DIVISION E
COMMISSION 49

INTERPLANETARY PLASMA AND HELIOSPHERE
PLASMA INTERPLANÉTAIRE ET HÉLIOSPHÈRE

PRESIDENT	**Ingrid Mann**
VICE-PRESIDENT	**P. K. Manoharan**
PAST PRESIDENT	**Natchimuthuk Gopalswamy**
ORGANIZING COMMITTEE	**Carine Briand, Igor V. Chashei Sarah E. Gibson, David Lario, Yoichiro Hanaoka, Olga Malandraki**
OTHER CONTRIBUTORS	**Eduard Kontar, John D. Richardson**

Abstract. After a little more than forty years of work related to the interplanetary plasma and the heliosphere the IAU's Commission 49 was formally discontinued in 2015. The commission started its work when the first spacecraft were launched to measure the solar wind in–situ away from Earth orbit, both inward and outward from 1 AU. It now hands over its activities to a new commission during an era of space research when Voyager 1 measures in–situ the parameters of the local interstellar medium at the edge of the heliosphere. The commission will be succeeded by C.E3 with a similar area of responsibility but with more focused specific tasks that the community intends to address during the coming several years. This report includes a short description of the motivation for this commission and of the historical context. It then describes work from 2012 to 2015 during the present solar cycle 24 that has been the weakest in the space era so far. It gave rise to a large number of studies on solar energetic particles and cosmic rays. Other studies addressed e.g. the variation of the solar wind structure and energetic particle fluxes on long time scales, the detection of dust in the solar wind and the Voyager measurements at the edge of the heliosphere. The research is based on measurements from spacecraft that are at present operational and motivated by the upcoming Solar Probe + and Solar Orbiter missions to explore the vicinity of the Sun. We also report here the progress on new and planned radio instruments and their importance for heliospheric studies. Contributors to this report are Carine Briand, Yoichiro Hanaoka, Eduard Kontar, David Lario, Ingrid Mann, John D. Richardson.

1. Introduction

The Commission 49 deals with the interplanetary plasma and the heliosphere including all its constituents. While always devoted to this overall theme, the focus of work within the commission shifted during the years and C49 now transitions into C.E3. We therefore take the opportunity to start this report by shortly describing the history of the commission and its evolving theme. As customary in these reports, we highlight some of the research topics that have seen particular interest over the most recent triennium. The

reported progress from 2012-2015 is stimulated by space measurements and other near observations, and is naturally influenced by discussions in the commission and impressions of the OC members of C49. We describe new developments with regard to space missions and radio instrumentation and finally provide an outlook to the work of the future Commission C.E3.

2. Historical context of Commission 49

The entire solar system is influenced by plasma, particle and radiation disturbances launched by the Sun, and their consequences throughout the heliosphere, the region of space around the Sun dominated by the solar wind. The impacts of the Sun range from the Sun - Earth relevant processes on time scales of hours and days, to the solar cycle, to the lifetime of the Sun. The heliosphere includes also the orbits of planets, small solar system objects and interplanetary dust that orbit the Sun as well as dust and gas that approach the Sun from the nearby interstellar medium. The Sun influences all these constituents of the heliosphere and also the extension of the heliosphere and the physical process at the boundaries of the heliosphere. The boundaries 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. The solar and heliospheric variability shapes the boundaries of planets and solar system objects to the interplanetary medium, i.e. to the solar wind and its other constituents. Understanding the physics of interplanetary and coronal plasmas is also seen as an important step toward understanding astrophysical plasmas in general. The research on this topic started based on observational results and in many cases developed from the studies of the Sun and the solar corona.

Commissions that focused on studies of the Sun were part of the International Astronomical Union, IAU, since it was founded in 1919 and Karel Schrijver and colleagues describe the early development of those commissions in the report of Commission 10 ("Solar Activity") in this issue. Starting with initially one commission on "Solar Radiation", the solar physics was addressed in several different commissions related to topics like: sunspots and sunspot numbers, photospheric phenomena, the solar atmosphere, solar eclipses, solar rotation, solar spectroscopy and solar activity. It was almost half a century after the IAU was founded that the space directly surrounding the Sun came increasingly into reach of observations and the terms heliosphere was coined. During the 1970's space missions and other advanced observations enabled more detailed studies of the solar corona and the interplanetary medium inside Earth orbit and space missions to the outer system were launched. The understanding of the solar wind developed and researchersaddressed topics of the distant solar wind and its transitions to the local interstellar medium. As a result the community initiated a new commission on heliospheric studies within the IAU.

The Commission 49 was founded during the 1972 General Assembly of the IAU. Ian Axford, first Commission President summarized in the first triennial report that the commission was set up *to study the following problems*:

• the region where the solar wind joins the sun (i.e. the solar corona and chromosphere interface);

• the zodiacal light as it pertains to the solar wind;

Table 1. Overview of Commission 49 presidents and triennial reports (as available in ADS) from 1972 onward. Reports flagged with an asterisk appear not to be available on line.

