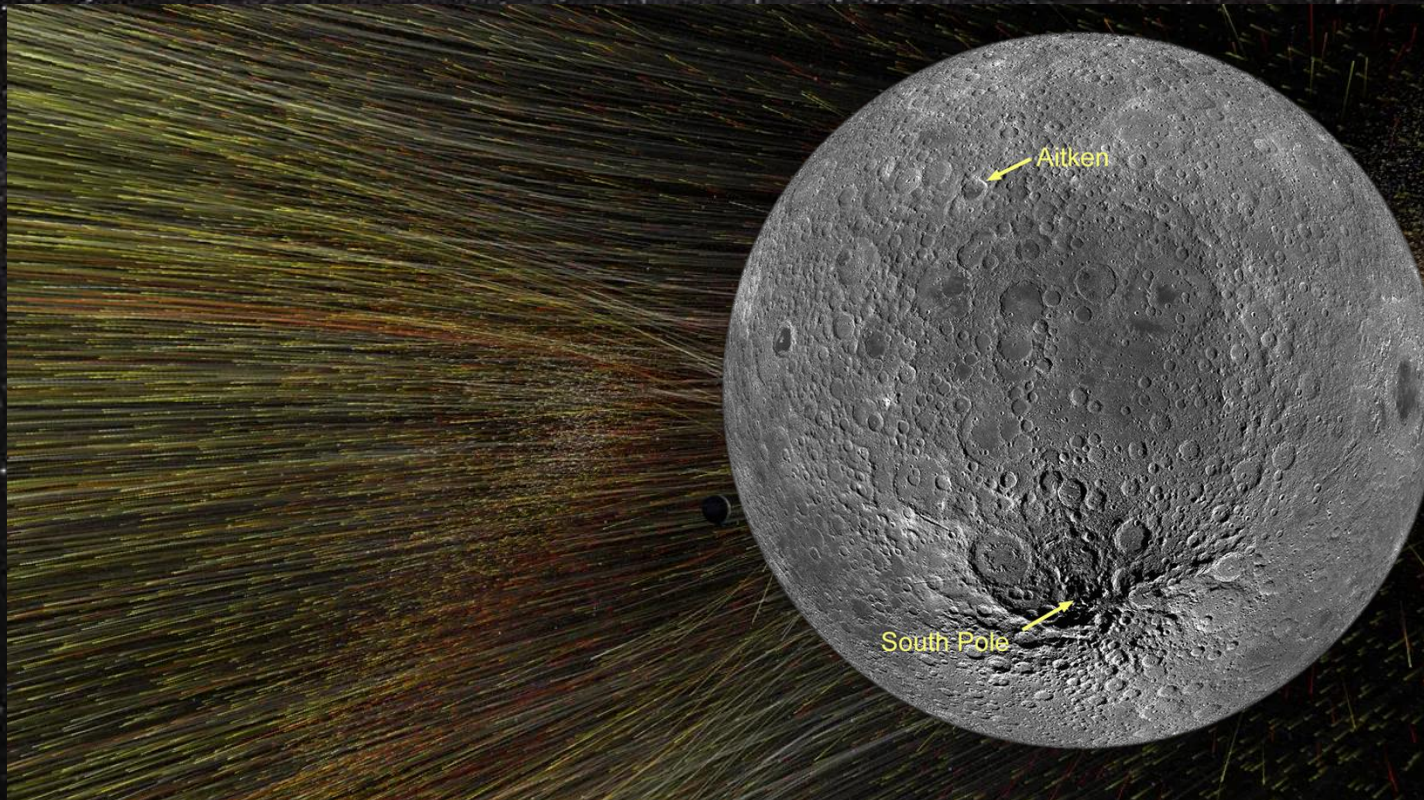
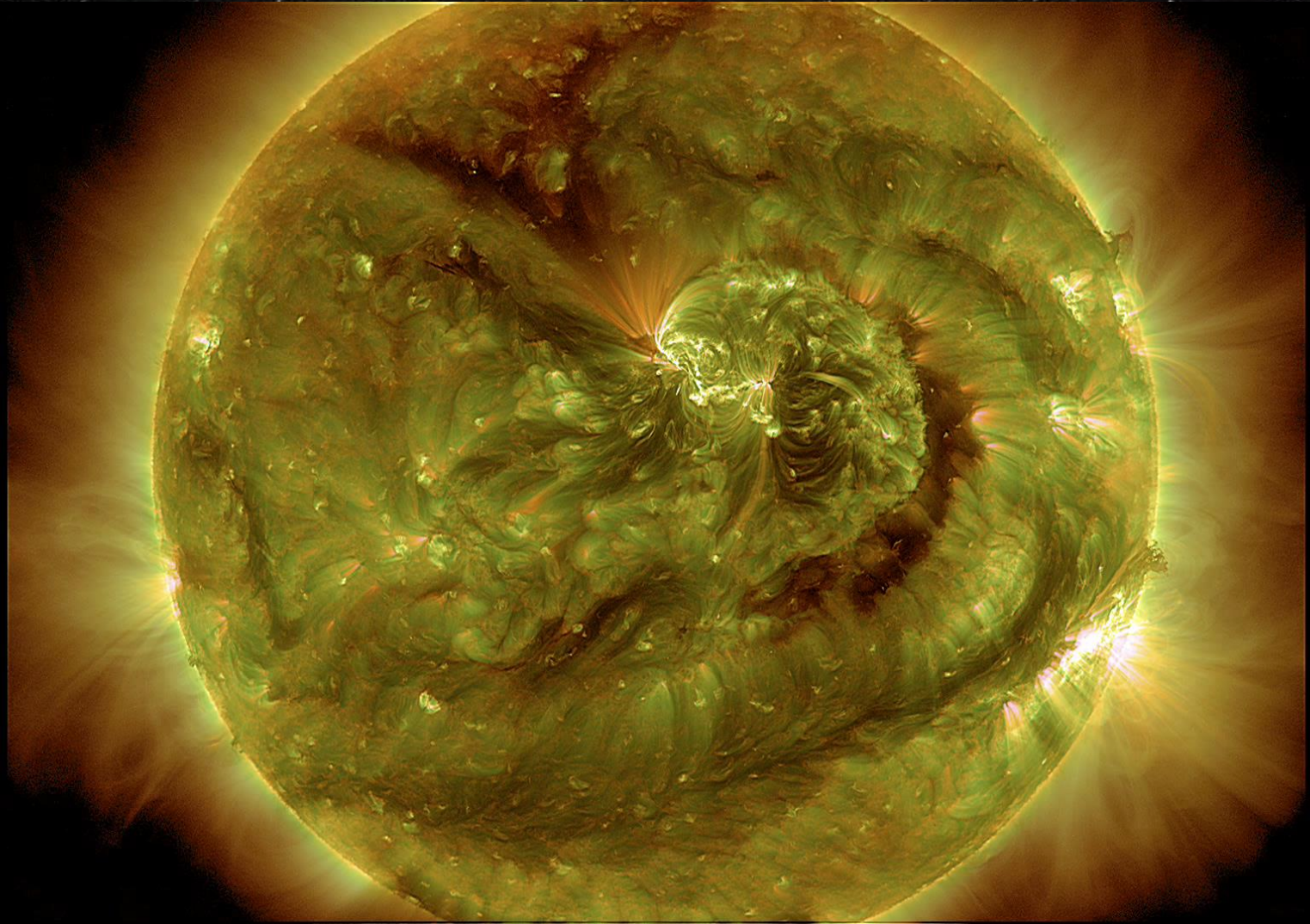


From Heliophysics to Moon and Mars: Impact of Sun on Space Exploration

V. S. Airapetian (NASA GSFC and American University)

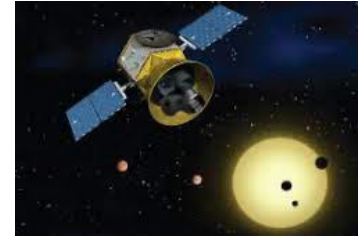
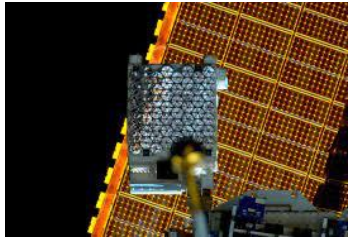
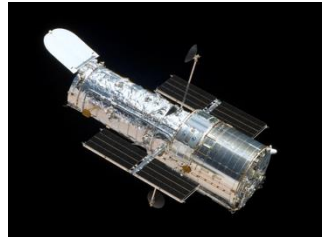


