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COMMISSION E3 — SOLAR IMPACT THROUGHOUT THE HELIOSPHERE

Impact solaire dans l'héliosphère

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TRIENNIAL REPORT 2018-2021

1. Introduction

The IAU Commission E3 "Solar Impact through the Heliosphere" covers observational and theoretical aspects of the impacts of solar variability on the heliosphere, on the planetary magnetospheres and/or atmospheres as well as on the boundaries of the heliosphere with the interstellar medium. The primary goals are to investigate and understand the solar wind variability and its effect on the Earth (space weather), other planets and the boundaries of the heliosphere as well as the conditions under which energetic particles from the Sun and charged cosmic dust fill the heliosphere. Solar variability may occur on timescales of hours and days of the solar activity cycle and even on the lifetime of the Sun and the impact of this variability at different time scales controls space weather and space climate effects. Space weather activities have gained global visibility in the recent years and the topic has extended these recent years from fundamental research to applied research.

Key research topics for commission E3 are listed below:

1. Solar wind and its variability
2. Plasma and magnetic disturbances in the solar wind (magnetic clouds, Interplanetary shocks and coronal mass ejections)
3. Solar energetic particles in the inner heliosphere : their sources and propagation
4. Solar wind interaction with planets ; Space Weather
5. Extreme solar events and their influence on Earth and planets
6. Solar forcing on the heliosphere after the end of the Grand Solar Maximum
7. Multi-point observations in the inner heliosphere
8. Outer regions of the heliosphere and boundaries with the interstellar medium
9. Coordination between in-situ and remote-sensing observations (space and ground-based)

This range of scientific topics is particularly timely with the arrival of new data from a fleet of new spacecraft flying in the inner heliosphere (Parker Solar Probe, Solar Orbiter, Bepi Colombo). Synergies between multi-point in situ observations with these missions and previously launched missions (STEREO, WIND,. . .) and remote sensing observations from space missions (SDO, STEREO, Solar Orbiter, Hinode,. . .) and ground-based instruments should be strongly encouraged in the coming period. Future space missions dedicated to solar and heliospheric studies should be launched in the near future by India (Aditya) and China (ASO-S), U.S. (PUNCH) and Japan (SOLAR-C-EUVST). Finally, NASA's Interstellar Mapping and Acceleration Probe (IMAP) looking outwards to observe the interaction of the solar wind with the interstellar medium should be launched in 2024.

During the past three years, ground-based radio observations from non-solar dedicated instruments have been largely used by the community to contribute to studies of the impact of solar activity on the heliosphere (Atacama Large millimeter/submillimetter array ALMA, the low Frequency Analyzer and Recorder (LOFAR) and Murchison Widefield Array (MWA). Together with the new observations from the Expanded Owens Valley Solar Array, these instruments pave the way for the use of observations from the future Square Kilometer Array (SKA) Observatory.The emerging field of space weather research will further develop in the coming years. The study of the influence of the recently discovered extreme solar events is a fast-evolving field of research which should be further developed. With the beginning of the new solar cycle which is largelly predicted to be moderate, there is a further possibility to study and understand the solar forcing on the heliosphere in the case of a moderate level of solar activity.

2. Scientific activities end developments in the last 3 years

We present here a selection of a few advances achieved in the field in the last three years.

2.1. *Coronal/Heliospheric Physics and Space Weather with ground-based radio observatories*

In the last 3 years, ground based radio observations from non-solar dedicated instruments have led to many studies and results in the field of coronal and heliospheric physics.

