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COMMISSION E3 — SOLAR IMPACT THROUGHOUT THE HELIOSPHERE

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TRIENNIAL REPORT 2015-2018

1. Introduction

The entire solar system is influenced by plasma, particle and radiation disturbances launched by the Sun, and their consequences throughout the heliosphere which is the region of space around the Sun dominated by the solar wind. The impacts of solar variability range from the Sun - Earth relevant processes on time scales of hours and days, to the solar cycle, to the lifetime of the Sun. Solar variability also influences the extension of the heliosphere and the physical process at the boundaries of the heliosphere which arise from interactions with the surrounding interstellar medium and e.g. generate anomalous cosmic rays. The solar and heliospheric variability shapes the boundaries of planets and solar system objects to the interplanetary medium, e.g. to the solar wind and its other constituents. The influence of solar variability on planets and solar system objects is observed in magnetospheres and atmospheres of planets and comae of comets. The impact of solar variability is especially important for space weather and space climate, topics that, in recent years, moved into the focus of fundamental research, application-oriented research and public service. Space weather addresses the immediate impact of its time-varying environment on Earth, although the term is used in different ways. The discussions within the commission developed to a definition: Space weather describes the immediate impact on the Earth of the time-varying cosmic environment. This cosmic environment is influenced predominantly, but not exclusively by plasma, particles, magnetic field, and radiation launched by the Sun, the disturbances they cause and the physical processes that they represent. Space climate generalizes the Space weather concept to longer time-scales, including indirect effects, feedbacks and long-ranging trends.

2. Commission Activities

There is an international effort related to coordinating space weather studies and a representative of the commission participated in the United Nations Expert Group on Space Weather: "Strategy for Developing an International Framework for Space Weather Services (2018-2030)". Work of the expert group was presented to the IAU membership during a related IAU symposium.

Commission E3 supported several conferences organized by the IAU and in particular their commission members chaired one IAU symposium in 2017 and are going to Chair a focus meeting in 2018 as described below.

IAU Symposium 335 -The IAU Symposium: Space Weather of the Heliosphere: Processes and Forecast to place at University of Exeter, United Kingdom, 17 - 21 July 2017. It was co-chaired by two members of the commission E3.

The topics of the symposium included:

• Impact of solar wind, structures and radiation on and within terrestrial and planetary environments (including magnetospheres, ionospheres and atmospheres);

• Solar drivers of Space Weather: origin, onset, activity levels, e.g. How to anticipate flares and super flares;

• How to predict the propagation and evolution of solar disturbances;

• Long-term trends and predictions, e.g. How to predict the next solar cycles, planetary magnetic field, effects of solar variability on planetary climate;

• Challenges for Earth and the interplanetary medium: variability, extremes and boundary conditions of the space environments, characterization, requirements, and terminology issues;

• Forecast Models: synergies in numerical simulations, advances in numerical approaches, computation, mathematics and physical processes, high-performance computing including need for visualization;

• Data Handling and Assimilation: data format for scientific usage and real-time data assimilation within models and forecast; data dissemination: best practices; big data analyses vulnerability, statistical analysis, tools and ensemble models;

• Future Missions and Instrumentation: requirements from each community, potential coordination of space and ground-based instruments;

• Relationships with the "civil" society: Societal needs, Predictability requirements, Disaster and Risk Reduction Concepts, Communication towards deciders; how to educate people without threat.

The meeting had 185 participants from 30 countries. The symposium brought a vast range of expertise together, discussing the activity and winds of other Suns and the effects on planets and other objects of the solar system such as Pluto. Aside from scientific sessions a town hall session was organized as a liaison to the United Nations Expert Group on Space Weather: "Strategy for Developing an International Framework for Space Weather Services (2018-2030)". And two round tables were organized on "Data Handling and Assimilation" and "Relationships with the "civil" society", respectively. The proceedings will be published in Spring 2018.

