The Martian Radiation Environment and Human Health Risks

A Science Strategy for the Human Exploration of Mars

Panel on Biological and Physical Sciences and Human Factors

Open Meeting

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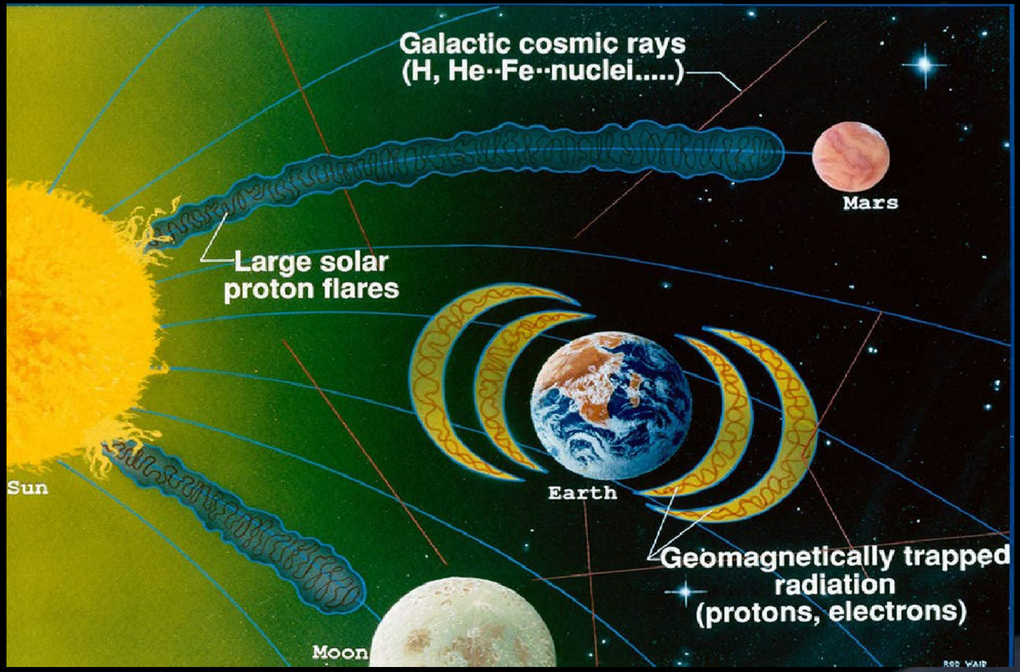
Space Radiation Environment

Solar Proton Events (SPE)

- Low to medium energy protons – most in <100 MeV range
- Travel along magnetic field lines, can arrive quickly if well connected to vehicle
- Real time dosimetry and shielding are effective to prevent acute exposure
- **Shortfall:** Accurate forecasting; Earth independence along Sun-Mars line

Galactic Cosmic Radiation (GCR)

- Continuous background of low dose radiation consisting of ~ 89% protons, ~10% alpha particles (He), and ~1% heavier nuclei
- Broad energy spectrum from 10's of MeV/n to >50 GeV/n
- Highly penetrating difficult to shield against - fragment into lighter, penetrating species
- **Shortfall:** Effective shielding; Uncertainty about biological effects limits ability to quantify risks and develop countermeasures



GCR intensity varies with ~9.5 to 12 yr solar cycle

Solar Maximum

- *Highest probability of SPE*
- *GCR intensity at lowest levels*

Solar Minimum

- *GCR intensities at highest levels*
- *Lower probability of SPE*

Comparison of Radiation Exposures & Environments

Terrestrial Exposures

- Round trip NY to London: < ~0.1 mSv
- One adult chest x-ray: ~0.1 mSv
- Computed Tomography (CT) of Brain: 1.6 mSv
- Background from natural radiation: 3 mSv/yr
- Radiation worker exposure limit: 50 mSv/yr
  - BUT Lifetime average 10 mSv

Deep Space – Gateway and Transit

- Outside Earth's magnetosphere in free space
- Dose eq. rate: 2 to 3 x's ISS (1.3 mSv/day)

Mars Mission:

- *870 to 1250 days; ~625 to 1650 mSv*

ISS Low Earth Orbit

- Typical dose-rates: ~ 0.6 mSv/day
- Magnetosphere offers protection against SPEs (except high energy tail) and low energy GCR
- Exposure from trapped radiation and high energy GCR
- 6 months (50 – 100 mSv) to 1 yr missions (100 – 200 mSv)

Mars Surface

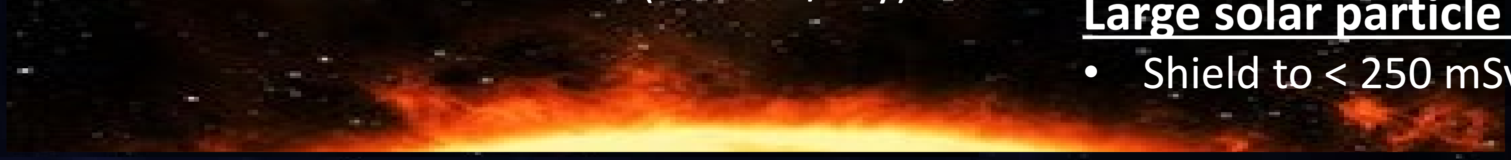
- Protection via atmosphere & planetary shielding
- Dose eq. rate similar to ISS (~0.65 mSv/day)

Lunar Mission

- Artemis sorties (30 day): 40 - 60 mSv
- *6 mos to 1 yr. cis-lunar space/surface; <250 to 500 mSv*

Lunar Surface

- Protection from planetary shielding
- Dose-rate ~1.5x ISS (0.9 mSv/day)



Large solar particle events:

- Shield to < 250 mSv

Gap type:
K- knowledge, requires scientific research
D – development (TRL 1-4)
T – Technology (TRL 5-9)
E – engineering (TRL 5-9) mission specific

Space Radiation Protection Gaps

Physical Mitigation Technologies

1.1 Space Weather Forecasting

- (D) SPE forecasting tools
- (D) Earth – independent alert system
- (K) GCR forecasts: Predictive models of solar cycle modulation

1.2 Radiation Monitoring

- (E) On-board dosimetry systems
- (T) Adv. space radiation env. characterization systems

1.3 Effective Shielding

- (E) SPE shielding
- (T/E) GCR shielding - passive
- (T) Combined GCR/SPE shielding - active

Major Asset: *Space Weather architecture*

Biological Mitigation

1.4 Predictive Models of Crew Health Risks

- (K) Probabilistic health risk models

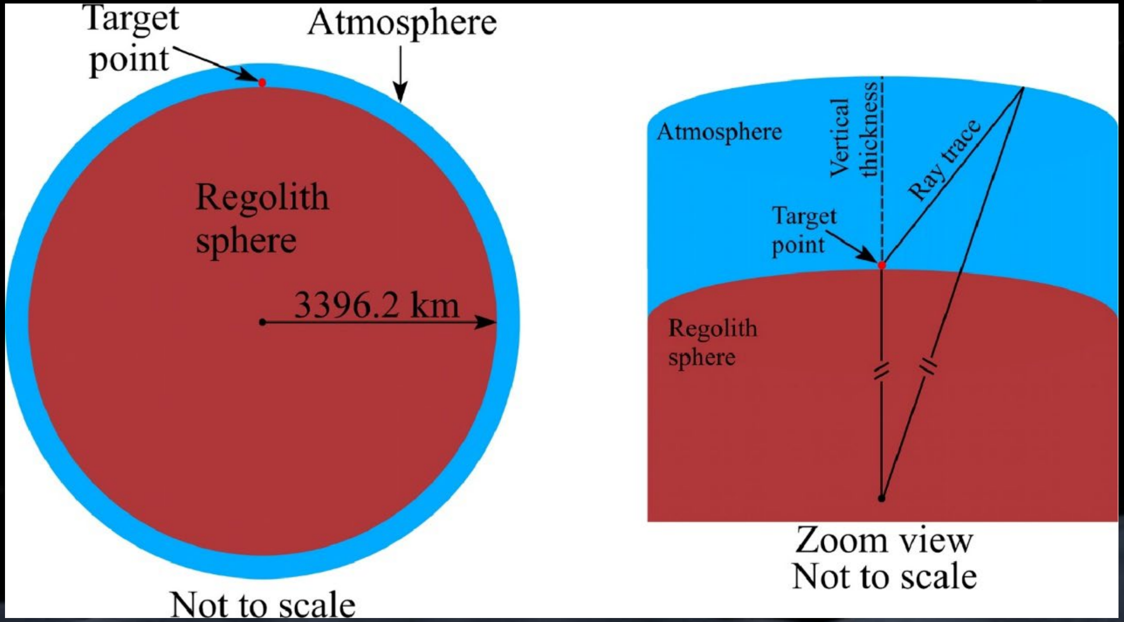
1.5 Biomedical Countermeasures and Surveillance

- (K) Biomedical countermeasures
- (K) Biomarkers & Technologies for In-flight Monitoring and Health Management

Major Asset: *NASA Space Radiation Laboratory*

Interaction of free space radiation creates a complex mixed radiation field on the surface of Mars

