015) have evaluated the EUV wave's initial energy using a blast-wave approximation, to be around 10% of that of the associated CME. Liu *et al.* (2012a) discovered quasi-periodic fast-mode wave trains within a large-scale EUV Wave with a periodicity of 2 min, running ahead of the laterally expanding CME flanks. Asai *et al.* (2012) presented the first simultaneous observations of the propagation of a large-scale EUV wave and an H α Moreton wave, showing that the wave fronts evolve co-spatially indicating that they are both signatures of a fast magnetosonic wave pulse.

5.7. CME evolution in the heliosphere

The STEREO mission, often in combination with SOHO/LASCO, offers observations of CMEs all the way from their origin on the Sun, and of their propagation in interplanetary space to beyond 1 AU from outside the Sun-Earth line. These data combined with a multitude of other in-situ space missions have been vividly used to connect remote sensing CME observations to the field and plasma data observed by in-situ spacecraft, to constrain models of interplanetary CME propagation, to study CME-CME interaction, and to forecast CME arrival times and speeds with the ultimate aim improving the prediction of their geo-effectiveness.

Howard and DeForest (2012) and DeForest, Howard, and McComas (2013) tracked a flux rope all the way from its solar origin to its in-situ signatures at 1 AU using the STEREO SECCHI EUV imagers, coronagraphs and wide-angle heliospheric imagers. They establish that the cavity in the classic three-part CME is the feature that becomes the magnetic cloud, implying material ahead of the cavity is piled-up material from the corona or the solar wind.

Modeling of the interplanetary propagation of CMEs makes use of empirical, analytic and numerical approaches. The analytical “drag-based model” (DBM) is based on the hypothesis that the Lorentz forces driving a CME eruption ceases in the upper corona and that beyond a certain distance the interplanetary CME (ICME) dynamics is governed solely by the interaction of the ICME and the ambient solar wind plasma (Vršnak *et al.* 2013). From the observational side, a variety of reconstruction methods have been developed and applied to the Heliospheric Imager data including one- as well as two-spacecraft (stereoscopic) observations and inclusion of in-situ data and radio type II bursts to better constrain the propagation direction, distance and speed profile of CMEs in interplanetary space (Rollett *et al.* 2012; Möstl and Davies 2013; Colaninno, Vourlidis, and Wu 2013; Liu *et al.* 2013). These efforts result in comparable typical uncertainties in the CME arrival time of about half a day (Vršnak *et al.* 2014; Lee *et al.* 2013; Möstl *et al.* 2014).

Studies using STEREO Heliospheric Imager data and in-situ plasma and field measurements established that the interaction of CMEs in the inner heliosphere, due to a faster CME launched after a slower one, seems to be a common and important phenomenon (Liu *et al.* 2012b; Harrison *et al.* 2012; Lugaz *et al.* 2012; Temmer *et al.* 2012; Möstl *et al.* 2012; Liu *et al.* 2013; Temmer *et al.* 2014). The interaction process may cause deflection or merging of CMEs, and either deceleration or acceleration of merged CME fronts (including heating and compression). Liu *et al.* (2014b), reporting in a fast CME causing an extreme storm, speculate that the interaction between two successively launched CMEs resulted in the extreme enhancement of the magnetic field of the ejecta that was observed in-situ near 1 AU.

5.8. Sun-in-time

The unusually deep and temporally-extended activity minimum between sunspot cycles 23 and 24, followed by a slowly rising and low amplitude cycle 24, has led to renewed interest in the underlying causes of solar cycle fluctuations, including Grand Minima. Much attention has focused on the so-called Babcock-Leighton solar cycle models, in which the regeneration of the solar surface dipole takes place via the decay of active regions. Most extant versions of these dynamo models are geometrically (axisymmetric) and dynamically (kinematic) simplified, yet they do remarkably well at reproducing many observed solar cycle characteristics (see, *e.g.*, Karak *et al.* 2014, and references therein). Explanations for the extended cycle 23-24 minimum and low amplitude cycle 24 have been sought in terms of variations in the meridional flow expected to thread the solar

convection zone (Upton and Hathaway 2014), and patterns of active region emergence and associated feedback on surface flows (Cameron *et al.* 2014; Jiang *et al.* 2015). These successes of the Babcock-Leighton modelling framework have however been challenged by helioseismic measurements (Zhao *et al.* 2013; Schad *et al.* 2013) indicating that the meridional flow within the convection zone has a far more complex cellular structure than assumed in the majority of these mean-field-like solar cycle models. Possible avenues out of this conundrum are being explored (see, *e.g.*, Hazra *et al.* 2014; Belucz *et al.* 2015).

Much effort has also been invested in implementing various form of data assimilation schemes in dynamo models, with the aim of achieving improved forecasting of the amplitude and timing of future sunspot cycles. At this point in time no existing dynamo model-based forecasting scheme has done significantly better than the known precursor skill of the solar surface magnetic dipole moment at times of cycle minima, nonetheless progress is likely forthcoming in this area.