Our Sun is a Magnetically Active Star



Space Weather Signatures Around Young Suns

DS TucA (Aug 2023; Mar 15-21, 2024), EK Dra (Mar 27-31, 2024)



FUV/HST

SXR/NICER

SXR/NUV/SWIFT

HXR/Nu-STAR

Optical/TESS



SEIMEI 2.6m/CRAO

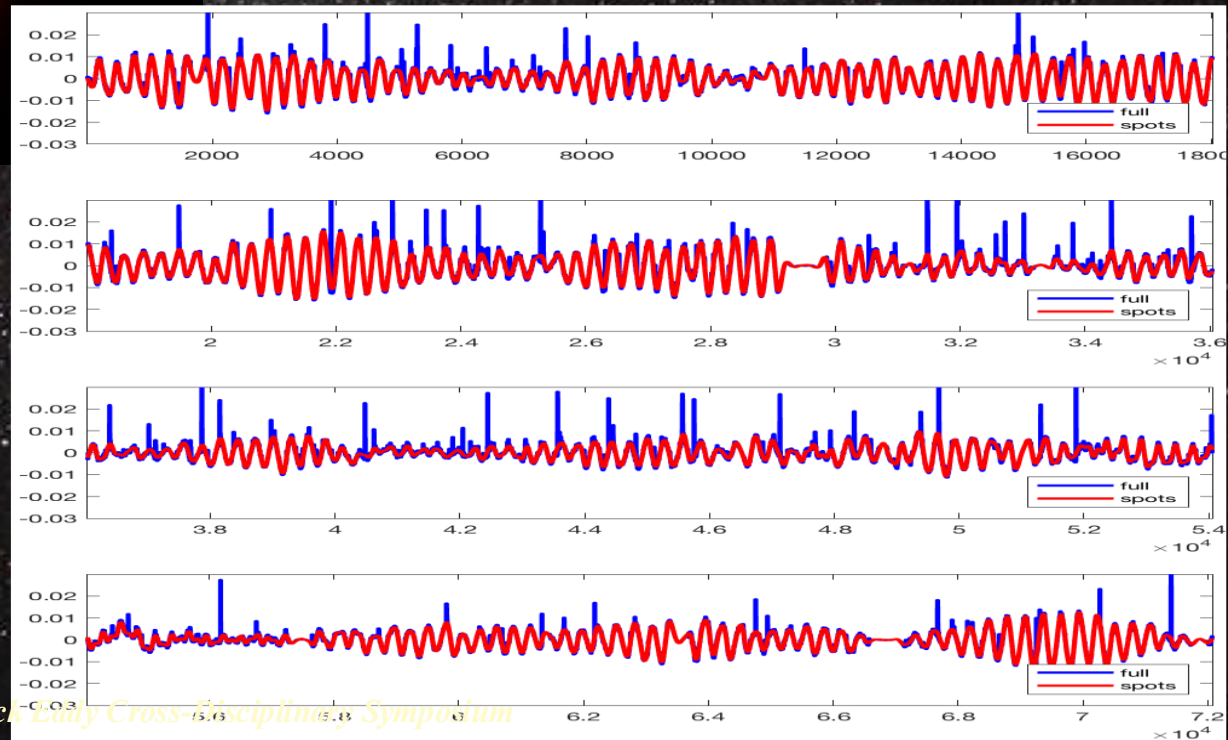
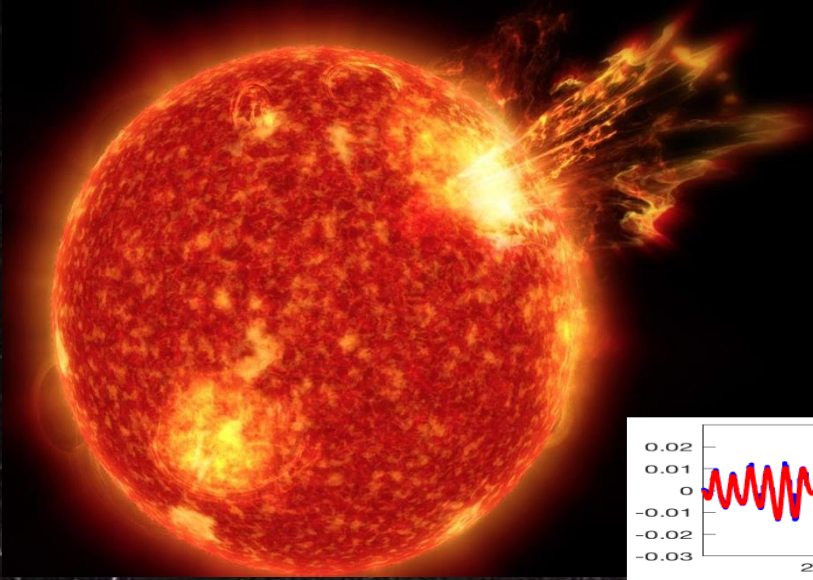
LCO/SAfrica

VLA

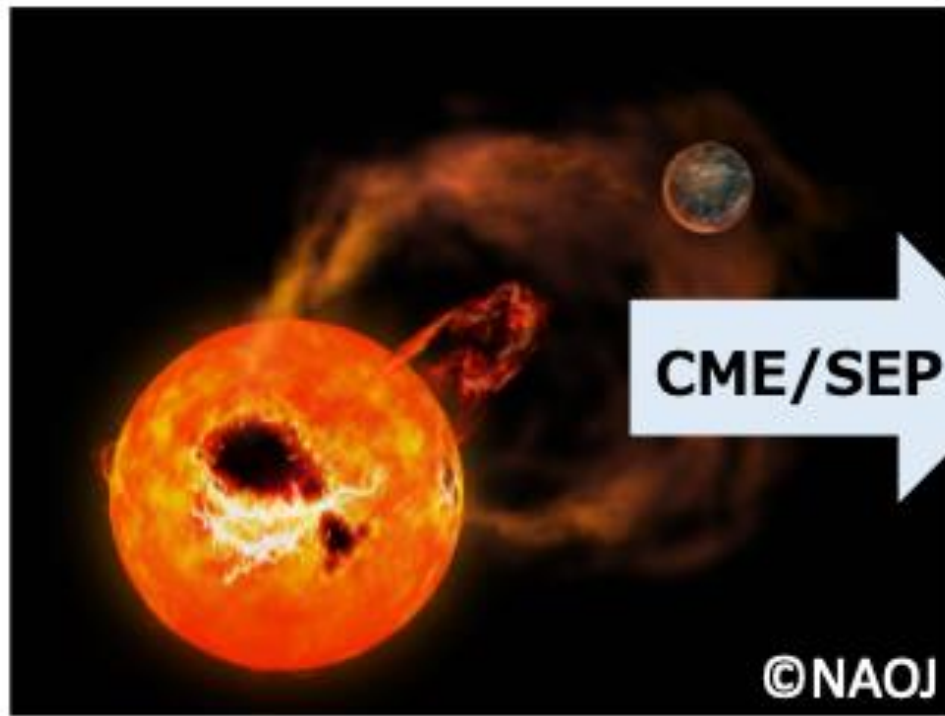
ATCA/Australia

MWA/Australia

Is the life on Earth a Unique Phenomenon? Was the Young Sun Slow, Moderate or Fast Rotator?