- No global magnetic field
- Thin Atmosphere: ~95% CO_2, ~3% N_2
- Vertical thickness: ~21 – 23 g/cm^2 at Gale Crater (~1000 g/cm2 Earth) -
- Surface Pressure: 6 to 8 millibars (< 1% atmospheric mass of Earth).
  - Diurnal variation /thermal tide (10%)
  - Seasonal variation / southern polar cap (30%)
- Rugged terrain – large topographical relief



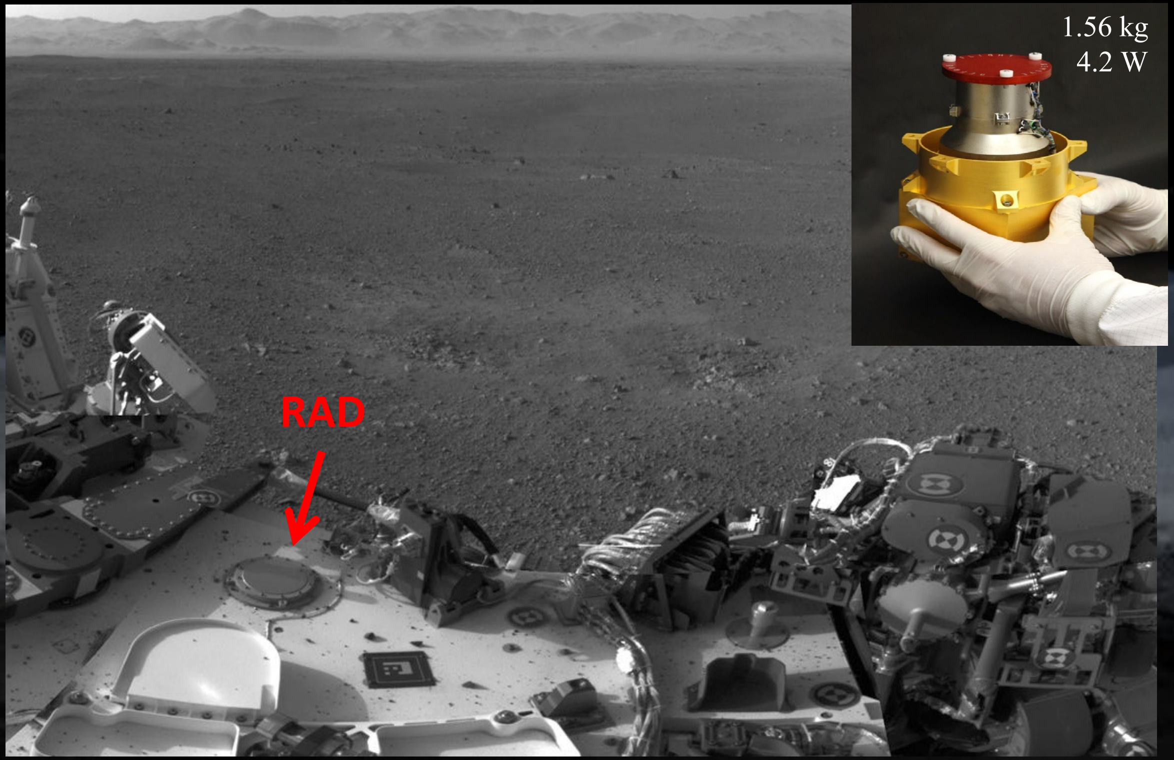
Slaba and Stoffle, Life Sci Space Res, 2017

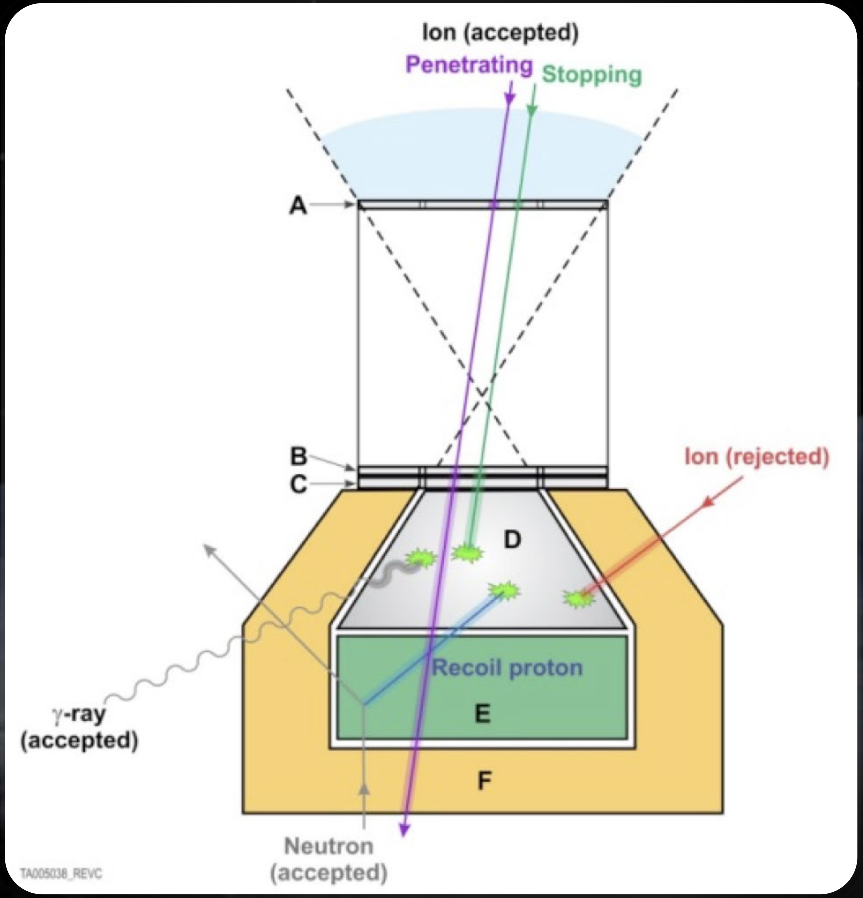
- GCR penetrates deeply and interacts with atoms in the atmosphere and ground creating a complex mixture of particles types spanning many orders of magnitude in energy
- Most SEPs have energies below 100 MeV, much of their flux does not reach the Martian surface, although even non-penetrating SEPs can create secondary neutrons that do reach the surface
- Precursor missions important to characterizing environment

MSL Radiation Assessment Detector (RAD) – operational since August 2012

Science Objective: Quantify through direct measurement the total radiation environment in advance of future manned missions to properly assess safety risks and to develop potential mitigation strategies:

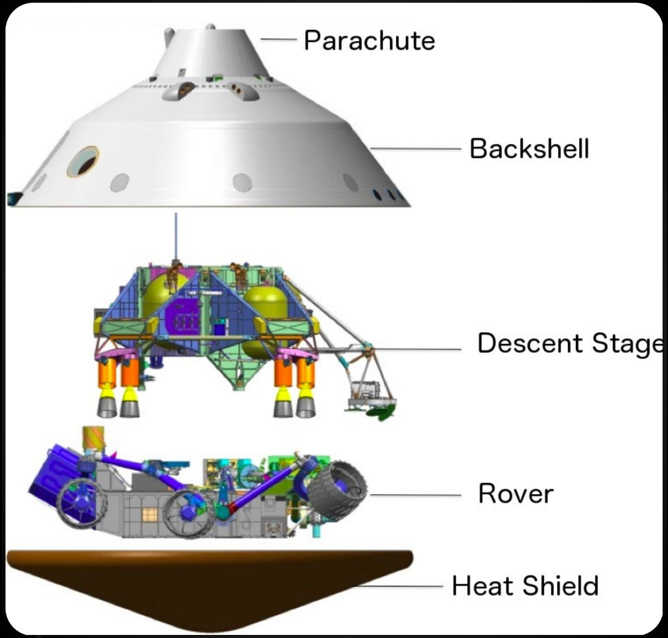
- Baseline GCR flux and secondaries
- Range of episodic SEP radiation
- Variation over the Solar Cycle





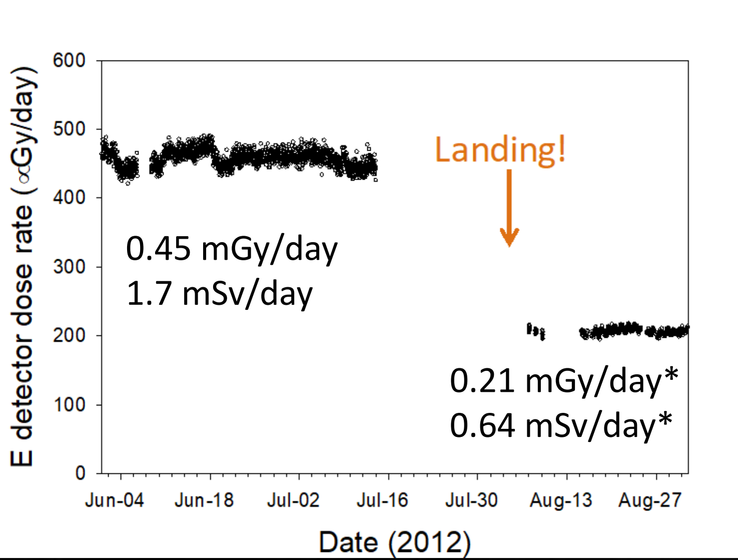
Hassler et al. 2012 , Space Science Reviews

