Interdisciplinary Soft X-ray Observations of the Earth's Magnetosphere Including from the Moon

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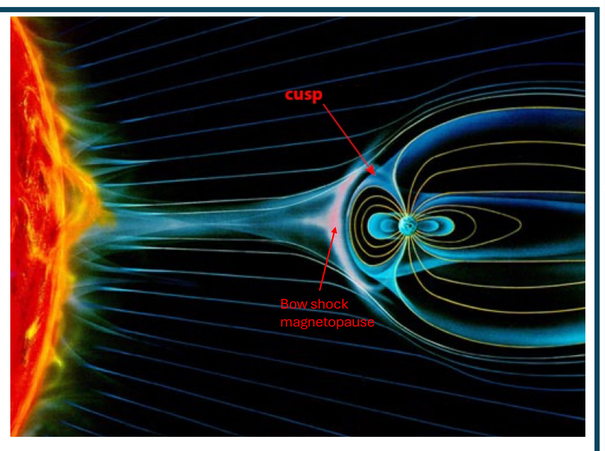
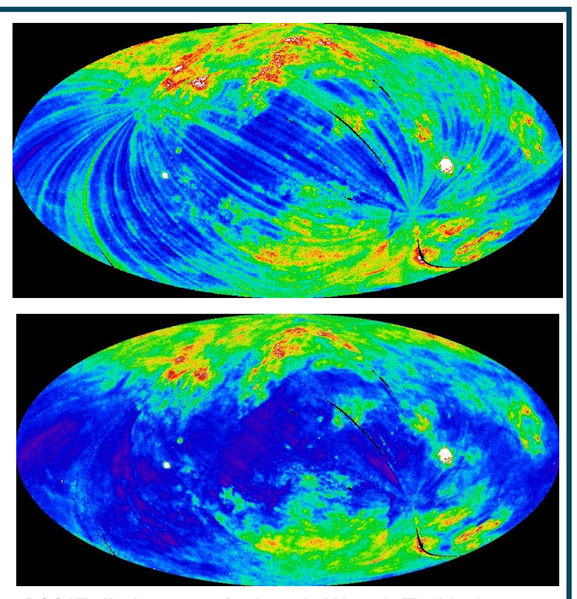
Abstract: The Earth's plasma environment is governed by the complex interaction of the solar wind with the Earth's magnetic field and the Earth's outer atmosphere. This interaction is the source of space weather in the Earth-moon system and a large field of ongoing research. The primary tool for studying the solar wind-magnetosphere interaction are in-situ satellites with suites of instruments that measure plasma and magnetic field parameters as they move through the system. What has been missing are global measurements that image the solar wind plasma as it circulates in the magnetospheric system. Luckily, the solar wind plasma emits strongly in the soft x-ray band as the solar wind plasma encounters the Earth's exoatmosphere, especially in the high-density plasma region near the Earth's magnetopause. This effect was first observed by ROSAT and subsequently by Chandra, XMM, Suzaku, SWIFT, and XRISM. Unluckily, this emission complicates soft x-ray astrophysical observations especially from low earth orbit. However, what is a complication for astrophysics is high profile science for space weather and heliophysics. Soft X-ray emission is the key to imaging the magnetosphere to improve the models that are needed to predict and account for foreground emission for astrophysical x-ray telescopes. Our astrophysics-heliophysics collaboration has led to a series of missions including four sounding rockets, a cubesat, the LEXI CLPS instrument on the moon, and the just launched European SMILE mission. However, more is needed. Larger, wide field of view X-ray telescopes with substantial throughput are needed to understand the dynamics of the magnetosheath and improve the models needed to predict foreground x-ray emission. Here we will discuss the science from both the heliophysics and astrophysics perspectives, the moon as an excellent vantage point to make these measurements, and what instruments and mission scale (large!) are needed to make progress.

Solar Wind: The solar wind is made up of predominately protons and alpha particles with trace amounts of the abundant elements including carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, and iron. The ionization state of the solar wind components reflect a frozen-in temperature of 0.1-1e^6 K and an average density of ~5/cm^3 at 1 au from the sun (i.e. at Earth). The solar wind speed varies from 300-800 km/s.