Global magnetohydrodynamical simulations of solar convection have also progressed rapidly in recent years, with many research groups worldwide now running simulations producing large-scale magnetic fields undergoing polarity reversals (*e.g.* Masada *et al.* 2013; Nelson *et al.* 2013; Fan and Fang 2014; Passos and Charbonneau 2014; Warnecke *et al.* 2014). Due to computing limitations all these simulations run in parameter regimes still far removed from solar interior conditions. Nonetheless, many are producing tantalizingly solar-like features, including rotational torsional oscillations (Beaudoin *et al.* 2013) equatorward propagation of activity “belts” (Käpylä *et al.* 2012; Warnecke *et al.* 2014; Augustson *et al.* 2015) cyclic in-phase magnetic modulation of convective energy transport (Cossette *et al.* 2013) and Grand Minima-like interruptions of cyclic behavior (Augustson *et al.* 2015). One particularly interesting feature is the spontaneous production of magnetic flux tube-like structures within the convection zone, as reported in Nelson *et al.* (2013). These were found to rise to the top of the simulation domain, partly through magnetic buoyancy, while maintaining their orientation in a manner compatible with Hale’ polarity laws (Nelson *et al.* 2014). This has revived the idea that dynamo action could be wholly contained within the solar convective envelope, rather than relying on the tachocline for the formation and storage of the magnetic flux ropes eventually giving rise to sunspots.

Major efforts have also taken place in reinterpreting and reanalyzing historical observations of magnetic activity. Noteworthy in this respect are the analyses of tilt angle patterns for bipolar magnetic regions (see Pavai *et al.* 2015, and references therein), and reanalysis of polar faculae data by Munoz-Jaramillo *et al.* (2012). Of particular importance is the recently completed revision of the international sunspot number (SSN) time series. SSN values for the period 1947-present now account for a discontinuity in the manner of counting spot groups having occurred at the Locarno reference station (Clette *et al.* 2014). Correcting for this leads to a significant ($\simeq 20\%$) decrease in SSN values during the space era. Consequently, reconstructions of solar activity into the distant past using the SSN as a backbone to extrapolate space-borne measurements will need to be reassessed.

Radionuclides generated by the atmospheric impact of galactic cosmic rays (GCRs) provide a crucial proxy for the evolution in the Sun’s activity (Usoskin 2008; Potgieter 2013) on time scales longer than a few years or a decade, depending on the radionuclide and its deposition in terrestrial natural archives. New ice core data on ^{10}Be and tree ring data on ^{14}C have been combined to provide better understanding of climate impacts on these records: a joint analysis of composite tree ring data with ice cores from Greenland and Antarctica have enabled the separation of the common signal (assumed to be dominated by solar and heliospheric variability) from terrestrial variability (Steinhilber *et al.*

2012). From this, we now have 94 centuries of data on a proxy for solar activity. But translating that proxy into details of solar activity that may drive space weather and terrestrial climate remains a challenge, as reviewed by, *e.g.* Solanki, Krivova, and Haigh (2013).

5.9. *Developments, discoveries, and surprises*

And then, of course, there were numerous surprising realizations and discoveries, in the real world as much as in the rapidly growing virtual world). We mention merely a small sampling in no particular order: a weak solar cycle following an uncommonly low and long solar minimum (McComas *et al.* 2013); a series of X-class flares from AR 12192 none of which were associated with a CME, contrasting with statistics to date (Chen *et al.* 2015; Sun *et al.* 2015; Thalmann *et al.* 2015); use of a Sun-grazing comet to probe the high corona and its connection to the innermost heliosphere (Downs *et al.* 2013; Raymond *et al.* 2014); an extremely large amount of dense, cool plasma falling back onto the Sun following a massive filament eruption providing a close-up example of distant accretion processes (Reale *et al.* 2013); reports of enormously energetic flares from what would appear to be Sun-like stars (Nogami *et al.* 2014) and potential evidence for strong SEP events associated with very energetic solar flaring from ^{14}C records albeit without obvious auroral counterparts (Miyake *et al.* 2012; Usoskin *et al.* 2013; Neuhäuser and Neuhäuser 2015); the successful creation of realistic looking sunspots in the computer (Rempel and Cheung 2014); the revision of sunspot numbers that suggests no long-term increase in solar activity occurred over the past few hundred years (Clette *et al.* 2014); radiative magneto-convective simulations have reached resolution scales of a few kilometers, and suggest comparable energy densities in magnetic and kinetic reservoirs (Rempel 2014); IRIS observations uncovering rapidly-evolving low-lying loops at transition region temperatures, heretofore inferred from emission measure studies but never yet observed (Hansteen *et al.* 2014); a new model was proposed for coronal heating based on magnetic gradient pumping (Tan 2014); non-potential field models for a continuously-driven corona over a 16-year period was achieved (Yeates 2014); a solar eruption in July of 2012 that would likely have powered a century-level extreme geomagnetic storm, as for the Carrington-Hodgson flare of 1859, had it enveloped Earth (Baker *et al.* 2013); the realization that Stokes' theorem combined with the induction equation could explain why polar fields should be a good indicator for the strength of the next sunspot cycle (Cameron and Schüssler 2015); the simulation of a sequence of homologous CMEs and demonstration of so-called "canniballistic" behavior (Chatterjee and Fan 2013); the discovery of nested toroidal line-of-sight flows and lagomorphic coronal polarimetric signatures within coronal cavities indicating the presence of magnetic flux ropes (Bak-Stęślicka *et al.* 2013); rapidly rotating magnetic structures ("magnetic tornadoes") have been identified, which provide a channel of energy and twist from the solar surface to the corona (Zhang and Liu 2011; Wedemeyer-Böhm *et al.* 2012); and the X-class flare SOL2014-03-29T made history by becoming "the best-observed flare of all time" (<http://www.nasa.gov/content/goddard/nasa-telescopes-coordinate-best-ever-flare-observations/#.VhJ4TrQ9Yow> according to NASA) as the ground-based Dunn Solar Telescope and the space-based IRIS, RHESSI, and SDO all observed it in detail.

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