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FRONTIERS IN ITALIAN STUDIES ON SPACE WEATHER AND SPACE CLIMATE

Italian research and development in space weather and space climate: a state-of-the-art overview

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Abstract

This article presents a concise overview of research developments and advancements in space weather and space climate, with a specific focus on the significant contributions made by members of the Italian Space Weather Community (SWICo). We highlight their achievements in instrument development, observational techniques, and modeling. Furthermore, we introduce a special collection of papers within this journal, entitled "Frontiers in Italian Studies on Space Weather and Space Climate." This collection features a selection of research articles and presentations from the Second and Third SWICo Congresses, held in Rome in February 2022 and November 2024, respectively, and hosted by the Italian Space Agency.

Keywords Space weather · Heliophysics · Geophysics · Instruments

1 Introduction

Frontiers in Italian studies on Space Weather and Space Climate is a topical collection of the Rendiconti dell'Accademia Nazionale dei Lincei that collects papers and contributions to the Congresses of the Space Weather Italian Community (SWICo). SWICo is an association established in 2014, gathering professors, researchers, and technologists from universities and research institutions as well as representatives of Italian industries and agencies operating in the framework of space weather. The aim of SWICo is to promote the development of scientific and technological Italian research in the fields of space weather, i.e., physics of the Sun, solar activity, interplanetary space, magnetosphere and physics of the upper atmosphere, cosmic rays, geomagnetism, planetary space

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weather, technological and biological impacts as well as space and ground-based instrumentation. More detailed information about SWICo can be found at http://www.swico.it.

The second and third congresses celebrated the scientific results obtained by participants to SWICo in the last years and provided a great occasion to discuss the whole range of topics that relates to space weather. The opening speeches were by the President of SWICo and by the President of the Italian Space Agency (ASI), followed by speeches by representatives of the major Italian research institutions involved in the space sector, i.e., National Institute for Astrophisics (INAF), Istituto Nazionale di Geofisica e Vulcanologia (INGV), National Institute for Nuclear Physics (INFN), National Research Council of Italy (CNR) institutes, etc.

The presentations, in both congresses, were organized in heterogeneous sessions to obtain the maximum participation of the community throughout the congress. The conferences provided an opportunity to discuss both the perspective of the study of space weather by ASI (Plainaki et al. 2020a) and the results of the CAESAR/ASPIS project (Laurenza et al. 2023), but also the efforts made in Italian universities that host classes in heliophysics, plasma physics, space weather, and space sciences, in addition to the commitment of large national research institutes, such as INAF, INGV, INFN, and CNR.

In recent years, it has become clear that a better knowledge of the phenomena occurring in the heliosphere can be obtained once the complete chain of processes, i.e., from the Sun, through the interplanetary space, to planetary atmospheres and their magnetic fields, is taken into account (see, e.g., Lilensten and Belehaki (2009); Messerotti et al. (2009); Watermann et al. (2009); Plainaki et al. (2020a). The science of *Space Weather and Space Climate* takes its roots from this new view of the *Sun–interplanetary space–planetary* connections and, for this reason, improvements in our understanding of these processes can stem from the combined efforts of specialists in different fields of research: solar physics, Earth magnetosphere and ionosphere physics, geomagnetism, physics of cosmic rays, space physics, planetary science, new technologies, etc., just to cite a few.

If this comprehensive and interdisciplinary perspective can appear, at a first sight, extremely complex and therefore difficult to implement due to the fact that several scenarios, approaches, and techniques need to be integrated together, we are nowadays aware of its intrinsic added value, as any advancement in each of these fields can trigger new insights in adjacent fields, with an avalanche effect on a better knowledge of the whole *Sun–interplanetary space–planetary* system, as well as at providing a handy benchmark and new awareness for the young science that studies the effects of stellar magnetic activity on exoplanets (Lalitha et al. 2018; Galuzzo et al. 2021; Vidotto et al. 2023).

2 Solar physics

We will start the description of the cause–effects chain underlying the space weather and space climate framework focusing on the Sun, i.e., the primary source of space weather events (see, e.g., Zuccarello et al. 2013; Temmer 2021). We know that its magnetic activity modulates a stationary flux of *electromagnetic* radiation (solar irradiance) and particles (solar wind) in the interplanetary space. Solar activity also varies the number of flares, a sudden conversion of magnetic energy in bursts of *electromagnetic* radiation, and eruptions of plasma and magnetic field from the corona, i.e., coronal mass ejections (CMEs). Both of these events can accelerate particles, the solar energetic particles (SEPs), to relativistic energies and can cause effects on the terrestrial and circumterrestrial environment.

The magnetic phenomena occurring on the Sun follow the 11-year cycle and we are now very close to the maximum of solar cycle 25 (Penza et al. 2021, 2023), as can be easily inferred from the number of bright regions present in the solar corona on January 22, 2025 (see Fig. 1). The ground-based large aperture solar telescopes, like the Daniel K. Inouye Solar Telescope (DKIST, Rast et al. 2021) already operating in the United States and the European Solar Telescope (EST, Quintero Noda et al. 2022), hopefully build in the next years in the Canary Islands, will provide unprecedented high-resolution observations of the solar atmosphere, shedding light on the tiny processes

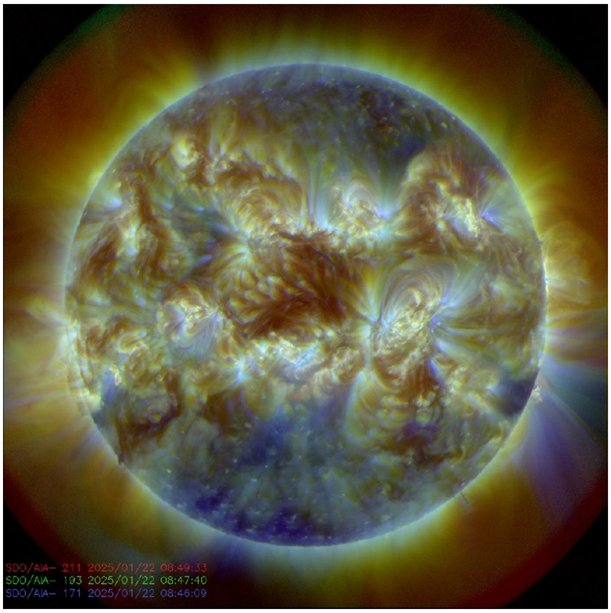

Fig. 1 Image obtained from the superposition of data acquired on January 22, 2025 at 211, 193 and 171 Å by the Atmospheric Imaging Assembly (AIA, Lemen et al. (2012)) on board the SDO satellite

related to magnetic field emergence and evolution in these layers. The continuous monitoring of the Sun from space, like for instance the one carried out by the Solar Dynamic Observatory (SDO, Pesnell et al. 2012) satellite, as well as the new datasets provided by the recently launched satellites, Solar Orbiter (SOLO, Müller et al. 2020) and Parker Solar Probe (PSP, Fox et al. 2016) are expected to provide an answer to the long-lasting questions concerning the operation and effectiveness of the dynamo mechanism, which regulates the transition from the poloidal to the toroidal magnetic field, and vice-versa. In particular, the out-of-ecliptic observations carried out by Solar Orbiter will be crucial for collecting data on the magnetic field at high latitudes, necessary to better understand the mechanism leading to the change of polarity at the solar poles, with consequences on a better comprehension of the still unclear phase of transition from the toroidal to the poloidal magnetic field configuration.

It is expected that in the coming years, both ground-based telescopes and satellites, together with new and more realistic modeling, will help us in solving the *mystery of coronal heating*, finally disentangling the role played by magnetic reconnection and/or magnetohydrodynamic (MHD) waves in the processes responsible for the increase of temperature in the outer atmospheric layers (Sobotka et al. 2016; Abbasvand et al. 2020; Stangalini et al. 2021; Viall et al. 2021). Concerning the mechanisms originating in the solar corona, it is worthwhile to stress the important advancement in the understanding of magnetic switchbacks, associated to the solar wind flow and observed both by the PSP and SOLO (Pecora et al. 2022; Telloni et al. 2022; Perrone et al. 2020, 2024; Toth et al. 2023).

The Sun's photospheric magnetic field, governed by magneto-convective processes, determines the large-scale structure of the corona and heliosphere. By comprehending these processes, we can unravel the mechanisms behind the Sun's long-term magnetic evolution and its impact on the heliosphere. The Italian community, with its long-standing expertise in analyzing photospheric data from both space and ground-based instruments, has significantly contributed to our understanding of photospheric dynamics (e.g., Berrilli et al. 1997, 2002, 2003, 2005; Consolini et al. 1999, 2003; Lepreti et al. 2000; Carbone et al. 2002; Viticchié et al. 2009, 2010; Zuccarello et al. 2009, 2014; Murabito et al. 2017; Guglielmino et al. 2019; Viavattene et al. 2019; Stangalini et al. 2022; Cantoresi et al. 2023; Cantoresi and Berrilli 2024; Berretti et al. 2024). Clearly, when we want to consider solar phenomena that can affect space weather, we have to refer to solar flares, **coronal holes** and CMEs (see Fig. 2).