Years	President and Vice President	ADS bibcode
1973-1976	Axford, I. W., Hewish, A.	1976IAUTA..16a..175A
1976-1979	Hewish, A., Fahr, H. J.	1979IAUTA..17a..199H
1979-1982	Fahr, H. J., Roxburgh, I. W.	1982IAUTA..18..651F
1982-1985	Roxburgh, I. W., Grzedzielski, S.	1985IAUTA..19..697R
1985-1988	Grzedzielski, S., Burlaga, L.	1988IAUTA..20..677G
1988-1991	Burlaga, L., Buti, B.	1991IAUTA..21..581B
1991-1994	Buti, B., Ripken, H.	*1994IAUTA..22..565B
1994-1997	Ripken, H., Verheest, F.	*1997IAUTA..23..165R
1997-2000	Verheest, F. Vandas, M.	*
2000-2003	Vandas, M., Webb, D. F.	*2003IAUTA..25..106V
2003-2006	Webb, D. F., Bourgeret, J. - L.,	2007IAUTA..26..103W
2006-2009	Bourgeret, J. - L., von Steiger, R.	2009IAUTA..27..124B
2009-2012	Gopalswamy, N. , Mann, I.	2012IAUTA..28...95G
2012-2015	Mann, I., Manoharan, P. K.	*(this report)*

- radio observations of the solar wind and the outer corona (especially interplanetary scintillations);
- the heliosphere and interactions of the solar wind with the interstellar medium;
- direct observations of the solar wind as far as they pertain to the above and to questions of an astrophysical nature (especially the composition of the sun, mass, and angular momentum loss from stars, etc).

While the name and overall theme of the commission remained for more than forty years, looking back to the triennial reports (listed in Table 1) shows that different aspects of this overall theme were prominent during different years, like neutral gas in the heliosphere and interstellar neutrals, solar wind composition and minor ions and pick-up ions in the solar wind, solar wind interacting with planets and comets, to name but some. The commission had from its beginning a strong link to space instrumentation and the work within the commission was often influenced by the results of the most recent space missions. Its first report, for instance, describes Pioneers 10 and 11 expanding the solar wind measurements outward to 5 AU and Mariner 10 and Helios expanding them inward to 0.3 AU. The present last report of Commission 49 covers the time span when Voyager 1 measured at 123 AU conditions that many researchers ascribe to the heliopause suggesting that the spacecraft now is in the local interstellar medium. As described below in this report in a short text on the outer heliosphere, Voyager 1 crossed this boundary of the heliosphere in August 2012, which is 40 years after the scientific community formed Commission 49.

The astrophysical interest in the heliospheric physics is motivated by the goal to understand basic plasma physical processes, but heliospheric physics also has a strong link to studies of the magnetosphere and ionosphere of the Earth. Already in the first commission report Joseph Holweg pointed out that "... *it may for some purpose be useful to develop a capability for predicting, from solar observations, the state of the solar wind at the earth (...), and such a predictive capability will require a more advanced theoretical understanding of solar wind physics than is available at present*".

Understanding ionospheric disturbances caused by solar and heliospheric phenomena is more and more topic of research activities to predict possible effects on Earth, as for instance on communication systems. These activities are often summarized as space

weather research. This research related to space weather covers several different disciplines including the heliophysics and it is addressed by several overlapping research communities, including geophysicist, space researchers and astronomers. The previous triennial report of Commission 49 also addressed the outcome and continuation of global activities that started during the International Heliophysical Year 2007-2008 an UN–sponsored scientifically driven international program of scientific collaboration.

The presidents and vice-presidents of the previous Commission 49 are listed in Table 1 above. To address in heliospheric research the fundamental astrophysical questions while at the same time responding to application–oriented issues of the modern society poses a challenge for the coming years that the new commission will address.

3. Recent scientific achievements and developments

3.1. *Solar Cycle 24*

Solar Cycle 24 has been the weakest in the space era as measured by both the sunspot number (SSN) and the total solar output in the form of solar wind speed, density, temperature, pressure and magnetic field magnitude (McComas *et al.* (2013)). The number of >10 MeV proton events in solar cycle 24 has decreased with respect to the prior solar cycle (Mewaldt *et al.* (2015)). However, the occurrence rates of >10 MeV proton events normalized to the SSN are reasonably similar during the rising phases of solar cycles 23 and 24 (Gopalswamy *et al.* (2015)). The big contrast is at higher energies, with only two Ground Level Enhancement (GLE) events being observed so far in solar cycle 24 on 2012 May 17 (Gopalswamy *et al.* (2013)) and 2014 January 6 (Thakur *et al.* (2014)) that contrast with the sixteen GLEs observed in solar cycle 23. The fluences of >10 MeV/nuc ions from H to Fe are reduced by factors ranging from ∼4 to ∼10 with respect to last solar cycle (Mewaldt *et al.* (2015)). The speed distributions of CMEs associated with SEPs are quite similar in the two cycles with little difference in the mean and median speeds. However, the fraction of halo CMEs is 97% in cycle 24 compared to 75% in cycle 23. It has been suggested that the weakened heliospheric magnetic field observed in solar cycle 24 reduces the efficiency of particle acceleration leading to the lack of high-energy SEP events (Gopalswamy *et al.* (2014)). Gopalswamy *et al.* (2015) conclude that the CME speed, connectivity of CME nose to Earth, and favorable ambient medium are the key factors that determine whether a SEP event has a GLE component. On the other hand, the conditions of the interplanetary medium during the development of a SEP event play also a role in the observations of elevated SEP intensities (e.g., Lario *et al.* (2013b), Lario & Karelitz(2014)).

