Experimental overview on Future Solar and Heliospheric research

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Solar and heliospheric cosmic rays provide a unique perspective in cosmic ray research: we can observe not only the particles, but also the properties of the plasmas in which the they are accelerated and propagate, using in situ and high-resolution remote sensing instruments. The heliospheric cosmic ray observations typically require space missions, which face stern competition against planetary and astrophysics missions, and it can take up to decades from the initial concept proposal until the actual observing of the cosmic rays can commence. Therefore it is important to have continuity in the cosmic ray mission timeline. In this overview, we review the current status and the future outlook in the experimental solar and heliospheric research. We find that the current status of the available cosmic ray observations is good, but that many of the spacecraft are near the end of their feasible mission life. We describe the three missions currently being prepared for launch, and discuss the future outlook of the solar and heliospheric cosmic ray missions.

I. INTRODUCTION

Cosmic rays originating in our heliospheric environment, and the galactic cosmic rays affected by the heliospheric plasma, are an interesting and cosmic ray population to study: We can observe not only the particles, but often also directly or indirectly the properties of the particle sources and the turbulent plasmas the particles propagate in. Thus, by studying the solar and heliospheric cosmic rays, we can improve our knowledge of the fundamental processes responsible for cosmic ray acceleration and transport in plasma environments in general. In this way, the heliosphere is our local laboratory for delving into the physics of the cosmic rays. The heliospheric cosmic ray research has also a practical application: the cosmic rays represent a Space Weather hazard to humans and technology at Earth and in space. For this reason, the cosmic ray research has also entered national and international awareness as significant risk for humans.

As any scientific research topic, the heliospheric cosmic ray research requires experiments to observe the particles. Due to the Earth’s magnetic field, large part of the energy range of interest for heliospheric particles precludes the use of instruments at the surface of the Earth, thus the research requires instrumentation that is attached to spacecraft. Therefore, the advance of the research area depends on the availability of current, and the outlook of the future scientific space missions, and the planned instrumentation.

The purpose of this overview is to outline the current status of the heliospheric cosmic ray instrumentation. We will first outline in Section II the main research topics in the heliospheric cosmic rays. We then will present the current status of the instrumentation in Section III, and discuss the future instrumentation in Section IV.

II. SOLAR AND HELIOSPHERIC COSMIC RAY POPULATIONS

The sources of the heliospheric cosmic rays observed in the heliosphere can be classified into three categories: the solar cosmic rays, or Solar Energetic Particles (SEPs); interplanetary cosmic rays; and particles originating from outside our heliosphere. A full review of these categories is beyond the scope of this overview, we will only briefly outline these categories below.

The SEPs originate at the Sun and its vicinity, related to the activity of the Sun, and are observed during and after violent magnetic eruptions at the Sun. The SEP signatures are seen indirectly in X-rays and gamma rays at the Sun, and as radio bursts in the corona and in the interplanetary space [e.g. 1]. The particles also escape from the Sun, and are observed with in situ instruments throughout the heliosphere, and, in the high-energy Ground Level Enhancement (GLE) events, also within the Earth’s atmosphere, by neutron monitors, at the surface of the Earth [2].

The SEPs have been considered to originate at two acceleration locations: solar flares, which can have field-aligned electric fields, strong turbulence and internal shock waves; and coronal and interplanetary shock waves that have been considered as blast waves and waves driven by the mass ejected during the eruption, the coronal mass ejection (CME) [3]. A two-class paradigm has been considered related to the two acceleration schemes, and the differences in particle abundances and flare and radio signatures in the so-called impulsive and gradual events [3]. In the classification, the impulsive events are rich in heavy ions, and the acceleration takes place in the narrow flare region, whereas the proton-rich gradual events are due to wide shock waves driven by the CMEs. Recently, the two-class paradigm has been challenged with evidence suggesting that the division to the two classes is not clear [4, 5]. In addition, the very wide SEP events analysed by multiple spacecraft show that the
heavy ions, traditionally related to impulsive events, can have a wide access to a wide longitudinal ranges [6, 7], which seems to contradict the idea of acceleration at small flare region. The questions around the two-class paradigm are currently unsolved, and subject of continuing research.