At low frequencies, both LOFAR and MWA have started to be largely used by the heliospheric community. Brand-new results have been obtained with these instruments on the different radio emissions produced in the solar corona during flares and CMEs. Radio emissions produced by the propagation of electron beams (type III bursts) in the solar corona were used on one hand to deduce characteristics of the electron beams and of the density in the structures in which electrons propagate (Mann et al 2018; McCauley et al 2018; Reid 2020; Zhang et al 2020).Through the analysis of spectral fine structures and of their spatial evolution, new results were obtained on the scattering of the emission in the corona leading to new investigation of the turbulent nature of the corona (Chen et al 2018; Kuznetsov and Kontar 2019). Weak non-thermal radio emissions linked to nanoflare coronal heating theories have been analysed using MWA high sensitivity observations(Sharma et al 2018). Radio emissions associated with the propagation of shocks in the corona (type II bursts) were analysed together with EUV and white-light observations of Coronal Mass Ejections (CMEs) to track not only the propagation of shocks but also the conditions of CME-shock related particle acceleration(Chrysaphi et al 2018; Magdalenić et al 2020; Maguire et al 2021). A rare spatially resolved diagnostic of a CME magnetic field could also be achieved with MWA observations(Mondal et al 2020). Observations of the scintillation of the radio signal from pulsars with LOFAR have been used to derive properties of the solar wind (Tiburzi et al 2021). Finally, LOFAR observations allow also to infer characteristics of the ionospheric scintillations(Fallows et al 2020). These new studies demonstrate the larger use of LOFAR and MWA by the solar and heliospheric community. To go further and use e.g. LOFAR as a space-weather dedicated facility would require sone upgrade of the system. This is the motivation behind the LOFAR4SW projet of the EU which aims at designing a system upgrade such that the instrument can perform space weather observations (solar,heliospheric and ionospheric) (Carley et al 2020a). The ultimate goal will be to have a large-scale research facility in which completely simultaneous and independent observing modes provide continuous access to two research communities: radio astronomy and space weather research.

The Square Kilometer Array (SKA) Observatory was launched in February 2021. As for LOFAR, MWA, JVLA, the solar and heliospheric communities should take the new opportinities offered by SKA in terms of spatial, spectral, and temporal resolution and sensitivity to obtain major new insights in solar and heliospheric physics (e.g.Nindos et al 2019).

The scientific solar observations with the Atacama Large Millimeter/submillimeter Array (ALMA) started in December 2016. Due to the difficulty of the image synthesis, the achievements from the ALMA solar data had not appeared soon after the observations. However, many papers that are written based on the data obtained with ALMA are published in these three years. Since we can receive the millimeter/submillimeter-waves that propagate from the lower-middle chromospheres, and its images show us the thermal structures in the layers. The comparison studies between ALMA data and radiative MHD simulations are done actively for understanding the chromosphere, which is the root of the solar wind(Wedemeyer et al 2020; Eklund et al 2020; Martínez-Sykora et al 2020; Chintzoglou et al 2021)

In parallel to the use of observations from new radio telescopes developed for general astronomical use, recent advances in dedicated solar radio instrumentation have been performed to obtain observations with a broader frequency coverage with high spatial, spectral, and temporal resolution (Expanded Owens Valley Solar Array (EOVSA), Siberian Radio Heliograph (SRH), Mingantu Ultrawide Spectral Radioheliograph (MUSER). Such a progress in solar and heliospheric radio astronomy has led to the recent publication of research and review papers in a special issue of Frontiers in Astronomy and Space Sciences dedicated to Solar and Space Weather Radio Physics (Nindos 2020; Carley et al 2020b; Alissandrakis 2020; Reid 2020; Loukitcheva 2020; Vourlidas et al 2020; Kuroda et al 2020; Yan et al 2021; Klein 2021a,b).