The 2009 solar-minimum period was characterized by a record-setting high Galactic cosmic-ray (GCR) flux observed at Earth. This, along with the unexpected low heliospheric magnetic-field magnitude, caused this period to be characterized as unusual compared with previous minimum epochs. Using solar-activity proxies and corresponding cosmic-ray observations for the past five solar cycles together with numerical modulation models, Strauss & Potgieter (2014) predicted that the GCR proton spectrum will be even higher during the coming A>0 solar-minimum period.

3.2. *Interplanetary scintillation and radio spectro-polarimeter observations*

Interplanetary scintillation (IPS) observations at 327 MHz have been carried out regularly using the multi-station system of the Solar-Terrestrial Environment Laboratory (STEL) of Nagoya University to elucidate 3D structure of the solar wind and its time evolution (Tokumaru, 2013). The multi-station system was upgraded in the period between 2013 and 2014 to improve its sensitivity. STEL IPS observations made during 1985-2013, i.e.

over cycles 22-24, have revealed not only systematic change of the solar wind structure associated with the solar cycle, but also peculiar aspects of the recent solar wind such as pronounced increase of equatorial fast winds, global reduction of density fluctuations, enhanced North-South asymmetry, which are regarded as manifestations of the weak solar activity in Cycle 24 (Tokumaru *et al.* (2012a), Tokumaru *et al.*, 2015). They also have revealed a close relation between the solar wind speed and the coronal magnetic field property, which is consistent with the Alfven-wave-driven solar wind model of Fujiki *et al.* (2015) and propagation dynamics of CMEs in the interplanetary medium (Iju *et al.*, 2013, Iju *et al.*, 2014), and plasma distribution in the Comet ISON tail (Iju *et al.*, 2015). Many collaboration studies have been performed using STEL IPS observations. The global feature of the heliosphere was reconstructed from 3D MHD simulation using STEL IPS observations as a boundary condition (Fujiki *et al.* (2014)). In order to gain insight into the solar wind acceleration mechanism, IPS observations of X-band radio waves of planetary exploration spacecraft Akaktsuki have been performed during its solar occultation. As result, the solar wind speed is found to rapidly increases up to ≈ 400 km/sat distances between 5-20 Rs. In addition, strong low-frequency acoustic waves, which are regarded as a promising source for coronal heating, are detected at 5-10 Rs from Akaktsuki radio observations (Tokumaru *et al.* (2012b), Imamura *et al.* (2014), Miyamoto *et al.* (2014), Ando *et al.* (2015)).

Using the new radio spectro-polarimeter AMATERAS Iwai *et al.* (2012) investigated the relationship between recurrent CMEs and solar radio type-I bursts observed by AM-ATERAS and discussed the possibility to forecast recurrent CMEs. The high resolution observations revealed that the peak flux distribution of type-I bursts follows a power law with a spectral index between 4 and 5 (Iwai *et al.* (2014)). Iwai *et al.* (2013) investigated the fine spectral structures of solar radio type-I bursts observed by the solar radio telescope AMATERAS. This study found there were almost no correlations between the peak flux, duration, and bandwidth. On the other hand, there was a strong correlation between the growth rate and peak flux of the bursts. Kaneda *et al.* (2015) investigated the polarization characteristics of a zebra pattern in a type-IV solar radio burst observed with AMATERAS. Cross-correlation analysis determined that the left-handed circularly polarized component was delayed by 5070 ms relative to the right-handed component over the entire frequency range of the zebra pattern. Katoh *et al.* (2014) investigated the fine spectral structures included in a type IV burst observed by AMATERAS, and proposed a generation model that suggests wave-wave coupling between Langmuir waves and whistler-mode chorus emissions generated in a post-flare loop. This was inferred from the similarities in the plasma environments of a post-flare loop and the equatorial region of Earth's inner magnetosphere.

Regarding the solar coronal structures observed in the decameter range of the spectrum, Melnik *et al.* (2015) proposed a new interpretation of the positive time-frequency drifts often observed in Type III bursts. When electron beams escaping the Sun enter in a plasma region where the temperature is low enough, the group velocity of the Type III emission is lower than the electron beam velocity. As a result the time-frequency drift is positive even with a beam moving outward to the Sun. The difference of group velocity between fundamental and harmonic electromagnetic waves during U-bursts (a typical coronal radio emission with a reversing frequency), due this time to density differences in coronal loops, could explain the observed time delay between the two radiations (Dorovskyy *et al.* (2015)).