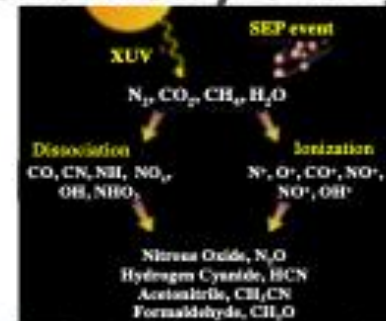


Extreme CME impact on (exo)planets



CME/SEP

Chemistry Change



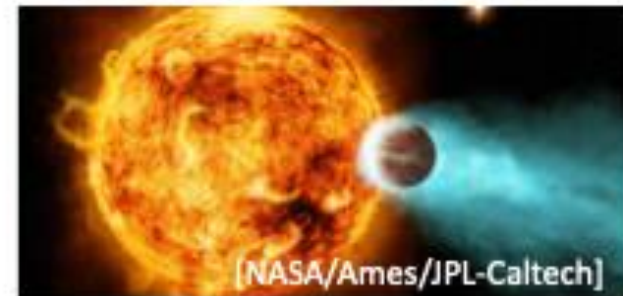
[cf. Airapetian+16]

Stellar mass & angular momentum evolution

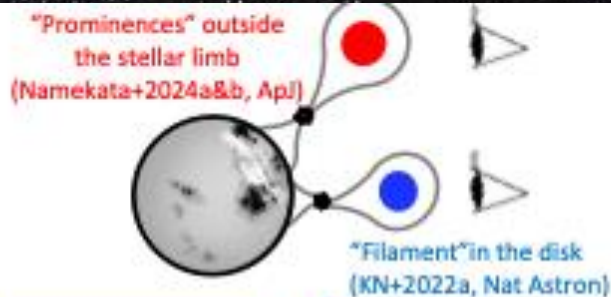
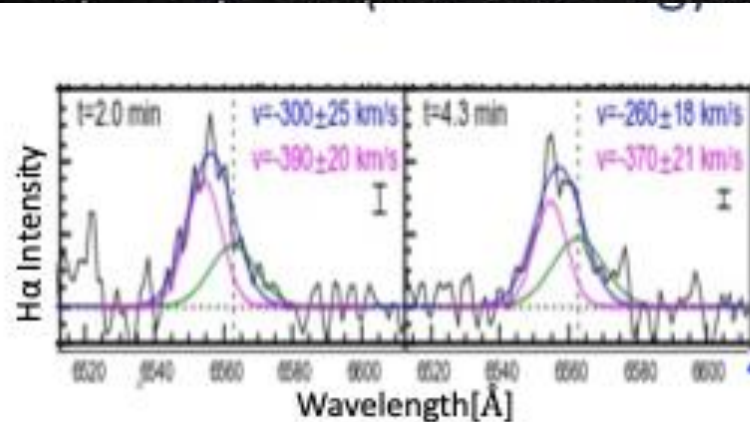
[Cranmer+17]

Erosion

Aurora

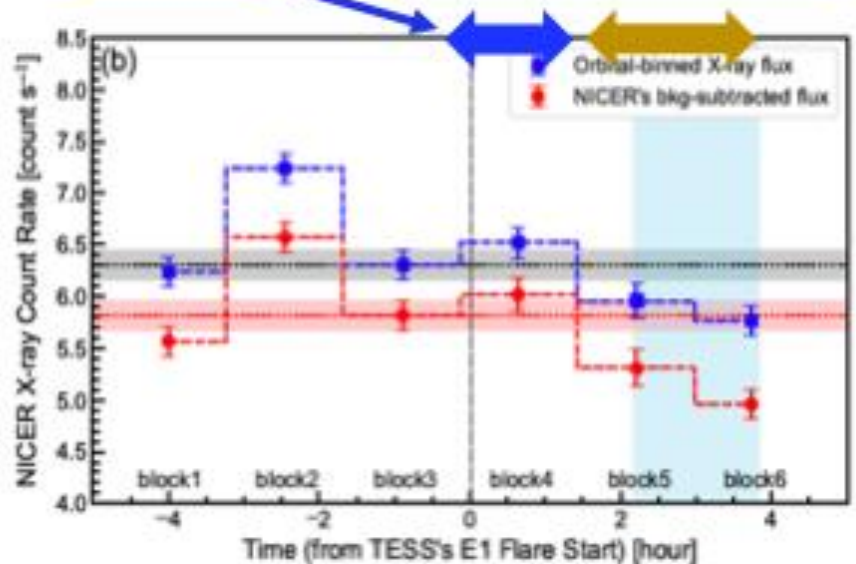
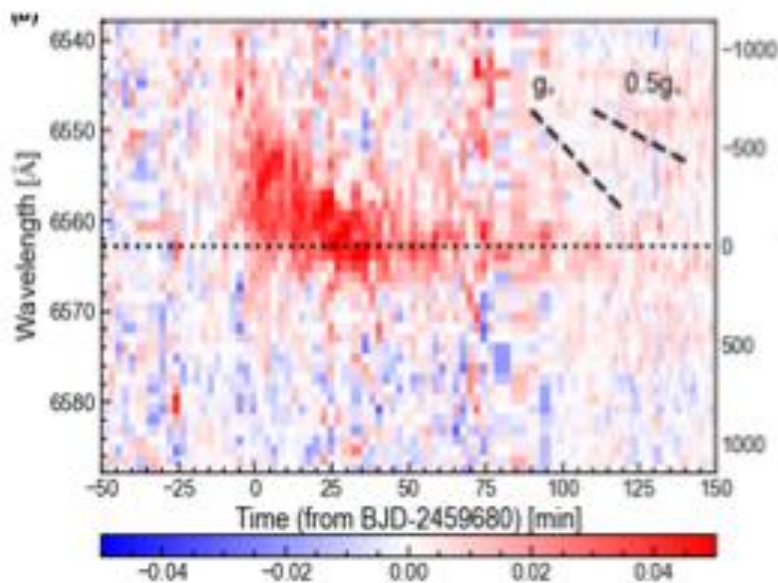


Searching for Signatures of Stellar CMEs

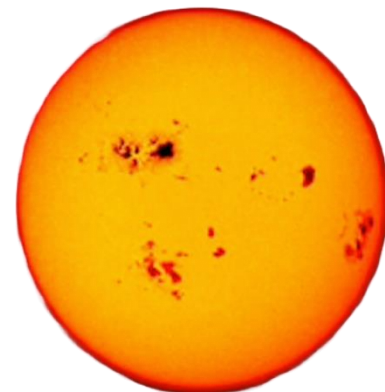
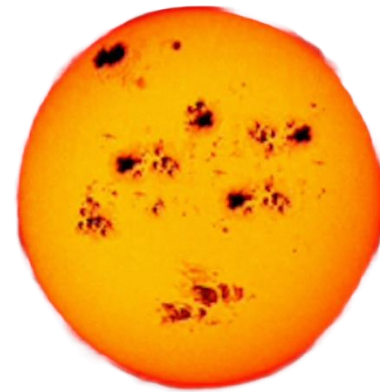
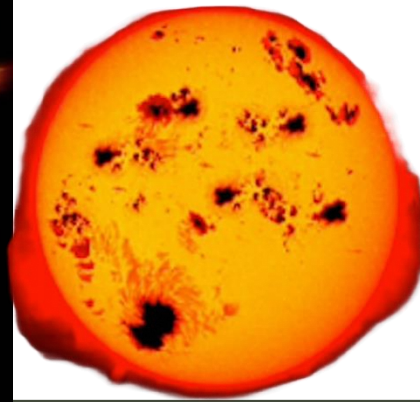
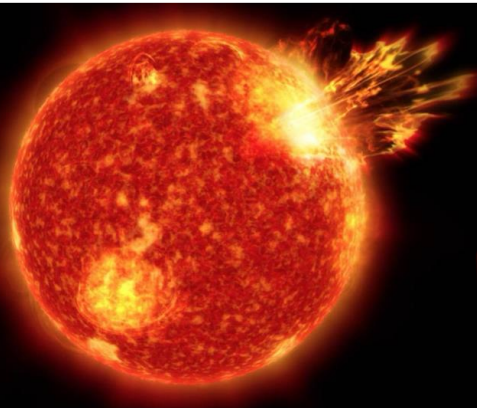