MSL RAD measured Dose Rates



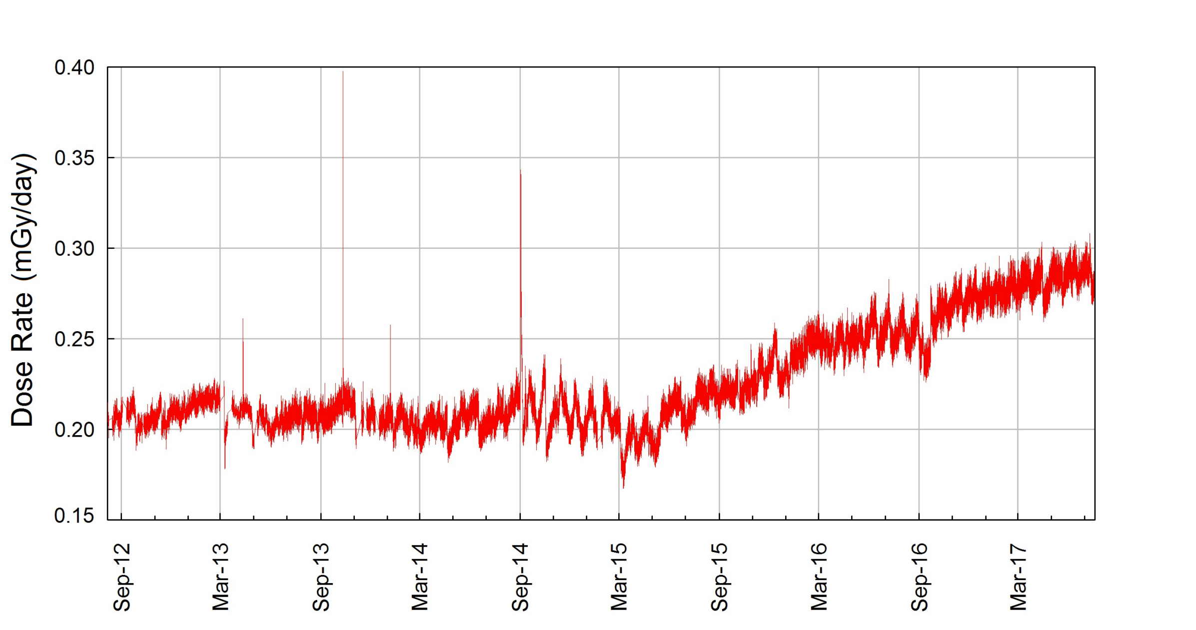
Transit-

- Average shielding depth was 16 g cm^{-2}
- Near-constant GCR + five SEP events seen
- Dose rates spike by factors of 10 to 100 during SEP events, but contribution to total dose equivalent over cruise is only ~ 5%



*Hassler et al. 2014

Measurements at Gale Floor (23 g/cm^2 CO_2) 2012 to 2017



- Dose drops by factor of 2.5
- Four small SPE's – contribution to total dose is small
- GCR flux & dose rate increase heading toward solar min

Mixed field Environment on Mars Surface - GCR

Radiation dose from secondary particles is comparable to that from the primary GCR -

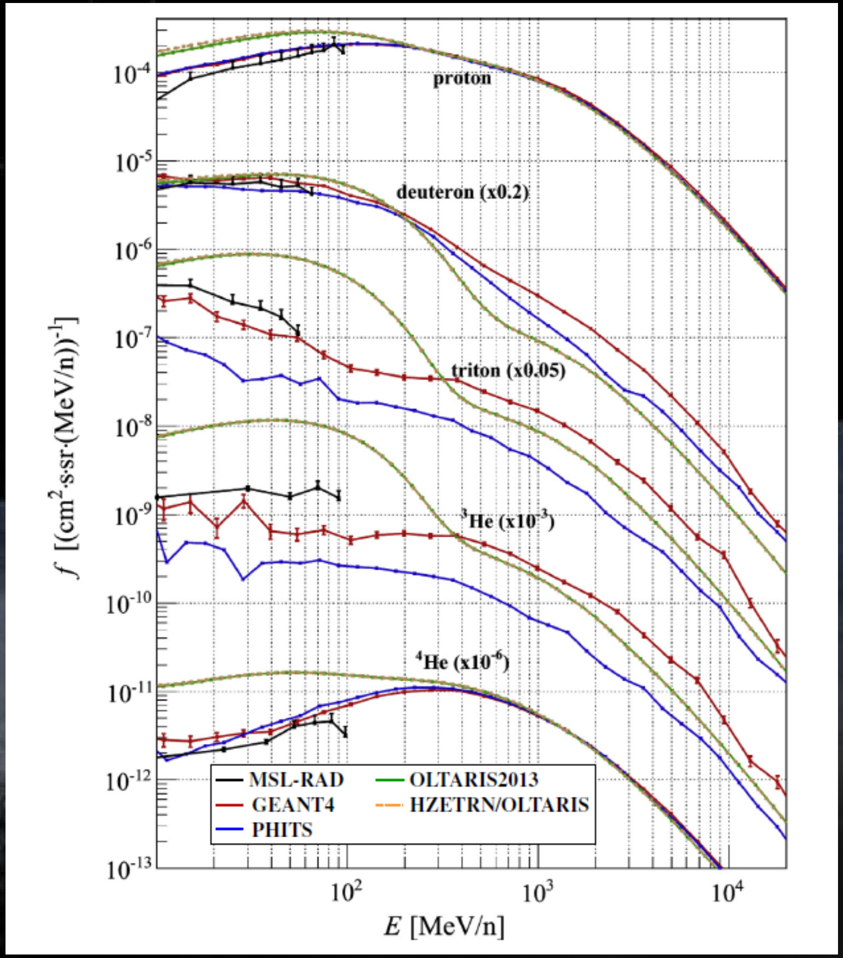
- At higher energies > a few 100 MeV/n – protons and heavier nuclei dominate environment
- Some GCR heavy ions, such as C, N, and O, are relatively abundant and have a significant probability of reaching the surface
  - These particles are most biologically damaging – quantifying particle fluxes are important to assess health risks
- At lower energies – secondary neutrons and gamma prevail
  - Gamma rays do not contribute significantly to dose, but neutrons do
  - Neutrons have high RBE and important to quantify for human health risks

Comparison of measurements with transport codes –

- Recent work has shown that dose rates derived from transport models agree within 7-12% of measured quantities
- Generally good agreement estimating many particle fluxes , but some can differ substantially - particularly for production of pions, neutrons, and isotopes of hydrogen and helium

- **Sufficient environmental understanding for short stay human missions**

Build up (1 to 2 orders of magnitude) of low energy hydrogen isotopes (deuterons, tritons) and ^{3}He from atmospheric interactions.



Matthia et. al, J. Space Weather Space Clim., **6**, A13 (2016)

Comparison of Daily Exposures – Model Results

Table 6.1.6-1. Daily Exposure within 0, 20, and 40 g/cm² Spherical Aluminum Shielding in Free Space and on Surface of Moon and Mars for Solar Minimum (2009) and Solar Maximum (2001) GCR Conditions

		Dose (mGy)[1]			Dose equivalent (mSv)[1,2]			Effective dose (mSv)[3]		
	g/cm² →	0	20	40	0	20	40	0	20	40
Solar max.	Free space	0.15	0.21	0.25	1.02	0.69	0.59	0.63	0.51	0.53
	Lunar surf.	0.10	0.12	0.14	0.58	0.39	0.33	0.38	0.31	0.32
	Mars surf.	0.12	0.13	0.15	0.30	0.28	0.30	0.28	0.30	0.32
Solar min.	Free space	0.46	0.52	0.56	2.85	1.50	1.22	1.46	1.09	1.07
	Lunar surf.	0.27	0.28	0.30	1.56	0.82	0.67	0.84	0.64	0.62
	Mars surf.	0.25	0.26	0.28	0.61	0.55	0.56	0.54	0.56	0.59

[1]Values have been calculated without the influence of any human tissue shielding and would be directly comparable to an area dosimeter placed at the center of the spherical shield.
[2]Dose equivalent is calculated using the ICRP 60 quality factor [ICRP 1991].
[3]Effective dose is calculated using the ICRP 60 quality factor [ICRP 1991] and ICRP 103 [ICRP 2007] tissue weights for a female astronaut [Slaba et al. 2010].

Improving Estimates of Mars Surface Radiation Environment for long duration stays

Better characterization of mixed field environment becomes more important as surface stays increase <u>AND</u> may be important to meet specific TBD science objectives

Requires improvements to nuclear models fundamental to radiation transport for the production and absorption of secondary radiation at large thicknesses

Additional data are necessary to fully validate models

- Reduce uncertainties of relevant light ion production cross sections using ground-based accelerators
- Extend spacecraft (ISS, Gateway) and lunar surface neutron measurements in the $\geq$100 MeV upto 1 GeV energy range
- Validate with in-space or lunar surface measurements at vehicle relevant thicknesses (~20 to 40 g/cm^2) and large depths (>80 to >100 g/cm^2) using simplified geometries

Results also inform vehicle and habitat GCR shield design

Physical interactions driving the albedo neutron environments on the Moon and Mars are qualitatively similar (20% of surface dose eq.)