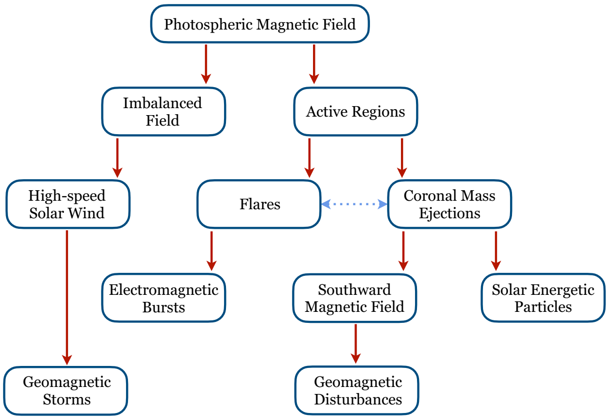

Fig. 2 Scheme illustrating the connection of photospheric magnetic field with solar upper atmosphere and space weather events, including electromagnetic bursts, solar energetic particle events, high-speed solar wind, and geomagnetic storms and disturbances. Red solid lines indicate direct connections, whereas the sky-blue dotted line signifies potential connections

High-speed solar winds originating from coronal holes associated with regions of imbalanced photospheric magnetic field can induce geomagnetic storms on Earth, whereas slow-speed solar winds typically result in periods of calm space weather.

While their inter-relation is still a matter of debate, it is now clear that the instability that triggers flares is associated with the process of magnetic reconnection, capable of converting the energy stored in a non-potential configuration of the magnetic field into kinetic, thermal, electromagnetic energy. Improving forecasting algorithms for the arrival time of high-speed solar wind and solar CMEs is crucial for space weather studies, as it allows for more accurate predictions of potential disruptions to Earth's technological infrastructure (Napoletano et al. 2018, 2022; Chierichini et al. 2024). The very recent possibility offered by high-resolution spectropolarimetric instruments, to provide information on the vector magnetic field also in chromosphere, has provided evidence of the non-simultaneous change of the magnetic field when photospheric and chromospheric data are compared (see, e.g., Ferrente et al.
(2023)).

Another important aspect that we want to stress in the framework of the study of solar flares, because of the critical effects that these eruptive solar phenomena can have on our technological systems, is that the ability to forecast solar eruptions has become a priority. In the last years, for instance, several groups focused their efforts on refining methods and techniques that can allow us to predict flare occurrence, both in terms of expected time and energy class. Some of these forecasting methods are based on proxies of the magnetic field complexity, like, for instance, the length of the polarity inversion line (PIL) (Mason and Hoeksema 2010), the R-value, which measures the total amount of unsigned magnetic flux surrounding the PIL in the photosphere (Schrijver 2007), the topological parameter D, representing the complexity of a solar active region, and the R*-value (Cicogna et al. 2021), the magnetic helicity flux and the fractal dimension, the B_{eff} parameter, which is related to the collective magnetic flux connections within an active region, where each connection line has a length (L) and net magnetic flux (Φ), with their contributions weighted by the square of their distances to yield a value in magnetic field units (Georgoulis and Rust 2007), or a tool based on sunspot group properties (Falco et al. 2019), and so on. Some other forecasting tools are instead based on the application of artificial intelligence (AI), as those based on neural networks and machine learning (Georgoulis et al. 2021). Most recently, Ref. Korsós et al (2024) has presented a very promising methodology that uses a combination of the methods mentioned before, utilizing both magnetic field observational data and results of magnetic field extrapolations, obtaining, therefore, the behavior of the proxies at different atmospheric heights. Recent analysis by Refs. Plutino et al. (2023); Berretti et al. (2025) have introduced an improved algorithm for detecting solar flares from geostationary operational environmental satellites (GOES) X-ray flux data, enabling more accurate identification and analysis of these energetic events and creating a database that increased the statistics of revealed events.

3 Interplanetary space physics and galactic cosmic rays

The solar particle and radiative fluxes expanding from the Sun in all directions and the magnetic field carried by the plasma impact the entire heliosphere. The solar wind is a supersonic, super-Alfvénic and high Reynolds number flow of fully ionized and magnetized neutral plasma, consisting mainly of electrons, protons, and alpha particles, and much less abundant heavy ions in different ionization stages, emerging from the solar atmosphere with a characteristic velocity in the range 300–800 km/s. This characteristic which certainly holds at 1 AU is, however, true also closer to the Sun as shown by old measurements at 0.3 AU by Helios mission (refer to Ref. Bruno and Carbone 2013, and references therein) and by Parker Solar Probe measurements during its first encounter with the Sun (see, e.g., Chhiber et al. 2021). In general, it would be more exact to say that there are two different types of solar wind: (i) a fast solar wind, whose velocity is higher than 500–600 km/s (typically ~ 700 km/s), which originates from the coronal holes characterized by open magnetic field lines and from the solar regions of open field lines, and (ii) a slow solar wind, whose typical velocity is less than 500 km/s and emerges mainly from the equatorial regions characterized by closed magnetic field lines that intermittently open due to some processes (as, for instance, interchange reconnection between open and magnetic field regions). However, the sources of slow solar wind are still a matter of debate (see Ref. Abbo et al. 2016, and references therein).

A peculiar property of this plasma flow is its turbulent nature. Indeed, since the early space missions in the years 70s of the past century, it was realized that both solar wind magnetic field and velocity fluctuations show features analogous to those observed in turbulent media (Carbone and Pouquet 2009; Bruno and Carbone 2013). This turbulent character made of the solar wind and of the interplanetary medium, a natural laboratory, where to study MHD turbulence (see, e.g., Zhou et al. 2004; Bruno and Carbone 2013, and references therein) and astrophysical plasma dynamics from large MHD scales down to the ion/sub-ion scales. In this framework, thanks to the availability of high spatio-temporal resolution observations from space missions as the European Space Agency (ESA) Cluster, the National Aeronautics and Space Administration (NASA) Magnetospheric Multiscale (MMS), NASA PSP, and ESA-NASA SOLO, the recent studies on solar wind turbulence moved from the MHD scales to the ion/sub-ion scales where dissipation is expected to occur. Anyway, at these small scales, it has been observed a novel power-law spectral domain (Kiyani et al. 2009), which has been interpreted as the possible occurrence of a different turbulent regime due to the interaction of linear/quasi-linear wave modes (e.g., kinetic Alfvén waves, whistler waves, ion-cyclotron waves, etc.) (Salem et al. 2012; Biskamp et al. 1999; Boldyrev and Perez 2012; Huang et al. 2020; Kumbhar et al. 2024; Dhamane et al. 2023; Bruno and Telloni 2015; Telloni et al. 2020).

Recent studies have shown that some properties of magnetic field fluctuations at ion/sub-ion scales can be reproduced by stochastic models (e.g., approaches based on stochastic Langevin equation) (see, Refs. e.g., Carbone et al. 2021; Benella et al. 2022, 2023; Stumpo et al. 2023a, and references therein). On the other hand, numerical simulations of magnetized plasma behavior at ion/sub-ion scales evidenced that in this domain, either viscous/ohmic dissipation and pressure play a relevant role in generating the observed spectral features (Hellinger et al. 2021; Papini et al. 2021; Yang et al. 2017).

Apart from the studies at the ion/sub-ion scales, it is important to mention also the investigation of solar wind heating mechanisms and the possible connection with the role that turbulence plays (see, e.g., Shaikh et al. 2023; Sorriso-Valvo et al. 2023; Marino and Sorriso-Valvo 2023; Carbone et al. 2009; Marino et al. 2008and references therein) and the more classical studies on the Alfvénic character of solar wind fluctuations and the fast/slow nature dichotomy of the solar wind (D’Amicis et al. 2021b, 2022), although the standard classification of the solar wind according to the flow speed has been recently questioned and overcome (D’Amicis et al. 2021a, and references therein).

Solar variability modulates the flux of galactic cosmic rays (GCRs) which pervade the whole heliosphere and impact the Earth's environment. Indeed, cosmic rays with energy above $\simeq 1$ GeV are of galactic origin and are believed to originate from shock acceleration in supernova (SN) explosions. The statistical process of shock acceleration was originally described by Fermi and results in a power-law spectrum (index $\simeq 2.7$) that combines the acceleration and propagation mechanisms in the galaxy. At higher energies ($\simeq 10^{15} eV$), the index increases and the particles are believed to have an extragalactic origin, although the mechanisms that allow particles to accelerate up to and above 10^{20} eV are still unknown.