The solar wind, including storms, coronal mass ejections, etc., powers the near-earth plasma environment and thus space weather within the Earth-moon system. The dynamics of the interplay between the solar wind input and the response of the Earth's magnetospheric system is a large field of study within Heliospheric science with many outstanding questions. Major questions include a basic understanding of global energy flow, particle acceleration, magnetic reconnection, collisionless shocks, and the dynamics of boundaries. Measurements of the magnetosphere are largely made *in-situ* by spacecraft circulating within the system. What is missing is a high cadence, global picture, of the movement of plasma within the magnetosphere and its response to its environment.

X-ray emission: Astrophysicists realized fairly late (Cravens, 2001) that the solar wind could generate soft x-ray emission near the earth. The analysis of the ROSAT all-sky-survey data (Snowden et al., 1997) revealed temporal variations on a timescale of hours-to-days that were not understood. Since the point of the survey was to measure the soft x-ray background due to the galactic halo, the local hot bubble, and other reservoirs of hot gas within the galaxy, the times of temporal variation were simply discarded. Cravens et al. (2001), then theorized that the temporal variations were the result of x-ray emission from charge exchange recombination between the solar wind and neutral atoms in the vicinity of Earth and also in interplanetary space.



ROSAT all-sky survey in the ¼ keV band. (Top) before the removal of temporal variations, and (bottom) after the data was cleaned.

Charge exchange is the process by which a highly charged ion steals an electron from a neutral or near-neutral atom. This is a process well known in other fields of physics, for example it is both a cooling mechanism and a critical diagnostic in magnetically confined fusion. For highly charged trace elements in the solar wind, the capture of an electron from exoatmospheric neutrals near the earth gives rise to inner shell transitions that produce X-rays.

The production of near-earth X-rays is concentrated in the nose of the magnetosheath where the solar wind ions forward motion is slowed by the Earth's magnetic field and the ions begin streaming along the Earth's magnetic field lines. This creates a significant overdensity of ions in a region where the Earth's exo-atmosphere is significant.

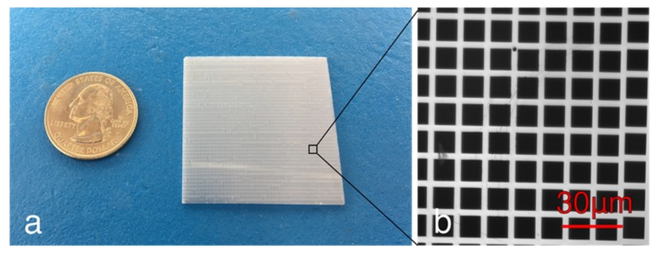
X-ray emission from the charge exchange process has now been observed in many systems within the solar system including solar wind interacting with comets, the Martian atmosphere, interplanetary neutrals, and plasma within the Jovian system. It has also been observed astrophysically, for example in the supernova remnant N132D with the XRISM observatory.

For the near-earth environment, X-ray generation within the Earth's magnetosphere complicates soft x-ray astrophysical observations from low earth orbit. This has been seen with ROSAT, Suzaku, Chandra, XMM, Swift, and XRISM, for example. ~20 years ago, we approached scientists studying the geospace plasma environment in order to acquire dynamic models of the magnetosphere so that we could model and subtract the soft x-ray foreground from observations using near-earth x-ray observatories. These same scientists were independently looking for a method to image the entire magnetospheric system at high-cadence in order to vet and improve these same models.

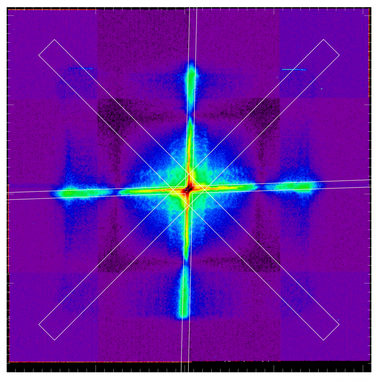
The resulting interdisciplinary Astrophysics/Heliophysics collaboration has now flown four sounding rockets, a cubesat, a lunar surface experiment, a small orbiting platform, and is pursuing a larger scale mission to make routine, high cadence observations.

Key Technology for global soft x-ray imaging: The figure of merit for observing low surface brightness extended objects is grasp, the product of effective area (aperture) and field-of-view. Most x-ray telescopes are fairly narrow field of view and grasp is coupled strongly to effective area. However, lobster eye optics (Angel, 1979) have a wide field-of-view (many degrees) with modest collecting areas (nominally 10s of cm^2) yielding telescopes with very large grasps.