Reducing the uncertainties in forecasts of solar cycle duration would enable more informed calculations of GCR exposure.

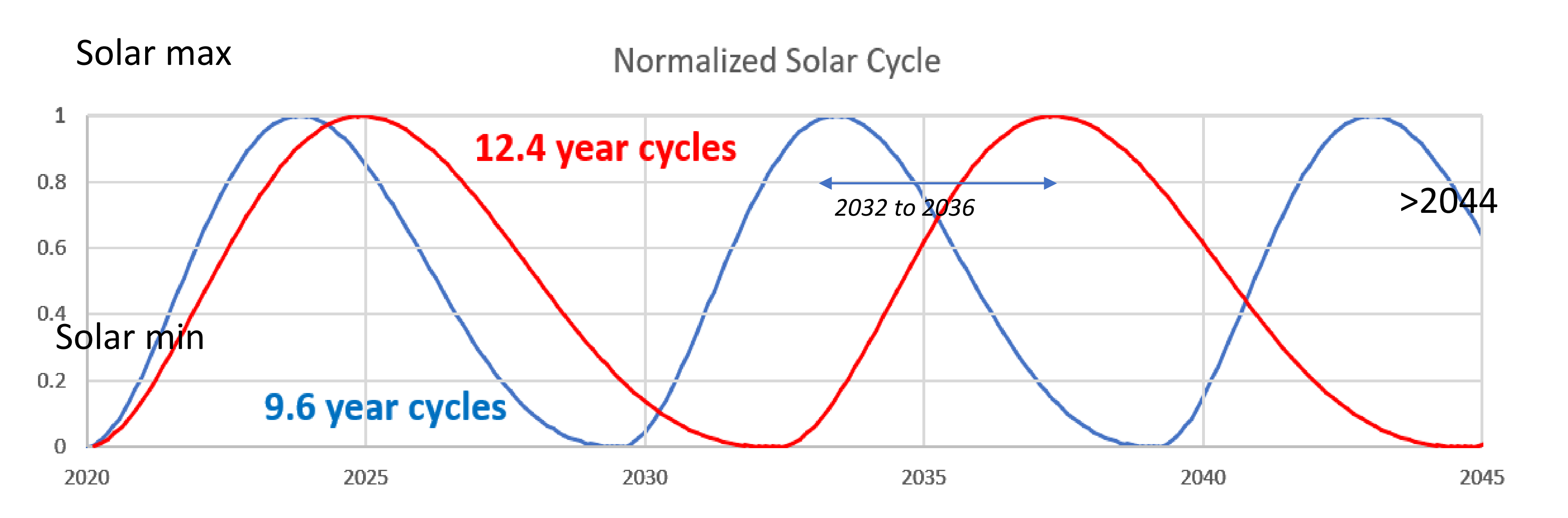
- Due to strong effect on radiation exposure, mission timing with respect to the solar cycle should be considered an input factor to Mars mission planning
- NASA should continue to support research into forecasting solar cycle amplitude and should initiate research into forecasting solar cycle duration.
- ***Caveat*** *- The schedule for a Mars mission is likely to be driven by factors other than expectations of solar activity levels: Launch windows, hardware development, budget profile, schedules…….*

- Research into forecasting solar cycles has focused on predicting the amplitude of the next solar maximum, but little has been done to forecast solar cycle duration.
- Solar cycle length variation will have a significant impact on estimates of mission dose if the projection is for 20 years out
- 6-month launch window to remain below 600 mSv starting in 2034 Variability reduced looking 10 years out (or one cycle); adjustments possible five years out

GCR SHIELDING: Time in Solar Cycle

Plan Mission during Solar Maximum (K)

Solar Cycle Variation: GCR effective dose ~50% less during Solar Max



Return crew safely and mitigate health impacts (RT 3)

Can we adequately predict when solar max is for mission planning?

- Most effort focused on predicting solar cycle intensity
- Solar cycle duration ranges from 9.6 to 12.5 years, making it difficult to forecast cycle activity two cycles out
- Next solar max between 2032 to 2036, then after 2043

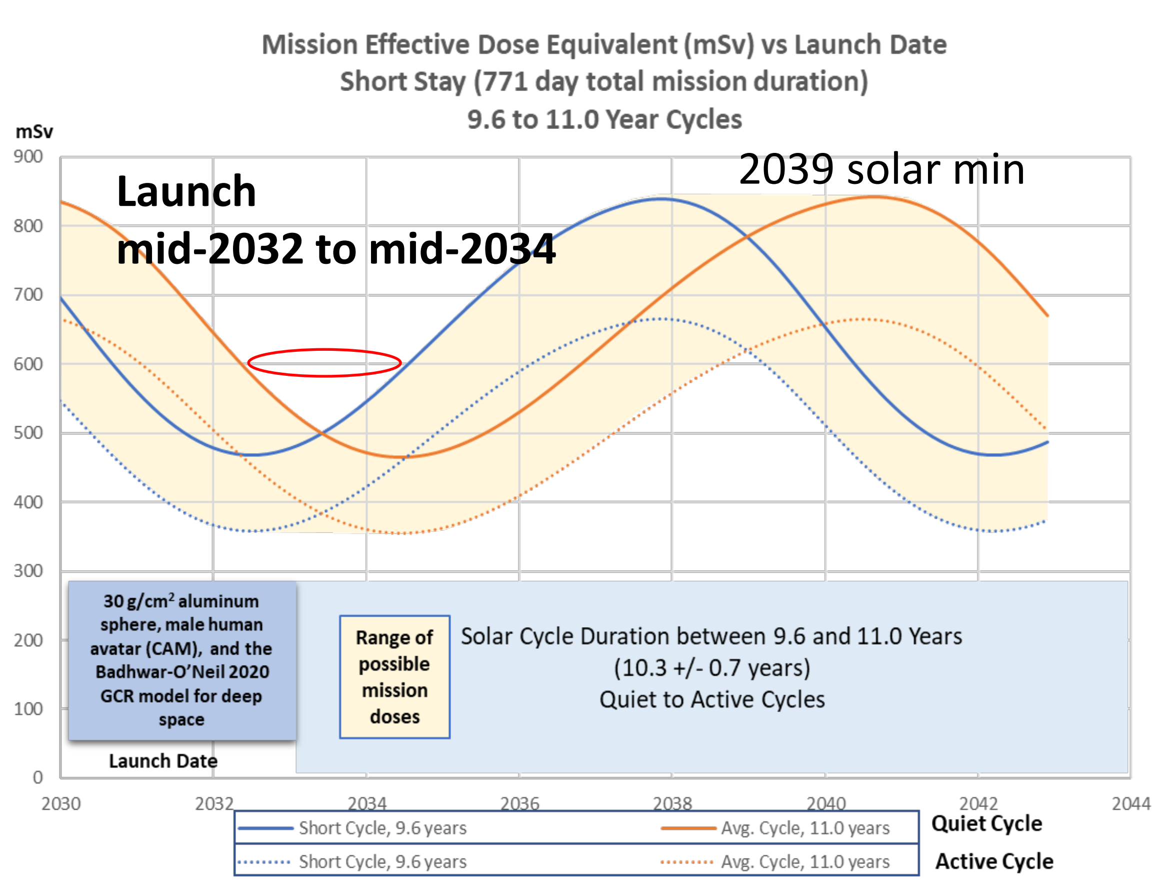
- Measurements / models supporting predictions of solar cycle durations >10 years in advance
- Alignment of mission architecture departure dates w/ solar max