Particles are also accelerated in the interplanetary space, further away from Sun. Some coronal mass ejection driven shock waves are capable of accelerating particles as they propagate throughout the heliosphere [3]. Such CMEs offer a possibility to observe the acceleration region directly, in situ. Particle acceleration can also take place in the corotating interaction regions (CIRs), where fast solar wind stream overtakes a slower solar wind, which, in the Parker spiral geometry, results in an interaction region between the two solar wind streams [8]. At distances beyond 1 AU from the Sun, the boundaries of the interaction region form a pair of shocks, which can accelerate particles to MeV energies [3].

Planetary magnetospheres, and their bow shocks, are also capable of accelerating charged particles. While the planetary particle research is outside the scope of this overview, the particles escaping from the planetary acceleration processes into the interplanetary medium are of interest to the cosmic ray community. In particular, the Jovian electrons, accelerated at Jupiter [9], which represents a steady-state point source in the heliosphere, have been used to probe the models of cosmic ray propagation in the heliosphere [e.g. 10].

Particles are also accelerated at the outer boundaries of the heliosphere. The anomalous cosmic rays (ACR), first observed in 1973, are an anomalous component in the spectra of some heavy ion species, as observed during solar activity minima [11]. The ACR have been considered as pickup ions accelerated at the termination shock [12]. However, the recent observations by the Voyager spacecraft have cast doubt to this view [13].

Finally, the cosmic rays that originate outside our heliosphere are also important for the heliospheric cosmic ray research. The galactic cosmic rays are modulated by the interplanetary turbulence [e.g. 14, and references therein], which gives information on the properties of the interplanetary turbulence, the particle transport within the turbulence, and the source spectrum of the particles outside the heliosphere. The Voyager 1 is now measuring the interstellar spectrum [15], thus the modulated observations in the inner heliosphere can be used to improve our understanding of the state of the interplanetary turbulence, and the physics behind the particle transport in such turbulent fields.

III. CURRENT MISSIONS

In this section, we will investigate our current abilities to measure the cosmic ray fluxes at different energies to study the different heliospheric cosmic ray sources. We will start our search from the surface of the Earth, reaching to outside the heliosphere. The mission and instrument details are collected in Table I.

Cosmic rays have been observed at the Earth’s surface using neutron monitors since 1948 [e.g. 16]. Rather than measuring the incident cosmic ray, these monitors detect the shower of secondary particles, and their analysis depends on the atmospheric conditions. In addition, the geomagnetic field affects the accessibility of the primary particles, with the rigidity cutoff 1-20 GV depending on latitude. Neutron monitors have been widely used to observe galactic cosmic rays, modulation and solar energetic particles [e.g. 2, 14, 16].

Spaceborne cosmic ray instruments can be used to avoid the complications in observation analysis due to Earth’s atmosphere and magnetic field. However, other complications arise, in particular at high cosmic ray energies that typically require large instruments, which are difficult to launch to orbits that allow measurement of both high and low energy particles. There are currently two spaceborne instruments that measure the ~ GeV/n energy range. PAMELA [18], launched to a quasi-polar low-earth orbit (LEO) with inclination of 70°, is a large magnetic spectrometer, which can measure ions at energy range from 80 MeV/n up to several hundred GeV/n, depending on the orbital phase. AMS [19] is similarly at LEO orbit, but located at the International Space Station at lower inclination, 52°. Thus, its rigidity cutoff is larger, 500 GV, with the range continuing up to 2 TV.

