NASA Space Radiation Analysis Group Moon to Mars Radiation Protection Gaps

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Space Radiation Analysis Group (SRAG)
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Objectives

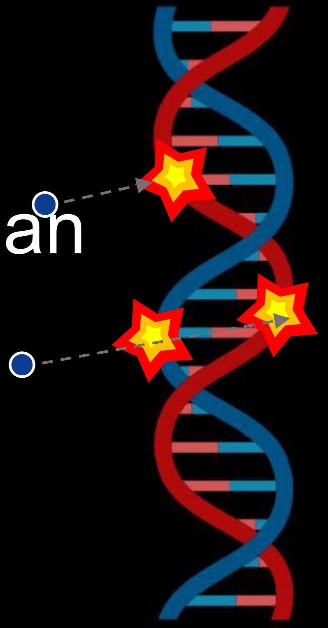
1) Why do we care about radiation?
2) Introduction to SRAG
3) Space Radiation Environment Overview
4) SRAG Operations
5) Space Weather Forecasting Efforts
6) Moon to Mars Space Weather Gaps

Why do we care about radiation?

- In-mission risks:
  - Large acute exposures can induce acute radiation syndrome
    - Nausea, vomiting, diarrhea, fatigue
    - Potential immune system impairment
    - Potential central nervous system damage
  - Acute exposures large enough to induce observable symptoms are *very unlikely* and would have *low severity*
- Long-term risks:
  - Cancer: excess risk related to dose, radiation type, age, and sex
  - Cataracts
  - Possible cardiovascular disease and late central nervous system effects
  - Increased cancer risk is a main concern for astronaut exposure to space radiation

Why do we manage exposures?

- Legal, moral, and practical considerations require NASA limit astronaut radiation exposures to minimize long-term health risks
- Linear-No-Threshold approach to exposure
  - Any exposure leads to an increase in subsequent cancer risk
- The components of space radiation are more damaging than typical sources of terrestrial radiation



- SRAG's job: human protection during space flight
  - Maintain radiation exposure ALARA:
    - As Low As Reasonably Achievable

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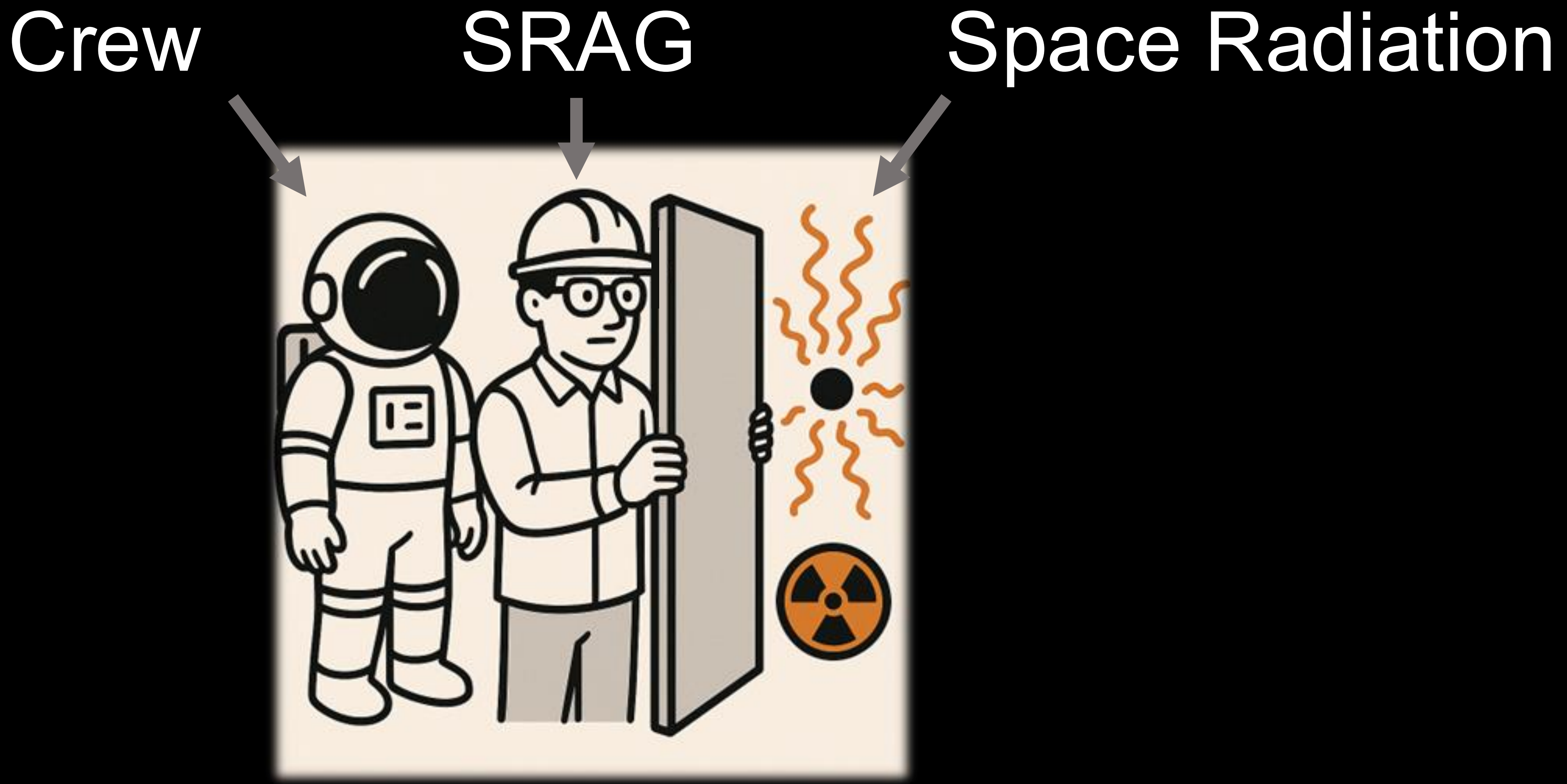
Space Radiation Analysis Group

- **Mission:** The protection of humans from impacts of space radiation exposure
- **Philosophy:** As Low As Reasonably Achievable (ALARA) to *accomplish mission goals while minimizing astronaut radiation dose*

Photo credit: Ricky Egeland; SRAG watching Artemis I splash down after 25 days of 24/7 console support.

Introduction to SRAG



Introduction to SRAG

Crew SRAG Space Radiation

We are happy to help!

Introduction to SRAG

- Who is SRAG?
  - Diverse group of physicists, health physicists, engineers, programmers
  - Focused on astronaut radiation protection

- What do we do?
  - Provide radiation monitoring to meet medical and legal requirements
  - Provide real-time astronaut radiation protection support to FCT
  - Provide operational dosimetry and risk assessment support
  - Maintain comprehensive crew exposure modeling capabilities incorporating all relevant space radiation environments
  - Maintain real-time situational awareness of and develop forecasting capabilities for the space weather environment

SRAG Modeling and Analysis

- 3D Spacecraft CAD Models
  - High fidelity models of spacecraft mass distribution for shielding analysis
- Environmental Models
  - Provide characterization of conditions encountered in space
- Radiation Transport Models
  - Allow accurate characterization of changes in radiation fields within matter (vehicles, habitats, human body, etc.)
- Radiogenic Cancer Risk Models
  - Provide an estimate of increased cancer risk due to cumulative radiation exposure
- Space Weather Models
  - Provide increased situational awareness during high solar activity
- Integrated Analysis Tools
  - Combined vehicle, environmental, and transport models for assessments of radiation environment within spacecraft

Visualization of vehicle model components used in analysis of radiation shielding effectiveness