Prominence Eruption

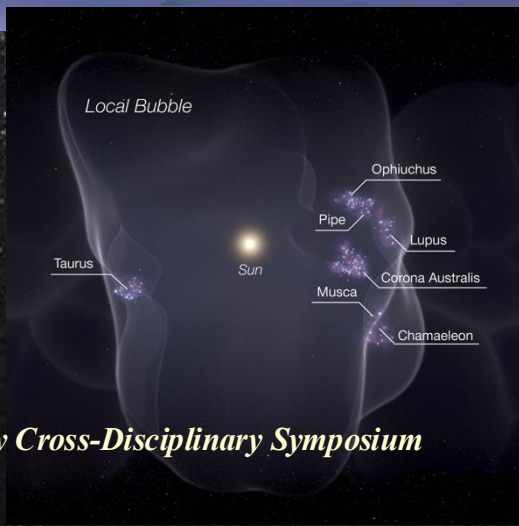
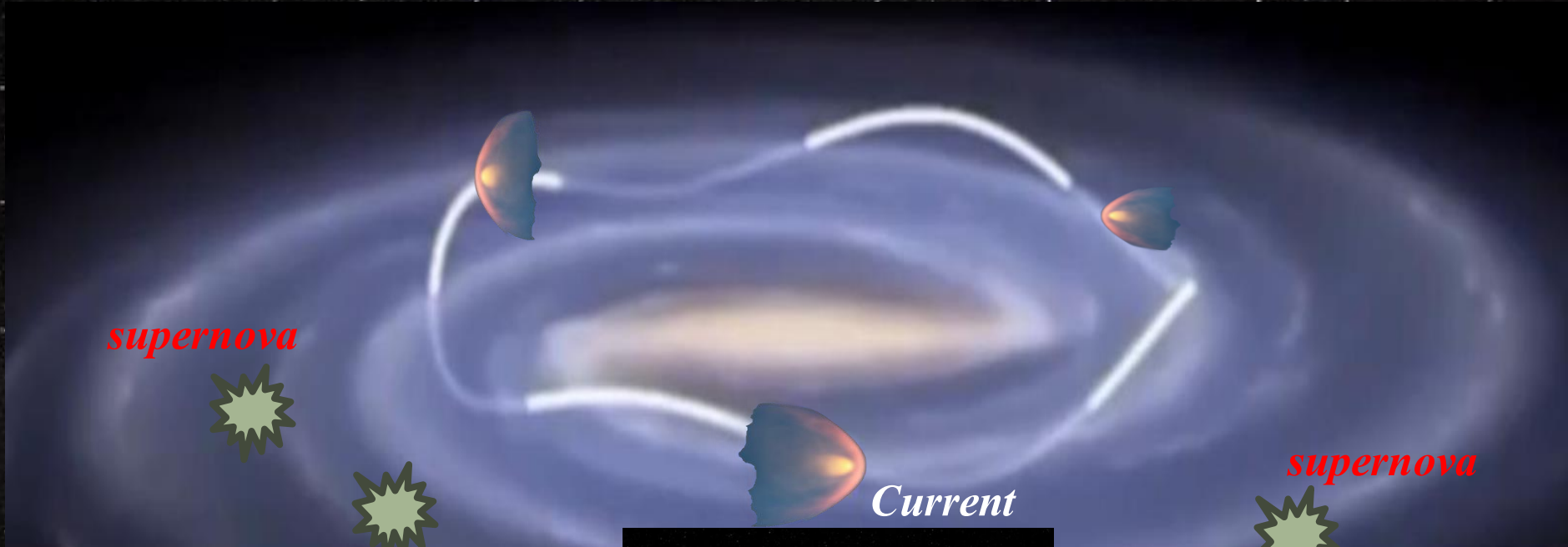
Possible X-ray dimming?? (2h after)



Evolution of the Solar Activity, the Source of the Space Weather



Impacts of Cosmic Weather Extreme on Earth, Moon and Mars Can Be Also Extreme



NEW INTERDISCIPLINARY DISCIPLINE

Heliobiology

A Gateway from Heliophysics to Astrobiology

"Heliobiology is the study of the co-evolution of stars, astrospheres and planetary environments, with an emphasis on how energetic and magnetic processes influence habitability and the origin of life."

Airapetian & Green (2025) · Nature Astronomy

Heliobiology bridges:

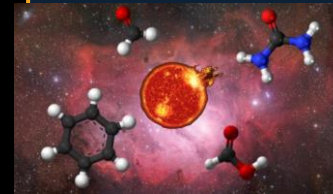
- * *Heliophysics & Solar-Stellar Physics*
-  *Planetary Science & Climate*
-  *Astrobiology & Prebiotic Chemistry*
-  *Galactic Cosmic Ray & Interstellar Environments*

Heliobiology · Airapetian

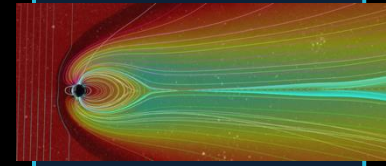
FOUR HELIOBIOLOGICAL THEMES



Young Sun & Prebiotic Chemistry



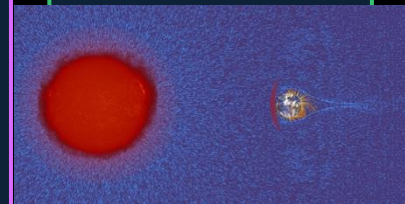
Extreme Space Weather on Earth



Galactic Cosmic Weather



Planetary Magnetic Shields & Fate



Airapetian, Green Nat Atsron 2026

FROM HELIOPHYSICS TO LIFE ACROSS THE COSMOS

Heliobiology: A Holistic Framework & Mission Roadmap



WHY HELIOBIOLOGY NOW?

- ★ *Sun-like stars produce superflares ~once per century, reshaping planetary chemistry*
- ★ *SEPs from young active stars may have synthesized prebiotic molecules on early Earth*
- ★ *Miyake events reveal modern Sun's extreme particle output modifies atmospheric chemistry and threatens biospheres*
- ★ *Galactic encounters, supernovae & interstellar clouds modulate heliospheric shielding*

UPCOMING MISSIONS & SYNERGIES

JWST

Atmospheric biosignatures on rocky exoplanets post-flare

Parker Solar Probe

In-situ SEP spectra — calibrate heliobiological models

TESS + PANDORA

Superflare statistics for solar analogues & young stars

Europa Clipper

Icy moon habitability under radiation & magnetic shielding

LIFE / HWO (future)

Direct imaging of Earth-like worlds; helio-context required

Why Explore the Moon and Mars?

Natural Time Capsules

The Moon and Mars lack plate tectonics and significant hydrologic cycles. Their ancient surfaces preserve a near-unbroken record of solar wind implantation, energetic particle bombardment, and UV irradiation at >4 Gyr.