3.3. *Solar Energetic Particle observations*

The fleet of spacecraft distributed throughout the inner heliosphere during the rising phase of solar cycle 24 has allowed the study of solar energetic particle (SEP) events from multiple vantage points. Combined measurements from the two spacecraft of the Solar TErrestrial RElations Observatory (STEREO) and from near-Earth spacecraft have shown SEP events that extend over much larger ranges of longitude than previously estimated. In some cases, the longitudinal span of the events nears 360° allowing us to talk about circumsolar SEP events (e.g., Gómez-Herrero *et al.* (2015) and references therein). The use of multi-spacecraft observations has allowed us to determine the longitudinal dependence of SEP event characteristics (e.g., Lario *et al.* 2013; Richardson *et al.* 2014). For example, longitudinal distributions of SEP peak intensities have been expressed as Gaussians, with peak intensities that fall off with longitude with $\sigma \sim 40\text{-}50°$. On the other hand, studies addressing the longitudinal dependence of elemental composition abundances in SEP events simultaneously observed at different longitudes are inconclusive (e.g., Cohen *et al.* 2013, 2014).

Mechanisms proposed to explain the wide longitudinal spread of SEP events have been summarized in several papers (e.g. Wiedenbeck *et al.* (2013), Lario *et al.* (2014), Richardson *et al.* (2014), Gómez-Herrero *et al.* (2015), and references therein). These include: (a) Acceleration at coronal and/or interplanetary shocks covering or propagating over a wide range of heliolongitudes; (b) Multiple particle injections from sympathetic solar eruptions occurring close in time but in different regions of the Sun; (c) Magnetic field configurations in either the corona and/or interplanetary (IP) medium that enable SEP transport to a broad range of longitudes, in particular to observers at nominally poorly connected longitudes; and (d) SEP transport processes in the corona and/or interplanetary space, including coronal diffusion, cross-field diffusion in the interplanetary magnetic field (IMF) and corotation of flux tubes filled with SEPs.

Particle acceleration by CME-driven shocks covering or propagating over large longitudinal distances facilitates the injection of SEPs over a broad range of longitudes. Several works have related wave-like large-scale disturbances propagating over the solar disk seen in extreme ultraviolet observations (usually referred to as EIT or EUV waves) with coronal shocks able to inject SEPs over a broad range of longitudes (e.g., Rouillard *et al.* (2012), Park *et al.* (2013), Park *et al.* (2015), Miteva *et al.* (2014), and references therein). For example, Park *et al.* (2013) hypothesized that EIT waves can be used to track the expansion of a coronal shock responsible for particle acceleration and injection at the footpoints of the interplanetary magnetic field (IMF) lines connecting to several spacecraft. However, other authors concluded that the propagation of the EUV waves close to the solar surface could not be used as a proxy for the expansion of the coronal source of SEPs since the EUV waves have not been always observed to reach the magnetic footpoints of spacecraft detecting SEPs (Prise *et al.* (2014), Lario *et al.* (2014), and references therein). The conclusion drawn by Prise *et al.* (2014) and Lario *et al.* (2014) was that the factor that determines the longitudinal expansion of the SEP events is the shock wave associated with the CME in the extended corona, rather than the EUV wave at the coronal base.

A particularly useful class of SEP events for studying the role that interplanetary particle transport plays in the longitudinal spread of SEPs are the events associated with impulsive solar flares. It is thought that such events are well represented as an impulsive release of energetic particles from a compact source at (or close to) the site of solar flares. Such events are typically identified by anomalously enrichments of ^{3}He and heavy ion intensities as well as short lived intensity-time profiles. It was thought

that the observation of these events required a good magnetic connection with the flare site. In fact, Reames(1999) reported an approximately Gaussian distribution over the nominal well-connected longitudes with a narrow standard deviation in the range 15°-20°. However, recent multi-spacecraft studies have shown that some ^{3}He-rich events can be observed over very wide longitudinal ranges (e.g., Wiedenbeck *et al.* (2013), Nitta *et al.* (2015)), their origin is sometimes associated with eruptions and motions of coronal material at larger scales than the previously identified small jets, and a single active region can produce events seemingly continuously over a couple of weeks or longer (e.g., Bučík *et al.* (2014), Nitta *et al.* (2015), Chen *et al.* (2015)).