Radiation Environment Monitors

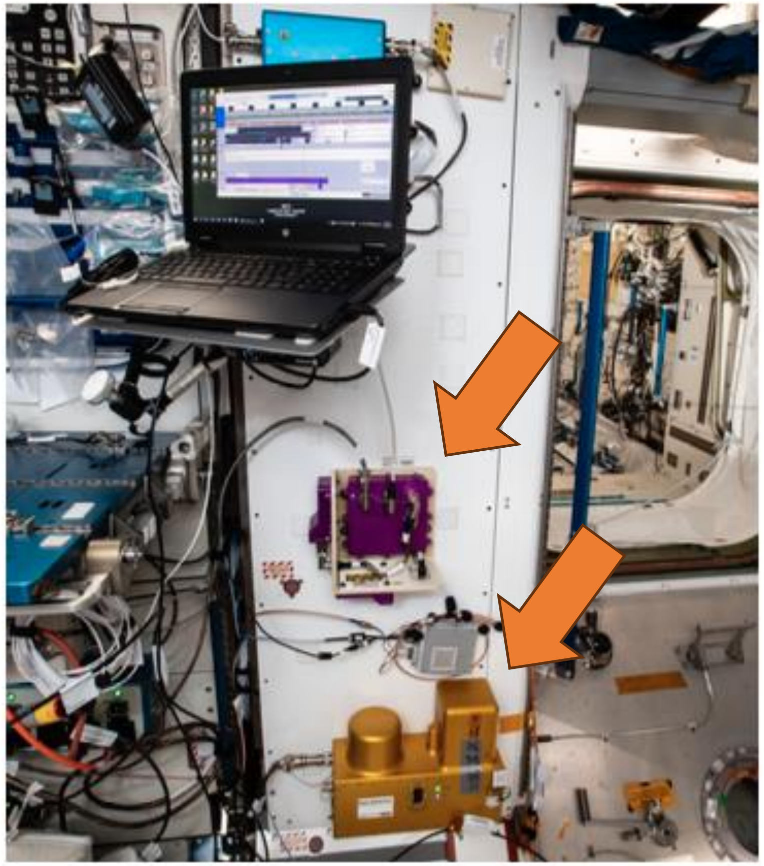


Figure 2: ISS HERA deployed with RAD in Node 2

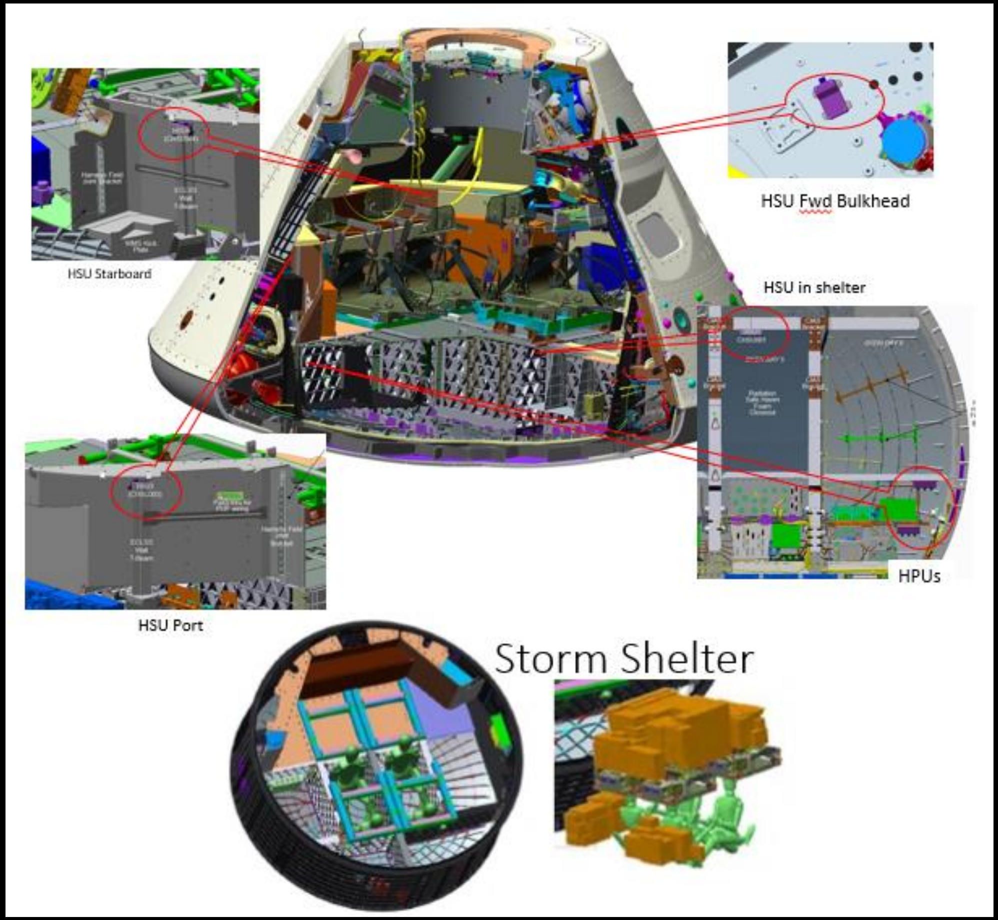
Dosimeters are mounted throughout the ISS. They are sometimes moved to different modules to measure the radiation environment throughout the Space Station.

Image credit: https://wrmiss.org/workshops/twentyfourth/Stoffle.pdf

Crew Active Dosimeters (CAD) are worn by astronauts and show a continuous readout of the current dose rate and the cumulative dose for the mission duration.
Image credit: https://srag.jsc.nasa.gov/spaceradiation/how/how.cfm

Vehicle Design for Radiation Shielding

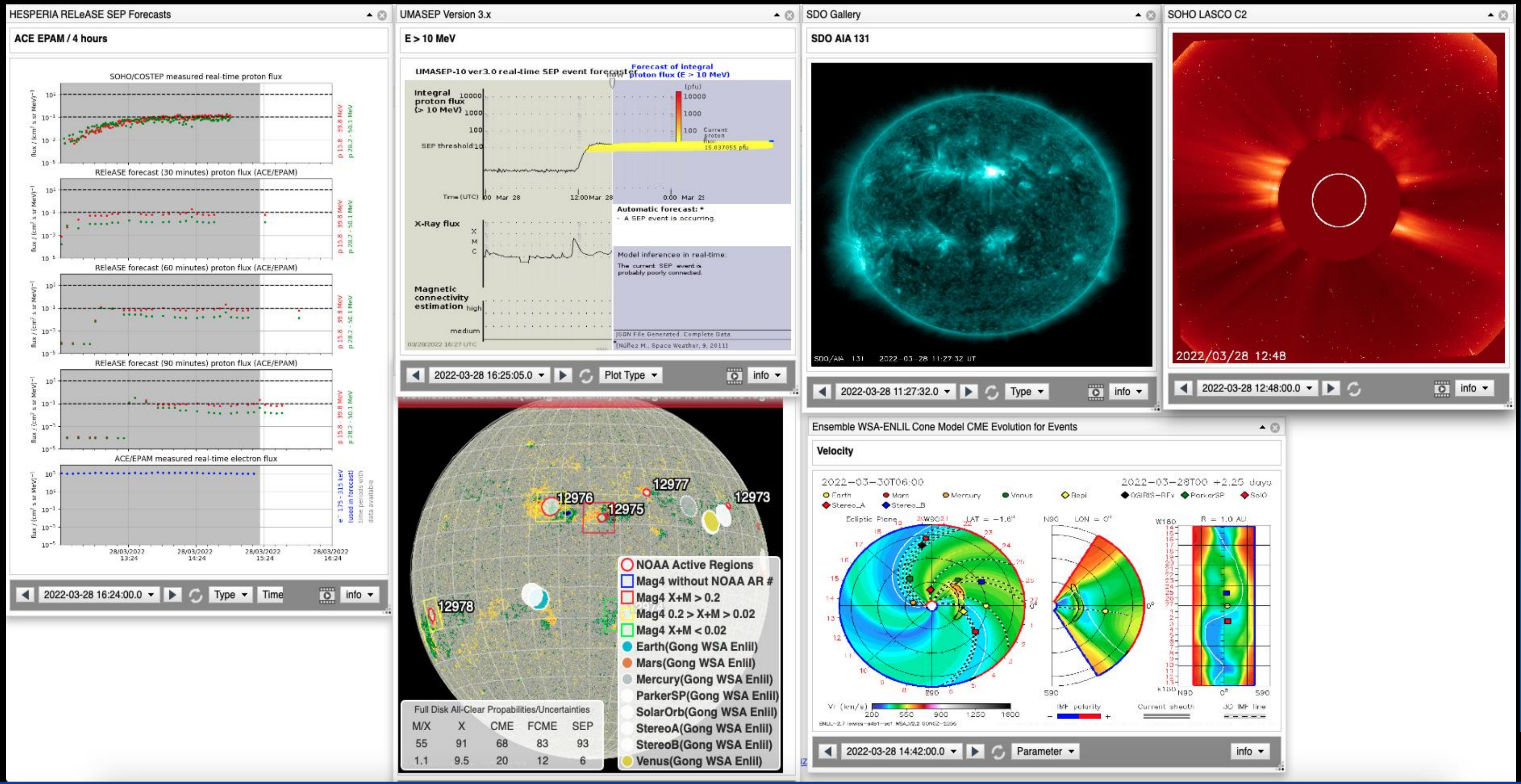
- MPCV represents the first time that crew radiation exposure considerations have been part of the iterative vehicle design process
- Iteration of shielding analyses performed for possible optimization of redistribution of vehicle mass for storm shelter