Focus Meeting during XXXth IAU General Assembly:

A Focus Meeting on "Nano Dust in Space and Astrophysics" will take place 28-29 August during the 2018 General Assembly of the IAU and it is co-chaired by a member of commission E3. The Focus Meeting brings together researchers from astronomy, space and astrophysics and it is sponsored by Division E and co-sponsored by the Division H. The meeting is devoted to nano dust and nano particles like e.g. PAHs, fullerenes, and nano tubes. Topics include formation, destruction, and physical and chemical interactions of the particles and its appearance and evolution in different regions in space: the interstellar medium, stellar atmospheres and different regions within the heliosphere. The Science Organizing Committee includes researchers from 10 countries who work in astronomy, chemistry, space, atmospheric and laboratory research.

The work of the commission is considered successful while there is plenty of

room for more activities and the commission should therefore be continued for another 3 years. Timely topics are:

- **Using the new observations in the vicinity of the to study heliospheric phenomena including the small-scale phenomena in the solar wind.**
- **Using high-performance computing for heliospheric studies.**
- **Connecting heliospheric and magnetospheric studies.**

3. Scientific Achievements and Developments

3.1. *Long-term solar activity*

Essential progress has been achieved with the level of understanding of solar variability on centennial time scales.

3.1.1. *Updated reconstructions of the sunspot numbers*

Sunspot numbers counted since 1610 form the most useful index of solar activity for the last century.However, the quality of the sunspot number is inhomogeneous: while it is relatively good for the 20th century, uncertainties are large in the past, reaching $10 - -20\%$ for the 19th centuries and being hardly assessable for the early 18th century. There were two historically established sunspot series: the Wolf sunspot number (WSN) and group sunspot number (GSN) series [24]. However, there was a need to revise the series because of some inhomogeneities and new data emerging. A group of solar scientists prepared a major revision of the sunspot series [9], which was inaugurated in July 2015. A press-release of the IAU General Assembly on this topic was controversial, partly due to lack of communication with the scientists. The prepared revision of sunspot groups sparked a discussion on methodologies that continues until today and quite a number of new sunspot number reconstructions were published as based on different methods [33, 53, 10, 63, 6, 70, 17] and new statistical methods have been developed [63, 70, 6] and are tested now. At present, there are seven alternative sunspot number reconstructions, which is very confusing for the end users. The uncertainties and the pitfalls have been unidentified, and a new sunspot number reconstruction based on modern advanced methods and the full complexity of the available data is needed. The solar community fully realizes that and joins efforts towards a consensus of a most probable sunspot number reconstruction. This work is organized as an international team (under the umbrella of the International Space Science Institute, ISSI) to reach a community-consensus approach in sunspot number reconstructions.

A significant progress has been achieved in digitizing existing (records and drawings of sunspots) and recovering new unknown datasets [19, 32, 2, 18, 13]. An updated database of the sunspot records has been created [64].

It was proposed by [53] and [74] that the Maunder minimum (1645–1700) was not very deep, but a revision and analysis of the available data [65, 60] confirmed that indeed the solar activity was very low during the main phase of the Maunder minimum, in full agreement with earlier assessments. Proxy data, such as cosmogenic isotopes 14C in tree rings, 10Be in ice cores or 44Ti in meteorites, are somewhat controversial [45] about details on this timescale but imply the unusual nature of the Maunder minimum and the existence of the Modern grand maximum [3, 35].

Presently the activity on sunspot number reconstruction is coordinated by the SILSO data center of the Royal Observatory of Belgium (ROB), which archives all versions in a public repository http://www.sidc.be/silso/datafiles.

3.1.2. *Proxy data in terrestrial archives*

The fidelity and confidence of reconstructions of the long-term solar variability, including extreme solar events on the basis of indirect proxy data has been greatly improved.

New millennium-scale reconstructions of solar activity, based on state-of-the art models and new datasets, are more robust and precise than earlier [62, 61, 45]. In particular, it has been shown that the Hallstatt cycle (approx. 2400 years) whose origin was long-debated [66] has solar origin [61]. Thanks to the improved quality of the reconstructions, statistic of Grand minima and maxima occurrence is more reliable now [26, 61]. In particular, it has been shown that Grand minima indeed form a special mode of the solar dynamo [72].