3.4. *Modeling Solar Energetic Particle events*

Modeling efforts have attempted to reproduce multi-spacecraft SEP observations by either including particle acceleration at broad interplanetary shocks (e.g., Rouillard *et al.* (2011), Verkhoglyadova *et al.* (2012), Pomoell *et al.* (2015), and references therein), and/or spatial diffusion of particles across the magnetic field (e.g., Giacalone & Jokipii(2012), Dresing *et al.* (2012), Dröge *et al.* (2014), Laitinen *et al.* (2013), Qin & Wang(2015), Strauss & Fichtner (2015), and references therein). Meandering of field lines due to plasma turbulence may also help to explain SEP events with extremely large longitudinal spans (Giacalone & Jokipii(2012), Laitinen *et al.* (2015)). Transport effects dependent on the charge-to-mass ratios of the energetic particles have also been included in SEP transport models to reproduce the evolution of the SEP abundances observed in the events (Mason *et al.* (2012)). The test for these models would be their ability to reproduce the observed onset time of the SEP events at well separated longitudes, the particle intensity-time profiles and compositional signatures observed throughout the events at different longitudes. The efforts in these coming years should lie in the characterization of the particle sources low in the corona where acceleration of particles at high energies is taking place. For example, combination of in-situ observations of SEP events with remote-sensing observations of solar eruptions has allowed us to determine that the acceleration and release of energetic particles can start at heights as low as ∼2 solar radii, whereas the magnetic connection between CME-driven shocks and spacecraft poorly connected to the site of the solar eruption may occur when the shocks are already at several solar radii above the solar surface (Lario *et al.* (2014), and references therein). The region between 1 and 10 solar radii remains extremely difficult to treat due to the complexity of the magnetic structure, the difficulty in understanding how CMEs are initiated, and how to treat the underlying particle acceleration. Theoretical estimates based on numerical MHD simulations and kinetic models (Kozarev *et al.* (2013)) demonstrate that understanding of particle acceleration and accurately describing the formation of CMEs in the low corona pose significant challenges. Ultraviolet observations from SOHO/UVCS and white-light images from coronagraphs have been used to extract the physical parameters of the shocks in the low corona (e.g. Bemporad *et al.* (2014)). Simulations and theories of particle acceleration have confirmed that the low corona is an environment that supports the conditions necessary for particle acceleration to high energies (Kozarev *et al.* (2011), Bacchini *et al.* (2015)). Several modeling efforts of particle acceleration at coronal shocks have been developed (e.g., Battarbee *et al.* (2013), Gargaté *et al.* (2014), Schwadron *et al.* (2015), and references therein).

3.5. *Cosmic ray, energetic particles and acceleration models*

Our knowledge of the unmodulated energy spectra of low-energy galactic cosmic rays increased markedly on 25 August 2012 when Voyager 1, then 122 AU from the Sun, entered a new region characterized by an increase in the magnitude of the magnetic field

and of the intensities of galactic cosmic ray ions and relativistic electrons, and by large reductions in the intensities of heliosheath ions and electrons and of anomalous cosmic ray ions (Webber & McDonald(2013), Krimigis *et al.* (2013), Stone *et al.* (2013), Burlaga *et al.* (2013a)). It is widely believed that around that time Voyager 1 crossed the heliopause, the boundary separating plasma of solar origin from that in the local interstellar medium (Webber & McDonald(2013), Gurnett *et al.* (2013)). However, this conclusion remains controversial (e.g., Fisk & Gloeckler(2014b)). The energy spectra in interstellar space of galactic cosmic ray hydrogen and helium ions with energies >3 MeV/nuc showed broad peaks in the energy range from about 10 to 30 MeV/nuc (Stone *et al.* (2013)). Pitch-angle distributions of galactic cosmic ray ions were not isotropic, but rather showed broad episodes of small anisotropies, with intensities depletions mainly for ions gyrating nearly perpendicular to the magnetic field, that were evidently associated with the passage of magnetic disturbances that originated at the Sun and propagated into the interstellar medium to at least 11 AU beyond the heliopause (Krimigis *et al.* (2013), Gurnett *et al.* (2015)).

It has been suggested that the suprathermal tails commonly observed in the energy spectra are the seed particle population for processes of particle acceleration at IP shocks. The continuous measurements of suprathermal populations with spectral tails close to v^{-5} (where v is the particle speed) have generated a broad range of theories and models (e.g., Fisk & Gloeckler(2012), Fisk & Gloeckler(2014a), Zhang & Lee(2013), Antecki *et al.* (2013), Lynn *et al.* (2013), Randol & Christian(2014), Jokipii & Lee(2010), Tessein *et al.* (2013), and references therein). Processes of particle acceleration associated with the presence of magnetic islands originated from dynamical processes of magnetic reconnection and turbulence in the solar wind have also been suggested as a source of ions in the keV–MeV range (Khabarova *et al.* (2015)). Local power-law solutions are predicted as a consequence of both the induced magnetic island electric field and island contraction, with power index that depends on the Alfvén Mach number and the ratio of the magnetic island contraction timescale to the particle diffusion timescale (Zank *et al.* (2014)).

3.6. *Energetic particles on long time scales*

Proxy data such as nitrate concentration in polar ice or records of cosmogenic radionuclides ^{10}Be measured in polar ice and ^{14}C measured in dendrochronologically dated tree rings are used to reconstruct the history of major SEP events in the past. Nitrate in polar ice was proposed to keep a record of major SEP events for several centuries (McCracken *et al.* (2001a), McCracken *et al.* (2001b)). However, this proxy has been disputed (Wolff *et al.* (2012)), so that nitrates may not serve as a quantitative index of SEP events. Data on ^{14}C allowed a reliable detection of a possible increase in cosmic rays in 775 AD and 993 AD that was ascribed to extreme SEP events (Miyake *et al.* (2012), Miyake *et al.* (2013), Usoskin *et al.* (2013), Jull *et al.* (2014)); however, its solar origin has also been disputed. Neuhaeuser & Neuhaeuser(2015) suggested that intense rapid ^{14}C increases in 770s AD can be explained by strong rapid decreases in solar activity and, hence, wind, so that the decrease in solar modulation potential leads to an increase in radioisotope production. Therefore, according to these last authors, large, short-term rises in ^{14}C do not need to be explained by highly unlikely solar super-flares nor other rare events, but by extra-solar cosmic rays modulated due to solar activity variations.