Since the discovery of cosmic rays, various mechanisms have been proposed to explain the acceleration of particles to relativistic energies and their subsequent propagation in the Galaxy. It was pointed out long ago (e.g., Lagage and Cesarsky 1983; Ginzburg and Syrovatskii 1964) that supernovae fulfill the power requirement to energize galactic cosmic rays to about $E \simeq 10^{15}$ eV. Several models were put forward to explain the acceleration of cosmic ray particles as diffusive shock acceleration ("first order Fermi acceleration") produced by supernova shock waves propagating in the interstellar medium (see Bell 1978; Malkov and O'C Drury 2001 for a review and Adriani et al. (2014) for an overview of the spectra of cosmic rays). This simple SN-only paradigm has been challenged several times in the past (see Butt 2009 for a report), with authors introducing several different sources or acceleration models to describe data in the 1– 10^7 GeV range (Bell and Lucek 1996; Bykov and Toptygin 2001; Zatsepin and Sokolskaya 2006).

Evidence for SN shock acceleration of cosmic rays to a maximum energy of $\simeq 3 \times 10^{15}$ eV comes from a number of observations. For example, TeV emission from the young supernova remnant (SNR) RX J1713.7-3946, detected by the High Energy Stereoscopic System (H.E.S.S.) collaboration (Aharonian et al. 2007), has been interpreted as originating from hadronic interactions of cosmic rays with energies above 10^{14} eV in the shell of the SNR (even though leptonic processes cannot be ruled out (Porter et al. 2006; Ellison et al. 2010)). X-ray measurements of the same SNR provide evidence that protons and nuclei can be accelerated to energies $\geq 10^{15}$ eV (Uchiyama et al. 2007). Recent AGILE observations of diffuse gamma ray emission in the 100 MeV–1 GeV range from the outer shock region of SNR IC 443 have been explained in terms of hadronic acceleration (Tavani et al. 2010). Likewise, Fermi observations of the shell of SNR W44 have been attributed to the decay of π^0s produced during interactions of accelerated hadrons with the interstellar medium (Abdo et al. 2010).

The hypothesis that cosmic rays are accelerated in supernova explosions is further corroborated by observations of other galaxies. In starburst galaxies (SG), the SN rate at the galactic center is much higher than in the Milky Way and the density of cosmic rays deduced from observations of TeV gamma rays is much higher. This has been confirmed by H.E.S.S. which measures gamma rays with energies $\geq$ 220 GeV. The inferred cosmic ray density in SG NGC 253 is three orders of magnitude higher than in the Milky Way (Acero et al. 2009). VERITAS measures gamma rays with energies $\geq$ 700 GeV and observations of SG M82 indicate a cosmic ray density 500 times higher than in the Milky Way (VERITAS Collaboration et al. 2009).

At the end of the acceleration phase, particles are injected into the interstellar medium where they propagate, diffusing in the turbulent galactic magnetic fields. Nowadays, this propagation is well described by solving numerically (e.g., the GALPROP simulation code (Strong and Moskalenko 1998)) or analytically (e.g., Jones et al. 2001; Donato et al. 2001) the transport equations for the particle diffusion in the Galaxy.

When GCRs enters the heliosphere from the interstellar medium, they are affected by the interplanetary magnetic field and solar wind and undergo several physical processes, including convection, adiabatic energy losses, diffusion, and drift (e.g., Potgieter 2013). The overall effect of particle propagation through the heliosphere is known as solar modulation, which can occur at many timescales. On long and medium timescales, the main modulation is at 11 year and about 2 year timescales (Laurenza et al. 2012, 2014), respectively, both related to the solar activity variability. On short time scales (days), phenomena such as Forbush decreases (see, e.g., Armano et al. 2019; Benella et al. 2020) can be observed in the GCR intensity, due to the passage of interplanetary coronal mass ejections (ICMEs), i.e., large-scale magnetic structures presumably connected to the Sun. The Sun itself can also produce solar cosmic rays, also called solar energetic particles (SEPs), during solar eruptions. SEPs are suprathermal particles, mainly protons, covering a very wide energy range from tens of keV up to relativistic energies of about 15 GeV. SEPs can be accelerated in solar flares, possibly due to electric fields associated with the magnetic reconnection or occur in stochastic manner ("second order Fermi acceleration"), through the phenomenon of resonance wave- particle, or with plasma waves generated by turbulence. SEPs can also be accelerated by the CME shock through diffusive shock acceleration in the solar corona, where factors such as the shock geometry and background magnetic field can be important factors for the acceleration efficiency (Frassati et al. 2022). Moreover, the presence of interplanetary shocks in front of ICMEs or at the boundaries of corotating interface regions plays an important role in the acceleration of energetic particles in the interplanetary space (Frassati et al. 2022; Chiappetta et al. 2021; Aran et al. 2021; Pallocchia et al. 2017).

4 Earth's magnetosphere and geomagnetism

The Earth's magnetosphere is the region of the circumterrestrial space where the magnetic field of the Earth is confined by the solar wind. This region plays a fundamental role in screening the Earth's environment from the solar wind particle radiation and preventing the deterioration of the upper layers of the Earth's atmosphere. The Earth's magnetosphere is highly structured, consisting of several different regions characterized by different physical conditions in terms of fields and plasma features, and displays a nontrivial dynamics in response to the changes of the interplanetary magnetic field and solar wind conditions. Indeed, the dynamics of the Earth's magnetosphere in response to solar wind changes resembles that of an out-of-equilibrium system near-criticality (Consolini et al. 1996; Consolini 2002; Consolini et al. 2008; Borovsky and Valdivia 2018). Manifestations of the Earth's magnetospheric dynamics are the magnetic storms and the geomagnetic substorms, these involve phenomena taking place in several different regions of the magnetosphere, and implying a reconfiguration of the current systems flowing inside the magnetosphere (see, e.g., De Michelis et al. 1999). For instance, during magnetospheric substorms, we may observe a reconfiguration of the cross-tail current flowing in the magnetospheric tail regions with the formation of field-aligned currents (FAC) connecting the high-latitude ionospheric electrojet to the tail regions. Understanding the dynamics of the response of the Earth's magnetosphere to the changes of the interplanetary conditions means also to understand the physics of some fundamental plasma processes responsible for the transfer of energy, mass, and momentum from the solar wind to the magnetosphere and the ionosphere.

Among the various physical processes taking place in the coupling of the solar wind with the Earth's magnetosphere, the most important and studied one is magnetic reconnection (see, e.g., Pontin and Priest 2022, andreferencestherein). In the past, several space mission where devoted to the study of reconnection process at both the Earth's magnetopause (see, e.g., Bavassano Cattaneo et al. 2006; Retinò et al. 2005, 2006) and the central plasma sheet (CPS), among them, a particular mention should be given to the ESA Cluster mission, the first multi-point mission to study plasma dynamics in the near-Earth environment (Escoubet et al. 2021; Matar et al. 2020). This mission allowed greatly advancing the understanding of the dynamics of reconnection, essentially at the observational scales where the MHD model is valid. More recently, the NASA MMS mission allowed the investigation of reconnection at kinetic scales (Burch et al. 2016; Burch and Phan 2016). It is important to remark how the effects of magnetic reconnection at the magnetopause can be observable also on the ground using, for instance, data from the Super Dual Auroral Radar Network (SuperDARN) network, even for northward condition of the interplanetary magnetic field (Marcucci et al. 2008).

Another relevant issue in the magnetospheric dynamics is the storm-substorm relationships. This is a crucial point to understand the role that ionospheric high-latitude ion outflow plays in the energization of the terrestrial ring current responsible for the low latitude geomagnetic effect. Indeed, since the first space missions, it was observed how oxygen ions (O^{+}) play a relevant role in the development of the ring current (Daglis et al. 1999). This topic has been widely studied using different approaches (see, e.g., De Michelis et al. 2011; Stumpo et al. 2020, 2023b, and references therein).

Other important aspects of the magnetospheric dynamics deal with the response of the Earth's magnetosphere to the occurrence of interplanetary sudden impulses, capable of generating long-periodicity oscillations of the magnetospheric cavity (Villante and Piersanti 2009, 2014; Piersanti et al. 2012; Francia et al. 2009) and the impact on the inner magnetospheric regions (Vellante et al. 2021; Takahashi et al. 2022). Low-frequency waves propagating within the magnetosphere (Lepidi et al. 2011), often associated with the impinging of compressional solar wind fluctuations (Di Matteo and Villante 2025), give further information on the triggering processes related to the solar wind-magnetosphere interaction. The understanding of the physical processes responsible for the magnetospheric dynamics is a crucial issue for developing reliable forecasting models. In the past, several attempts to develop forecasting models of the magnetospheric dynamics as monitored by geomagnetic indices have been done. Most of these models are based on artificial neural networks (see, e.g., Pallocchia et al. 2006, 2008; Amata et al. 2008; Siciliano et al. 2021, and references therein). However, some limitations on the prediction of short timescale dynamics of the magnetospheric activity have emerged. These limitations are essentially due to the inner magnetospheric plasma processes which are not directly driven by the interplanetary conditions' changes (Alberti et al. 2017), but perhaps due to the near-criticality character of the fast dynamics (Consolini and De Michelis 2024).