It was shown from both theoretically [12] and experimentally [71, 52] that nitrate in polar ice cores cannot serve as a reliable proxy for solar energetic particle events, as claimed earlier [36].

A breakthrough has been made with understanding of extreme solar particle events. The event of 775 AD originally discovered in radiocarbon in a single tree [41] has been confirmed in many other samples and also in cosmogenic beryllium-10 and chlorine-36 [50, 37]. The new data confirmed that the event of 775 AD was indeed a solar energetic particle event (or a consequence of events) happening in the second half of 774 AD [52]. The energy spectrum was estimated by [37] as very hard and being a factor of $\approx$40 greater than the strongest solar particle event directly observed (23-Feb-1956). The atmospheric effect of the event has been evaluated by [52] to show that a moderate effect in the ground winter temperature is expected in the polar region for winter period. Two more event of similar kind but a factor of 1.5 weaker have been identified, in 885 AD [40] and 3372 BC [69]. It is apparent now that such events are 'typical' for the Sun on a millennial time scale, and that he 775 AD event can serve as the 'worst case scenario' for a solar particle storm [52].

3.2. *Solar Energetic Particle (SEP) Event Forecasting and Analysis*

SEPs emitted from the Sun are a major space weather hazard. The motivation behind the recently completed HESPERIA (High Energy Solar Particle Events forecasting and Analysis) project of the EU HORIZON 2020 programme was to further our scientific understanding and prediction capability of high-energy SEP events, by building new forecasting tools while exploiting novel as well as already existing data sets. HESPERIA was led by the National Observatory of Athens. Within HESPERIA, two novel real-time tools to predict SEP events were developed. The developed and operational HESPERIA UMASEP-500 tool makes real-time predictions of the occurrence of Ground Level Enhancement (GLE) events, from the analysis of soft X-ray (SXR) and differential proton flux measured by the Geostationary Operational Environmental Satellites (GOES) satellite network [48, 47]. Using near-relativistic as well as relativistic electrons as precursors for the arrival of energetic protons, the developed HESPERIA REleASE tools make real-time predictions of the proton flux-time profiles of 30-50 MeV protons at L1 [47]. Both predictions are publicly available via the HESPERIA web site (http://www.hesperia.astro.noa.gr).

3.3. *Solar wind at small scales*

3.3.1. *Turbulence*

[55, 54] provided new evidence for the important role played by the Alfvén ion cyclotron and kinetic Alfvén waves. Turbulence in the solar wind is a very active field of

research. Being an archetype of turbulence in collisionless plasma, the solar wind turbulence is explores both from in-situ observations and numerical approaches. More than 350 papers are identified from ADS database since 2015 combining the words "Solar Wind" & "turbulence", evidencing the very high level of activity behind this domain. Among the questions that are tackled by the community the following are pointed out:

• Is the turbulent dissipation sufficient to explain the slow radial decrease (compare to the decrease expected from an adiabatic cooling of a radially expanding plasma) of the proton temperature in the solar wind?

• At what frequency starts the dissipation "(ends the cascade)" Or when do kinetic effects play a significant role?

• What are the physical processes responsible for the final energy dissipation "wave-particles interaction", "Reconnection") ?

• What is the nature of the cascade ("Kinetic Alfvén waves", "Whistler waves", "others")?

Several space instruments enable *in situ* measurements of the magnetic field and density fluctuations since many years, covering several solar cycles and many solar wind conditions. [7] recently published a summary on the latest achievements in plasma turbulence from solar wind observations.