Improve Forecasting Capabilities to avoid high GCR Exposures at Solar Min

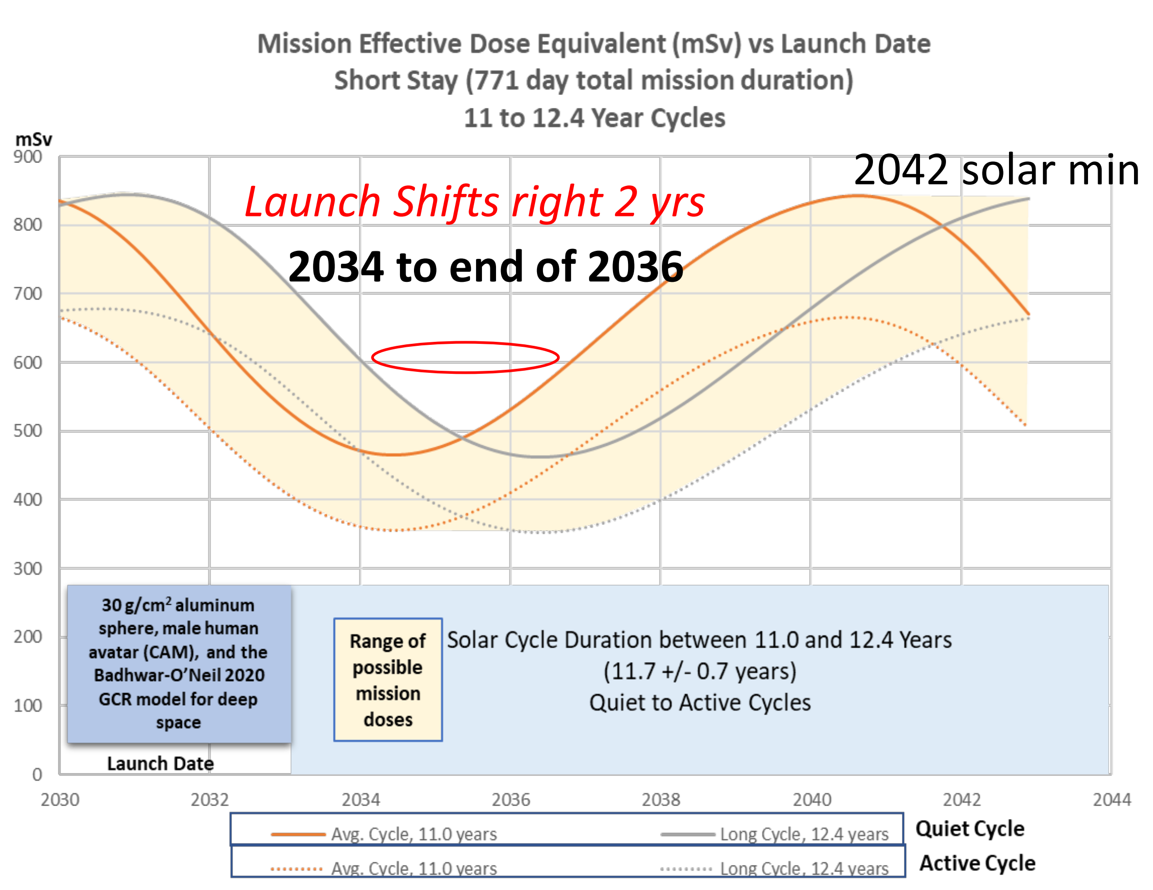
Analysis by Ron Turner

771 Day Mission Dose Range
Assuming duration uncertainty reduced by half

Cycle Duration between 9.6 and 11 years.



Cycle Duration between 11 and 12.4 years.



Reducing the uncertainty in solar cycle duration by half (from 2.8 to 1.4 yrs) increases the length of the launch window to meet 600 mSv limit from 6 months to 2 years

Solar Particle Events
Requirements & Design Guidance

Permissible Exposure Limit: Effective dose from a solar particle event shall not exceed 250 mSv

SPE shielding guidelines: Design reference spectrum – Sum of Oct 1989 events

Table 6—Recommended Shielding Guidelines for SPEs

Mission Location and Duration	*Shielding**	*Type(s) of Shielding*	*Comments*
Celestial surface any duration	*10 cm (or g/cm²) water equivalent surrounding the astronaut; Considers celestial surface shielding contribution*	*Reconfigurable shielding already within the vehicle*	*Timeline of SPEs allows for reconfiguration*
Beyond low Earth orbit <6 months	*15 cm (or g/cm²) water equivalent surrounding the astronaut*	*Reconfigurable shielding already within the vehicle; Shielding may include personal protective equipment (PPE)*	*Timeline of SPEs allows for reconfiguration*
Beyond low Earth orbit > 6 Months	*20 cm (or g/cm²) water equivalent surrounding the astronaut*	*Integrated vehicle and/or reconfigurable Shielding which may include PPE*	*Long-duration missions increase the probability of the crew being exposed SPEs*

The shielding required to meet the standard (utilizing existing mass when feasible).

Standard 3001 Vol. 1 (update 2022)

Estimated SPE effective dose using guidelines for new programs

Mars Surface:

- 25 mSv with 10 cm water equiv. storm shelter
- 40 mSv no shielding

Mars Transit:

- 107 mSv with 20 cm water equiv. storm shelter

Research & Technology Gap

Accurate forecasting and Earth Independent Monitoring Required

Solar Particle Events – Research 2 Operations

Heliophysics Research: Understand of the nature of the Sun and the dynamic processes of space weather *2*
Human Operations: Protect crew and maintain high levels of human health and performance

Research and Technology needs:

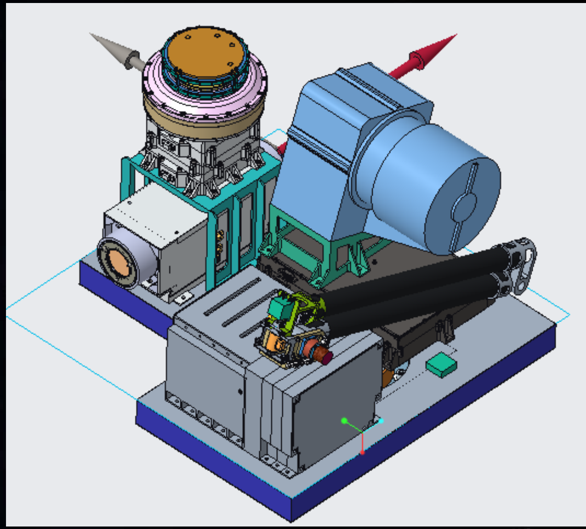
Accurate real-time operational forecasting of solar particle events

- Develop an integrated suite of multiple independent solar event and flare forecasting models utilizing current sun-Earth observation assets (e.g., GOES, SOHO)
  - Increase accuracy & warning times in advance of storm – 24 hrs
  - Reliable predictions of peak flux, duration, magnitude and time evolution of event – over hours to >7 days
  - All-clear periods
- Demonstrate during cis-lunar and lunar surface operations: Artemis II-V
- Advance to use with on-board space environment observation data in prep for Mars

Earth-independent monitoring and forecasting

- Miniaturized onboard instrument suite for space weather observation
- Possibility of new space weather architecture platforms along Sun-Mars Line
- Autonomous forecasting & warning software

Major Asset – Space Weather Architecture



HERMES on Gateway

Space Weather Architecture: M2M

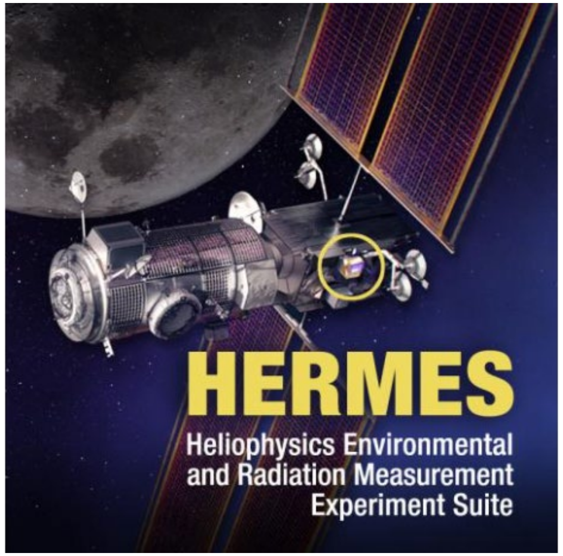
Current Assets Support Early Artemis

- ➢ Measurements along Sun–Earth line L1 (~1 AU)
- ○ **GOES/ACE** (soft X-ray spectrograph, energetic charged particle detectors)
- ○ **SDO/HMI** (magnetograph & solar imager)
- ○ **SOHO/LASCO/STEREO/CCOR** (Coronagraph)

Gateway as Testbed

NASA HERMES - Launch NET 2024

- ➢ ***Compact instruments observing solar particles & wind***

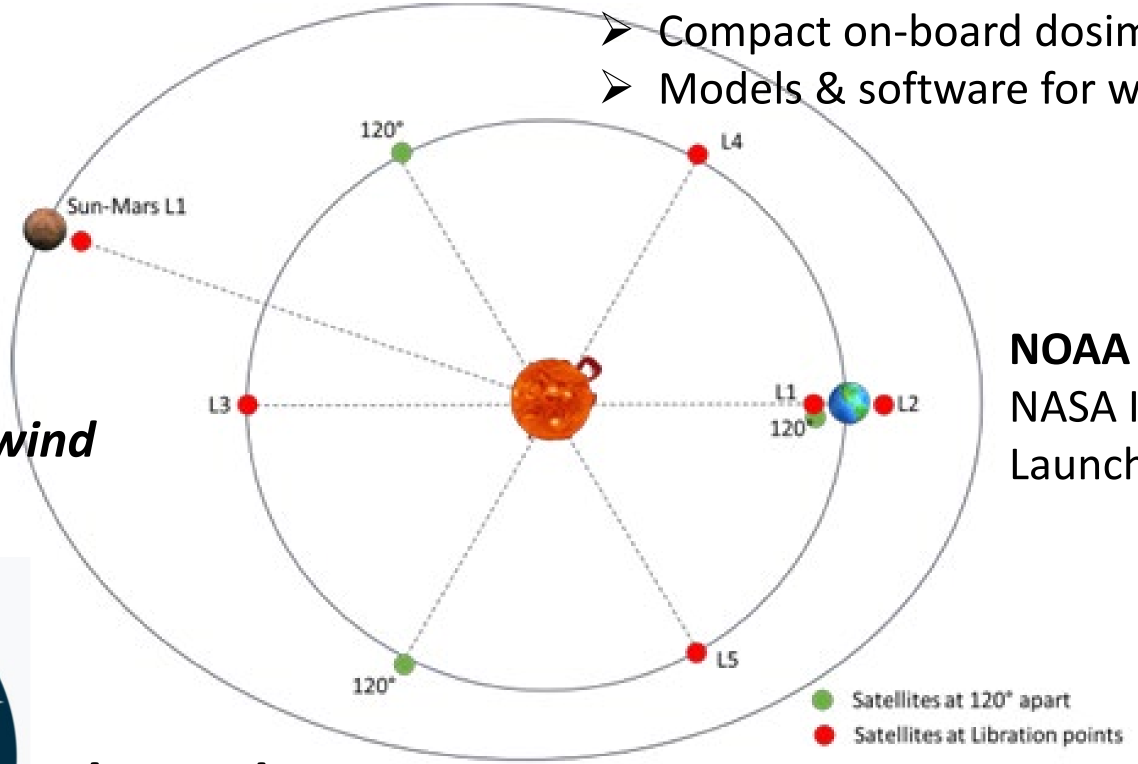


- ➢ ***Develop and test forecasting software***

NEW

Mars – Earth Independent

- ➢ Observations along Sun-Mars Line
- ➢ Targeting L4 for additional assets
- ➢ Essential for all-clear forecasts
- ➢ Compact on-board dosimetry
- ➢ Models & software for warning