2.2. *Missions to the Sun*

New solar and heliospheric missions have been launched in the last 3 years. The NASA mission Parker Solar Probe (PSP) was successfully launched in August 2018 and has already achieved 7 perihelia close to the Sun. This mission carries a set of in-situ instruments allowing to measure, close to the Sun, the parameters of the solar wind, the magnetic field, plasma waves and radio electromagnetic radiation, energetic particles, as well as an heliospheric imager. Already during the first perihelii, PSP returned a large amount of science data that led to a new picture of the source region of the solar wind. The first results were presented in Nature (2019)(Bale et al 2019; Howard et al 2019; Kasper et al 2019; McComas et al 2019) and a Special issue of the Astrophysical Journal Supplement Series was published in 2020 (https://iopscience.iop.org/journal/0067-0049/page/Early Results from Parker Solar Probe) with more than 50 science papers that provide more detailed results from the first two orbits. One of the surprising results is the existence of hundreds to a thousand intermittent reversals of the magnetic field accompanied by increases in the speed of the solar wind and reversal of the pitch angle of the suprathermal electron strahl indicating a kink of the magnetic field (switch-backs, jets, or spikes). A lot of papers have been published on their properties as well as on their origin and generation mechanisms. Plasma waves and micro-instabilities have been observed very close to the Sun leading to exceptional detections of electrostatic and electromagnetic waves, electron holes, reconnection in current sheets, and type III radio bursts. The evolution of plasma turbulence between 0.17 and 1 AU has also been studied. A great number of small energetic particle events, small coronal mass ejections has been observed despite the fact that the first orbits were performed close to the solar minimum. Small plasma structures ejected from the Sun could be seen with the heliospheric imager on the PSP, as well as magnetic islands resulting from tearing-mode instability in the current sheet.

The ESA/NASA mission Solar Orbiter launched in February 2020 is the first mission combining in-situ and remote sensing observations of solar and heliospheric plasma together with an out of the ecliptic view of the phenomena at the end of the mission. A special issue of Astronomy and Astrophysics is in preparation to present the first results of the mission. Some of the new results are: observations of small impulsive energetic particle events within 1 AU despite the minimum phase of the solar cycle, radial dependence of CIR-associated suprathermal ions in the inner heliosphere(Mason, G. M. et al 2020, 2021; Gomez-Herrero, R. et al 2021; Allen, R. C. et al 2020)

2.3. *Advanced studies of extreme solar events*

An impressive progress has been achieved in studies of extreme solar events which form a severe hazard for the modern technological society. All severe solar energetic particle (SEP) events detected on Earth (ground-level enhancement, GLE) have been re-analyzed using a revised response function and an improved analysis method (e.g., Koldobskiy, S. et al 2021), making basis for a more precise analysis of such SEP events. The accuracy and reliability of reconstructions of the extreme SEP events for the past millennia has been greatly improved using terrestrial proxy data such as cosmogenic isotopes. The current state of the art has been summarized in a collective book by Miyake et al (2019) and further developed by an ISSI international team. Three extreme SEP events are known in the past: at 774 AD, 993 AD and 660 BC (Miyake et al 2012; Miyake et al 2013; O'Hare et al 2019), and two candidate events in 1052 and 1279 AD are still awaiting for confirmation (Brehm et al 2021). All these events are a factor $20-100$ stronger than the strongest SEP event (23-Feb-1956) recorded during the instrumental era.

Another method to estimate the occurrence rate and severity of extreme SEP events is based on a projection of the statistic of super-flares recorded by the Kepler telescope on a large ensemble of sun-like stars (e.g., Notsu et al 2019). This statistic suggests an order-of-magnitude higher probabilities of super-flare occurrence on the Sun than that evaluated from the terrestrial solar proxies.

Thus, although the very fact of the super-flares (a factor of 100 or more stronger than those directly observed during the instrumental era) on the Sun is beyond any doubts, the exact occurrence probability and the severity of such events are not precisely known and need to be clarified in the future.