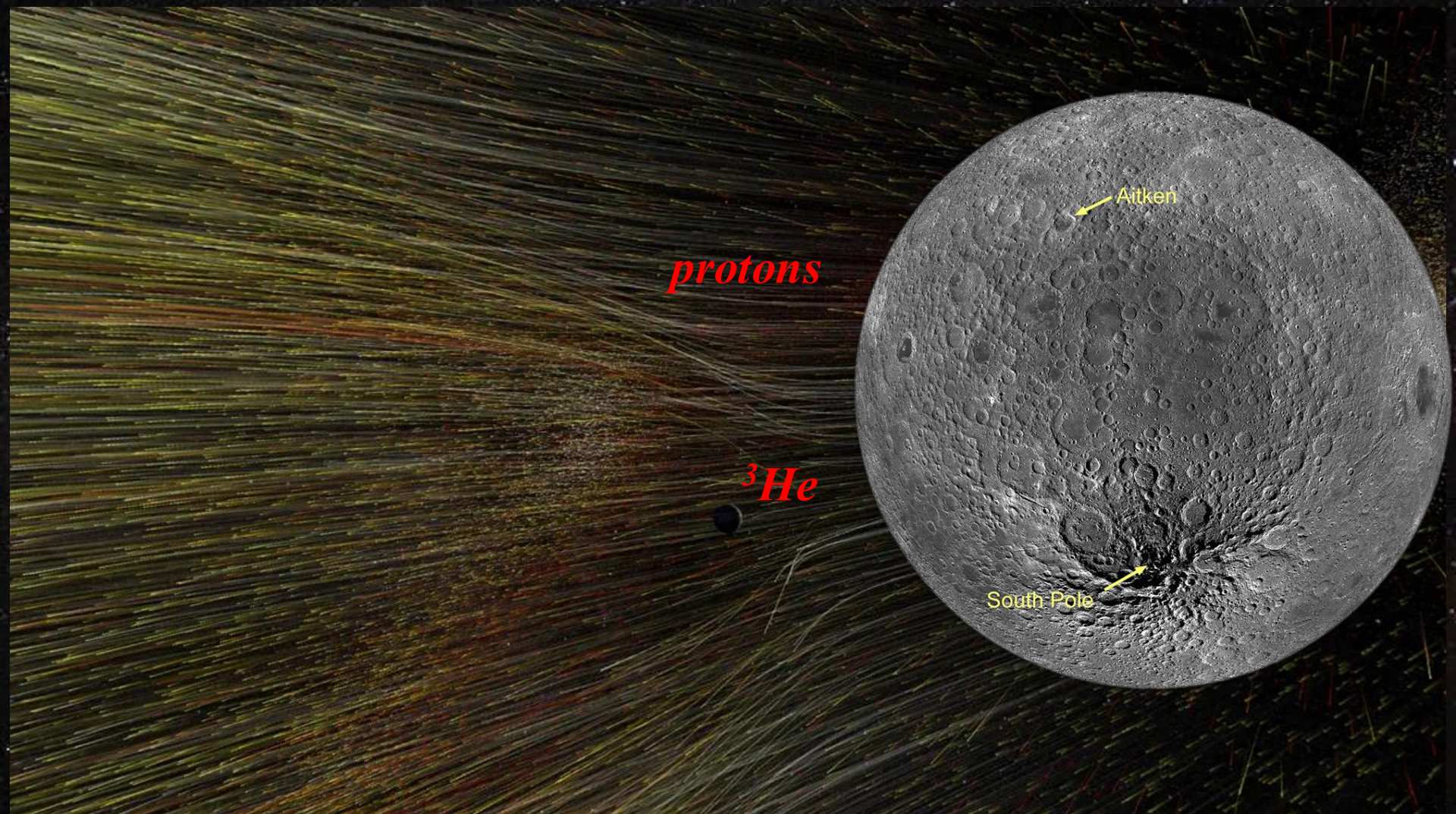
Solar Wind Archives

Regolith grains record implanted solar wind ions over geological time — integrating solar flux, composition, and variability that no spacecraft observation can directly access.

Solar Flare, CME and SEP Records

Cosmogenic nuclides (^{10}Be , ^{26}Al , ^{36}Cl) in surface rocks record paleo-solar energetic particle (SEP) events. Crater production rates constrain the early solar UV and particle environment.

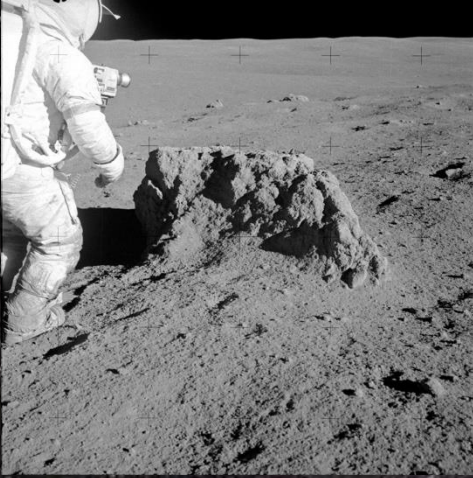
The Moon as New Frontier - Traces on Solar Storms on The Moon?



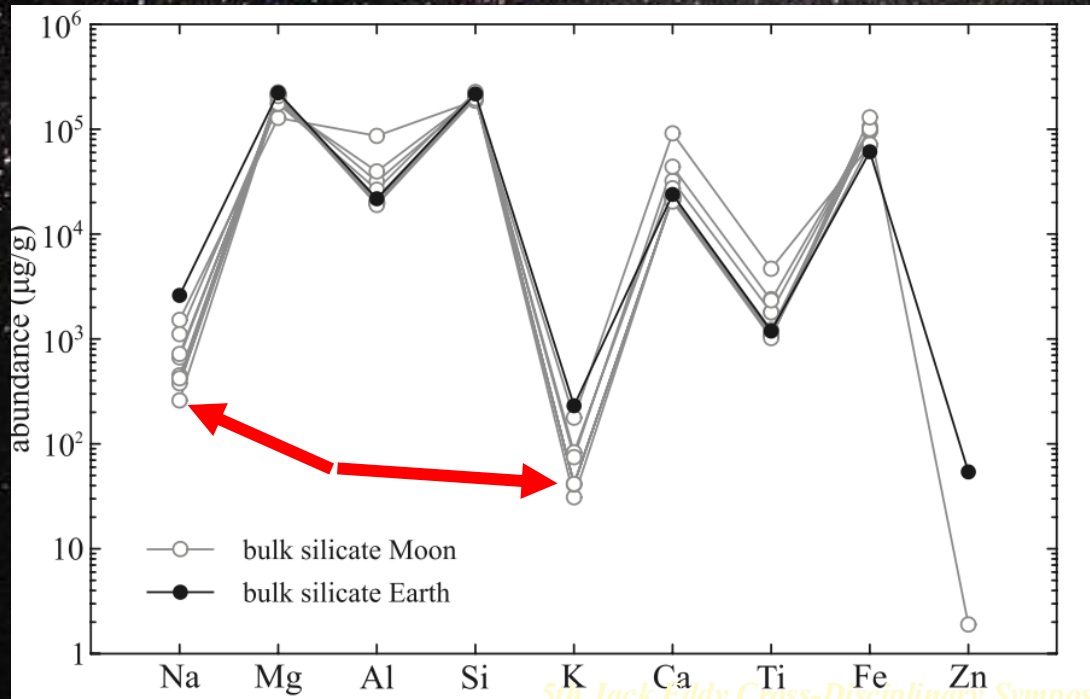
What Apollo Taught Us

- He-3 is implanted by the solar wind (~ 1 keV/amu), in the top ~ 20 – 50 nm of individual grains (~ 10 – 20 ppb by weight in mature regolith)
- He-3/He-4 ratio is $\sim 1:2500$, so He-4 vastly dominates and must be resolved from He-3
- Mare basalt regolith retains more He than highland anorthosite
- Ilmenite-rich soils (Mare Tranquillitatis, Mare Imbrium) are the best targets
- The top 1–3 meters of regolith is the most He-3-enriched — deeper layers have been less exposed to solar wind

Less Sodium and Potassium Than Earth



Apollo 16 lunar sample



Helium -3 on the Moon

There are at least 1.1 million tons of helium-3 on the lunar surface, most of which exists in the first few centimeters of regolith (moon dirt).

Recent landing data from the Chinese National Space Agency's Chang'e lunar exploration program, the true amount is now estimated to be significantly higher.



The Moon as a New Frontier - Traces on Solar Storms on The Moon?

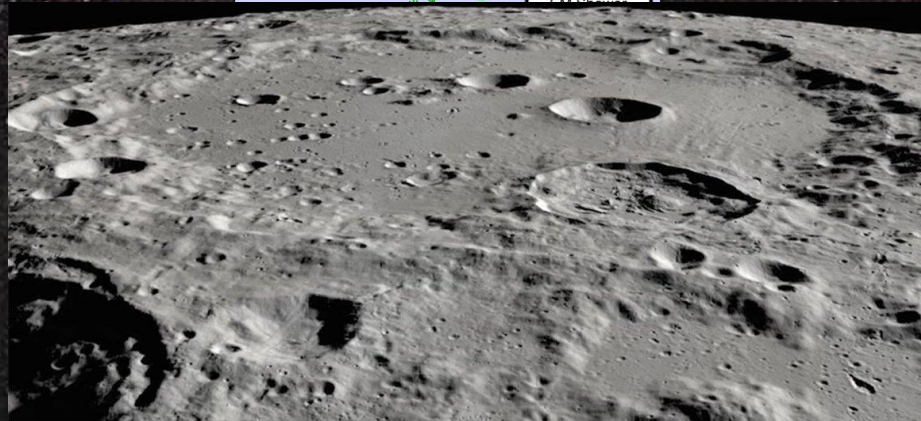
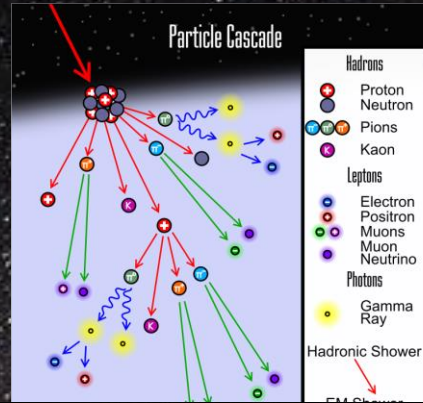


