PLANETARY SPACE WEATHER IN THE CONTEXT OF SOLAR SYSTEM EXPLORATION. C. Plainaki[1] [1]Agenzia Spaziale Italiana (ASI), Via del Politecnico snc, 00133, Rome, Italy (christina.plainaki@asi.it)

Introduction: Space weather is the physical and phenomenological state of natural space environments. Any variability of the energy release from the Sun, in form of photon flux, solar wind streams, coronal mass ejections, and solar energetic particle events has been known to be the principal source of space weather in the Inner Solar System environments. Space weather phenomena within a giant planetary system, e.g. the Jovian or the Saturnian systems, are mainly due to the properties of the system itself [1]. The study of either circum-terrestrial or planetary space weather considers different cross-disciplinary topics, such as the interaction of solar wind and of magnetospheric plasmas with planetary and satellite surfaces, atmospheres, and ionospheres; the variability of planetary magnetospheres under different external conditions (solar or non-solar driven); the interactions of planetary radiation belts with atmospheres, satellites and rings.

In this paper some scientific aspects of solar and non-solar driven space weather, at different regions of the Heliosphere, will be discussed, especially in the context of Solar System exploration.

Planetary Space Weather and Solar System Exploration – some technical issues: Planetary space weather can have significant impacts on space missions, affecting spacecraft, communication systems, and even the health of astronauts. Solar flares can lead to radiation storms, posing a threat to astronauts in space. Moreover, spacecraft may need to implement radiation shielding to protect sensitive instruments. Geomagnetic storms can induce electric currents in power lines and pipelines on Earth, increasing atmospheric drag and changes in orbital parameters of satellites, especially at Low Earth Orbit (LEO). Coronal Mass Ejections (CMEs) may also interact with spacecraft or satellites, resulting in increased radiation exposure, electrical malfunctions, and potential damage to onboard electronics. Degradation of solar panels over time due to exposure to energetic particles may also occur. High-frequency radio communication disruptions due to ionospheric changes, at Earth or other planets, can be also caused by solar activity. During solar flares or geomagnetic storms, radio signals passing through the Earth's ionosphere can be disrupted, affecting communication between ground control and spacecraft. Last, the presence of auroras or atmospheric cascades due to relativistic particles of solar origin penetrating the Earth's magnetosphere, can interfere with scientific observations and measurements made by certain instruments onboard spacecraft. For a detailed review on space weather impacts on technology please refer to [2].

While space missions are meticulously planned, unexpected space weather events can still pose challenges. There are several examples where space weather has created problems during planetary missions.

In 2001, the Mars Global Surveyor (MGS) experienced anomalies in its operations. It was later determined that a series of solar flares had caused a high-energy particle event, which disrupted the spacecraft's computer memory and led to temporary communication and attitude control issues. The unusually dense Martian ionosphere on 15 and 26 April 2001, detected through enhancements in radio signals from the MGS, was attributed to some extra production of ions and electrons after the occurrence of several flares. Similar modifications in the Earth's ionosphere at these times were also measured (the Sun, Earth and Mars were nearly in a straight line at that time [3]).

The Galileo spacecraft, in orbit around Jupiter, experienced difficulties during its mission in the 1990s. The spacecraft's systems were exposed to intense radiation from Jupiter's magnetosphere, leading to the degradation of certain instruments and challenges in data transmission [4]. To mitigate the risk of critical system failures, the mission planners carefully managed the spacecraft's operations and prioritized data collection during its operational life. The risk to have space weather effects on spacecraft in the Jovian system has been taken into account during the design phases of missions next to Galileo. For instance, to minimize exposure to Jupiter's intense radiation environment, the NASA Juno mission design included highly elliptical polar orbits that carry the spacecraft beneath the most intense radiation belts, especially early in the mission [5]. ESA's Juice mission has been designed to withstand a number of core challenges, such as high radiation and harsh temperatures. Numerous studies focusing either on simulations performed to optimize the shielding of the instruments and to determine the radiation damage during the mission (see, for instance [6]) or the development of software tools for detailed radiation analysis (see, for instance, [7]) have been precious in this context.