5 Aeronomy and upper atmosphere physics

Approaching to the Earth, we encounter the upper atmosphere that is generally intended as that portion of the atmosphere going from approximately 50 km of altitude and extending up to the exosphere, thus including the thermosphere. Here, the ultraviolet (UV) radiation emitted by the Sun plays the fundamental role of ionizing the gases, thus giving rise to the formation of a region, the ionosphere, that is, that portion of the upper atmosphere where the electron density is such to influence radio waves propagation. The ionosphere profoundly influences the accuracy of positioning achieved through global navigation satellite systems (GNSS) and, by reflecting radio waves, it allows for long-distance communication. So, the comprehensive understanding of the ionosphere's behavior is important to properly rely on these technologies (see, e.g., Zolesi and Cander 2014; Materassi et al. 2019). Indeed, solar storms and cosmic particle radiation can have profound effects on the ionosphere, as well as Earth-directed CMEs or changes in the state of the magnetosphere (see, e.g., Spogli et al. 2024; Piersanti et al. 2020). For this reason, the ionosphere is monitored through very different instruments both ground-based and onboard satellites. Among the most diffused ground-based instruments, we mention the ionosondes that allow obtaining how electron density varies with height. This information is essential for a reliable high frequency (HF) communication so some efforts have been devoted to obtaining accurate real-time estimations of the main features of the ionospheric F2 layer (see, e.g., Pietrella et al. 2018; Scotto and Sabbagh 2020,), also investigating their dependence on the solar cycle and geomagnetic activity (Ippolito et al. 2020). Another important parameter to study the ionospheric response to space weather events is the total electron content (TEC) (Alfonsi et al. 2011; Piersanti et al. 2017), this is measured by wide worldwide networks of Global Navigation Satellite Systems receivers; over Italy TEC is monitored and modeled by IONORING (Cesaroni et al. 2021). Interesting results can be obtained also by the combined use of ionosondes and GNSS data as in Refs. Alfonsi et al. (2013) and Cesaroni et al. (2017). Differently from ionosondes and GNSS receivers, incoherent scatter radars (ISRs) are poorly distributed on the Earth's surface, but they provide very important information as they measure the altitude dependence of a set of ionospheric parameters such as electron density, ion and electron temperatures, ion composition and ion drift velocities. Recently, ISR electron temperature measurements have been successfully used to test the reliability of electron temperature measurements made onboard one of the ESA Swarm satellites (Pignalberi et al. 2021, 2024). As mentioned above, among ground infrastructures, also SuperDARN plays an important role by representing a network of radar installations located at mid and high latitudes in both the Northern and Southern hemispheres. SuperDARN is designed to map ionospheric convection and to investigate its behavior during space weather events (see, e.g., Greenwald et al. 1995; Coco et al. 2005). Concerning satellite measurements, we cite those made onboard the satellites of the ESA Swarm mission (Friis-Christensen et al. 2008), NASA ICON missions (Immel et al. 2018), as well as the COSMIC mission (Fong et al. 2008). Swarm data allowed investigating the turbulent nature of the ionosphere (De Michelis et al. 2020, 2021; Consolini et al. 2020) and estimating both its parallel (Giannattasio et al. 2021) and perpendicular conductivities (Giannattasio et al. 2024). Data from the COSMIC mission have been used to improve models of the topside ionosphere as is the case of the NeQuick model (Pignalberi et al. 2022; Pezzopane et al. 2024). Satellite-based measurements are largely focused on the same parameters measured from the ground. A major difference lies in the fact that satellite measurements are not confined to a single point in space but cover different locations at different times. Ground-based and satellite measurements are, therefore, complementary for investigating the ionosphere response to the different solar, interplanetary and geomagnetic conditions on different space and time scales. Interesting results have been obtained using data from different kinds of instruments, both ground and satellite based, including also ground magnetometers (Spogli et al. 2016).

It is established that the thermosphere exhibits a strong coupling with the ionosphere and magnetosphere, primarily due to solar and geomagnetic activity (e.g. Masutti et al. 2016; Regi et al. 2022). The thermosphere experiences significant fluctuations in density because of the intricate interplay of solar dynamics through the direct solar UV input and through the solar (fast) wind and plasma fluxes impacting Earth's magnetosphere (e.g., Perrone et al. 2021,). Predicting these density variations is crucial for successful space missions in low Earth orbit (LEO) and very low Earth orbit (VLEO). Accurate thermospheric models are essential for:

- Mission lifetime prediction: atmospheric drag influences the rate at which satellites lose altitude, directly impacting their operational life.
- Attitude control: fluctuating atmospheric density can exert unpredictable forces on satellites, disrupting their stability and orientation.
- Space debris mitigation: understanding the thermosphere's behavior is vital for predicting the trajectories and potential collisions of space debris, ensuring the safety of operational spacecraft.

By combining data from proxies of solar UV radiation with magnetospheric indices, it is possible to reconstruct thermospheric density, as demonstrated for instance by Ref. Bigazzi et al. (2020). This approach can be extended to forecast thermospheric behavior at various altitudes.

6 Planetary space weather and exoplanets

The continuum flux of solar electromagnetic radiation and particles and the magnetic field carried by the plasma of solar origin pervade the whole planetary system. Actually, electromagnetic and particle radiation and magnetic field interact with all planets and small solar system bodies by modifying the physical conditions of their external environment. Moreover, the detailed study of the Sun–Earth interaction allows us to investigate the physical and habitability conditions of exoplanets with an Earth-like magnetosphere, hosted by Sun-like or M and F stars, associated with the interaction between the stellar winds and the exoplanet's atmosphere/surface.

Planetary space weather science aims at understanding the interaction of the Sun with solar system bodies as well as the complex processes taking place within planetary magnetospheres characterized by temporal and spatial variability (Lilensten et al. 2014; Plainaki et al. 2016). The Italian scientific community boasts a long-standing expertise and heritage in planetary space weather, being engaged in theoretical research, multi-instrument and multi-point observation analysis, as well as scientific payload and mission design and development (a detailed, however not exhaustive, description of such contributions was presented in Ref. Plainaki et al. (2020a)). In this paper, we refer to some recent contributions in planetary space weather science with special emphasis to the Italian involvement in ongoing planetary missions that aim, among other objectives, to study the related phenomena.

The ESA/JAXA BepiColombo mission to Mercury is a complex two-spacecraft mission launched in 2018 aiming to study and understand the composition, geophysics, atmosphere, magnetosphere, and history of Mercury (Benkhoff et al. 2021). The Search for Exospheric Refilling and Emitted Natural Abundances Experiment (SERENA) on board BepiColombo is a suite (of Italian leadership; Orsini et al. 2010) composed of four units of complementary neutral and ionized particle detectors, providing information on the coupling between Mercury's surface, exosphere, and magnetosphere, along with the related phenomena that are strongly influenced by solar activity (Mangano et al. 2021; Milillo et al. 2023). The SERENA observations, therefore, are crucial for providing insights on the evolution of the space weather phenomena in the vicinity of Mercury and in the interplanetary space. Although the BepiColombo orbit insertion is foreseen for November 2026, there have already been opportunities for characterizing the solar wind (e.g., Alberti et al. 2023) and investigating the planet's magnetosphere (e.g., Orsini et al. 2022), integrating previous efforts based on the data of the NASA MESSENGER mission. Moreover, Ref. Ippolito et al. (2022) modeled the position of the active regions on the solar surface associated to energetic proton events observed at Mercury in the period 2011-2013, using MESSENGER and ACE data.

Planetary space weather in the outer solar system planets can be of solar or non-solar origin. In the vicinity of the satellites embedded within the giant magnetospheres, space weather phenomena are mainly driven by volcanism, plumes, and the fast planetary rotation. The Jupiter system is an outstanding paradigm for investigations in this sense. The Italian scientific community participates in the NASA Juno mission to Jupiter which provides observations of the planet and its magnetosphere since 2016. The Jovian Infrared Auroral Mapper (JIRAM) is an imaging spectrometer on board Juno (of Italian leadership; Adriani et al. 2017) designed to study the Jovian infrared aurorae in response to plasma precipitation on the planet's upper atmosphere (Mura et al. 2017), as well as features associated with the orbital motion of the moons (e.g., Moirano et al. 2023).