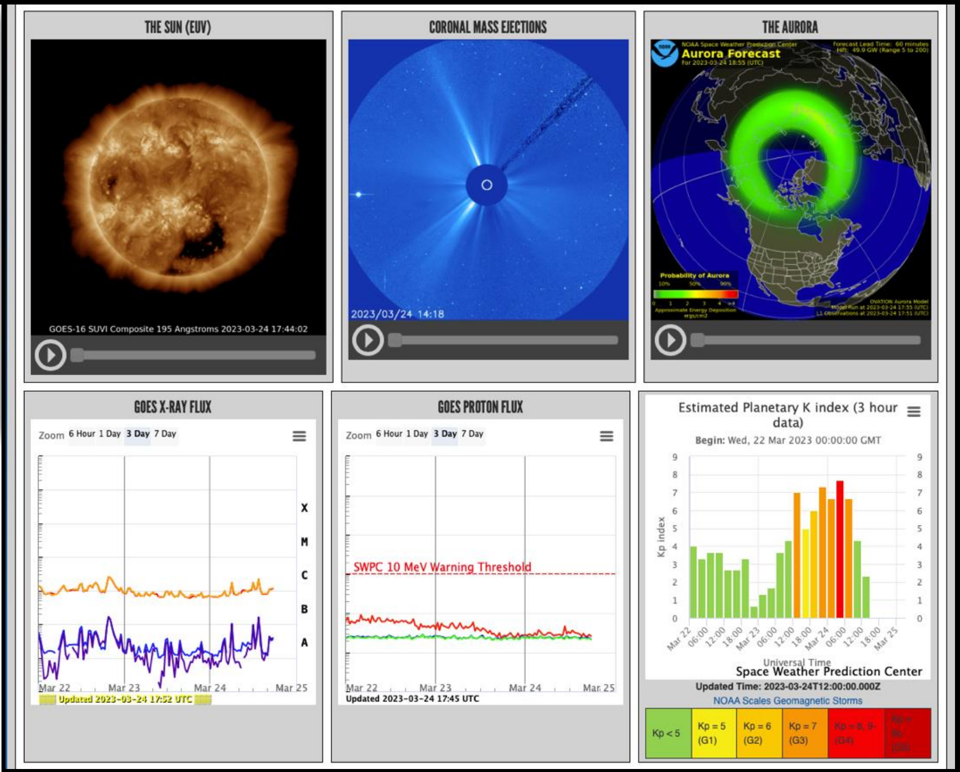
Space Weather Situational Awareness

Real Time Measurements and Forecasts

NASA CCMC’s iSWA Web Tool



NOAA SWPC’s Operational Data



SRAG Expertise

SRAG is a unique group with combined expertise in:

- Space radiation environment regimes
- Space weather environment and forecasting models
- Radiation transport physics and models
- Radiation measurements and detector design
- Biological risk
- Operations

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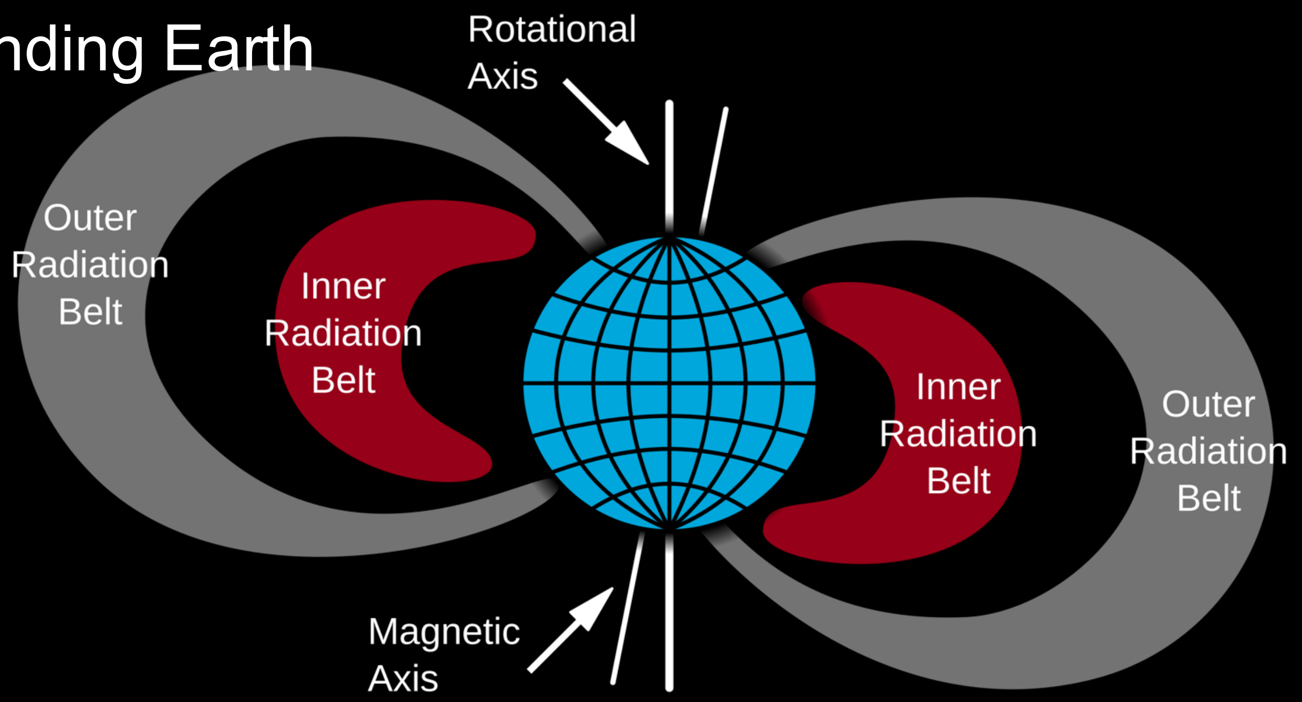
Space Radiation Environment Review

- Three categories of space radiation
  - Geomagnetically Trapped Radiation (trapped)
  - Solar Energetic Particles (SEP)
  - Galactic Cosmic Rays (GCRs)

Geomagnetically Trapped Radiation (trapped)

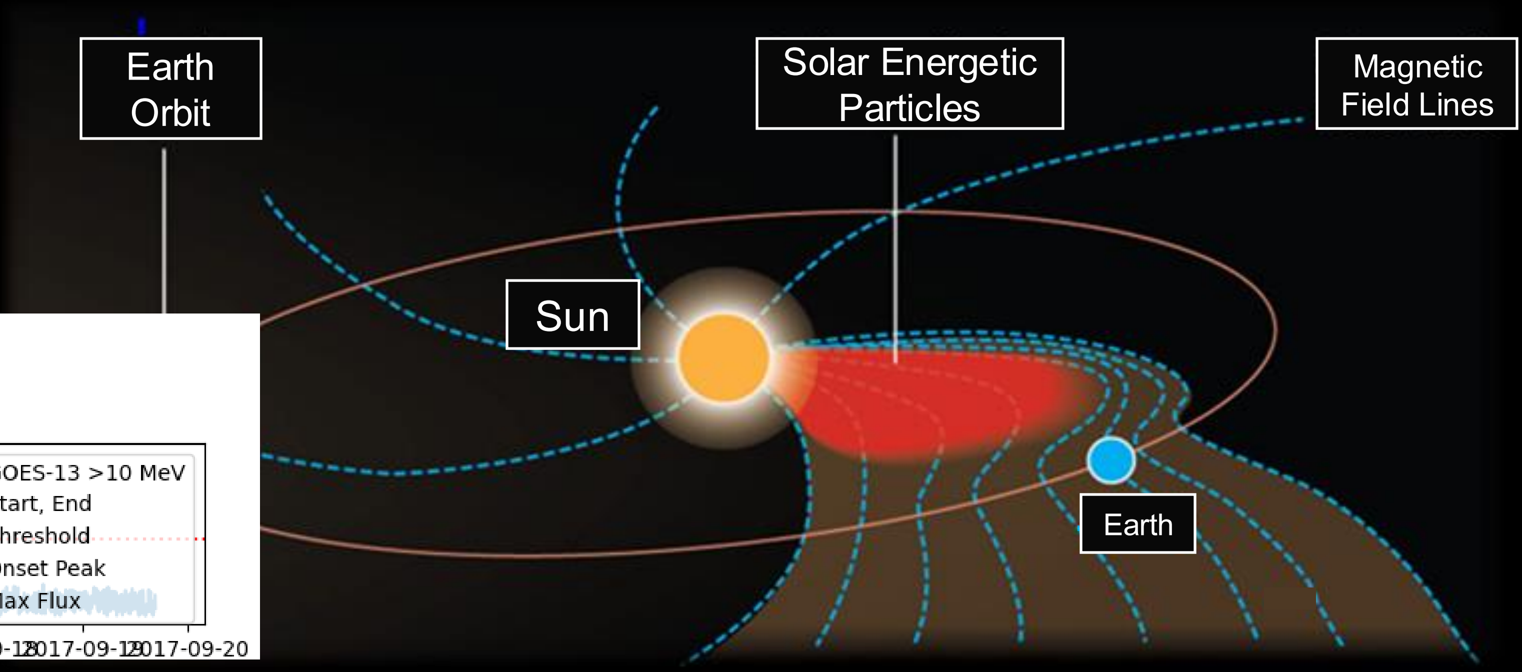
- Electrons and protons trapped in Earth's magnetic field
  - Van Allen Belts
  - Two donut-like shapes surrounding Earth