NOAA SWFO-L1
NASA IMAP
Launch 2025

Planned Assets Lagrange - L5

ESA VIGIL – Launch 2029

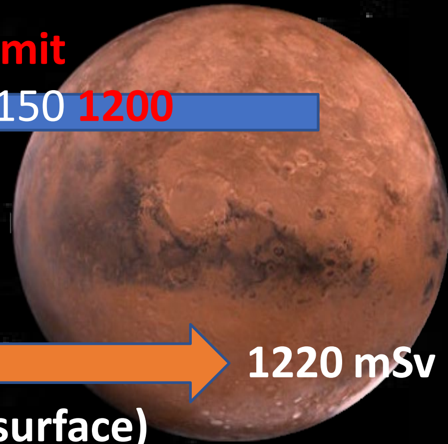
- ➢ **Early warnings of increased solar activity**
- ➢ **4-5 days of forecasting**

Risk Posture for Mars Demo Mission

Cumulative Effective Dose mSv

NASA LIMIT — **Twice Limit**

50 100 150 200 250 300 350 400 450 500 550 **600** 650 700 750 800 850 900 950 **1000** 1050 1100 1150 **1200**



Gateway 75 mSv

Lunar 40 mSv — Long duration increments 6 mos - 1yr

105 mSv

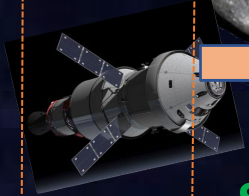
Solar Minimum *(Architectures proposing 870 to 1250 days)*

Opposition Mission 870 days with 30 days on surface → **1220 mSv**

Conjunction Mission 905 days with 545 days on surface → **940 mSv (all crew to surface)**

- Reduce GCR exposure by factor of two*, opp. missions <870 days

Solar Maximum *& 20 cm SPE shelter (870 days with 30 days on surface)*



SPE → 685 mSv

- Fly at solar maximum & Reduce SPE exposure by factor of 3

Solar Min Fast Transit ~400-day mission

Experienced Crew

~500-day mission

Un-Experienced Crew

- Sprint Missions

RISK ACCEPTANCE

- Quantify risks
  - Inflight monitoring
    - Provide medical countermeasures (pre-/in-/post-mission)*
      - Enhanced surveillance (post-mission)

**Technologies do not exist or mass prohibitive*

**Long term development*

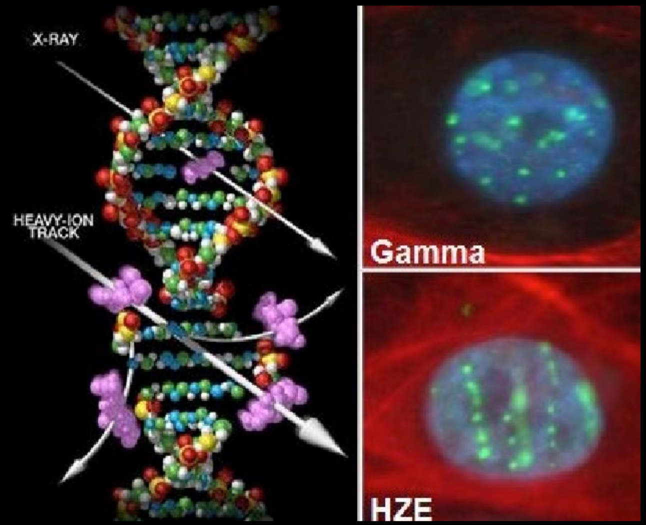
Space Radiation Health Risks

Major Risks -

- Acute Radiation Syndromes from solar particle events
- Central Nervous System Effects – inflight and post mission
- Radiation Carcinogenesis
- Degenerative Diseases – cardiac and vascular

Unique Biological Challenges -

- *Radiation Quality Effects*
- *Low dose-rates in space*
- *Translation to humans*
- *Understanding individual radiation sensitivity*
- *Quantifying combined spaceflight stressors*



(Cucinotta & Saganti, Patel & Huff, NASA)

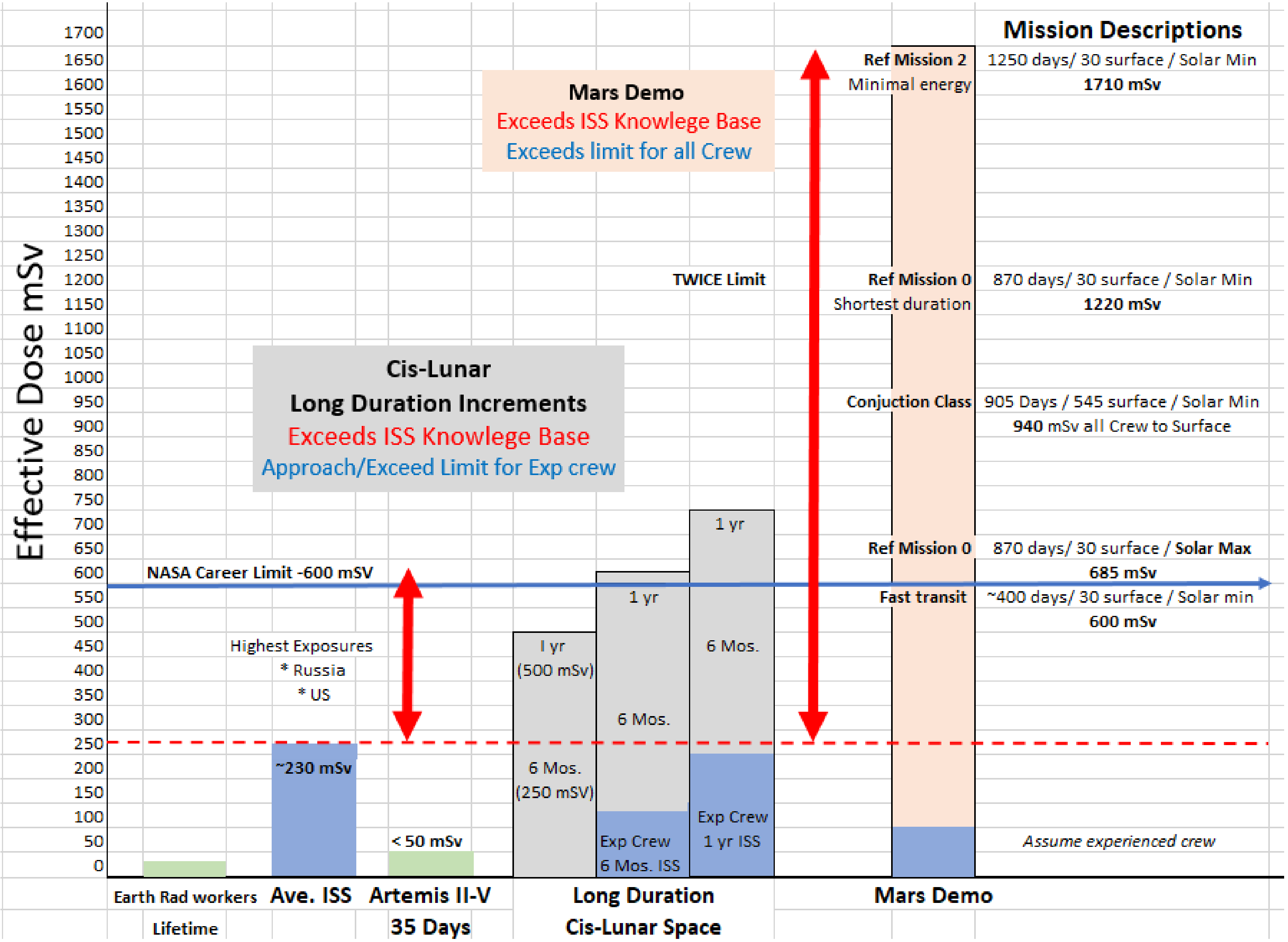
Densely ionizing radiation along particle track cause unique damage to biomolecules, cells, and tissue