Mining ^3He , the source for fusion and quantum computers, by Interlune

\$20M/kg

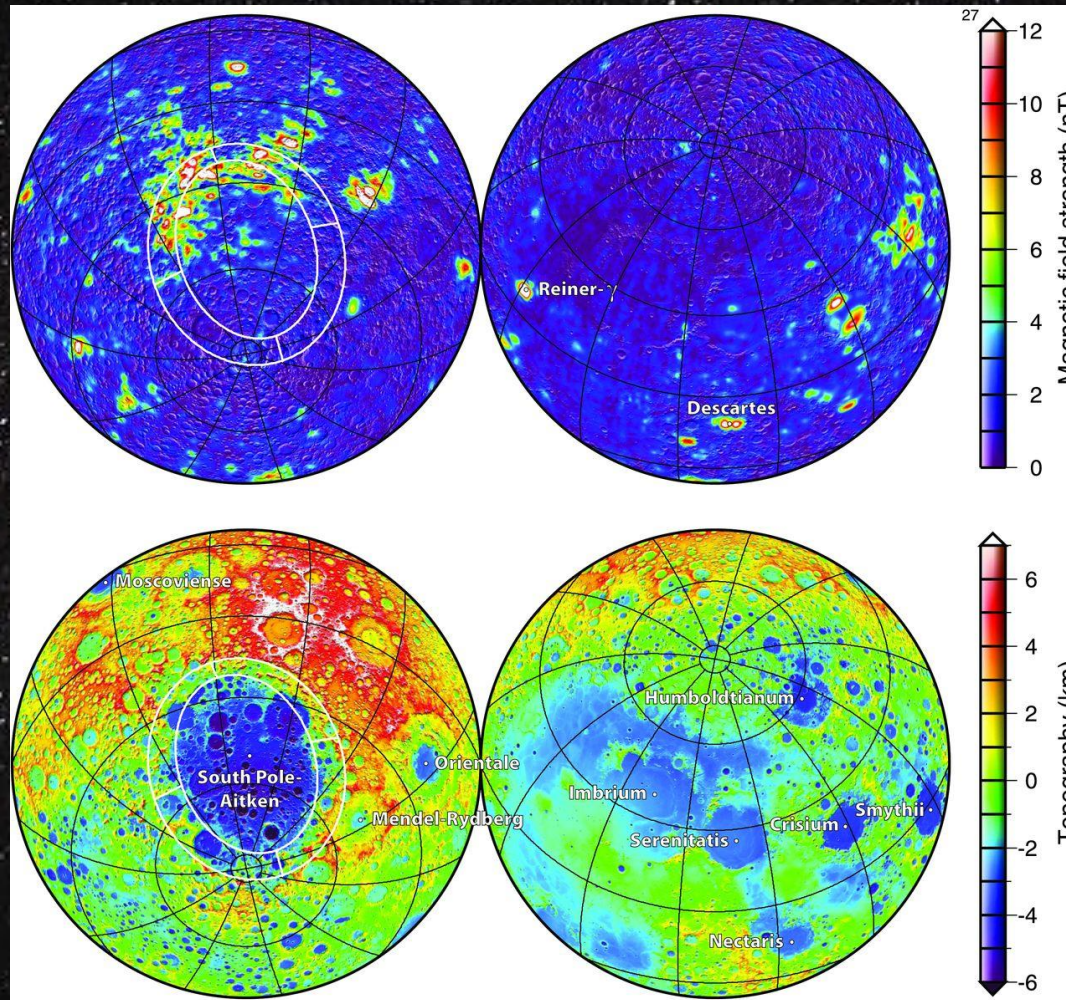


Traces of Solar Energetic Particles on The Moon?



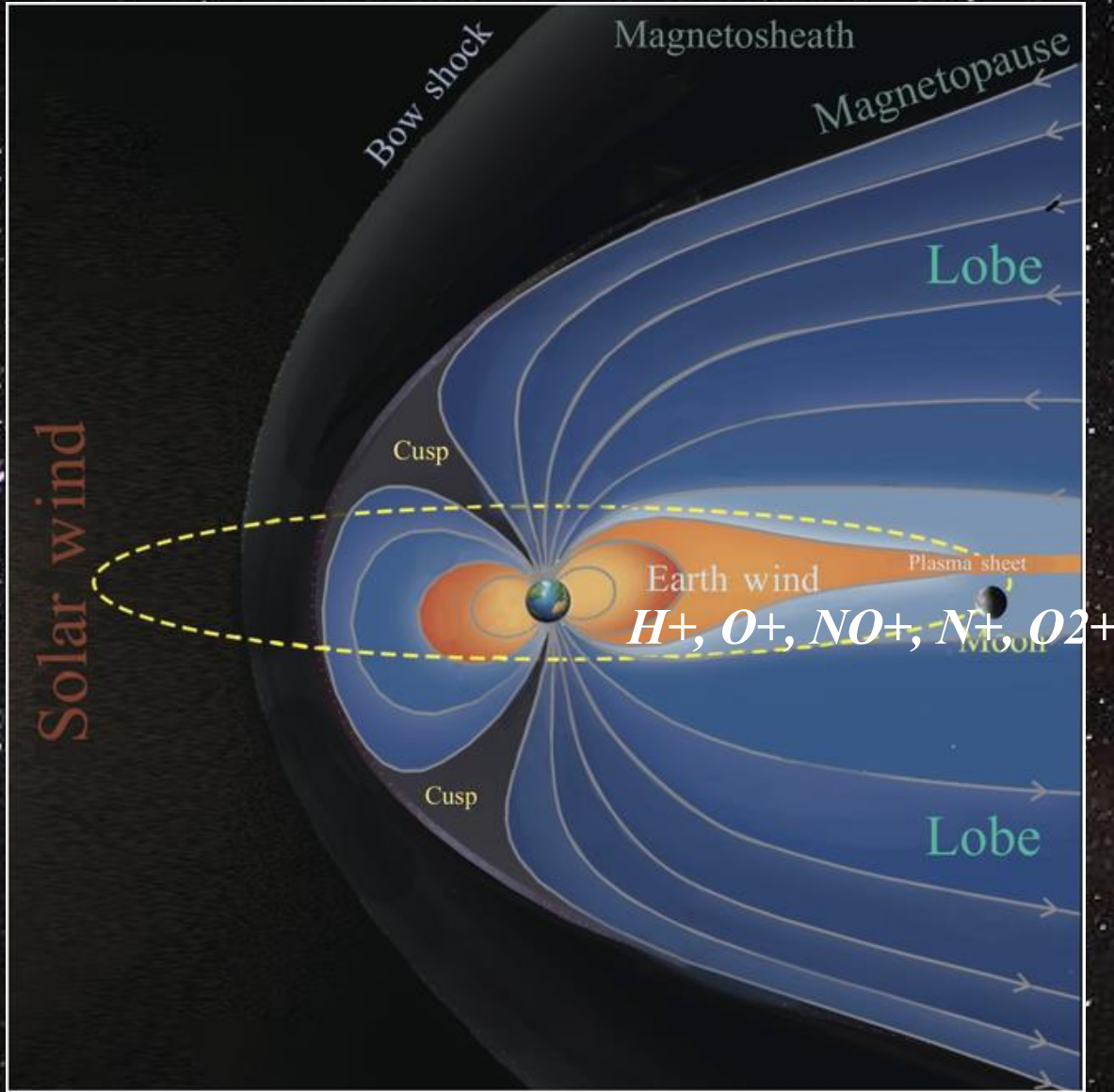
*The Moon is a recorder of ^{60}Fe formed in supernova explosions
 ^{41}Ca , $^{10}\text{B}/^{11}\text{B}$, $^{14}\text{N}/^{15}\text{N}$ isotopic ratios*

Magnetic field strength and topography centered over the South Pole–Aitken basin and opposite hemisphere of the Moon.