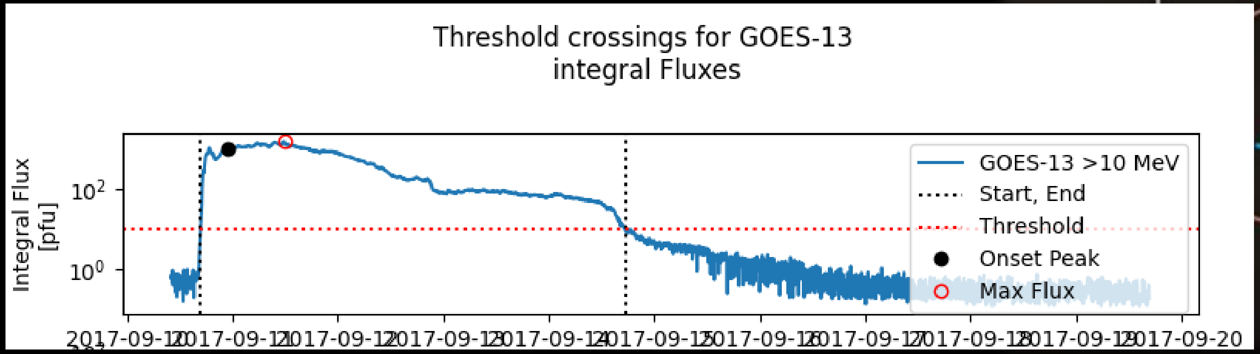
- Inner belt → protons
- Outer belt → electrons



Solar Energetic Particles (SEP)

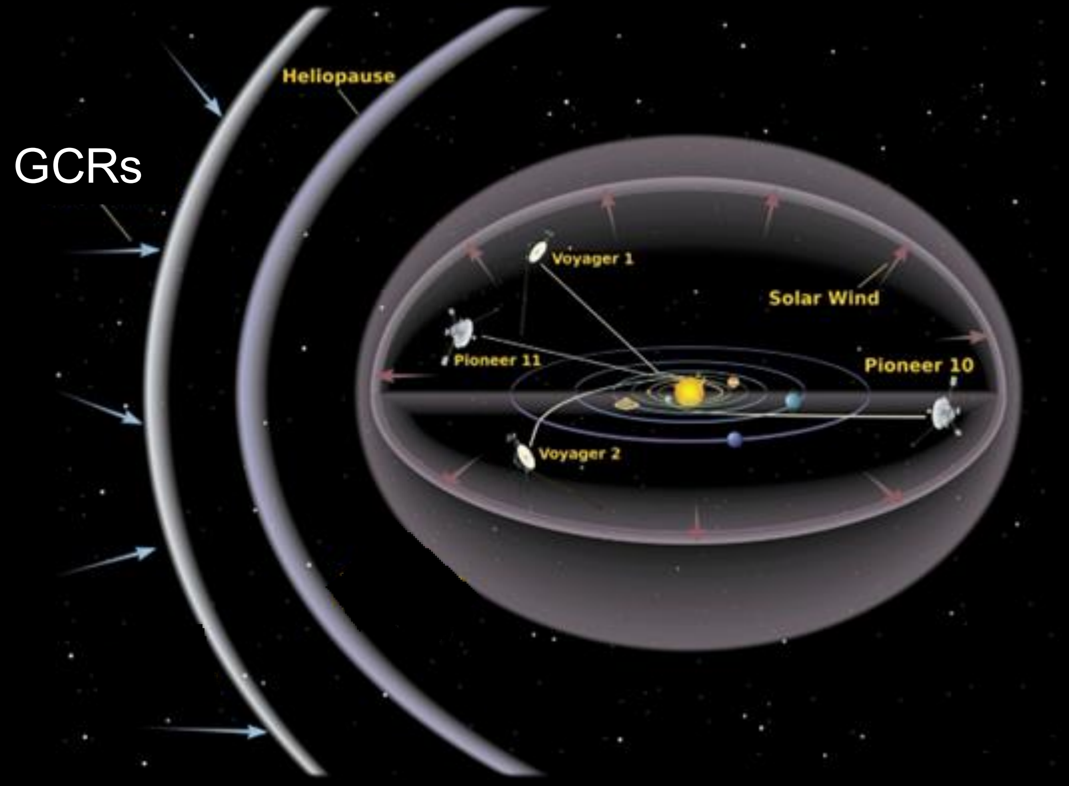
- SEPs are charged particles (primarily electrons and protons) accelerated from Sun's surface after a solar flare and/or coronal mass ejection (CME)
- High flux
- Can last hours to days
- Difficult to forecast





Galactic Cosmic Rays (GCRs)

- Highly energetic, heavy, charged particles originating from outside the solar system
- Low flux
- Constant background radiation
- Difficult to shield, highly penetrating



Artemis II Mission Trajectory

- 3 trapped radiation belt passes
  - 2 of significance
    - Pre-Translunar Injection LEO
    - Pre-Translunar Injection HEO
    - No action by crew
- GCRs always present
- SEP occurrence depends on solar activity
  - Possible action by crew depending on severity

https://www.nasa.gov/image-article/artemis-ii-map-2/

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Mission Control

Flight Director
Leads FCT

GC
Manages Mission Control hardware

PLUTO
Manages portable electronics

CAPCOM
Communicates with crew

SPARTAN
Manages spacecraft power system

ISO
Tracks spacecraft inventory

CRONUS
Manages onboard data systems

EVA
Manages spacesuit and spacewalk tasks

ISE
Liaison between spacecraft and visiting vehicles

ADCO
Manages spacecraft orientation

ROBO
Manages robotic arm

BME
Monitors health-related systems

VVO
Manages visiting vehicles

OSO
Manages maintenance systems and logistics

RIO
Interfaces with international partners

PAO
Interfaces with media

TOPO
Manages spacecraft trajectory

OPSPLAN
Coordinates crew schedule

ETHOS
Monitors air quality and temperature

Surgeon
Monitors crew health

Radiation
Monitors space radiation environment

SRAG Real-Time Support

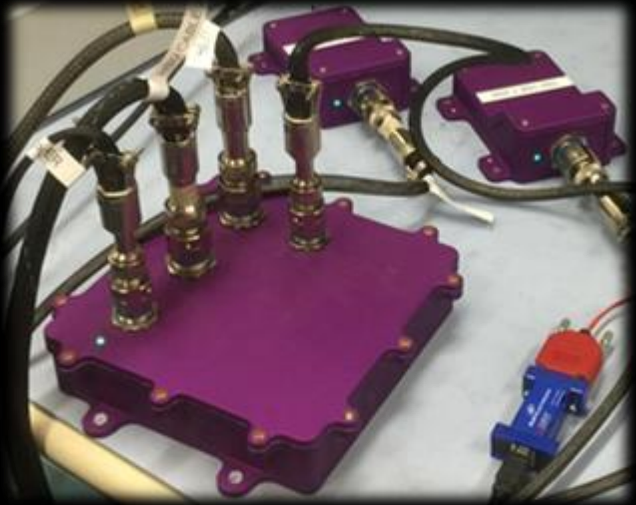
- Operational Support on Console
  - 4 hr/day, 3 days-a-week during nominal conditions
  - 24/7 console support during Artemis II
  - NOAA SWPC space weather forecasts provided daily
- Nominal Activities
  - Maintain situational awareness of the space weather environment
  - Report crew exposure status to flight management
- Contingency Support
  - 24/7 console support during space weather events
  - NOAA SWPC space weather alerts