3.7. *Interstellar and interplanetary dust in the heliosphere*

One of the surprises mentioned in the previous triennial reports was the discovery of nanodust in the interplanetary medium. The nanodust originates most likely from the

inner heliosphere and reaches, near AU velocities of the same order as the solar wind velocity (Czechowski & Mann(2010), Czechowski & Mann(2012)). The acceleration bears some similarities to the ion pick–up process and a basic understanding of the nanodust dynamics in the solar wind and at the edge of the heliosphere can be obtained from applying the guiding center approximation (Mann *et al.* (2014)), while more detailed studies are in progress. In spite of the large velocity the nanodust momentum flux in the solar wind is small and for instance it does not influence the magnetosphere of the Earth (Mann & Hamrin(2013)). The interstellar dust measurements with the Ulysses spacecraft have been subject to a large number of publications and discussed in previous reports. Another analysis of the measurements between 1992 and 2007 has now been published in a series of papers again (Sterken *et al.* (2015), Strub *et al.* (2015), Krüger *et al.* (2015)). Recent model calculations show that interstellar dust trajectories at the edge of the heliosphere strongly depend on solar wind magnetic field polarity (Slavin *et al.* (2012), Mann *et al.* (2014)). During the last couple of years several instruments on spacecraft detected dust impacts with field measurements. The detections base on hypervelocity impacts producing local plasma clouds (Meyer-Vernet *et al.* (2015)). The WAVES radio instrument onboard the two STEREO spacecraft near 1 AU measured signals caused by dust impacting the spacecraft and an analysis of the 2007 to 2010 measurements provided flux measurements for the mass intervals $\sim 10^{-22} - 10^{-20}$ kg and $\sim 10^{-17} - 5 \times 10^{-16}$ kg (Zaslavsky *et al.* (2012)). The former mass interval corresponds to nanodust, the latter to larger dust. The detection of the smaller nanometric dust with STEREO was highly variable in time, different for the two spacecraft (Zaslavsky *et al.* (2012)) and for one spacecraft disappeared at a later stage of the mission and a better understanding of the nanodust measurements is expected after the recovery of the spacecraft in November 2015. A similar detection of nanodust in the solar wind was reported from Cassini, but in this case, to avoid instrumental effects the analysis could only cover short intervals along the Cassini orbit (Schippers *et al.* (2015)). Based on STEREO observations between 2007 and 2013, Le Chat *et al.* (2015) discuss the possible link of nanodust fluxes and coronal mass ejections. The flux of the larger dust agrees with measurements of other instruments on different spacecraft and one can distinguish in the data between interstellar and interplanetary dust components (Belheouane *et al.* (2012), Zaslavsky *et al.* (2012), Malaspina *et al.* (2015)). The WIND electric field measurements also were analyzed to derive information on hypervelocity dust impacts, the observed flux variation was found to be in good agreement with measurements from dust detectors, while the direction of the interstellar dust flux could not be directly compared and spacecraft orbits are hugely different (Wood *et al.* (2015)).

3.8. *The outer heliosphere and local interstellar medium*

Voyager 1 crossed a boundary in August 2012 at 123 AU where the galactic cosmic ray intensities increased, the heliosheath energetic particles disappeared, and the magnetic field magnitude increased (Stone *et al.* (2013), Krimigis *et al.* (2013), Burlaga *et al.* (2013a)). The magnetic field direction did not rotate across this boundary, but plasma wave observations show that plasma densities are 0.1/cc as expected in the local interstellar medium (LISM) increased (Gurnett *et al.* (2013)); this result indicates that the boundary was the heliopause and Voyager 1 is now in the LISM (although some disagree (Gloeckler & Fisk(2015)). The LISM is surprisingly dynamic, with shocks driven by solar wind transients, plasma wave and radio emissions, and associated cosmic ray changes in intensity and anisotropy increased (Burlaga & Ness(2014), Burlaga *et al.* (2013b), Gurnett *et al.* (2015), Liu *et al.* (2015)). Voyager 2 is still in the heliosheath and observes very different plasma flows and particle intensities than observed at Voyager 1; Voyager

1 observed a slowing of the plasma to zero and a fairly constant energetic electron flux in the heliosheath whereas Voyager 2 observes no slowdown in speed, a flow rotation to 60 from radial and order of magnitude changes in the energetic electrons intensities increased (Richardson & Decker(2014), Hill *et al.* (2014)). Based on observing features in polarized starlight that could possibly origin form the outer heliosheath of the heliosphere, ?frisch15) propose that interstellar dust grains are magnetic field aligned at the outer heliosphere.

