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Plasmas Across the Heliosphere: From the Sun to the Edge of the Solar System

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The heliosphere is a vast plasma bubble around the Sun moving together with our star through the interstellar medium. The heliosphere is filled with plasma streams ranging from slow to fast speeds (canonical speeds: ~400 km s^{-1}, and ~700 km s^{-1} respectively) and is composed of solar magnetic fields, electrons, protons, and ions, flowing out from the Sun as *the solar wind*, as well as energetic particles, interstellar neutral atoms, and dust particles. The solar wind extends out and interacts with the local interstellar medium forming the heliospheric boundary at 120 astronomical units (au; 1 au is a distance from Sun to Earth; 120 au ~20 billion kilometers) from the Sun. The heliosphere encapsulates the whole Solar System and all the planetary bodies within.

Nearly all plasma flowing through the heliosphere originates from the Sun. This plasma is composed of the aforementioned solar wind streams but is also populated by transient structures such as flows, and eruptions known as solar *coronal mass ejections (CMEs).* Fast CMEs drive shock waves that can generate relativistic energetic particles, which reach Earth within minutes of creation. CMEs are some of the most energetic events produced in the solar system, and an average sized CME can produce over 10^{22} Joules of energy [1], exceeding estimated human energy consumption per year, which is around 10^{20} Joules [2]. The solar wind streams, and eruptions are the main components of *space weather*, the time varying conditions that can affect planetary systems and human infrastructure.

The process known as magnetic reconnection underpins the conversion of magnetic energy into kinetic and thermal energy, reconfiguring magnetic fields throughout the heliosphere, driving both small and large-scale energy release. In the lower solar atmosphere, magnetic reconnection drives solar wind formation, impulsive events across a broad energy spectrum (e.g., *solar flares*, and CMEs), and energetic particle acceleration.

The heliospheric plasma and aforementioned energetic particles bathe planets throughout the solar system, and interact with their atmospheres and *magnetospheres*–a planet's intrinsic magnetic field–driving their dynamics, and energetic phenomena such as aurorae. A planet's magnetosphere can act as a shield, protecting the planet from the solar wind, solar energetic particles, and extra-solar particles known as galactic cosmic rays. Under certain conditions magnetic reconnection can occur between the heliospheric and magnetospheric magnetic fields, which can unlock the magnetosphere injecting plasma into the Earth system. However, not all planets in our solar system have protective magnetospheres; immersing the surfaces and atmospheres of these exposed planets in harsh solar radiation and high energy particles, which can produce dramatic atmospheric effects, such as atmospheric erosion [3, 4]. Luckily for us, Earth is one of the planets with a magnetosphere, protecting us and allowing life to thrive. Nevertheless, the solar wind interacts with the Earth's magnetosphere, altering the radiation environment and causing its electrical charge and density to fluctuate. In particular, these changes can influence the performance of satellite electronics, communication systems, GPS signals, and impact the health of humans in space. Moreover, space weather *can* interfere with ground-based instrumentation, and during extreme conditions it can even produce *ground level enhancements* of energetic particles, which can disrupt electrical utility grids. A recent example of the adverse effects of space weather was the loss of 40 Starlink satellites early in 2022 [5], resulting from a *geomagnetic storm*, a major disturbance of Earth’s magnetosphere, driven by the solar wind, which rapidly changed the atmospheric conditions for the satellites, and ultimately increased spacecraft drag. Studying the Sun, space weather, and the heliospheric plasma conditions can help us understand and predict these complicated events. Understanding how the magnetosphere reconfigures and responds to a solar storm, and every-day solar wind energy input, remains an active area of research.

Many different types of instruments and observational techniques are used to measure plasma properties and investigate plasma interactions in the heliosphere. These are broadly divided into *remote sensing* and *in-situ* instrumentation and observations. As the name suggests, remote sensing instruments observe from afar. Remote sensing observatories not only allow us to track structures and energetics near the Sun, but also allow us to infer plasma parameters such as temperature, density, and composition, through our understanding of the underlying atomic and spectral physics generating the observed emission. Being unable to sample the inner coronal plasma directly, these remote observations have left heliophysicists with several intriguing open questions, such as: how is the solar atmosphere heated? [6], what triggers solar eruptions, and dictates their kinematics? and how is the solar wind formed?