SRAG Multi-Purpose Support Room

SRAG console operators and observers during Artemis I

Artemis II Radiation Hardware

- Hybrid Electronic Radiation Assessors (HERAs)
  - Active radiation detector with full vehicle integration
  - 2 HERA Units, 3 sensors each = 6 sensors total
  - Caution & Warning Alarm capability
- Radiation Area Monitors (RAMs)
  - Passive detection measured post-mission
  - 6 total
- Crew Active Dosimeters (CADs)
  - 4 total – 1 for each crewmember



HERA Unit (1 HPU, 2 HSUs)

CAD

RAM

Artemis I as a Testbed for Artemis II

- Uncrewed Mission
- Launch:
  - Nov 16 0300Z
  - Same-day VA Belt pass
- Lunar approaches:
  - Nov 21 1257Z (70 nmi)
  - Dec 05 1620Z (<70 nmi)
- Landing:
  - Dec 11 1640z

Artemis I pulled together recent advancements in monitoring hardware, particle transport modeling, and space weather modeling into an updated real-time mission support strategy.

Mission Support for Artemis I

- Free space mission necessitated move from on-call to full in-person support
- Shift scheduling to support both ISS and Artemis
- Increased communication with SWPC and M2M (3x/day)
- Increased interaction with Flight Control Team
- Assess impact of space environment on hardware “funnies”

SRAG Multi-Purpose Support Room (MPSR) in Mission Control

Operational Approaches for Radiation Protection

• Shuttle/ISS (Low-Earth Orbit)

Transient exposure

- Monitor environment
- Determine highest vehicle shielding locations
- Design areas specifically for radiation shielding (e.g., Crew quarters)
- Inform crew when to shelter

• Artemis Crewed Missions (cis-lunar)

Free Space Mission

- Monitor environment
- Attempt to predict/forecast environmental changes
- Design the vehicle with radiation protection in mind
- Crew procedure to build shelter that enhances thinly shielded part of Orion

Lunar and Planetary Surface EVA

- ConOps still in development

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“Big Three” Questions to SRAG Operators

What the Flight Control Team in Mission Control asks	What they mean
1. Will an event occur?	1. Do we need to worry?
2. How intense will the event be?	2. Will we need to stop mission activities so crew can shelter?
3. When will the event end?	3. When can we resume mission activities? When can we stop worrying?

NASA's ISEP Project

Integrated Solar Energetic Proton Alert/Warning System

Ingredients for effective R2O2R2O

- Space Radiation operations
- Expert end users
- Validation
- Model development

- Human-in-the-loop products
- Provide necessary inputs for models to run on the SEP Scoreboards
- Space weather monitoring and analyses

- Development of the SEP Scoreboards
- Onboarding and hosting models
- Technical expertise
- Model expertise

SRAG, CCMC, M2M points of contact

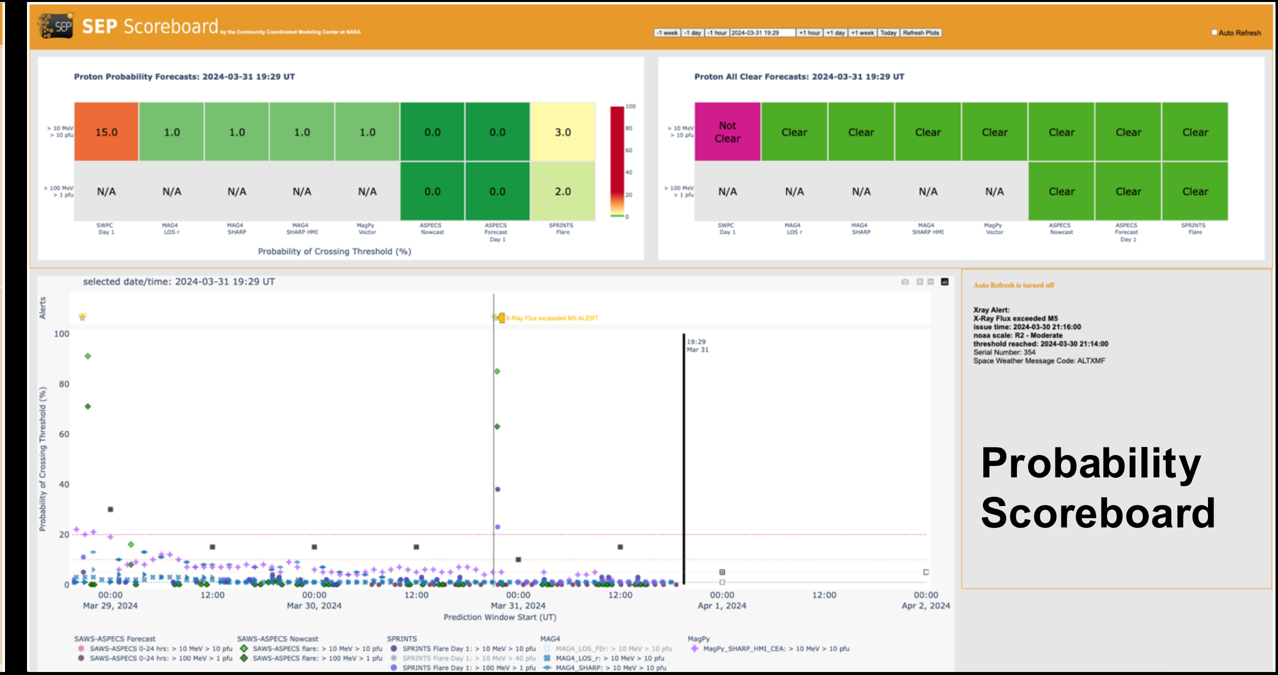
Model Developers at Research Institutions

Space Weather Forecasting with the SEP Scoreboards

- SRAG console operators use the SEP Scoreboards to obtain situational awareness
- SRAG, CCMC, and M2M work with modelers on model development
- CCMC develops the Scoreboards and onboards models
- M2M provides human-in-the-loop space weather analyses to run models in real time
- SRAG, CCMC, and M2M work on the validation of model performance

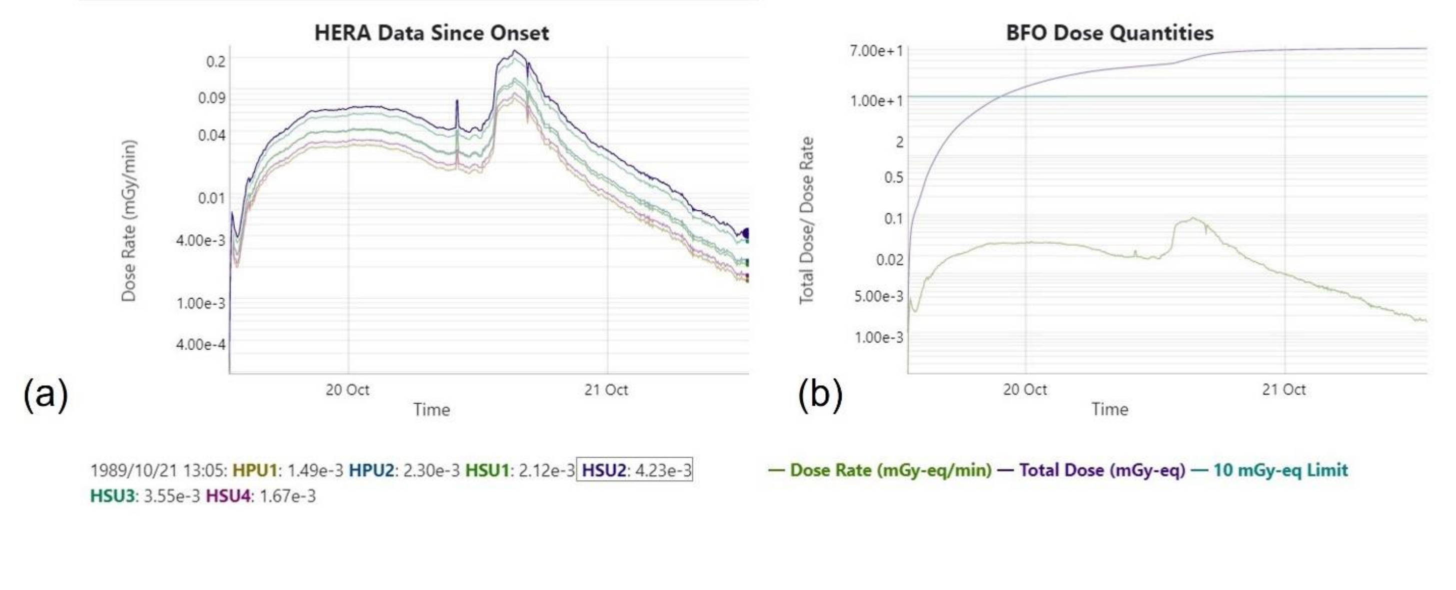
https://sep.ccmc.gsfc.nasa.gov/intensity/

https://sep.ccmc.gsfc.nasa.gov/probability/



Acute Radiation Risk Tool (ARRT)