4. Recent progress on space measurements and radio instruments

Many of studies of the interplanetary plasma and heliosphere are based on measurements from spacecraft and therefore the research follows to some extent the space programmes in different countries. Heliophysics studies have benefited from progresses in radio astronomy. Radio astronomy is a powerful tool to study the Sun, the heliosphere and the magnetosphere of the planets. Spanning over several orders of magnitude in frequencies (from hundred of GHz to a few Hz,) these emissions are produced either by thermal processes (like bremsstrahlung and thermal gyro-resonance emissions), non-thermal particles (like gyro-synchrotron) or plasma instabilities (leading to coherent emissions). This variety of mechanisms offer the possibilities to study many physical processes (particle acceleration, plasma emissions and instabilities, non collisional shocks, energy transfer, magnetic reconnection), and determine many physical parameters (density, temperature, particle beam velocities, magnitude of the coronal magnetic fields and their fluctuations). The range a few GHz to a few hundred of MHz gives access to processes and parameters of the low and high corona. The lower range of frequencies (below a few tens of MHz) concerns mostly the very high corona and interplanetary medium. The planetary magnetosphere are also strong radio transmitters, in particular the giant planets. Finally, radio emissions are necessary in the frame of space weather forecast as they usefully provide information on energetic particles before they arrive on the Earth environment. Due to the Earth ionospheric cut-off at 10MHz, only emissions above this value is accessible from ground based radio observatories. To follow CME or flaring activity of our star toward the interplanetary medium, or study the space environments of the planets, space instruments have been launched since many years. We here summarize the development in both, the space measurements and the radio instruments.

4.1. *Ongoing and future space missions*

The period 2012-2015 has been rich of events for space missions dedicated to heliophysics. The Solar Dynamics Observatory (SDO) mission, Wind, ACE and SOHO, all described in previous reports, continued to provide information. The STEREO mission with two spacecraft orbiting the Sun faster (ahead) and slower (behind) than the Earth provided unprecedented views of coronal mass ejections until their orbits seen from Earth passed behind the Sun. STEREO A was recovered mid November 2015. Heliophysical studies benefit from WIND and ACE still being operational. WIND is the only L1-instrument that is still in operation to provide daily high spectral resolution, radio dynamic spectra of the solar emissions. After at present 18 years of operation, nothing is foreseen for the replacement of the instrument that provides data that can be considered fundamental in terms of Space Weather.

In this recent years, multiple efforts have been focused on the development of the future exciting new missions such as the ESA Solar Orbiter (Müller *et al.* (2013)) and the NASA Solar Probe Plus (Fox *et al.* (2015)) that will explore the inner heliosphere. Among their scientific objectives there is the study of the mechanisms that accelerate

and transport energetic particles and understand how solar eruptions produce energetic particle radiation that fills the heliosphere. The in–situ measurements will also allow to better address (McComas *et al.* (2007)) the basic questions of coronal heating and solar wind acceleration.

Also, regarding our closer environment, MMS (Magnetospheric Multi-Scale mission) has been successfully launched in March 2015. This ESA mission, specifically dedicated to the study of the magnetic reconnection and particle acceleration in the Earth's magnetosphere, will complete other two missions still in activity: Cluster and THEMIS. Farther away, Juno is approaching its final objective: the magnetosphere of Jupiter.

4.2. *Progress and development of radio instruments*

Below we discuss the new radio instrumentation facilities that are provided to the heliophysics community during the 2012-2015 period and the international projects in preparation. We do not discuss the many other radio instruments that have been already used earlier, e.g. UTR-2 in Ukraine, Nançay radio-telescopes in France, Nobeyama telescope in Japan, and VLA in the US.

4.2.1. *Long Wavelength Array*

The Long Wavelength Array provides high resolution images in the range 10-88MHz. Located in the New Mexico state of US (Taylor *et al.*, 2012). Plasma astrophysics and space science are one of the four key science drivers of the instrument. Its first station (LWA1) opened to the community in 2012.

4.2.2. *AMATERAS*

A new radio spectro-polarimeter for solar radio observation has been developed at Tohoku University and installed on the Iitate Planetary Radio Telescope (IPRT) at the Iitate observatory in Fukushima prefecture, Japan. This system, named AMATERAS (Assembly of Metric-band Aperture TElescope and Real-time Analysis System), performs observation in the frequency range between 150 and 500 MHz. This telescope composed of a 32 m mesh parabola antenna and digital spectrometer made by the FPGA. The time resolution of this telescope is 10 ms and a frequency resolution is 61 kHz. This high resolution spectral data have found various kinds of fine spectral structures of the metric solar radio bursts.

4.2.3. *LOFAR*

LOFAR (van Haarlem 2013) is a radio interferometer constructed in the Netherlands and across Europe. It covers the range 20-240MHz in the four Stokes parameters. Several observing modes are available in particular interferometric imaging and beam-formed mode to produce dynamic spectra. "Solar Physics and Space Weather studies is one of the key science project. In the last years the instruments has been used to study solar radio bursts (Morosan *et al.* (2014), Morosan *et al.* (2015)) and ionospheric scintillations observations for studies of the ionosphere (Fallows *et al.* (2014), Zakharenkova *et al.* (2013)) but also to derive the interplanetary density fluctuations. Note that a low-band extension of LOFAR (10-90MHz) in standalone mode is under development at the French Nancay radio-station. Named "NenuFAR", it will be able to provide unprecedented sensitive observation in beam-formed mode (Zarka *et al.*, 2012). In the future, imaging capabilities will be added to NenuFAR. The Swedish LOFAR station is also used for stand-alone observation, especially solar system observations and work on observational techniques (Carozzi(2015)). Sodankyl Geophysical Observatory installed a LOFAR array

in Northern Scandinavia (McKay-Bukowski *et al.* (2015)) where observing conditions prevent most astronomical observations and this is used for ionospheric studies.