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The potential environmental impacts associated with solar powerâ€"land use and habitat loss, water use, and the use of hazardous materials in manufacturingâ€"can vary greatly depending on the technology, which includes two broad categories: photovoltaic (PV) solar cells or concentrating solar thermal plants (CSP). The scale of the systemâ€"ranging from small, distributed rooftop PV arrays to large utility-scale PV and CSP projectsâ€"also plays a significant role in the level of environmental impact. Land use. Land use. Depending on their location, larger utility-scale solar facilities can raise concer...Â CSP plants with once-through cooling technology have higher levels of water withdrawal, but lower total water consumption (because water is not lost as steam). Outside the heliosphere, this solar plasma gives way to the interstellar plasma permeating the Milky Way galaxy. Radiation levels inside and outside the heliosphere differ; in particular, galactic cosmic rays are less abundant inside the heliosphere, so that the planets inside (including Earth) are partly shielded from their impact.Â The heliosphere is the area under the influence of the Sun; the two major components to determining its edge are the heliospheric magnetic field and the solar wind from the Sun.Â Extending throughout the heliosphere, the heliospheric current sheet could be considered the largest structure in the Solar System and is said to resemble a "ballerina's skirt".[26]. Outer structure[edit]. Solar wind and heliosphere; Impact of solar wind, structures and radiation on and within terrestrial and planetary environments (including magnetospheres, ionospheres and atmospheres); Long-term trends and predictions for space weather; Challenges and strategy plans for Earth and the heliosphere; Forecasting models; Space weather monitoring, instrumentation, data and services. The Symposium aims to further knowledge on space weather by linking various aspects of research in solar, heliospheric and planetary physics, and by putting great emphasis on cross-disciplinary developments, merging diff

The potential environmental impacts associated with solar powerâ€"land use and habitat loss, water use, and the use of hazardous materials in manufacturingâ€"can vary greatly depending on the technology, which includes two broad categories: photovoltaic (PV) solar cells or concentrating solar thermal plants (CSP). The scale of the systemâ€"ranging from small, distributed rooftop PV arrays to large utility-scale PV and CSP projectsâ€"also plays a significant role in the level of environmental impact. Land use. Land use. Depending on their location, larger utility-scale solar facilities can raise concerns about land degradation and habitat loss.Â CSP plants with once-through cooling technology have higher levels of water withdrawal, but lower total water consumption (because water is not lost as steam). 4 Solar superstorms 4.1 Outline description 4.2 The history of large solar storms and their impact 4.3 Quantifying the geophysical impact 4.4 The environmental chronology of a superstorm 4.5 Probability of a superstorm 4.6 Solar Superstorm environment â€" summary and recommendations. 5 Impacts on the electrical power grid 5.1 Introduction 5.2 Consequences of an extreme event on the UK grid 5.3 Mitigation 5.4 National electricity grid â€" summary and recommendations. 16 10 Impacts on GPS, Galileo and other GNSS positioning, 16 navigation and timing (PNT) systems 17 10.1 Introduction 18 10.2 GNSS fo... 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 energetic particles that are present in the heliosphere. Interactions at the heliospheric boundaries are also influenced by the changing conditions of the interstellar medium surrounding the Sun, in turn influencing particle components at the high end of the energy spectrum, galactic and anomalous cosmic rays.Â Commission E3 addresses these topics in view of recent observational results and ongoing observations, present top-level science questions and matters that will benefit from coordination in the community. The Current Top Level Science Questions The solar disturbances provide large-scale laboratory to study plasma processes over various time and spatial scales, the highest spatial scale being the size of the heliosphere itself (~100 AU). These solar disturbances are related to solar activity in the form of active regions and coronal holes. Solar eruptions are accompanied by particle acceleration and the particles can be hazardous to life on earth in various ways from modifying the ionosphere to damaging space technology and increasing lifetime radiation dosage to astronauts and airplane crew. Particle acceleration in solar eruptions poses fundamental physics questions because the underlying mechanisms are not fully understood. What to expect in a Grand Solar Minimum. How does an increase in galactic cosmic rays affect the Earthâ€™s climate and also tectonic activity? Here is a simplified description of the basic mechanism: A solar maximum is the period within the 11-year solar cycle of high solar magnetic field and high sunspot count. Sunspots areâ€¦Â Much of the galactic cosmic ray flux is blocked from entering the heliosphere of the solar system. Also, more of the electromagnetic radiation such as Gamma- and X-rays from space are blocked from entering the inner solar system.Â â€œQuantifying the impact of solar activity on climate from observations is found to be 5-7 times larger than from solar irradiance, and agrees with empirical variations in cosmic rays and clouds.â€