- Acute Radiation Risk Tool (ARRT)
- Collaboration between SRAG (S Hu) and LARC (C Mertens)
- Project blood-forming organ (BFO) dose from HERA input
- Short term (48hr) and long term (6 week) effects
- Selected Acute Radiation Syndrome impacts, blood cell counts, and Performance Decrement



ARRT output for historical event (Oct 1989) as it would be measured at 6 HERA locations in the modern Artemis-era vehicle

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Measurement Needs for SRAG Operations

- Measurements that fully characterize the current state of space weather and the radiation environment:
  - **Geomagnetic storms** (LEO only) – geomagnetic indices, auroral predictions; on call in case an SEP event occurs while particles have increased access due to compressed magnetosphere and also to inform astronauts when they can view aurora
  - **Solar eruptions** – active region, flare, and CME measurements
  - **Current space radiation environment** - in situ particle measurements
  - **Radiation environment inside the vehicle** - personal and vehicle-mounted dosimeters
  - **Model Forecasting** - all measurements used as inputs into models to produce forecasts

SRAG Radiation Protection Gaps

- No reasonable, feasible human health-related experiments on the lunar surface for radiation protection - emphasis is on crew protection from space radiation
- Characterization of relevant radiation environments prior to or in conjunction with human exploration (Solar Decadal*, p. 536, Goal 3)
  - Free space at Moon, includes effects from magnetotail crossings (e.g. in orbit, external to Gateway)
  - Internal in vehicles: Orion, Gateway, Human Landing System (HLS), Lunar Terrain Vehicle (LTV)
  - Particle measurements on lunar (Martian) surface to characterize environment variability – albedo particles, regolith composition, field of view effects (crater, cave)
  - Energetic neutron measurements >20 MeV
  - Valuable for validation of SRAG tools and radiation dose estimates
- Space Weather forecasting gaps related to SEP prediction (Solar Decadal, p. 534 Goal 1, p. 538 Goal 6, p. 542 Goal 9 & 10), including 360^{o} view of the solar surface
- Autonomous Earth-Independent forecasting and radiation protection system (e.g. vehicle-mounted)
- If at Mars, pre-positioned radiation detectors and space weather systems

*The Next Decade of Discovery in Solar and Space Physics: Exploring and Safeguarding Humanity's Home in Space (2024) http://nap.nationalacademies.org/27938

Radiation protection and mitigation must be applied to support any human explorers in space or on the lunar or Martian surface

Back Up

NASA STD-3001 Radiation Limits

- As Low As Reasonably Achievable (ALARA)
  - Minimize radiation exposure within mission specifications and within reason

- Space Permissible Exposure Limit (SPEL)
  - Career effective dose from space radiation exposure shall be < 600 mSv
  - Calculated using NASA Space Cancer Risk model (NSCR-2012)
  - Purpose: reduce/prevent deleterious long-term stochastic effects (cancer)

NASA STD-3001 Radiation Limits

- Organ-Specific Limits
  - Short- and long-term non-cancer limits

RBE = Relative Biological Effectiveness
Suggested RBEs

Radiation Type	Recommended RBE	Range
1 to 5 MeV neutrons	6.0	4 to 8
5 to 50 MeV neutrons	3.5	2 to 5
Heavy ions	2.5	1 to 4
> 2 MeV protons	1.5	N/A

Organ-Specific Non-Cancer Dose Limits

Organ	30-Day Limit	1-Year Limit	Career
Lens of Eye	1000 mGy-eq	2000 mGy-eq	4000 mGy-eq
Skin	1500 mGy-eq	3000 mGy-eq	6000 mGy-eq
Blood-Forming Organs (BFO)	250 mGy-eq	500 mGy-eq	N/A
Circulatory System	250 mGy-eq	500 mGy-eq	1000 mGy-eq
Central Nervous System	500 mGy	1000 mGy	1500 mGy
Central Nervous System ($Z \geq 10$)	N/A	100 mGy	250 mGy

Radiation Dose Units

- Gy – how much radiation is absorbed in a material?
- Sv – how harmful is the radiation to human health?
  - Associated with the risk of cancer
- Gy-eq – how harmful is the radiation to human health?
  - Associated with the severity of a specific injury/ailment

<u>Gray (Gy)</u>
1 Gy = 100 rad = 1 J kg^{-1}

Energy Deposition per Unit Mass

Absorbed Dose

<u>Sievert (Sv)</u>
1 Sv = 100 rem = 1 J $kg^{-1} \times Q$ or w_R

Biological Damage
(long term effects)

Dose Equivalent
Equivalent Dose
Effective Dose

<u>Gray-equivalent (Gy-eq)</u>
1 Gy-eq = 1 J $kg^{-1} \times$ RBE

Biological Damage
(acute effects)

RBE-Weighted Dose

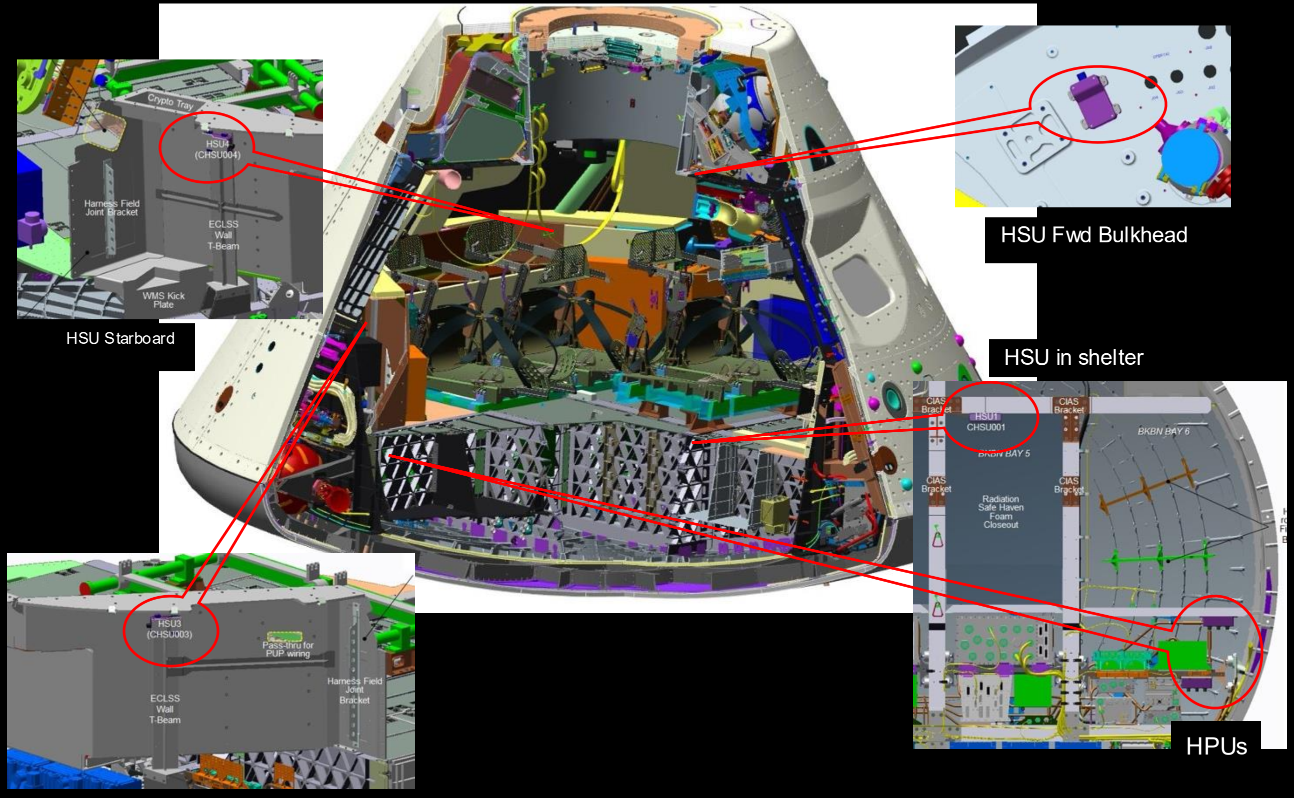
HERA Sensors on Orion

- 6 HERA Sensors
  - Distributed throughout
  - Wide range of shielding
    - Highest dose rate readings used to drive operational actions