Typical case studies for space weather in the outer solar system are Jupiter's moon Europa (Plainaki et al. 2018), a satellite without any intrinsic magnetic field, and Ganymede, not only the largest moon but also the only known satellite in the solar system possessing its own magnetosphere. Recent modeling work (e.g., Plainaki et al. 2015, 2022) deepened our understanding of the charged particle environment around Ganymede and the impacts of space weather on the moon's surface (Plainaki et al. 2020b). Several scientific instruments operating on board the ESA Jupiter Icy Moons Explorer (JUICE) mission, launched in April 2023, have the potential to study space weather at Ganymede as well as the evolution of its water-exosphere generated by the interaction of the moon's icy surface with the surrounding particles. Among them, the Moons and Jupiter imaging spectrometer (MAJIS; Poulet et al. 2024) has the capability to detect the moon's exosphere providing useful information for evaluating the effects of space weather at Ganymede (Plainaki et al. 2020c).

The study of planetary space weather, particularly when approached from a comparative science perspective, is crucial for our understanding of the related phenomena and their temporal and spatial variability. The lessons learned from the study of the interactions of planetary bodies with plasma, energetic particles, and solar photons can be an important feedback also for a better understanding of the circumterrestrial space weather phenomena. Finally, a better comprehension of the planetary space weather conditions in a circumplanetary environment is crucial for the robotic solar system exploration, in terms of mission and payload design, component shielding, and observation planning.

Solar physics and space weather research significantly contribute to exoplanet studies for two primary reasons: (i) stellar noise characterization: studying the Sun, the only star whose surface we can observe in detail, allows for accurate estimation of the impact of stellar activity on radial velocity (RV) measurements, a crucial technique in exoplanet detection; (ii) planetary atmospheric and magnetospheric effects: investigating the effects of space weather events on the atmospheres and magnetospheres of planets within our own solar system provides valuable insights into how these phenomena influence exoplanets.

It is important to note that several sources of noise, including instrumental limitations and intrinsic stellar variability, contribute comparably to the overall precision of state-of-the-art RV measurements (e.g., Lunine et al. 2008). Stellar noise encompasses various sources, potentially mitigated by characterizing the noise source's temporal spectrum and, where feasible, extending observation periods (Fig. 3). Short-term convective phenomena, such as photospheric granulation, necessitate observations spanning several hours (e.g. Mayor and Udry 2008). Anisotropies arising from active regions, starspots, or faculae introduce "jitter" into the astrometric signal, proving more challenging to mitigate due to their inherent unpredictability. In the Sun's case, these effects can limit the detectability of planets with RV techniques to velocities as low as 0.25 m/s at a signal-to-noise ratio of 3-4 (e.g. Makarov et al. 2009).

It is crucial to acknowledge the growing interest within the Italian research community in exoplanet studies. This is evident in several key initiatives. For example, nearly 10% of publications utilizing data from the Telescopio Nazionale Galileo (TNG) are dedicated to observing the Sun as a star, leveraging the low-cost solar telescope to feed HARPS-N (see "The Annual Report 2023 of the Fundación Galileo Galilei" at https://www.tng.iac.es/news/2024/09/03/annual-report-2023/). Furthermore, the recent first light of the LOCNES solar telescope, feeding Giano-B and enabling near-infrared observations of the Sun as a star, marks a significant advancement (e.g. Claudi et al. 2020). These research efforts are paramount for disentangling the effects of stellar activity on the RVs of extrasolar planets.

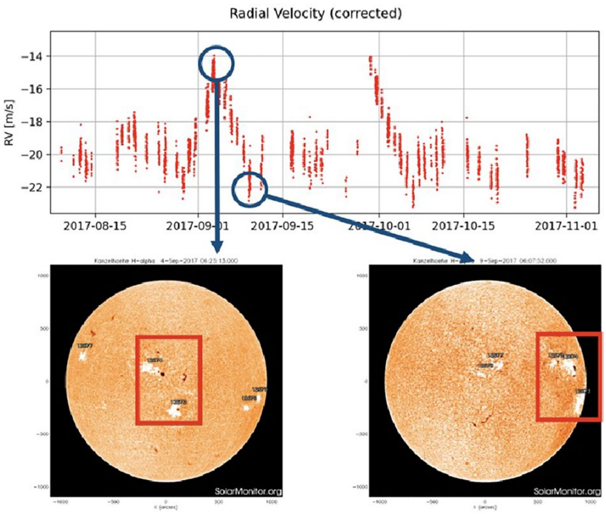

Fig. 3 Top: radial velocity variations of the Sun measured by the HARPS-N solar telescope. Bottom: full-disk images of the Sun in the H-alpha band observed at Kanzelhöhe Observatory and downloaded from the site https://www.solarmonitor.org/. Left: Image taken during a local maximum of the radial velocity. Right: Image taken during a local minimum of the radial velocity. Adapted from the PhD thesis "Machine Learning Algorithms for Understanding Solar Radial Velocity: Implications for Exoplanet Detection" by P. Giobbi

Regarding the second reason for the relevance of solar physics and space weather research in contributing to exoplanet studies, this research contributes to exoplanet studies in two key ways: *i*) application of Earth-based climate models: Earth-based climate models are being adapted for use in exoplanet research to investigate aspects such as the detectability, climate, and habitability of exoplanets (e.g., Galuzzo et al. 2021; Vidotto et al. 2023); *ii*) understanding exoplanetary magnetospheres: by studying how the Earth's magnetosphere is influenced by solar activity levels and solar wind properties, we can gain valuable insights into the behavior of exoplanetary magnetospheres around Sun-like stars. To this end, utilizing solar proxies such as the Ca II K index and solar wind OMNI parameters is crucial for establishing connections between solar activity variations on decadal timescales and solar wind properties (e.g., Reda et al. 2023; Di Mauro et al. 2022).

7 Human exploration and biological impacts

The human exploration of space beyond the shielding of the terrestrial magnetosphere, and in general any extravehicular activity of the astronauts, will have to face the challenge of the harsh ionizing radiation environment of deep space. This is pervaded by GCRs and SEPs modulated by solar magnetic activity. Intense SEP emissions are often associated with flares and CMEs, and extreme space weather events can induce acute *ionizing* radiation syndromes, including sudden effects ranging from simple fatigue to the possibility of an in-flight fatality.

Therefore, understanding the ionizing radiation environment in space (see Sect. 3) and its effects on human physiology is important, in light of activities on the International Space Station (ISS) and future missions to the Moon or Mars. Space ionizing radiation originates from cosmic rays of various energies and sources. Apart from the galactic component, which is influenced by solar activity at low energies, there are also solar energetic particles linked to phenomena like solar flares and coronal mass ejections. In addition, inside Earth's magnetosphere, trapped particles in low Earth orbit, particularly over the Brazilian region, significantly contribute to ionizing radiation. This complex and ever-changing environment necessitates diverse detectors, both active and passive, to characterize and measure the ionizing radiation dose and assess the associated risks for astronauts. In this context, several devices have been developed since 1995 and deployed on the Mir and International Space Stations (e.g., Bidoli et al. 2000; Casolino et al. 1997, 2006b; Narici et al. 2004, 2015; Romoli et al. 2023).

8 Technological impact

Space weather events can have a significant impact on space and ground infrastructures, damaging them even permanently. For instance, high-energy particles emitted from the Sun can affect satellites causing misoperation or equipment damage; ionosphere perturbation can cause the malfunctioning of HF communication and also of GPS positioning; magnetic disturbances can induce electric currents in long conductors such as power lines and pipelines causing power system outages or pipeline corrosion (Boteler et al. 1998).

Starting from the ground, space weather events can significantly impact critical infrastructures as electric power grids by inducing malfunctions or even temporary damages. Indeed, under disturbed conditions, the electric currents flowing in the ionosphere and magnetosphere are responsible of large geomagnetic field variations. These, in turn, induce in the ground the so-called geomagnetically induced currents (GIC) that, being quasi-DC currents with respect to those flowing in power grids, can cause the heating of the windings of transformers leading to overloads and even to blackouts as that of the Hydro-Québec system in 1989 (Boteler 2019). Actually, all long metallic infrastructures can be affected by GICs that can cause corrosion in long either oil or gas pipelines and also misoperation of railways signaling systems (Patterson et al. 2023). A significant amount of research has been devoted to understand the sources of GICs (e.g., Piersanti et al. 2019, and references therein) and their potential impact on the performance of technological infrastructures to evaluate and mitigate possible effects (Ngwira and Pulkkinen 2019). Countries most at risk are those at high latitudes but in the last decade, it has become clear that the risk posed by GICs to critical infrastructures should not be neglected either at low or middle latitudes (e.g., Tozzi et al. 2019b, a; Watari et al. 2009; Zois 2013; Hejda and Bochnícek 2005; Viljanen et al. 2014,). Indeed, in recent decades, global vulnerability to GIC activity has grown due to the widespread adoption of transmission lines operating at extremely high voltages (up to 700–750 kV) and low resistance.