In contrast to remote sensing instrumentation, in-situ instruments sample *local* plasma conditions, on dedicated observatories positioned around the inner solar system, in planetary and solar orbits, as well as on trajectories escaping the Solar System. In-situ observatories directly measure local plasma properties, including: magnetic field strength, particle velocities, charge states, and densities amongst other parameters. Linking in-situ measurements with remote sensing observations is a constant challenge for heliophysicists who attempt to identify the source of plasma disturbances. Sophisticated modeling of the global solar and heliospheric environment [7, 8] are often required to accurately link remote and in-situ observations.

Although sparse, the selection of instruments have allowed us to connect observations near the Sun to those throughout the solar system, allowing us to map space weather to its origins. Figure 1 shows a series of observations made between 15 and 17 March 2015, when a dramatic CME interacted with the Earth producing a geomagnetic storm and spectacular aurorae. Panel (a) in Figure 1 shows a composite image of the CME near the Sun, using observations taken at around 03:45 Universal Time (UT) on March 15 using remote sensing instrumentation. The innermost image (brown) shows the Sun through an extreme ultraviolet filter (corresponding to a temperature of around 1.2 million degrees), extending out to 1.3 solar radii ($R_\odot$; One solar radius is about 700,000 km) from the center of the Sun–where the white circle highlights the eruption source region. The middle image (red) and outer image (blue) of panel (a) show white-light images from two LASCO coronagraphs extending from 1.5 to around 12 $R_\odot$. The leading edge of the eruption is highlighted by the white arrow. The eruption interacted with Earth's magnetic field and atmosphere, producing dramatic aurorae observed on March 17. The initial auroral activation was recorded by the white-light THEMIS all-sky imagers starting around 06:34 UT (b), and peaking around 08:00 UT (c). This event highlights our capabilities to monitor space weather events as well as the background solar wind, from their origins on the Sun and their continuous evolution throughout the heliosphere.

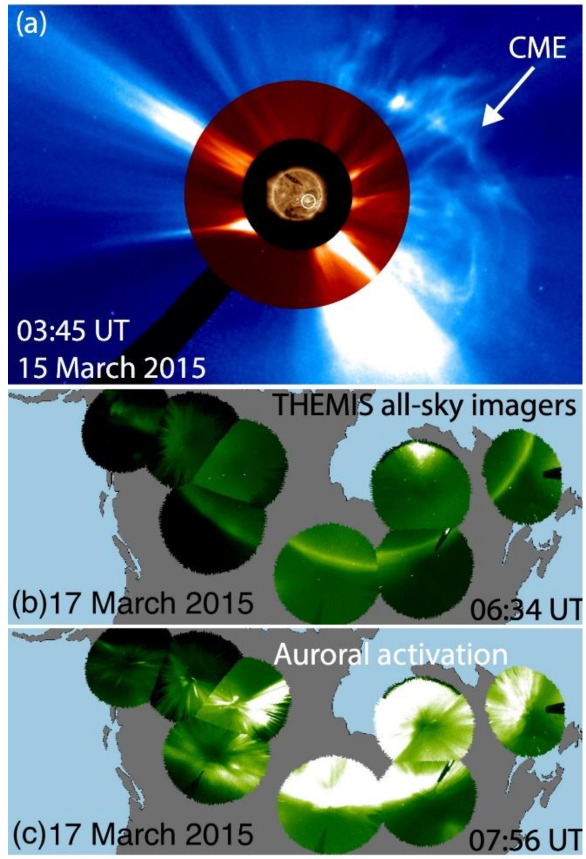

Figure 1. On March 15, 2015 a CME was observed by the AIA instrument and LASCO coronagraphs (panel a). This plasma activity was later detected near Earth by the THEMIS all-sky imaging system monitoring the northern lights (panels b-c).