Above the LEO orbits, the effect of geomagnetic cutoff is reduced as the spacecraft leave Earth’s magnetic field. On the other hand, at higher orbits, the ability of measuring high-energy particles is reduced, due to the weight limitations for instruments as the missions get farther away from the Earth. At geosynchronous orbit the GOES satellite series has been upgraded with the new GOES-R satellite, which was recently renamed as GOES-16. GOES-16 provides ion measurements at considerably lower energies than the LEO instruments, with the SEISS instrument providing measurements of protons in the range of 30 eV to 700 MeV, with electrons up to 12 MeV, and heavy elements up to 200 MeV [20]. The spacecraft remains mostly within the magnetopause, however ions down to 4 MeV/n have been shown to be able to penetrate the geosynchronous orbit [28], depending on orbital and geomagnetic conditions. Thus, the proton observations of 1–700 MeV are typically used in cosmic ray analysis, while the lower energy instruments are designed for magnetospheric particle analysis.

The effect of the Earth’s magnetic field on the cosmic ray observations can be avoided by placing the
TABLE I: The current fleet of particle-observing spacecraft.

| Spacecraft          | Launched | Orbit                   | Instruments                  | particles                      |
|---------------------|----------|-------------------------|------------------------------|--------------------------------|
| Neutron monitor     |          | N/A                     |                              |                                |
| Pamela[18]          | 2006     | Quasi-polar LEO         |                              | 0.08–20 GeV/n                  |
| AMS[19]             | 2011     | LEO (ISS)               |                              | 1 GV – 2 TV                    |
| GOES, GOES-16[20]  | various  | Geosynchronous          | SEISS                        | e;>0.6 MeV, p, He: 1-700 MeV/n  |
| WIND                | 1994     | L1 (current)            | 3DP[21]                      | e: 3 eV – 400 keV              |
| SOHO                | 1995     | L1                      | ERNE[22], COSTEP[23]         | 0.25–10 MeV, ions: 1-120 MeV/n |
| ACE[24]             | 1997     | L1                      | CRIS, ULEIS, SWIMS, EPAM, SIS, SEPICA, SWEPAM, SWICS | 0.03–0.31 MeV, ions: 0.1 keV–500 MeV |
| STEREO A/B          | 2006     | 1AU heliocentric        | IMPACT[25](HET, LET, SEPT, SIT) | e: 0.03-6 MeV, ions: 0.06–100 MeV/n |
| Voyager 1/2         | 1977     | 137 AU/113 AU           | LECP[26], CRS[27]            | e: 4 eV - 100 MeV, ions: 10 eV - 550 MeV/n |

observing spacecraft further into the interplanetary space. Stable vantage points for cosmic ray observations are provided by the Lagrange points of the Earth-Sun system, and L1 has been used for this purpose by several space science missions. The L1 is used currently by three spacecraft with particle instruments. The WIND spacecraft, launched in 1995 originally as a geospace mission on a complicated Earth-Lunar-L1 orbit [29] is now located at L1, and offers electron measurements in the range of 3 eV–400 keV by the 3DP instrument [21]. The ESA and NASA’s SOHO spacecraft was launched to L1 in 1995, with electron and ion measurements at ranges 0.25-10 MeV and 1-120 MeV/n respectively, with the instruments ERNE [22] and COSTEP [23]. Further, in 1997 also NASA’s Advanced Composition Explorer ACE spacecraft [24] joined L1, with a wealth of instruments (see Table I), detecting electrons between 30–310 keV and ions between 0.1 keV and 500 MeV. All three spacecraft are still in operation, and have produced valuable research over the two decades of their operation too numerous to list here.

A wider perspective to cosmic rays in the heliosphere is offered by the two STEREO spacecraft, launched in 2006, which orbit the Sun at approximately Earth’s distance from the Sun. STEREO-A advances 22° in heliolongitude each year ahead of Earth, while STEREO-B trails Earth by the same rate [30]. Both spacecraft have identical set of instruments, including the IMPACT in situ instrument set, with four particle sensors measuring electrons between 30 keV and 6 MeV, and ions between 0.06–100 MeV/n. The STEREO spacecraft, together with instruments at L1, have been extensively used for SEP event analysis. In particular, the STEREO observations have given new understanding into the longitudinal extent of the SEP events, showing that in some events SEPS can have access throughout the 360° of heliolongitude in the inner heliosphere, challenging our understanding of SEP event physics [e.g. 6, 7, 31, 32].