Planetary Space Weather in the Outer Solar System – science and beyond: While much of the attention in space weather studies focuses on the Sun and its impact on the inner planets, the outer planets, also experience unique space weather phenomena.

All planets in the outer Solar System possess magnetic fields, which can be assumed to have approximately either a dipole form or a multipole form. Space weather at the environments of the outer planets mainly depends on one hand on the solar wind density and the IMF intensity and direction, and on the other hand on the planetary magnetic field tilt and plasma pressure inside the magnetosphere.

Uranus is an ice giant, and like other gas and ice giants in the outer solar system, it has a different set of characteristics compared to the inner rocky planets. Uranus has a unique and tilted magnetic field, which is tilted at an angle of about 60 degrees relative to its rotation axis, quite different situation from the relatively aligned magnetic fields of other planets. Its magnetosphere is also asymmetrical, and this asymmetry has an impact on the way it interacts with the solar wind. Understudying the upper atmosphere physics is also a challenge. The Voyager 2 spacecraft, which flew by Uranus in 1986, provided valuable data (e.g., [8]). Still, there is much to learn about this distant ice giant, currently observed with HST [9], VLA [10] and other telescopes. Future missions and observations may shed more light on Uranus' unique space weather characteristics. Neptune has also a strong and complex magnetic field, which is tilted at an angle of about 47 degrees relative to its rotation axis. This tilt contributes to a dynamic interaction with the solar wind, leading to various space weather effects. While Neptune's space weather is intriguing, it's important to note that our overall understanding of the related physical phenomena is still very limited. Future missions and advanced telescopic observations (e.g., with HST, Keck Observatory, JWST, and other) may provide more insights into the unique space weather characteristics of Neptune.

Planetary space weather in the Jovian system involves a variety of dynamic and intense phenomena driven by Jupiter's strong magnetic field, its rapid rotation, and interactions with its moon system. Jupiter's powerful magnetic field traps charged particles, creating intense radiation belts [11]. As charged particles interact with the planet's atmosphere, they produce auroras near Jupiter's polar regions. JIRAM onboard Juno recently observed Jupiter's IR aurora, arising from the precipitation of electrons from its magnetosphere on the planet's upper atmosphere, above the magnetic poles [12]. They are accompanied by magnetic footprints of the three natural satellites Io, Europa and Ganymede (e.g., [13]). JIRAM discovered that these footprints resemble, in shape, the motion of an obstacle in a fluid although there is still no clear explanation of how this happens [12].

Ganymede, one of Jupiter's largest moons, has its own intrinsic magnetic field that interacts with Jupiter's magnetosphere, creating a dynamic region of magnetic reconnection and plasma interactions. This complex interplay contributes to the overall space weather dynamics in the Jovian system. Recent simulations of the ion and electron circulation within Ganymede's magnetosphere evidenced the role of the environment variability in the evolution history of the moon's surface[14][15]. Studying space weather at Ganymede contributes not only to our understanding of this moon but also enhances our knowledge of magnetospheric dynamics and interactions in the broader context of planetary systems. The upcoming JUICE mission is expected to provide new insights into Ganymede's space weather and the complexities of the Jovian moon system.

Concluding Remarks: By adopting a synergistic approach approach that combines engineering solutions, operational strategies, and collaborative efforts, space agencies and universities can enhance the resilience of missions to the challenges posed by space weather. Continuous advancements in technology and our understanding of space weather will contribute to the development of more robust and adaptive mission protection measures in the future. Predicting space weather is not only important for safeguarding spacecraft but also for enhancing the overall quality and reliability of scientific research across various disciplines. It enables researchers to account for external influences, improve the interpretation of observational data, and make informed decisions about mission operations.

References:

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