As the solar wind expands with supersonic speeds (faster than the local speed of sound) away from the Sun, to distances greater than Earth's orbit, its density, temperature, and magnetic field strength drops. At around 10 au from the Sun the solar wind begins to feel the effects of *interstellar neutral atoms* from interstellar space, moving freely into the heliosphere, without being influenced by electromagnetic fields. Collisions and charge exchange–where a neutral atom interacts with an ion and exchanges an electron–between solar wind ions and interstellar atoms create a new population of ions in the heliosphere called *pick-up ions*. These ions are very energetic compared to typical solar wind ions, and while pick-up ions constitute only 20% of solar wind ions in the outer heliosphere, they carry 80% of the energy. Pick-up ions are thought to play a major role in heating the solar wind in the outer heliosphere, and dominate the pressure balance upholding our heliosphere against the local interstellar medium.

The two Voyager spacecraft, launched in 1977, were the first satellites to have measured in-situ plasma at the heliospheric boundary. They discovered the *heliospheric termination shock* at 90 au from the Sun [9], where the solar wind sharply slows down from supersonic to subsonic speeds. Later at 120 au the Voyagers traversed the *heliopause* [10], the ultimate heliospheric boundary which separates the solar wind and interstellar plasma (Figure 2). Today the Voyagers continue their journey in the space between stars providing first insights into the heliosphere`s galactic neighborhood.

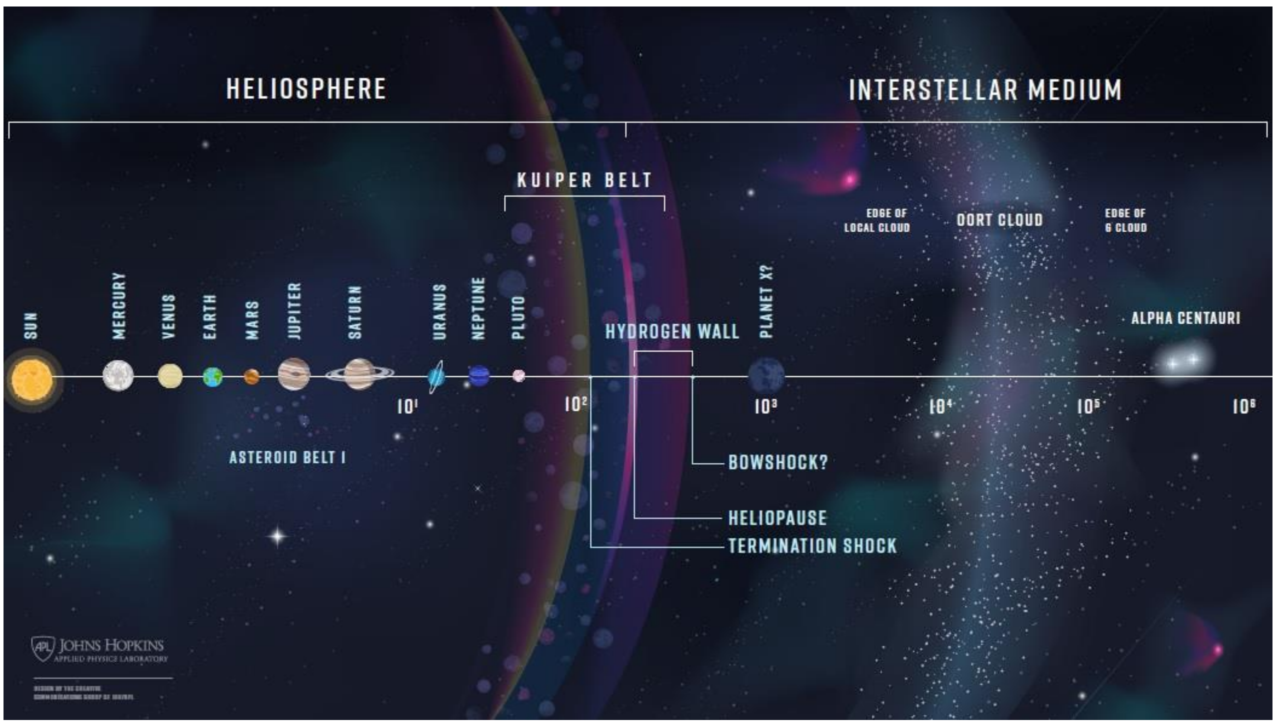

Figure 2. The heliosphere encircling the solar system extends beyond the orbit of Pluto. The termination shock marks a boundary where the supersonic solar wind slows down to subsonic speeds. The boundary of the heliosphere - the heliopause - separates two distinct types of plasmas - solar and interstellar. Image Credit: Johns Hopkins APL. Objects are not to scale.