The two STEREO spacecraft reached superior conjunction in 2015, crossing behind the Sun as viewed from Earth. Due to interference from Sun at this time, communication to the spacecraft was not possible. After emerging from the conjunction, the contact to STEREO-B could not be established before August 2016, after which contact was soon lost again. Recovery operations for STEREO-B are being planned for later in 2017 [33].

Finally, we must mention the Voyager 1 and Voyager 2 which, together with the Pioneer 10 and Pioneer 11 are the most distant man-made objects. The LECP [26] and CRS [27] instruments onboard the Voyagers measure electrons between 4 eV and 100 MeV and ions between 10 eV and 500 MeV/n. Voyager 1 has reached the interplanetary space [15], whereas Voyager 2 is in heliosheath, and observed how the cosmic ray intensities change throughout the heliosphere [e.g. 13, 15, and many others].

In addition to the above-discussed spacecraft that carry instrumentation dedicated to cosmic ray research, additional instrumentation can be found in several planetary missions (Table II). The instruments are typically designed not from the viewpoint of cosmic ray research but rather from the point of view of planetary and space physics research. However,
TABLE II: Planetary missions with particle instruments capable of solar and heliospheric particle observations.

| Spacecraft   | Launched       | Planet   | Instruments                          | particles                      |
|--------------|----------------|----------|--------------------------------------|--------------------------------|
| Messenger    | 2004–2015      | Mercury  | EPPS/EPS[34]                        | e: 20–700 keV, ions 10 keV – 5 MeV |
| MAVEN        | 2013           | Mars     | MAVEN SEP[35]                       | e: 0.025–1 MeV, ions 0.025 – 12 MeV |
| MSL          | 2011           | Mars     | RAD[36]                             | e: –10 MeV, ions: –100 MeV/n    |
| Cassini      | 1997           | Saturn   | MIMI[37]/LEMMS, INCA                | 0.02–130 MeV                   |
| Juno         | 2011           | Jupiter  | JEDI[38]                            | e: 0.01–10 MeV, ions: 0.01-100 MeV |
| New Horizons | 2006           | Pluto    | PEPSSI[39]                          | e: 25-500 keV, ions: 0.025–1 MeV |

some planetary mission instruments have been used for analysis of SEP events [e.g. 40, 41].

**IV. FUTURE MISSIONS**

The Tables I and II give a view of a wide network of spacecraft capable of observing solar and heliospheric cosmic rays. However, one must note that there are several issues that threaten to limit the observation capabilities already in near future. The spacecraft WIND, SOHO and ACE at L1 are all 20 years old or more, and their missions have been extended several times. The STEREO B spacecraft is currently not in operation [33]. Voyager 1 has departed the heliosphere, with Voyager 1 soon to follow, and the two spacecraft have power only until 2025, with instrument shutdown commencing in 2020 [42]. Several of the planetary missions are already at the end of their planned operations, and as the particle instruments are designed for planetary science, their orbits may not be optimal for cosmic ray observations. As an exception, The New Horizons mission, with the PEPSSI particle instrument [39], has now passed Pluto and is continuing to outer heliosphere, where it can continue the Voyagers’ record of observing outer heliosphere cosmic rays.

The most imminent future missions, summarised in Table III, concentrate on solar research. The ESA’s Solar Orbiter (SoLO) and NASA’s Solar Probe Plus (SPP) will be launched in 2018, with the heliocentric orbits taking the spacecraft into the vicinity of the Sun. SoLO will descend to 0.285–0.91 AU from the Sun, to a high-inclination orbit up to 34° at the extended phase of the mission [43]. SPP will go much closer to the Sun, with the closest perihelion at 8.5 R⊙, or 0.04 AU. Both missions carry in situ instruments, including cosmic ray detectors. The SoLO particle suite EPD, measuring electrons up to 15 MeV and ions up to 450 MeV/n, is described in detail in [44], in this volume. The SPP’s ISIS instrument reaches somewhat lower energies, up to 5 MeV electrons and 100 MeV/n in ions [45]. In addition to the in situ suite, SoLO will carry a full set of remote sensing instruments [43]. SPP, on the other hand, will only house a wide-field heliospheric imager in addition to the in situ instruments [46].