However, observations are limited at the sub-ion scales, where the dissipation is supposed to take place. Owing to the international computer centers (e.g. CINECA, IDRIS) that provide huge numerical resources, large scale (in space and time) simulations are now possible. Several numerical studies have been published very recently, adopting either a 3D-MHD approach (e.g. [42]) or including kinetic processes through large 2D (e.g. [16]) or 3D hybrid Particle-In-Cell (PIC) approach (e.g. [5, 25, 20, 15, 67]), even fully kinetic, 3D-simulations [68] and gyrokinetic models [58]. Thus, new results on the turbulent heating on large scale (almost 1AU in the inner heliosphere) were obtained. With the inclusion of the kinetic aspects, the turbulent cascade has been computed over more than two orders of magnitude showing the breaks in the power law, the competition between forward and inverse cascade and the non-linear energy transfer and the dissipation in Alfvén wave turbulence. Finally, theoretical work has been also devoted to express the exact law to describe the 3D compressible Hall MHD, including density fluctuation, hall current, and spatial anisotropies due to the magnetic field (see [1]). A specific issue in "Philosophical Transactions A" published several reviews covering theoretical, observational and numerical aspects of the *Dissipation and heating in solar wind turbulence* (see the introductory paper of [28]).Finally, the plasma instruments of the Rosetta mission have provided very new data about waves around a comet (in that case Churyunov-Gerasimenko). They can constitute another opportunity to study the development of the turbulence (at least at high heliospheric latitudes - see the recent discussion of [59]).

3.3.2. *Coherent solar radio emissions*

Solar radio emissions from the micro-wave to kilometer range of wavelengths (i.e. from GHz to kHz) are very powerful diagnose of transient, eruptive phenomena of the solar upper atmosphere. For example, the so-called Type I bursts enable to detect region of magnetic reconnection above active regions, while Type II and Type III bursts are intensively used to follow beams of energetic electrons during their journey in the interplanetary medium after a flare or ahead an ICME, and gyrosychronous emissions enable the determination of the coronal magnetic field strength. Owing to the presence of space instruments on board of WIND and STEREO that routinely record the radio emission in the kHz-MHz range since more than twenty years now, our understanding of the Type

II and III bursts has strongly progressed. A particular attention has been paid to these emissions also for the potential impact of the particles associated to them in terms of space weather.

A large consensus exist to attribute to beams of non-thermal electrons to the Langmuir waves observed in the vicinity of Type II and III electromagnetic radiations. A controversy however appears when trying to identify the electrostatic to electromagnetic conversion mechanism(s). To further test the different scenarii, new kinetic simulations appear in the last years. In particular, after some first studies on small-box, small number of particle per cell, [56] performed 2D-PIC simulations of fundamental and harmonic radio emission from a large box and large number of particle, allowing for a better description of the modes and reducing the numerical heating. A similar work was performed by [21] with even better numerical set-up, which allowed to discuss the efficiency of the conversion process toward the harmonic emission and the directivity of the electromagnetic emissions. Also [57] study the role of the small-scale density inhomogeneity in the acceleration of the particles, while [49] showed, from 1D-1V Vlasov simulations, how small-scale density holes can ease the development of Langmuir waves even in non favorable condition for the rest of the background plasma. These simulations are however restricted to an unmagnetized plasma but its inclusion is necessary to allow for the extraordinary mode to be present in the box and study the polarization aspect.

Note that the work of [21] also aims to prepare dedicated laser-experiments to study the harmonic emissions from three wave coupling mechanism. Laboratory experiments for astrophysical studies gain importance in the astrophysical community since a few years. Only recently, experiments are also designed for heliophysical conditions (often more difficult to perform in lab since the characteristics of the medium is less extreme than in other astrophysical contexts). [23] published a review paper on the recent synergies between space exploration and laboratory experiments. Next to data analysis of space data and huge numerical simulations, lab experiments provide a new way to explore the small-scale physics of astrophysical plasma, under controlled parameters.