Space Radiation Health Risks

- **Risk of Radiation Carcinogenesis**
  - Morbidity and mortality risks
- **Risk of Acute (In-flight) & Late Central Nervous System Effects from Radiation Exposure**
  - Changes in cognition, motor function, behavior and mood, or neurological disorders
- **Risk Of Cardiovascular Disease & Other Degenerative Tissue Effects**
  - Degenerative changes in the cardiovascular system and lens
  - Diseases related to aging and immune system dysfunction
- **Risk of Acute Radiation Syndromes due to Solar Particle Events**
  - Prodromal effects (nausea, vomiting, anorexia, and fatigue)
  - Skin injury
  - Depletion of the blood-forming organs and immune dysfunction

Risks documented in HRP Evidence Books

Radiation Risk Posture for the Moon 2 Mars Mission Segments



Foundational Exploration Segment (6 mos to 1 yr. cis-lunar space/surface; <250 to 500 mSv)

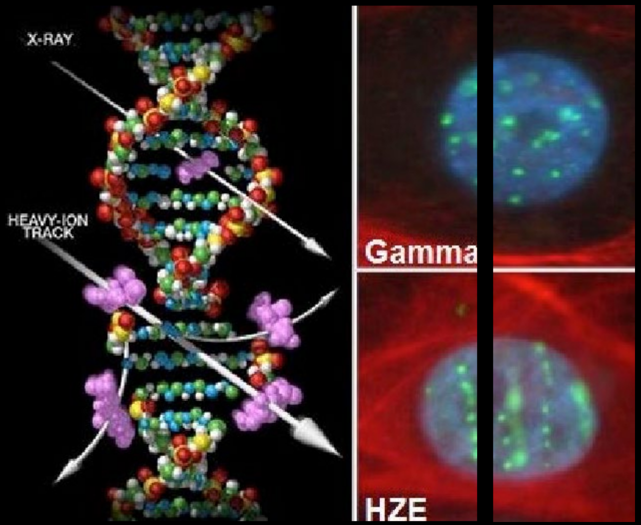
- Knowledge gap between our average ISS experience (200-300 mSv) and limit (600 mSv)
  - ➢ Possibility exists of crossing thresholds for increased risks of cardiac, vascular, cerebrovascular, and neurocognitive diseases
  - ➢ Evidence of excess risk in terrestrial cohorts, but data are inclusive.
- Additional protection strategies needed for experienced crew and those most sensitive to radiation

Mars (870 to 1250 days; ~685 to >1700 mSv)

- Exposure levels well outside spaceflight knowledge
- Lack of risk characterization: significant gap between 200-300 mSv and >1700 mSv.
- In >600 mSv dose range, added potential exists for in-mission CNS performance decrements
  - ➢ Risk levels are not well understood
  - ➢ Effects of the combined stressors of spaceflight unknown
- Additional protection required for all crew

The Biological Perspective: Research Challenges

- **Understanding radiation quality effects on biological damage**
  - Qualitative and quantitative differences between space radiation compared with x-rays or gamma-rays
- **Quantifying low dose and dose rate dependencies**
  - Biology of repair, cell, and tissue regulation
- **Translating experimental data to humans**
  - Lack of human data exist to estimate risk from high LET GCR exposures
  - Animal and cellular models with simulated space radiation must be used
- **Understanding Individual radiation sensitivity**
  - Genetic, dietary and healthy worker effects
- **Quantifying synergistic modifiers of risk from other spaceflight factors**



(Cucinotta & Saganti, Patel & Huff, NASA)

Densely ionizing radiation along particle track cause unique damage to biomolecules, cells, and tissue

Protection from Galactic Cosmic Radiation (GCR): Long-Duration Increments & Mars

Goal: Return crew safely and mitigate health impacts (RT 3)

- Within the current architecture, shield technologies and fast Mars transit to further reduce GCR exposures - by any significant (>~50%) amount - are mass prohibitive.

- Breakthroughs in Physical Technologies and/or additional Biological Strategies are needed to protect crew

- *Biological Strategies Include:*
  - Provide tools to assess risk for crew informed consent and appropriate acceptance of risk by Agency decision makers (8900.1B requirement)
  - Increase protection for crew which are most susceptible to radiogenic health risks and/or select most resilient crew for the longest durations (Mars demo)
  - Provide in-flight monitoring and preventative medical countermeasures
  - Monitor long-term health of crew member > 5yrs post mission
    - ✓ Maintain high quality of life – Inspire next generation
    - ✓ Enable return to flight for multiple missions

Protection from GCR: Mars Demo Mission

Goal: Return crew safely and mitigate health impacts (RT 3)

Biological Strategies

Risk Acceptance

- (K) Perform necessary research to understand risks
- (K) Provide tools for crew informed consent and appropriate acceptance of risk by Agency decision makers (8900.1B requirement)

Personalized Protection

- (K) Understand the biology of individual sensitivity/susceptibility
- Increase protection for crew which are most susceptible to radiogenic health risks and/or select most resilient crew for the longest durations (Mars demo)

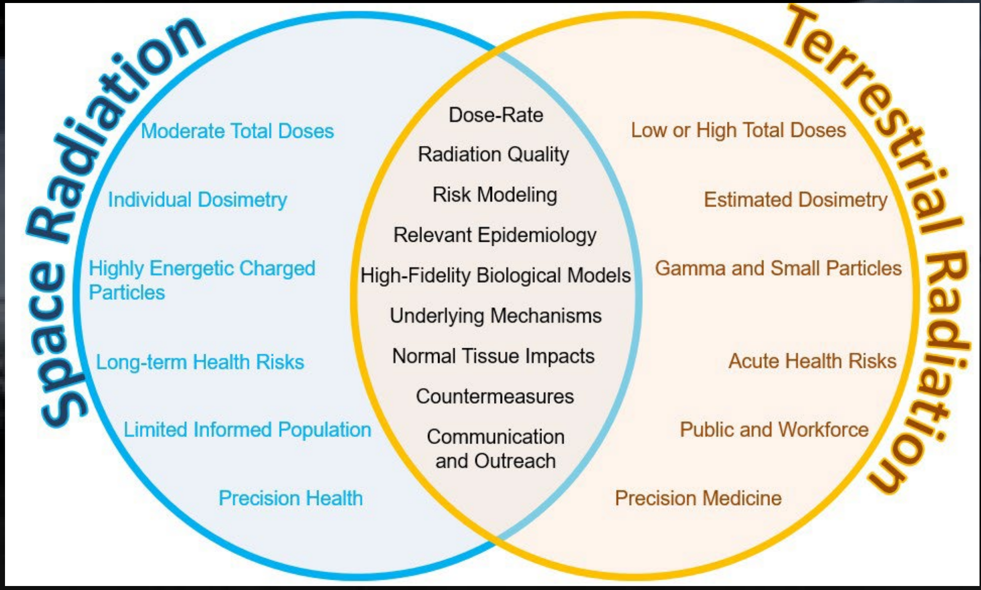
NASA Space Radiation Laboratory

In-flight monitoring and preventative medical countermeasures

- (K) Identification of biomarkers of tissue injury & behavioral health
- (K/T) Compact diagnostics
- (K) Validated countermeasures focused on disease prevention

Monitor long-term health of crew

- Maintain high quality of life – Inspire next generation
- Enable return to flight for multiple mission



Biological Mitigation Research Objectives

1. **Perform necessary research to quantify risks from GCR**
   - In 450 mSv to ≥600 mSv – understand risk of cardiac & vascular diseases and late neuro cognitive impairments (*Foundational Exploration*)
   - In >600 mSv – understand in-mission CNS performance decrement (*Mars Demo*)
   - Evaluate combined spaceflight hazards
   - Develop computational tool set to inform risk
2. **Understand the biology of individual sensitivity/susceptibility**
   - Leverage terrestrial radiation research (*incl. NCI, ICRP*)
   - Capability for personalized risk assessment and protection plan
3. **Provide *In situ* monitoring of crew health to inform countermeasure deployment**
   - Biomarkers of tissue injury or early disease indicators*
   - In-space validation during missions >6 months
4. **Provide cross-risk^ biological countermeasures to reduce adverse health outcomes**
   - Focus on disease prevention
   - Target common disease pathways^^
   - Validate terrestrial approaches for space applications
5. **Post mission, leverage terrestrial advances in early detection and personalized treatments**
   - Enable return to flight for multiple missions
   - Maintain high quality of life

Space Radiation Protection Gap Details

Biological Mitigation

1.4 Predictive Models of Crew Health Risks

- **(K) Probabilistic health risk models**
  - ➢ Long-term health models for cancer, cardiovascular disease, late neurodegenerative diseases
  - ➢ Capability to provide personalized risk estimates to inform medical countermeasures and disease surveillance
  - ➢ Capability to evaluate in-mission radiation risks for CNS
  - ➢ Methodologies to evaluate interaction of radiation with 4 other hazards of spaceflight

Ground Based Only

1.5 Biomedical Countermeasures and Surveillance

- **(K) Biomedical countermeasures**
  - ➢ Validated CMs with known safety profile, mode of action, and efficacy in reducing space radiation induced damage covering the large range of radiogenic cancers and other degenerative health effects.