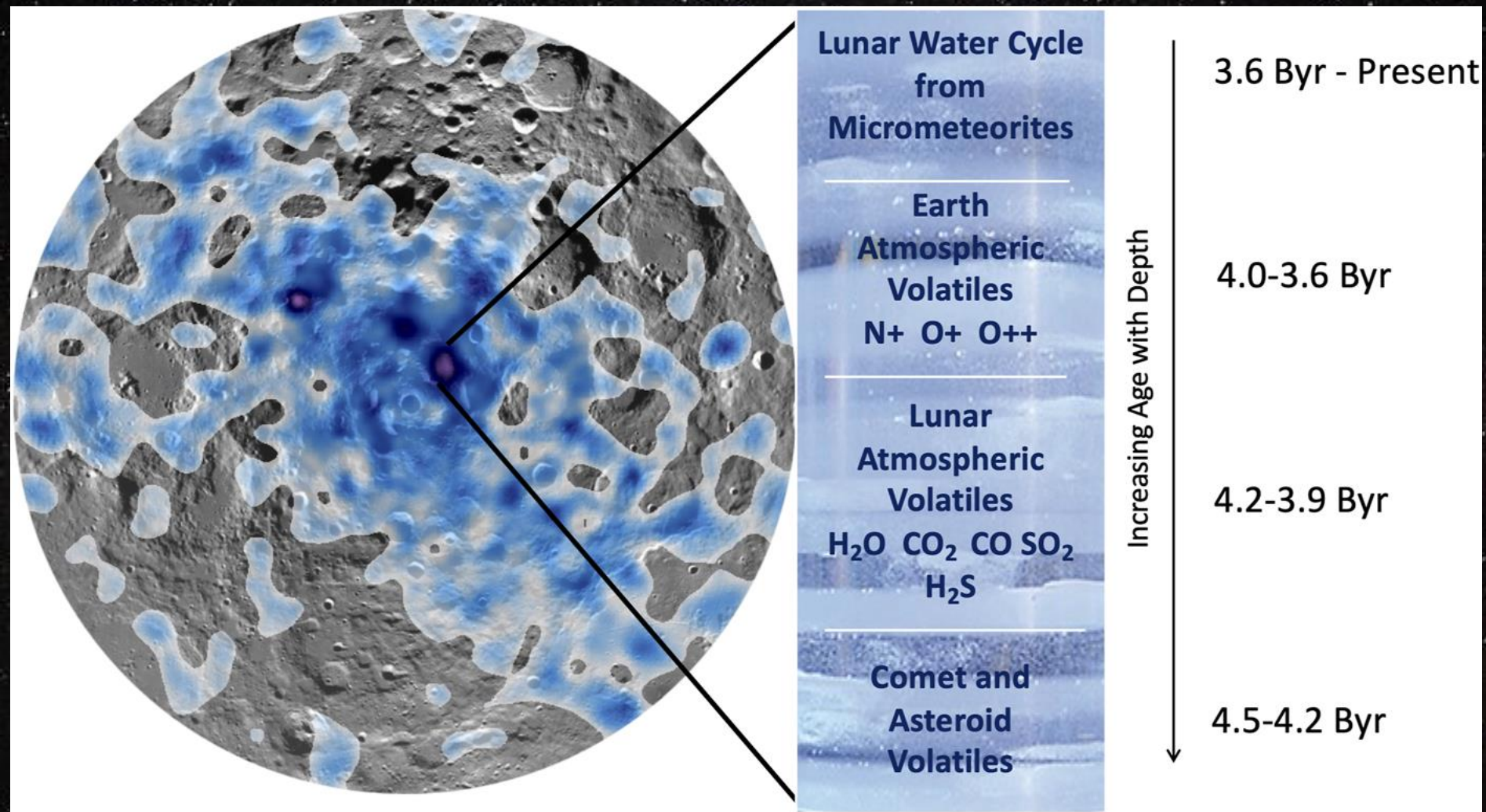
Wieczorek+12

Impact of Solar and Earth's Winds on the Moon



Cao+24

The Moon as New Frontier - Traces on Solar Storms on The Moon?

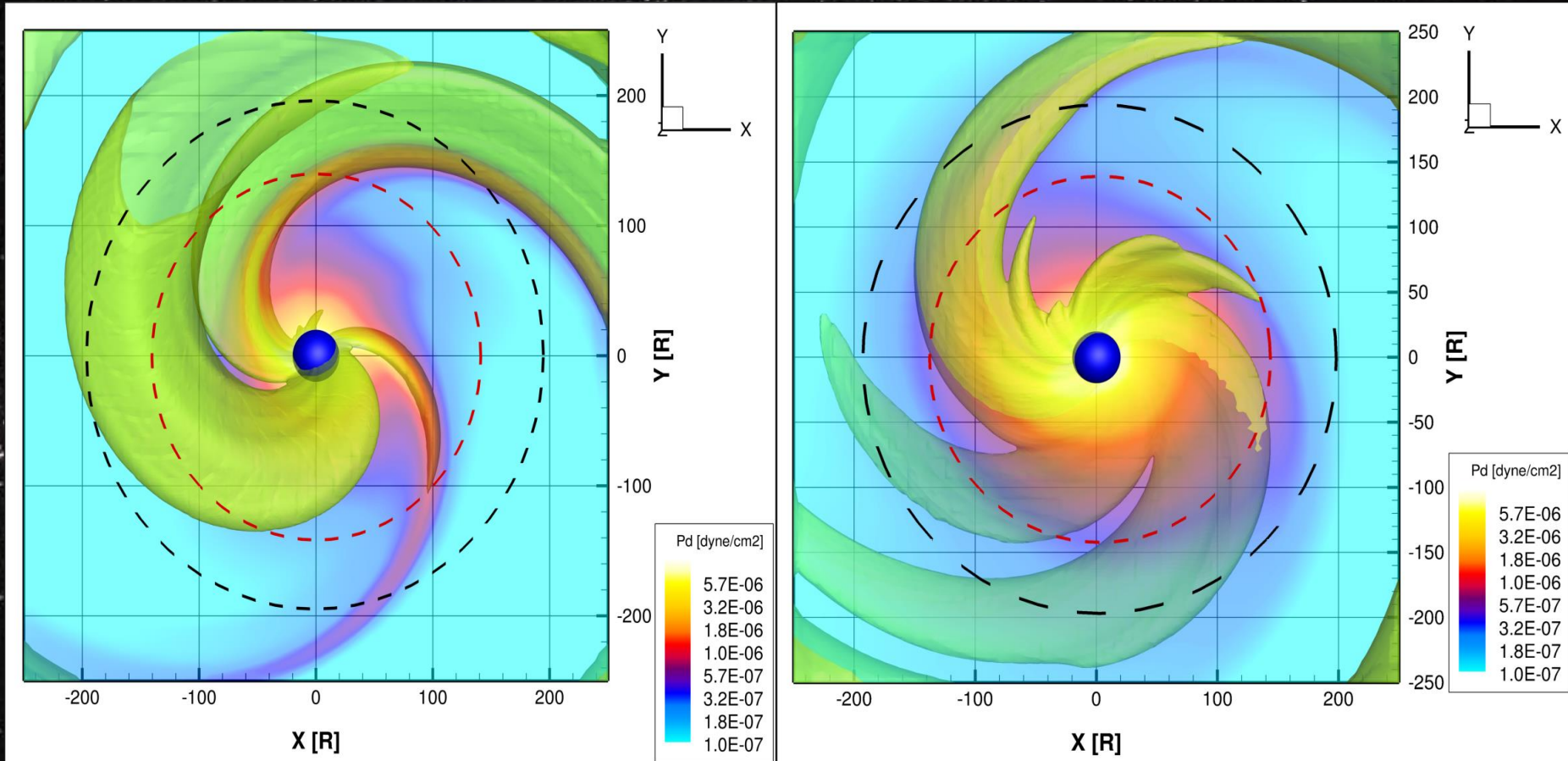




- India's Chandrayaan-1 mission had spotted hematite, an iron-rich mineral, Fe_2O_3 , that can form when rocks react with water and oxygen, near the Moon's poles³.
- The Moon's chemical environment isn't conducive to the presence of oxygen, meaning that the **oxygen for the hematite might have arrived from somewhere else, possibly from the Earth wind.**
- Experiments of pelting the minerals with high-energy oxygen caused some of the crystals to transform into hematite. And pelting the hematite with hydrogen caused some of it to revert to iron.