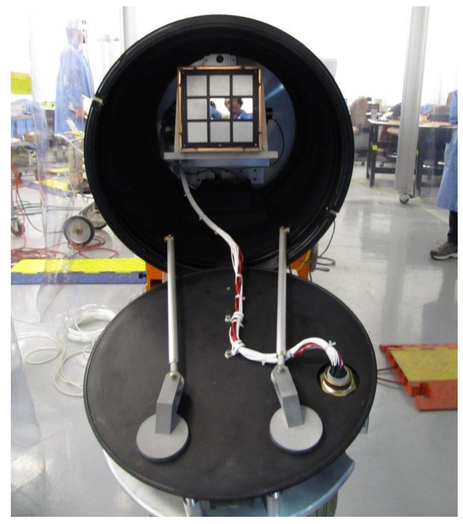
"Lobster" optics, also called MicroPore optics (MPOs), focus x-rays by reflecting off of two adjacent walls of a square pore. An array of square pores slumped on a sphere produces a strong focus. The optics are light weight, easy to assemble, but suffer from optical aberrations including a line focus due to single reflections, and lowered contrast due to unreflected x-rays



4x4 cm "Lobster" optic produced by Photonis

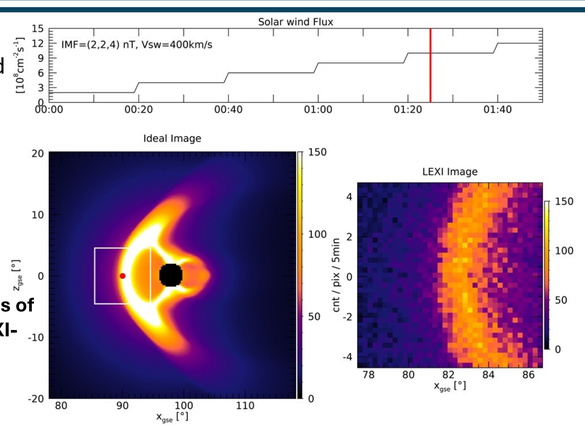


X-ray Beamline measurement of a NightVision MPO optic at GSFC showing a strong central focus but also line foci from single reflections and a background haze of non-reflected X-rays



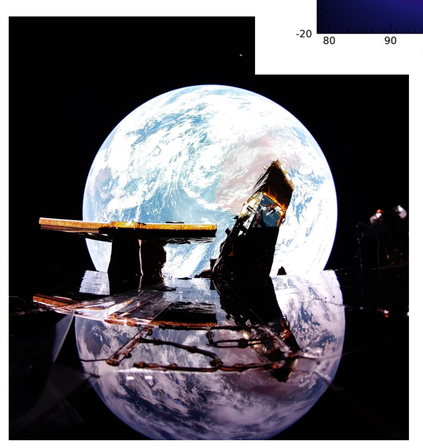
First flight of MPO optics on the DXL/STORM sounding rocket payload in 2012

Small scale pathfinder missions: The first demonstration of MPO optics in space was on our DXL I sounding rocket mission that included the DXL/STORM instrument as a ride-on technology demonstration in 2012. This was followed by the CUPID cubesat instrument demonstrated on the DXL II sounding rocket in 2015 and then flown as a 12U cubesat in 2021. Cupid did not succeed due to failures of the radio and attitude control system, but the DXL/STORM instrument was refurbished as the LEXI instrument which landed on the moon in 2025 on the Blue Ghost lander.

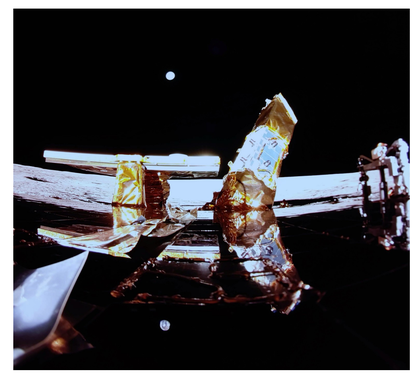


Simulated X-ray observations of the magnetosphere for a LEXI-like instrument

Firefly's Blue Ghost lander, with the LEXI instrument in the upper left corner. The mission was launched in January 2025 and landed on the moon in March 2025.