Another detrimental effect of space weather events on technological systems is that associated with the development and growth of ionospheric irregularities, whose cause can be manifold. These irregularities might seriously degrade the quality of GNSS since they cause variations in the electromagnetic properties of the ionosphere giving origin to interference and diffraction of electromagnetic signals traveling through them, resulting in scintillations (e.g., Sreeja et al. 2011; D'Angelo et al. 2021; Mitchell et al. 2005). The occurrence of scintillations may reduce significantly the positioning accuracy also triggering loss of locks (LoLs) between the receiver (either on the ground or in situ) and the GNSS satellite. When a LoL occurs, the GNSS receiver can no longer track the signal sent by the satellite with the consequence of a decrease of accuracy of positioning provided by GNSS such as Galileo, GPS or GLONASS. Recent studies have investigated the relation between the occurrence of LoLs and the variability of electron density and TEC both on a global scale (Pezzopane et al. 2021) and on a regional scale (Damaceno et al. 2020). Interestingly, also the relation between their occurrence and the developing of turbulence in the ionosphere has been studied (De Michelis et al. 2022) globally, as well as LoL occurrence in presence of polar cap patches (Tozzi et al. 2023).

Perturbation of the ionosphere during space weather events significantly affects also radio communication, especially the HF range (e.g., Bianchi et al. 2013). These frequencies are widely used by amateur radio operators, aviation, and government agencies. Changes in the ionospheric structure due to the formation of irregularities can alter transmission paths, while changes in its density can completely prevent HF signals from being reflected, even causing radio blackouts. A radio signal of a given frequency can be absorbed in the ionospheric D-region, reflected by the ionospheric E or F-region or even pass through the ionosphere, depending on electron density (Fiori et al. 2022). So, it may happen that a frequency that is used for quiet condition communications is no longer reflected under disturbed conditions. Also using a wrong frequency makes HF communication not possible. This is what happened to the survivors of the shipwreck of the airship "Dirigibile Italia", occurred in 1928. To launch the alarm messages, they used a frequency that allowed the signal to be received only by a Russian radio amateur about 1900 km away, instead by the ship "Città di Milano" of the Italian Navy, anchored just 400 km away (Zolesi et al. 2020).

Existing literature largely focuses on the impact of space weather events on GNSS signal degradation, specifically in terms of localization errors. This highlights the critical need for transport control and safety agencies to evaluate and implement robust backup systems for critical operations. Potential alternatives being considered include: (i) enhanced LORAN: an updated version of the older LORAN system for air traffic tracking; (ii) OPNT (optical positioning, navigation, and timing) systems: utilizing optical fiber networks for positioning and timing information. The operation of the electricity grid in Italy, however, is not reliant on localization services to function. Nevertheless, since it utilizes GNSS primarily for synchronizing devices (phasor measurement units—PMUs) distributed across vast distances, the Italian power grid functioning does not only suffer the risk associated to GICs but also to GNSS malfunctioning.

Indeed, this synchronization is achieved through precise 1pps signals. PMUs play a crucial role in grid monitoring and control. While some are already deployed across Italy, further installations are planned as outlined in Terna's "2020 Development Plan" (refer to the georeferenced representation of PMUs within the plan).

Moving to infrastructures in space, space weather events also significantly impact satellites, degrading their communication capabilities, performance, reliability, and ultimately, their lifespan. This degradation is exemplified by the gradual decline in power generation from solar panels, a crucial factor that must be considered during satellite design. In this case, the main factors affecting space solar arrays are:

- Temperature variations: extreme temperature fluctuations due to solar irradiation and eclipses impact array performance and lifespan.
- Ionizing radiation effects: exposure to the Van Allen belts causes degradation of solar cells due to high-energy particles.
- Atomic oxygen erosion: reactive atmospheric oxygen at low Earth orbit erodes materials, particularly silver in interconnects.
- Micrometeoroid and debris impacts: collisions with space debris and micrometeoroids can cause damage to the array structure and cells.

All the effects listed originate from solar activity directly or indirectly. For example, fluctuations in the UV radiative flux modify the density of the thermosphere or the composition of the ionosphere, and indirectly modify the deorbiting times of debris.

In addition, the augmented ionizing radiation levels associated with space weather phenomena may result in heightened health hazards for astronauts, encompassing both present-day occupants of the International Space Station and future explorers of the Moon and Mars.

9 Space- and ground-based instruments and new technology

Space weather, due to its highly interdisciplinary nature, requires multi-instrument and multi-messenger observations. The scientific and industrial community is involved in the design and construction of space instrumentation, for remote or in situ observations, and in ground-based next generation instrumentation. Previous assessments, conducted within the ESA Space Situational Awareness (SSA) program (ESA/PB-SSA(2009)7 rev.4, Paris, 17 April 2015) and at the national level (e.g., Amata et al. 2006), have identified potential space and ground-based assets that could contribute to space weather research and monitoring. This section summarizes and updates the key space-based and ground-based technology projects relevant for the Italian space weather community.

Italy's journey into space began concurrently with the early days of space exploration. Driven by the pioneering work of Edoardo Amaldi, who established a cosmic ray research station on the roof of the Physics Institute at the University of Rome, close to Istituto Nazionale di Geofisica (ING) facilities for ionospheric and geomagnetic studies, a strong interest in space research emerged within the Italian scientific community. In the late 1950 s and early 1960s, several researchers from these groups pursued advanced studies at prominent American institutions like NASA institutes and Massachusetts Institute of Technology (MIT) (e.g., Mariani 1959; Mariani et al. 1970; Ness et al. 1966; Conversi et al. 1959; Egidi et al. 1969; Cantarano et al. 1965,). This exchange of knowledge and expertise laid the foundation for the development of Italy's own space program.

The Italian space program in the field of heliophysics in the years following the 80s mainly concerned three technological lines: magnetometers, particle analyzers, and coronagraphs. A significant development in space magnetic measurements were the tri-axial fluxgate magnetometers employed on the Helios 1 and 2 missions. These instruments enabled precise measurements of the interplanetary magnetic field vector up to $\simeq$ 0.29 au and allowed the identification of the shape and location of the warped current sheet separating regions of opposite magnetic field polarities (e.g., Mariani et al. 1984, 1978, 1979; Bavassano and Bruno 1992; Bruno et al. 1986; Bruno and Bavassano 1991; Villante et al. 1979,).

A key component of the Solar Orbiter mission (e.g., Müller et al. 2013) is the solar wind plasma analyzer (SWA), a sophisticated suite of sensors designed to comprehensively characterize the solar wind (e.g., Owen et al. 2020). The SWA instrument, by providing precise measurements of crucial solar wind parameters such as composition, density, velocity, and temperature, has enabled the detailed analysis of wave–particle interactions within the solar wind (e.g., D'Amicis et al. 2021; Bruno et al. 2024,). In the contest of particle analyzers, the PAMELA mission stands out (e.g., Picozza et al. 2007). Designed primarily to measure the flux of antiparticles, specifically antiprotons and positrons, in GCRs, this mission has also yielded significant contributions to the field of heliophysics (e.g., Bruno et al. 2021; Casolino et al. 2006a, 2008,). Moreover, the China Seismo-Electromagnetic Satellite (CSES) significantly contributes to heliophysics research. By collecting data on electromagnetic, particle, and plasma perturbations within the ionosphere, magnetosphere, and inner Van Allen belts, CSES provides valuable insights into the effects of cosmic rays and solar events and activity on the near-Earth space environment (e.g., Martucci et al. 2023,).

As regards coronagraphs on board space missions, the Italian community has achieved results of absolute value. The ultraviolet coronagraph spectrometer (UVCS) (e.g., Noci et al. 1995; Kohl et al. 1995), an instrument aboard the joint ESA/NASA Solar and Heliospheric Observatory (SOHO) spacecraft, revolutionized our understanding of the solar corona by providing high-resolution UV spectroscopic measurements. These measurements enabled unprecedented determination of key plasma parameters, including temperature, density, and velocity, across an extended region of the corona, from its base out to distances of 10 solar radii (e.g., Noci et al. 1997; Antonucci et al. 2012; Telloni et al. 2019,). More recently, the Metis instrument, developed for the ESA-NASA Solar Orbiter mission, represents the first solar coronagraph capable of simultaneously imaging the solar corona beyond the solar limb in both visible and ultraviolet wavelengths (e.g., Fineschi et al. 2020). This groundbreaking capability has enabled a new era of coronal research, facilitating in-depth studies on various aspects of coronal dynamics, including energy budget within the solar corona, density fluctuations in the slow solar wind or eruptive prominences and CMEs (e.g., Bemporad et al. 2022; Grimani et al. 2024; Ventura et al. 2023; Zimbardo et al. 2023; Frassati et al. 2024; Telloni et al. 2023,).