In addition to the two missions entering orbits close to the Sun, also L1 will receive attention. India will launch its first solar observatory, Aditya-L1 in 2019–2020, with a full suite of in situ and remote instruments. Included in the instrument set is the energetic particle detector ASPEX [47], which will measure electrons between 0.1 and 20 keV and ions between 0.02 and 5 MeV/n.

Several new mission proposals have considered the Sun-Earth system’s L5 point, trailing Earth by 60° on Earth’s orbit, as an optimal point for a solar mission, particularly from the Space Weather perspective. The L5 mission suggested by Akioka et al [48] concentrated on CME observations with wide field coronagraph. Subsequent proposals, EASCO [49] and INSTANT [50], contained full set of in situ and remote sensing instruments, including cosmic ray detectors. An L5 mission is also included in NASA’s Heliophysics Science and Technology Roadmap [51]. However, so far none of the L5 missions have been selected. Currently, the most advanced concept is the Carrington-L5 mission [52], which is an operational Space Weather mission. It should be noted that as an operational mission concept, the drive for the mission is on what is relevant for Space Weather forecasting: such missions do not necessarily have scientific goals.

Heliospheric boundary and interstellar missions are being discussed, with mission proposals such as the IHP/HEX proposed for ESA “Cosmic Vision 2015–2025” framework [53]. In addition, interstellar probe is included also in the NASA’s Heliophysics Science and Technology Roadmap [51]. No interstellar missions, however, have been selected as of now.

Also the new planetary missions should be noted. The ESA’s Bepi Colombo mission will carry the SIXS instrument, designed to use X-rays for planetary analysis, and housing a particle detector to evaluate the effect of solar energetic particles [54]. While SIXS’s primary task is not in cosmic ray physics, its ability to observe the 0.1–3 MeV electrons and 1–30 MeV protons may provide an opportunity for solar energetic...
V. SUMMARY

The current fleet of spacecraft observing cosmic rays, summarised in Table I, is quite extensive, but many of the spacecraft are at the end of their missions, and new missions are needed to continue to improve our understanding of solar and heliospheric cosmic ray physics. There are currently three missions, SoLO, SPP and Aditya-L1 (Table III, which will provide continuation for solar and heliospheric cosmic ray research as well as probing regions of the heliosphere. Aside of these spacecraft, and the Bepi Colombo’s SIXS, there are a few mission concepts being proposed, and cosmic ray missions are discussed on relevant Roadmaps. However, the cosmic ray missions are typically competing against astronomy and planetary missions. Thus, the future of solar and heliospheric research needs continuing activity from the community to ensure continuity of solar and heliospheric cosmic ray research over the coming decades.

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## TABLE III: Future missions.

| Spacecraft       | Launch      | Orbit                     | Instruments     | particles                  |
|------------------|-------------|---------------------------|-----------------|----------------------------|
| Solar Orbiter    | 2018        | Solar, 0.285-0.91 AU,    | EPD suite[44]   | e: 2 keV – 15 MeV, ions: 3 keV/n – 450 MeV/n |
|                  |             | up to 34°                 |                 |                            |
| Solar Probe Plus | 2018        | Solar, down to 8.5        | ISIS[45]        | e: 0.02–6 MeV, ions: 0.04–100 MeV/n |
|                  |             | R⊙                       |                 |                            |
| Aditya-L1        | 2019–2020   | L1                        | ASPEX[47]       | e:0.1–20 keV, ions 0.02–5 MeV/n |

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