Our heliosphere is the only known *astrosphere* that harbors life. However, astrospheres are abundant in the galaxy, and similarly form around other stars, generated by stellar winds blown into interstellar space. Analogous to how the Sun's solar wind and radiation can drive geomagnetic storms at Earth, stellar winds can affect physical and chemical processes in atmospheres of exoplanets, planets orbiting other stars. The vicinity of our heliosphere provides a unique laboratory where humans can explore plasma processes in the solar wind, interactions with solar system bodies, and with the surrounding local interstellar space, as well as fundamental plasma processes, such as the universal nature of particle acceleration, magnetic reconnection, turbulence, and high energy emission that cannot be replicated in the laboratory on Earth.

Further Reading

[1] https://spacemath.gsfc.nasa.gov/weekly/4Page17.pdf

[2] https://www.theworldcounts.com/challenges/climate-change/energy/global-energy-consumption

[3] https://solarsystem.nasa.gov/resources/2288/the-solar-wind-across-our-solar-system/

[4] https://www.science.org/doi/epdf/10.1126/science.7732377

[5] https://www.nytimes.com/2022/02/09/science/spacex-satellites-storm.html

[6] https://science.nasa.gov/news-articles/the-mystery-of-coronal-heating

[7] https://www.swpc.noaa.gov/products/wsa-enlil-solar-wind-prediction

[8]https://www.nasa.gov/feature/goddard/2021/scientists-use-nasa-data-to-predict-corona-of-dec-4-antarctic-eclipse

[9] Stone, E. C., Cummings, A. C., McDonald, F. B., Heikkila, B. C., Lal, N., & Webber, W. R. (2008). An asymmetric solar wind termination shock. *Nature*, *454*(7200), 71-74.

[10] Stone, E. C., Cummings, A. C., Heikkila, B. C., & Lal, N. (2019). Cosmic ray measurements from Voyager 2 as it crossed into interstellar space. *Nature Astronomy*, *3*(11), 1013-1018.

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DR ELENA PROVORNIKOVA is a Senior Scientist at The Johns Hopkins University Applied Physics Laboratory. My research interests focus on developing physics-based computer simulations to understand the evolution of large-scale structures in the solar wind in the region from the Sun to Earth and beyond Earth's orbit to the heliospheric boundary. I apply magnetohydrodynamics to uncover the plasma and magnetic structure of the solar coronal mass ejections and how they propagate in the heliosphere, shaping plasma and energetic particle environment. Dr. Provornikova was awarded NASA Living with the Star Jack Eddy Postdoctoral Fellowship in 2015 and AFOSR Young Investigator Award in 2020.

DR BEA GALLARDO-LACOURT is a research associate at Catholic University of America and NASA Goddard Space Flight Center. The overall theme of my research is the interaction between the solar wind and Earth's magnetic field to create a dynamic plasma environment around our planet, one consequence of which is the aurora. The aurora allows us to visualize important plasma processes that occur in the coupled magnetosphere-ionosphere system. In my research, I combine in-situ satellite data with ground-based instruments to understand space plasma dynamics at high and mid-latitudes on Earth.

DR MATTHEW J. WEST is a Senior Research Scientist at Southwest Research Institute. Specializing in research on both the small and large-scale solar corona. His main focus is on how energy can be liberated through solar eruptions, magnetic reconnection, and can drive space-weather. Dr West has worked in both theoretical and observational areas of research, and recently on mission design and management. He is the co-founder of the Middle Corona working group, and has long-term goals to develop new methods to probe the previously un-measurable properties of this region. Dr West's honors include: The Stefan Hepites prize, and the Roxburgh award.