Since 2020, ASI has significantly increased its focus on CubeSat missions for space weather and solar research. This initiative has resulted in the successful completion of the initial design and development phases (Phases A and B) for several groundbreaking missions, including HEliospheric pioNeer for sOlar and interplanetary threats defeNce (HENON), Sun CubE OnE (SEE), and CUbesat Solar Polarimeter (CUSP).

The HENON mission represents a pioneering effort to significantly advance space weather forecasting and scientific understanding (Marcucci et al. 2022). This mission directly addresses the widely acknowledged need for improved capabilities in predicting and mitigating the impacts of solar activity on Earth and space-based systems. The SEE mission, a 12U CubeSat, aims to characterize solar flares fluctuations across a broad energy spectrum, from soft X-rays to gamma rays and monitor solar activity by observing the Mg II doublet emission at 280 nm using a full-disk imager payload (Giovannelli et al. 2023). The SEE mission builds upon the legacy of the ADAHELI and ADAHELI+ projects (Berrilli et al. 2010a, 2015). The CUSP project is a planned CubeSat mission dedicated to measuring the linear polarization of solar flares in the hard X-ray band using a Compton scattering polarimeter (Fabiani et al. 2024).

The Plasma Observatory (PO) deserves a special mention. PO is a proposed space mission submitted in response to the ESA M7 call and subsequently selected for Phase A study (Marcucci and Retinò 2024). PO is specifically designed to investigate plasma energization and energy transport processes within Earth's magnetosphere. This will be achieved through a comprehensive suite of instruments capable of making simultaneous measurements at both fluid and ion scales, providing crucial insights into the fundamental physics governing this dynamic region of space.

In addition to the direct coordination of missions or instruments as principal investigators, Italian researchers are involved in some of the major future missions such as ESA Vigil or the proposed Solar-C mission of JAXA.

The Italian scientific community has made substantial contributions also to ground-based instrumentation for space weather **and space climate** studies. These contributions include pioneering research in cosmic ray detection, with a focus on neutron monitors, in radio astronomy to monitoring the radio Sun, in magnetospheric studies through the establishment and operation of extensive magnetometer networks, and played a key role in ionospheric research. Furthermore, Italian researchers have played a key role in the development of cutting-edge instrumentation and image algorithms for high-resolution two-dimensional spectroscopy in solar telescopes.

Ground-based neutron monitor (NM) detectors are designed to indirectly measure the flux of cosmic rays that strike the Earth's atmosphere from outer space observing—as the name suggests—the secondary neutron component of the hadronic cascade in the atmosphere. These detectors have been used for decades to monitor the long- (11/22 years) and short-term (27 days) solar modulation of galactic cosmic rays as well phenomena related to space weather such as Forbush decreases (e.g., when a CME hits the Earth) or ground-level enhancements (when energetic particles from solar events reach the Earth). Each NM is operating at a geomagnetic cutoff (GC) that depends on the geomagnetic latitude it is located. The GC is related to the minimum energy cosmic rays must have to reach the surface of our planet: from the network of NM, it is possible to reconstruct the energy spectrum and time profiles of the various events associated to space weather. See Ref. Storini and Signoretti (2009) for a description of NMs, in particular the one located in Rome.

The Sun emits radio waves across a wide spectrum, produced by various thermal and non-thermal plasma processes in its atmosphere and beyond. These emissions, originating from different layers, characterize solar radio weather, reflecting the Sun's activity. Analyzing these radio phenomena provides crucial insights into plasma physics, enabling the identification of precursors and contributing to space weather forecasting.

Solar radio emissions offer crucial insights into solar energetic processes, enabling assessment of their direct geoeffectiveness (radio interferences) and serving as precursors/proxies for energetic particle events. Successful implementation requires dedicated space- and ground-based radio instrumentation, robust emission models, and validated forecasting tools. solar radio weather science and operations have been defined and analyzed for both scientific and applied purposes (Messerotti 2011, 2016, 2018b, c, 2019, 2022, 2018a) The Trieste Solar Radio System 1.0 was operated from 1967 to 2010 by INAF for monitoring. It played a role in averting a nuclear war in 1967 (Messerotti 2023) and its data archive is planned to be modernized for full data exploitation (Molinaro et al. 2024). The new Trieste Solar Radio System 2.0, a solar radio polarimeter in the 1–18 GHz band, has been under commissioning (Jerse et al. 2020b, a).

The Sun emits continuous, slowly varying broadband radio waves, primarily thermal in nature, with increased flux density from active regions. While thermal emission dominates during periods of quiescence, non-thermal processes (e.g., gyro-radiation) contribute during active periods, making this “S-component” a useful indicator of solar activity. The 10.7 cm radio index (2880 MHz) mirrors the sunspot cycle and has been the subject of forecasting research using deep learning (Jerse and Marcucci 2024) and the basis for a new hybrid solar activity index incorporating X-ray flare data (Messerotti et al. 2024). In the wide variety of radio solar emissions, intense radio bursts in the L-band (1–2 GHz) can interfere with radio communications and with the reception of radio signals from satellite geolocation systems, drastically reducing the signal-to-noise ratio. Effective interference to GNSS receivers occurs only when the dominant circular polarization of the interfering solar radio burst is right-handed as that of the signals emitted by the GNSS satellites as reported in the extensive analysis by Ref. Muhammad et al (2015). Non-dedicated, single-dish INAF radio telescopes were successfully used for imaging the radio Sun in the centimeter–millimeter band (Pellizzoni et al. 2019, 2022), demonstrating the capability to fill a worldwide observational gap by providing active region radio maps. The development of this technique was complemented by the derivation of the solar radius (Marongiu et al. 2024a) and the emission from active regions based on the study of solar radio brightness profiles (Marongiu et al. 2024b). Dedicated solar radio telescopes are located in Antarctica and North and South high-latitude countries to image the radio Sun at very high frequencies (100 GHz) for monitoring and solar radio weather science and applications have been developed in the framework of the innovative project SOLARIS of Italian leadership (Pellizzoni et al. 2024). SOLARIS has the potential to change the monitoring and forecasting scenario by confirming the flare solar radio precursor presently under analysis in INAF single-dish solar radio observations. The mentioned solar radio weather observations have already been considered in the framework of coordinated LOFAR space weather observations, which will be fostered by the availability of the Italian LOFAR node, hopefully upgraded to space weather observation, and will contribute to square kilometer array (SKA) heliophysics observations as well.

Regarding Italian contributions to the ground-based network of magnetometers, it is crucial to highlight the following:

- SEGMA (South European GeoMagnetic Array), comprising a five-station magnetometer array located in Italy, Hungary, and Bulgaria.
- Geomagnetic observatories over the Italian territory: one in the North (Castello Tesino, IAGA code CTS), two in the center (L’Aquila, AQU, and Duronia, DUR), and one in the Lampedusa island (Lampedusa, LMP) (Di Mauro et al. 2021). All observatories are equipped with tri-axial fluxgate and Overhouser magnetometers, for ultra-low frequency (ULF) magnetic field variations and total field measurements.
- Magnetic station in Italy. In detail at Gagliano Castelferrato (GLA) in Sicily.
- Magnetic observatories in Antarctica. Two are operational: one near the Italian base Mario Zucchelli at Terra Nova Bay (IAGA code TNB) and another near the Italian-French base of Concordia at Dome C (DMC) on the Antarctic plateau. Both of these Antarctic **observatories** are equipped with tri-axial fluxgate and induction magnetometers for ULF (up to 1 Hz) magnetic measurements, as well as with Overhouser magnetometers for the total field measurements. All instruments provide continuous measurements even during the harsh austral winter. Between 2020 and 2024, an autonomous station has been temporarily installed in Antarctica, at Talos Dome (TLD), a remote site on the Antarctic Plateau, about 300 km away from the Italian base Mario Zucchelli (Santarelli et al. 2023).

Geomagnetic data recorded by INGV are available at http://geomag.rm.ingv.it/index.php; the location of magnetic stations and observatories managed by INGV in Italy and Antarctica is shown in Fig. 6.

Besides magnetometers, INGV manages a dense network of GNSS receivers, that includes also scintillation receivers, and ionosondes. GNSS receivers are mainly located at high (Arctic and Antarctic regions) and equatorial latitudes and also in the Mediterranean region. Ionosondes are located in Italy, specifically in Rome, Gibilmannna (in Sicily), Argentina and Africa, the latter being hosted by ASI at the Broglio Space Center. More detailed information on the network and data access can be obtained at http://eswuax.rm.ingv.it/index.php/network/overview.