Implantation via Corotating Interaction Regions

Dynamic Pressure ~ 1500 times of the current background wind



Top Ten Unknown-Unknown in Lunar Science

- Was the Sun a slow, intermediate or fast rotator?
- Mass Loss Rate of Paleo Solar Wind
- E/LHB impacts + intense solar wind/CIRs simultaneously
- Did solar wind + CME ions synthesize organics on the young regolith surface like they did on Bennu?
- Hadean atmospheric record of early Earth implanted in the Moon.
- Flare-specific isotopic chemistry of the lunar crust: latitudinal distribution
- Volatile cycling unknowns ^3He , H_2O , N implantation rates vs CME ejection rates—net early volatile budget of lunar polar cold traps is unconstrained
- Lunar dynamo mechanism: Was it thermochemical, impact-stirred, or precession-driven?
- Did the early Sun undergo Maunder-type grand minima, and are they detectable in cosmogenic proxy records on airless bodies?
- CME-induced transient re-magnetization Early super-CMEs ($10\text{--}100 \times$ present energy) could have magnetized surface rocks—indistinguishable from dynamo signal in Apollo samples. **We may be misreading the entire paleomagnetic record.**

Required Observations, Missions & Capabilities

What would it take to answer these questions in the next 10 years?

Sample Return

- Artemis human lunar sample collection (diverse lithologies, >4 Ga highlands)
- Chang'e 7/8 south pole samples (water ice + ^3He co-location)
- Mars Sample Return from Jezero Cr. (cosmogenic nuclide record, noble gas ratios)
- Dedicated far-side Mare sample targeting high- TiO_2 terrain

Remote Sensing

- High-resolution neutron spectrometry (LEND/LRO successor) — H/He mapping at <5 km resolution
- Gamma-ray spectrometry for global TiO_2 and Fe maps (calibrate ^3He models)
- MAVEN/EMM extended missions — atmospheric escape flux through full solar cycle
- Lunar far-side radio observatory — solar radio burst history proxy

Modeling & Theory

- Coupled solar evolution + planetary atmosphere escape models (T-Tauri to modern)
- SEP event statistics from solar analog stars (young G-type with JWST/Chandra)
- Regolith gardening models linking implantation rates to surface age and maturity
- Global circulation models for early Mars atmosphere with SEP ionization chemistry

Interdisciplinary Success Requires: Heliophysics + Planetary Science + Astrobiology working from a shared data framework

The Exoplanet Connection

The Moon and Mars as ground truth for stellar and planetary habitability models

Every exoplanet we observe orbits a star with a history



A Decade-Defining Opportunity

The Moon and Mars are not just targets — they are instruments.

Sample Science



Returned samples from Moon and Mars carry ~4.3 Gyr of solar particle history. Prioritize cosmogenic nuclide analysis and noble gas measurements in existing and future collections.

Future Missions



Artemis 4+, Chang'e 7/8 must explicitly include heliobiology science objectives. In-situ solar wind monitors co-located with surface geochemistry experiments would be transformative.

Cross-disciplinary Bridges

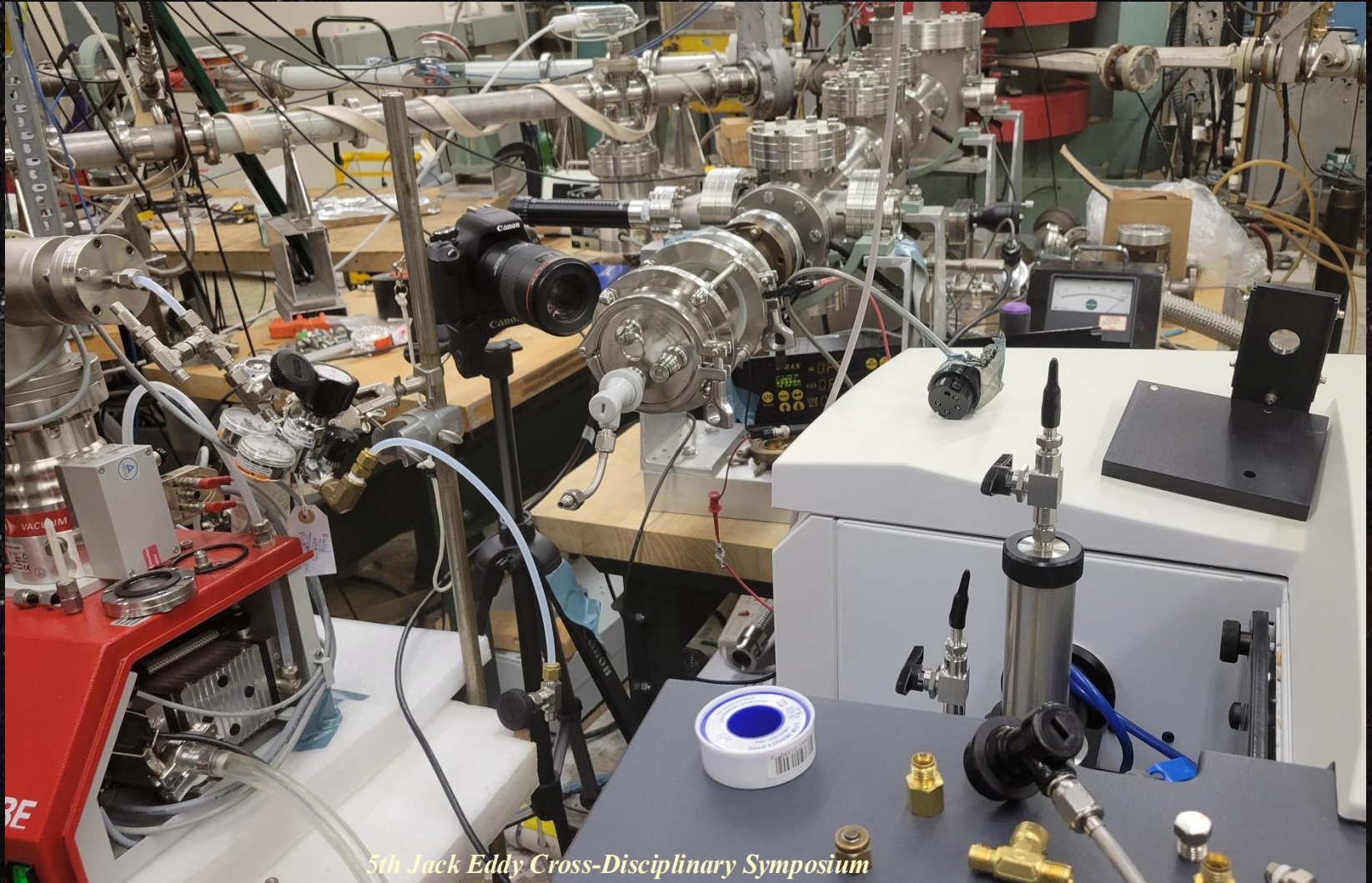
Helio + Planetary + Astrophysics Science must develop coherent models, data standards, and mission reqs from concept to archive.

10

The next human steps on the Moon and robotic samples from Mars offer a unique chance to decode the biography of our own star and every star that harbors a potentially habitable world.

Experimental Heliobiology

ExoPlanetary Particle Irradiation Chemistry (EPIC)



5th Jack Eddy Cross-Disciplinary Symposium

Aurora and He-3 samples from EPIC



Irradiated ilmenite by 1 MeV He-3 ions

Parameter	Ilmenite (FeTiO ₃)	Aluminosilicate (Plag.)
Target density (g cm ⁻³)	4.70	2.65
Grain size (μm)	10-50	10-50
Beam energy (MeV)	1.5	1.5
Fluence (ions cm ⁻²)	5.6×10^{15}	0.85×10^{15}
Projected range (μm, SRIM)	~5.0	~4.5
Measured ³ He (ppmm)	20.9 ± 2.69	1.24 ± 0.16
Implantation efficiency (%)	87 ± 5	86 ± 5
Peak diffusion temp. (°C)	~1000-1200	~1000-1100