Differences in surrounding mass

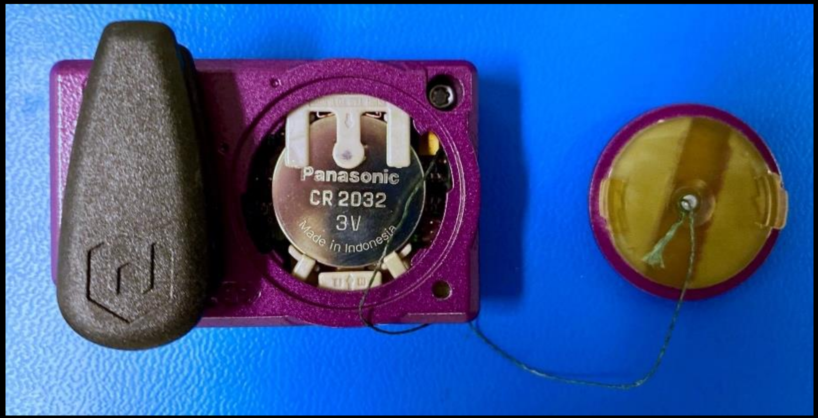
=

Differences in measured dose rate



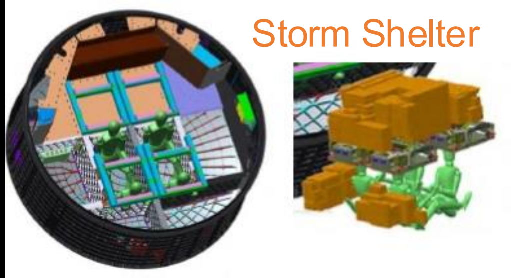
Crew Active Dosimeters (CADs)

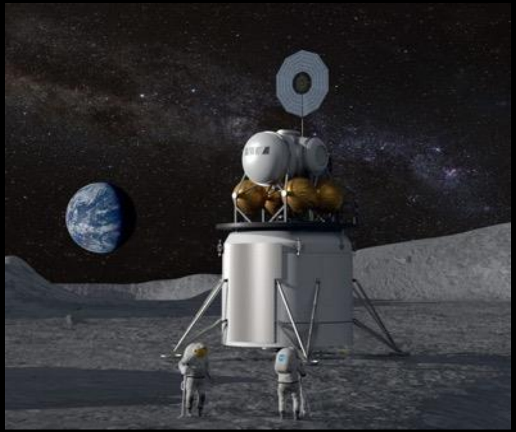
- Active dosimeters
  - Measure and display absorbed dose
    - Cumulative and rate
  - Personal crew dose
  - Connects to computer via native Bluetooth



Operational Relevance of SEP Forecasts

- Operational relevance stated here is presented from the perspective of SRAG for space radiation impacts to humans
- Limited SEP impact on the ISS in Low Earth Orbit due to the protection of the Earth's magnetosphere
- Astronauts onboard Artemis will be able to build a shelter within 30 minutes
- Astronauts performing a lunar EVA are required to stay within a 1-hour radius from the lander (life support systems requirement)

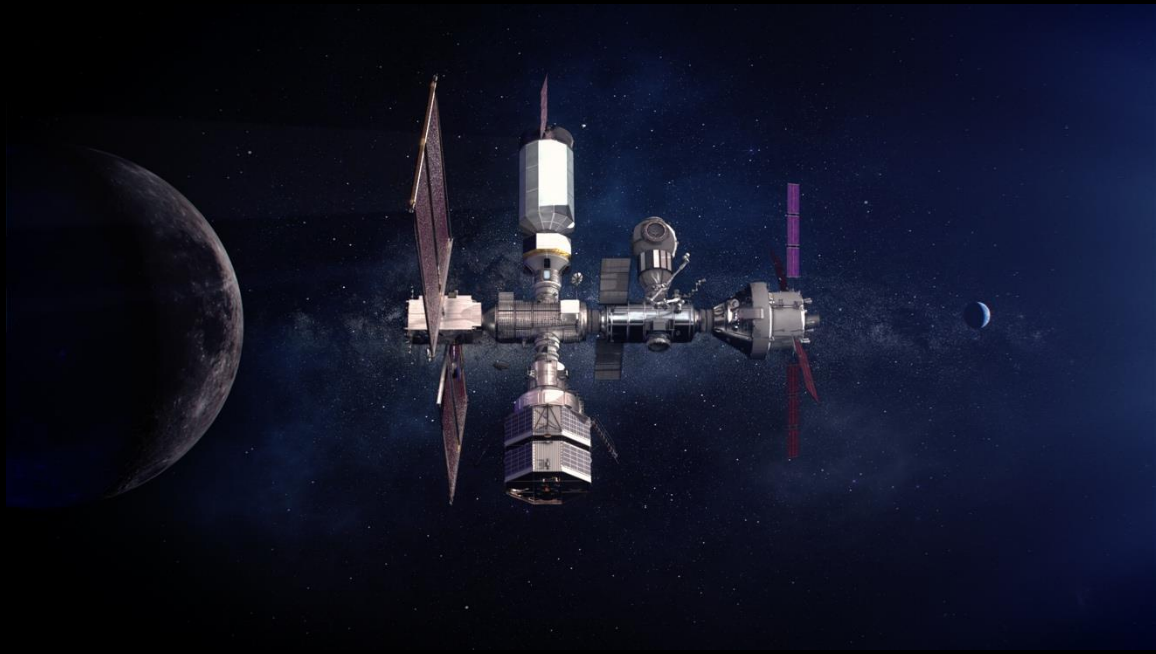




- Astronauts can respond to an SEP event within a 30 – 60-minute timeframe. Therefore, regardless of All Clear status, if an eruptive event has not yet occurred (flare, CME), it is advantageous to carry out planned EVAs or other important tasks as the task could be completed prior to an eruption. If an SEP event does occur, astronauts can respond quickly.
- Two types of useful SEP forecasts:
  - All Clear or probability prior to an eruption (issued every 6, 12, 24, 48, etc hours)
  - All Clear and forecasts of all kinds (timing, peak, time profile, fluence) immediately following an eruption to enable quick response

Gateway

- HERMES (NASA) and ERSA (ESA) space weather instrumentation onboard lunar Gateway will provide:
  - New measurements for the testing and validation of SEP models that are already running in real time in the SEP Scoreboards
  - A full characterization of the radiation environment in cis-lunar space outside of the Earth's magnetosphere
  - A full characterization of the radiation environment inside of the habitat



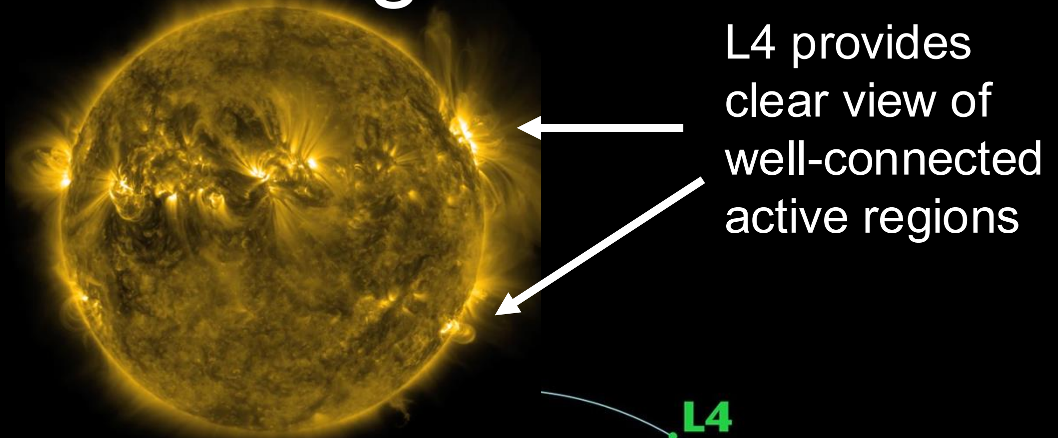
Key Measurements to Support SRAG Operations in Cis-Lunar Space