Significant advancements in high-resolution panoramic spectroscopy for imaging the solar photosphere and chromosphere were achieved through Italy’s contributions to the 90 cm Ritchey-Chrétien optical solar telescope

THEMIS. Italy collaborated with France in a joint project to operate this telescope from the 1990s until 2004. During this period, a consortium comprising the University of Florence, the Tor Vergata University of Rome, and the Arcetri Astrophysical Observatory, successfully designed, built, and operated two innovative interferometric imagers for solar atmospheric research. These instruments, the Italian Panoramic Monochromator (IPM) and the interferometric bidimensional spectrometer (IBIS), utilized a pair of Fabry–Perot interferometers operating at distinct wavelengths (Berrilli et al. 1999a, 1993; Cavallini et al. 1992, 1997, 2000; Cavallini 2006). This dual-wavelength approach enabled the study of different photospheric and chromospheric lines, providing valuable insights into the three-dimensional structure of the solar atmosphere, the turbulent convection processes acting on the photosphere, and dynamics and evolution of magnetic field associated to emerging active regions, and filament eruptions (e.g., Berrilli et al. 1999b, 2002; Consolini et al. 1999; Caccin et al. 1999; Del Moro et al. 2002; Del Moro 2004; Lepreti 2001; Spadaro et al. 2004; Contarino et al. 2003; Zuccarello et al. 2005, 2007,). To prepare for its relocation to the Canary Islands, the IBIS instrument, which had previously been utilized at the NSO's Dunn Solar Telescope, was returned to Italy for a significant upgrade. (Ermolli et al. 2024).

As previously reported in Sect. 1, the European Solar Telescope represents the most pivotal future ground-based endeavor for conducting high-resolution solar research within the European scientific community, including Italy. The project is led by the European Association for Solar Telescopes (EAST), a collaborative effort involving research institutions from 18 European nations.

Italian contributions to the EST technology are significant and span across various subsystems. Notably, Italy has played a crucial role in the development of an adaptive secondary mirror, integrated within the multi-conjugate adaptive optics (MCAO) system (Stangalini et al. 2016; Tintori et al. 2024). Furthermore, Italian expertise is evident in the design and development of the F1 heat rejecter (see Fig. 4), employing efficient jet impingement techniques for effective heat removal at primary focus of large solar telescopes (Berrilli et al. 2010b; Yan et al. 2021). Key advancements include a controllable large-diameter etalon with a digital controller (Greco et al. 2022) (see Fig. 5), EST control software and data handling for high-volume focal plane instruments (Ermolli et al. 2012; Di Marcantonio et al. 2012), and the development of broadband white light channel (Munari et al. 2012) and narrowband channel in the near-infrared for interferometer TIS-EST (Fig. 6).

A complete description of all Italian synoptic facilities for full-disk solar observations at various wavelengths is beyond the scope of this work. Refer to the literature for detailed information on these telescopes (e.g., Amata et al. 2006; Giovannelli et al. 2020; Romano et al. 2022; Ermolli et al. 1998; Oliviero et al. 2002).

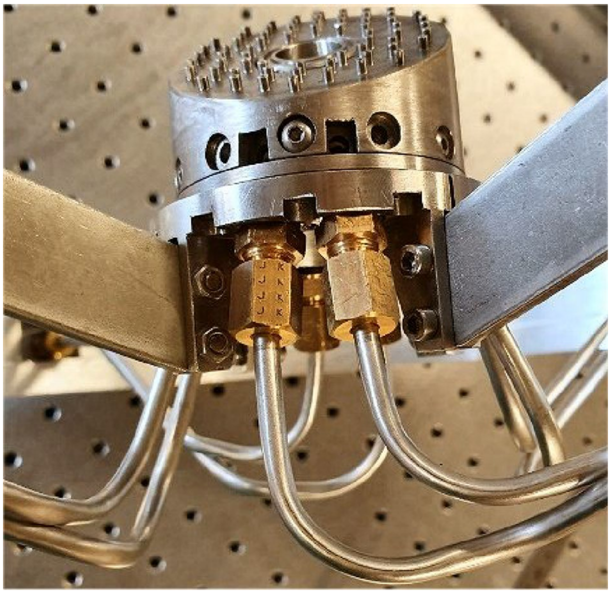

Fig. 4 Heat rejecter prototype for EST: internal view showcasing multiple nozzles for jet impingement. Upper surface (exposed to solar **electromagnetic** radiation) removed

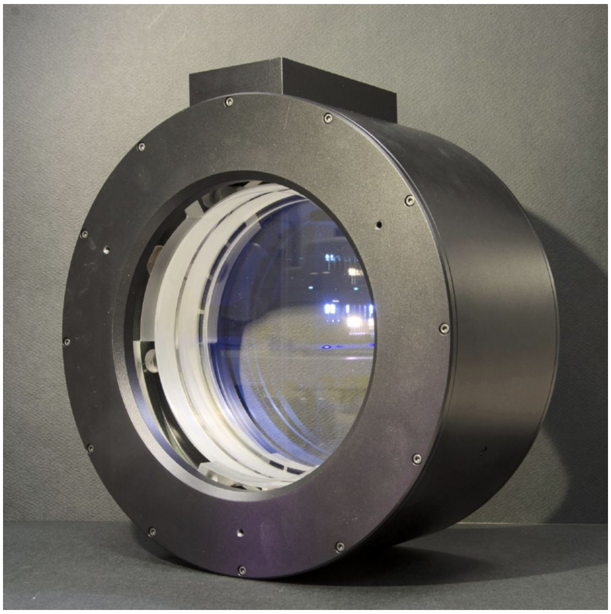

Fig. 5 ICOS large Fabry–Pérot interferometer ET150

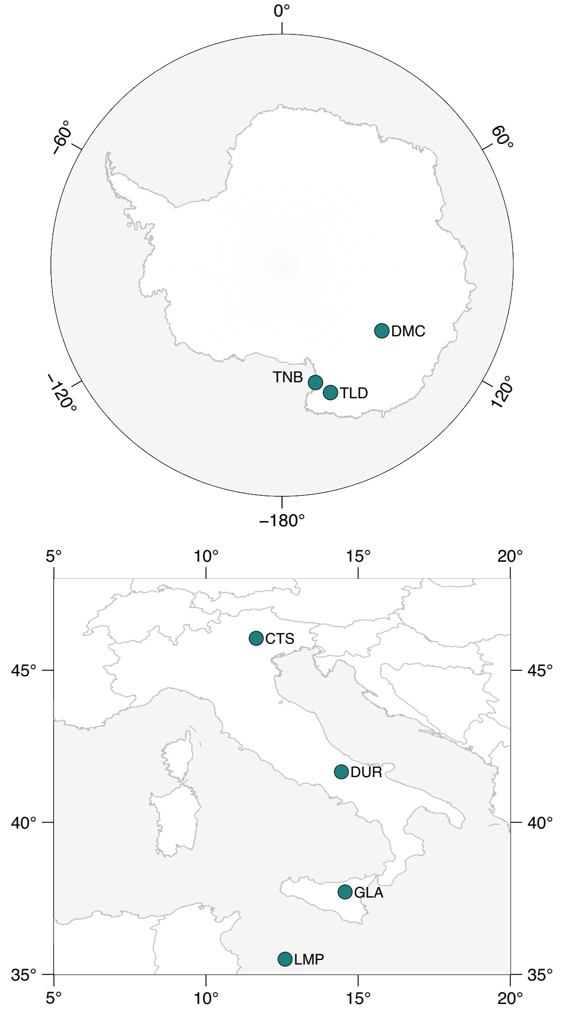

Fig. 6 Top: position of two magnetic observatories, Dome C (DMC) and Terra Nova Bay (TNB), and of the geomagnetic station Talos-Dome (TLD) in Antarctica. Bottom: position of the three magnetic observatories, Castello Tesino (CTS), Duronia (DUR), and Lampedusa (LMP) and of the Gagliano (GLA) station in Italy. Maps are in geographical coordinates

10 Conclusion

This paper was initially conceived as an introduction to the Topical Collection opened for the second SWICo congress held in Rome from February 9–11, 2022, and subsequently for the third congress held on November 27–29, 2024. However, its scope has evolved. Now, it aims to provide an overview of recent advancements in space weather science, with a particular focus on significant Italian contributions to heliophysics and space science. This paper does not intend to be an exhaustive review of all Italian contributions but rather offers a concise summary of the work conducted in recent years through collaborations among Italian institutes, universities, and companies active in this field.

This Topical Collection remains open to host original papers of high scientific and technological value presented at other meetings of our community and which contribute to advances in all the topics of interest to SWICo.

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Declarations

Conflict of interest The authors declare no competing interests.

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