4.2.4. *Murchinson Widefield Array*

Murchinson Widefield Array provides low frequency radio-telescope located in western Australia (Tingay *et al.*, 2013a, Tingay *et al.*, 2013b). Among the scientific cases "'solar imaging and characterization of the heliosphere and ionosphere via propagation effects on background radio source emission". From mid-2013, the MWA is available to the community. This instrument provides low frequency (30-300 MHz) images of the Sun (30.72 MHz bandwidth and spectral resolution of 10 kHz) at a cadence of 2 images per second with polarimetric information.

4.2.5. *EISCAT3D*

The EISCAT Scientific Association at present prepares the construction of a new high power large aperture radar, EISCAT3D for studies of the high–latitude ionosphere at a location within the auroral oval and at the edge of the stratospheric polar vortex (McCrea *et al.* (2015)). While the focus of the project lies in studies related to ionospheric processes and to the long-term variability in the atmosphere and global change, EISCAT3D will also offer improved measurement capabilities for observing e.g. interplanetary scintillation, small solar system objects and meteors. The future EISCAT3D will work at 233 MHz centre frequency and comprise a high –power phased–array transmitter and several phased–array receivers. The system will detect an estimated annual mean of about 190 000 meteor orbits per day in a specific mass and velocity range (Pellinen-Wannberg *et al.* (2015)) and among others permit estimating the amount of interstellar objects in the meteor size range based on their orbital parameters.

4.2.6. *SKA*

The development of Square Kilometer Array (SKA) (phase 1 since 2014) will provide new insights in many topics of fundamental importance (see, e.g. Dewdney *et al.* 2009), such as the physics of impulsive energy releases, magnetohydrodynamic oscillations and turbulence, the dynamics of post-eruptive processes, energetic particle acceleration, the structure of the solar wind and the development and evolution of solar wind transients at distances up to and beyond the orbit of the Earth. There is also a newly formed SKA Working Group on Solar and Heliospheric physics† works to optimise SKA (which is not only solar instrument) for solar and heliospheric studies.

5. Closing remarks: Trends in the research community and the new Commission C.E3

In October 2014, some of the members of Commission 49 together with other IAU members proposed a new commission within the Division II with the title: "Solar Impact throughout the Heliosphere: Space Weather, Space Climate and Physical Processes". This was approved and a new commission formed during the IAU XXIX General Assembly in Honolulu in August 2015.

The new Commission C.E3 is set up to deal with the heliosphere and the physical processes that the Sun causes throughout the heliosphere. The proposal to form the new commission describes the heliosphere as "t*he region of space dominated by Sun and its generated particles and fields, with its composition, links to the interstellar medium*

† http://astronomers.skatelescope.org/science-working-groups/solar-heliospheric-physics/

of the Galaxy, and impacts on the planets (including Earth) on all timescales", and continues that the time-varying Earth "*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*". While space weather addresses the immediate impact of its time-varying environment on Earth, the term space climate is used to denote address the longer-term variation of the heliosphere on time scales of solar cycles and beyond.

For the work during the coming years the new commission identified the following outstanding top-level science questions:

• How does the variable interplanetary medium containing solar wind, solar transients (i.e. CMEs) and their impacts, energetic particles and cosmic dust influence the Earth and the extension of the heliosphere?

• How does the recent exploration of the edges of the heliosphere with space mission influence our understanding of the heliosphere, its evolution in time and its influence on the Earth?

• How do small-scale processes shape the heliosphere on large scale?

• How do solar wind and other interplanetary medium components interact with planets and with other solar system objects?

To address these questions during the coming years the joint analysis and co-ordination of in-situ and remote sensing measurements will become increasingly important. And the combination of remote observations and in-situ measurements from spacecraft, in particular provides information on astrophysical processes that is complementary to the standard astronomical methods. It is recognized in the community that heliospheric studies would hugely benefit from the development of high-performance computing to span the multi-scale processes, and from open access to modeling data and tools.

Astronomers working on Heliophysics are also more and more confronted with the connection of their research to topics that are, aside from the progress in basic research also of direct relevance to topics that are important for the modern society. 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. Both fields are highly relevant for civilization on Earth, but also for astrophysical research, like on the evolution of habitable planets. The goal of the commission is to support researchers to organize, coordinate and carry out fundamental research on space weather and space climate and to point out its importance.

Finally the Space Weather topic bears the opportunity to demonstrate the importance of astronomical research for society and the IAU can provide an independent forum for discussion within the community. A number of new working groups are presently under discussion and interested researchers are invited to join the discussion on how to arrange the working groups and the work of the new commission in the coming years.

Acknowledgement

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