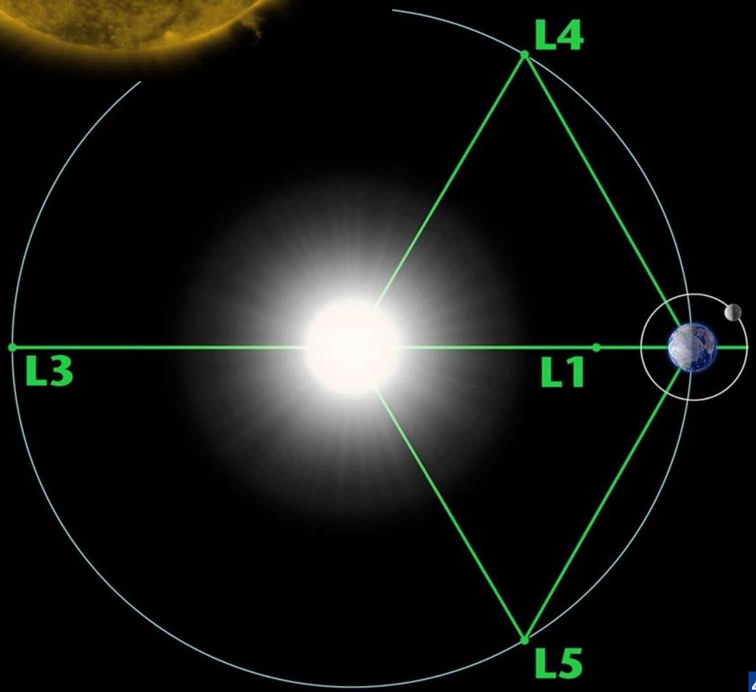
- Dosimetry onboard the vehicle
- Energetic protons
- Energetic electrons
- Solar radio bursts
- Magnetograms
- Coronagraph images
- In situ solar wind plasma
- Continuum white light solar images
- Soft X-rays
- X-ray imager
- EUV images
- H-alpha images

Source: Space Weather Architecture Options to Support Human and Robotic Deep Space Exploration, Minow and Mertens (April 2020)

Benefits of L4 Observations for Space Weather Situational Awareness and Forecasting

- Magnetograms from L4
  - Reduce magnetic field projection effects
  - More coverage → better solar wind simulations
- X-rays, EUV, Radio from L4:
  - Remove occultation or total blind spot for West flares
- Coronagraph at L4
  - Ensure multiple vantage points of CME eruptions
- Solar wind plasma and energetic particles at L4
  - Multi-point measurements improve understanding of the vast physical system
  - Insight into particle transport
  - *Model development and validation* of solar wind, CME, and SEP predictions
  - Value for forecasting during a mission to Mars (Posner et al. 2021)



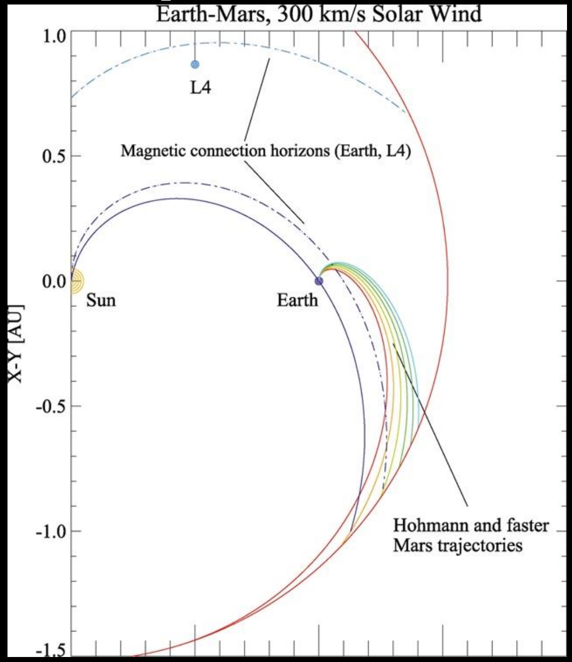


Where do we need these measurements for Earth-independent operations?

- "The panel suggests that NASA take full advantage of the upcoming Artemis lunar missions to design and prototype onboard space weather instrumentation packages and develop monitoring and forecasting tools for stand-alone use by astronauts." (Decadal Survey of Solar and Space Physics, 2024 – 2033)
- **Exterior to the crewed vehicle:** energetic proton and electron detector, radio antenna
- **Interior to the crewed vehicle:** dosimeters, space weather forecasting system, such as the REleASE model, which uses the exterior measurements for forecasting

Where do we need these measurements for Earth-independent operations?

- "Due to the orbit of Mars, instrumentation on the Sun-Earth line will not be sufficient." (Space Weather Architecture study p.43)
- Pre-positioned satellites with space weather packages at L4 and Mars-L1
- 360-degree space weather measurements of the Sun from the equatorial plane



Posner 2021

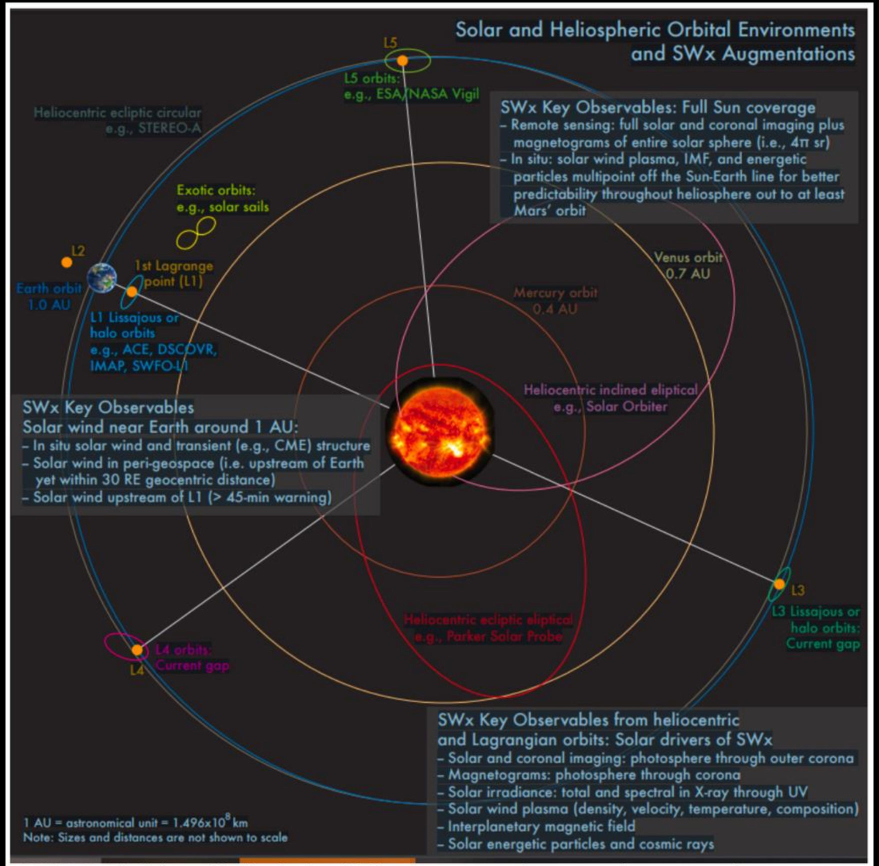


FIGURE E-9b Solar and heliospheric orbital environments and space weather augmentations.
SOURCE: Sun image from NASA.

SWAG recommendation (Decadal p.554, Figure p. 553):
Develop global full-Sun science measurements (360-degree longitudinal and polar region coverage) of the solar photosphere and outer atmosphere, with magnetic field, outer atmosphere, and corona imaging and in situ energetic particle measurements.