The Earth reflecting off the solar panels on the top deck of the lander with the LEXI instrument on the upper right

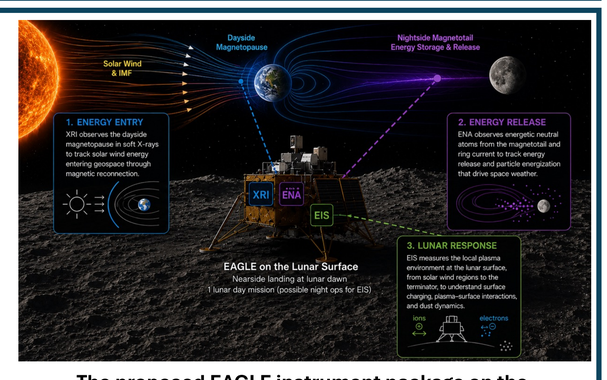


LEXI on the lunar surface in March 2025

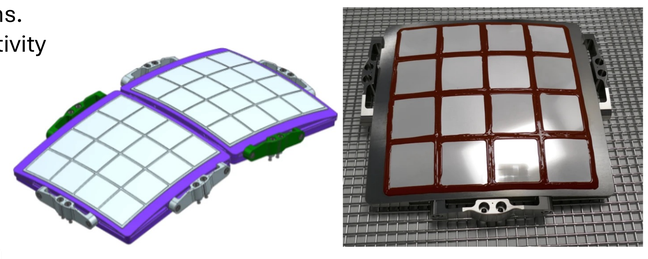
Need for larger observatories and a good vantage point: The ultimate goal is to measure dynamics in the magnetosphere on timescales that differentiate and vet global models. This is currently understood to be about 2 minutes. The field of view also has to be large enough to capture critical features such as the magnetopause boundary that generally manifests at about 8 earth radii but can move inwards or outwards from ~4 to 12 earth radii. This necessitates a large grasp instrument from a good vantage point outside the magnetosphere.

LEXI has shown that the moon is a good vantage point for a global imaging suite, and we are currently proposing a multi-instrument, but still small-scale observatory ("EAGLE") through the PRISM program. The SMILE mission (ESA/CAS) includes a mid-scale MPO X-ray instrument that launched in May 2026. SMILE is in a highly elliptical orbit that only peeks outside the magnetosphere, but with somewhat higher sensitivity that will produce global images during solar storms.

To make substantial progress, we need a large grasp, high sensitivity instrument at a good vantage point (~30 RE, or lunar orbit, or lunar surface). One such instrument was proposed as part of the STORM MiDEX mission in (proposed 2019, phase A 2022, not selected). STORM, like many Heliophysics missions, contains a suite of instruments to observe Earth's magnetospheric system. We are continuing to study a monolithic observatory like STORM, a dual vantage tomographic system, and a disaggregated system that can ride share with other NASA, military, or commercial spacecraft.

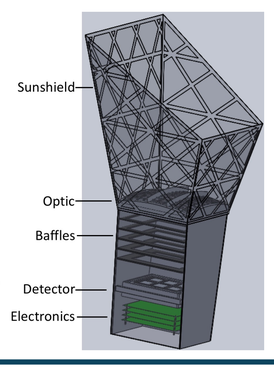


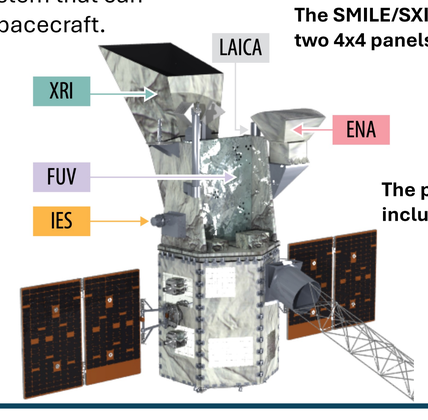
The proposed EAGLE instrument package on the lunar surface includes the XRI soft X-ray imager



The SMILE/SXI soft x-ray imager includes two 4x4 panels of MPO optics

The proposed STORM/XRI instrument has a 23x23 degree FOV using a 10x10 array of MPO optics and a 0.5 m focal length. Since it is a morphology experiment it has a microchannel plate focal plane. The instrument has a total effective area of ~10 cm^2 at 1 keV.





The proposed STORM Midex mission includes the XRI soft x-ray imager.