3.4. *Progress from radio instruments*

Regarding instrumentation, during the last decade, several ground-based radio interferometers working in the range 20 - 300MHz have been put in operation: Long Wavelength Array in the USA, the LOw Frequency ARray (LOFAR) over Europe, Murchison Widefield Array (MWA) in Australia and the Giant Ukrainian Radio Telescope (GURT) in Ukraine. Also, Nenufar, a low-frequency extension of the LOFAR capability is under development in France. These infrastructures provide both very high temporal and spectral resolution but also imagery capabilities. Combining imagery capabilities of LOFAR and URAN-2 high spectral observations, [29] tackled the question of the role of small scale inhomogeneities in the solar corona on the electromagnetic emissions propagation vs. the characteristics of the source. Apart from the results itself, which confirms the major role played by the inhomogeneities, this study shows the very innovative possibility provided by the combination of a tied-array interferometer and radio imagery for studies on turbulent heating in the solar corona (see also [44]). Traditional works on the fine structures of the low frequency radio spectra (e.g. drift pairs, zebra spectrum, Type IIIb) have continued during the last years and will strongly benefit in the future from the new infrastructures, preparing for the SKA observations (see for example a recent review of [46] about the solar and heliospheric physics with SKA).

Apart from the solar results obtained from these instruments, density fluctuations in the interplanetary medium and solar wind velocity can also be deduced from the scintillation of the signal coming from astrophysical sources. Scintillations destroy the coherency of the radio emission, as seeing does for optical observations. This is very critical for topics that require very accurate measurements like the Epoch of Reionization, dark ages etc. Correcting to get these signal provide by-products on the density fluctuations along the line of sight. Knowledge on the density fluctuation is mandatory to estimate their role in the scattering of waves (like Type II and III) and correctly interpret the data (source size, directivity of the electron beams). Few estimations of the power spectrum of the density fluctuations in the solar wind are available in the literature (e.g. [4, 34,8]). Regarding velocity, this parameter is of course fundamental to be able to forecast the time of arrival of a CME at Earth (or any other planet). The time variability of these fluctuations is also crucial to follow on long-term basis (several solar cycles). Ground-based radio instruments provide such a capability, combining observations over a broad range of wavelengths or simultaneous observations of a same radio source from different observatories. Thus, [73] provided a 3D reconstruction of interplanetary observed scintillations. If the time resolution is still not compatible with space weather forecast, this approach enables studies on the kinematics of CMEs. Different strategies must be adapted to used IPS to deduce the proprieties of the interplanetary medium: [43, 27] performed measurements with MWA, [14] with LOFAR (for ionospheric studies).

Finally, in the frame of space weather, the real-time knowledge of the interplanetary magnetic field in the vicinity of the Earth is crucial. In particular (but not only) the B_z component will drive more or less intense disturbances in the Earth magnetosphere following its orientation. Faraday rotation of the background linearly polarized sources enable to deduce the magnetic field along the line-of-sight. Multi-sources, simultaneous observations put a large number of constraints that enable to infer informations on the direction of the interplanetary magnetic field. For recent works using Faraday rotation to deduce some proprieties of the interplanetary density and magnetic field see [22] (through LWA measurements), [30] (through VLA measurements).

3.5. *Interstellar and interplanetary dust in the heliosphere*

From the STEREO mission new white light observations with STEREO/SECCHI could be analyzed to track the the evolution of the symmetry axis of the F-corona between 2007 and 2012 for elongations from 4 degree to 24 degree indicating that the zodiacal dust cloud exhibits a warped plane of symmetry, with an estimated center of symmetry at about 0.5 $R_\odot$ from the Sun center on the side of the heliosphere containing Jupiter [51]. The dust deposition of Kreutz Sun-grazing comets can possibly influence the dust cloud that is observed in the whitelight, this effect is however small. It has been found before that nanometer-sized grains (nanodust) is strongly affected by electromagnetic forces. A study of nanodust trajectories during CME shows that about a third of the nanodust can reach very high speeds (up to 1000 km/s) during a CME [11]. For analysing measurements of nanodust with instruments from spacecraft several studies were carried out to better understand the observations [38, 39, 31].

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