(K) Biomarkers & Technologies for In-flight Monitoring and Health Management

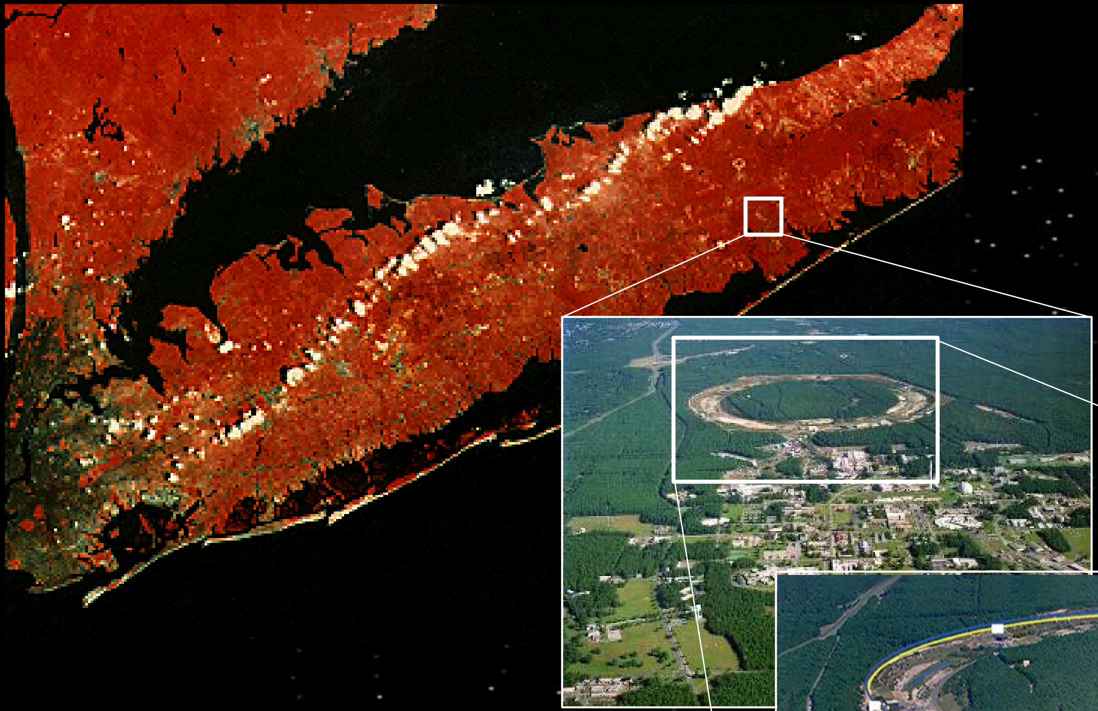
- ➢ Deliver evidence base of at least 2 predictive biomarkers
- ➢ Miniaturize commercial diagnostic technologies.

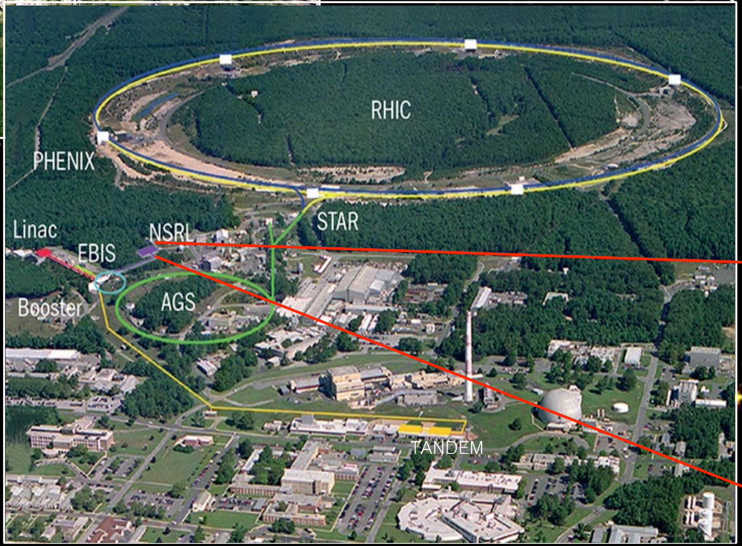
Spaceflight Validation: Incremental Approach

- Understand pharmacokinetics and pharmacodynamics (PK/PD) for human dosing in space environment. Utilize ISS as research platform (If CM identified for flight by end-of-life - needed) or Commercial LEO destinations (possible), Gateway (possible) (Missions >14 days).
- Monitor efficacy on Gateway and lunar surface for missions of ~180 days.

- Test measurement technology in space environment on ISS if technology is identified by end-of-life (2030 - needed) or at Commercial LEO destinations (possible).
- In-situ monitoring (biomarkers) of crew for missions of ~180 days on Gateway and Lunar Surface.

NASA Space Radiation Laboratory (NSRL) at DOE Brookhaven National Lab





- Simulates space radiation - high energy ion beams (H^+, He, Fe, Si, C, O, Cl, Ti, etc.)
- GCR Simulator
- 3 experimental campaigns per year
- Animal and cell biology facilities
- Heavily utilized by NASA & commercial spaceflight and DOD Missile Defense Agency

NSRL Beam Line

Images courtesy of BNL

NSRL

GCR Simulator Beam Definition

Normalized to 500 mGy

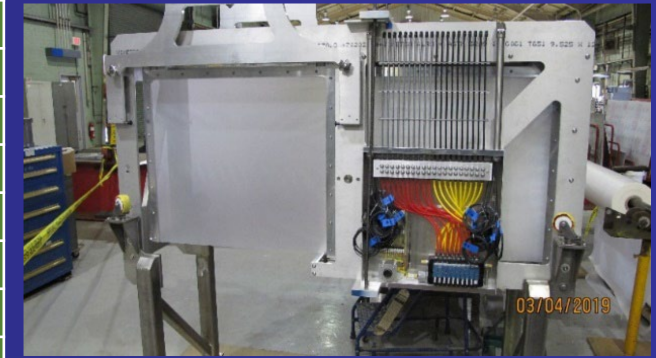
GCR Simulation Beam consists of 33 beams

- *4 H energies plus degrader (65-75% dose)*
- *4 He energies plus degrader (10-20% dose)*
- *5 Heavy ions: C, O, Si, Ti, Fe (6-8% dose)*

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	100	*Polyethylene degrader to*		
^{1}H	150	15.9	0.54	35.0
^{1}H	250	38.1	0.39	68.9
^{1}H	1000	326.6	0.22	123.6
^{4}He	100	*Polyethylene degrader to*		
^{4}He	150	16.0	2.17	7.5
^{4}He	250	38.3	1.56	16.4
^{4}He	1000	327.8	0.88	24.9
^{12}C	1000	110.1	7.95	11.7
^{16}O	350	17.0	20.8	15.4
^{28}Si	600	22.7	50.2	8.1
^{48}Ti	1000	32.5	109.5	4.5
^{56}Fe	600	13.1	175.1	4.1
Total				***500.0***

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	20.0	0.43	2.59	30.4
^{1}H	23.3	0.56	2.29	6.7
^{1}H	27.2	0.75	2.02	7.4
^{1}H	31.7	0.98	1.79	8.0
^{1}H	37.0	1.30	1.58	8.7
^{1}H	43.2	1.72	1.39	9.3
^{1}H	50.3	2.26	1.23	10.0
^{1}H	58.7	2.99	1.09	10.6
^{1}H	68.5	3.95	0.97	11.1
^{1}H	79.9	5.20	0.86	11.2
^{1}H	100.0	7.76	0.73	**27.2**

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{4}He	20.0	0.43	10.34	**11.0**
^{4}He	23.3	0.57	9.14	**2.1**
^{4}He	27.2	0.75	8.06	**2.2**
^{4}He	31.7	0.99	7.12	**2.3**
^{4}He	37.0	1.31	6.29	**2.5**
^{4}He	43.2	1.73	5.56	**2.6**
^{4}He	50.3	2.28	4.92	**2.7**
^{4}He	58.7	3.01	4.36	**2.7**
^{4}He	68.5	3.97	3.86	**2.7**
^{4}He	79.9	5.23	3.43	**2.7**
^{4}He	100.0	7.81	2.90	**6.1**



Large binary filter system used to deliver lower energy H and He beams – installed 2019

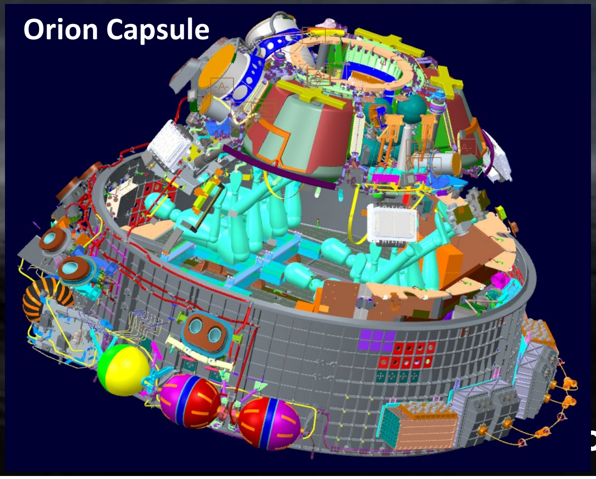
Significance of Environmental Data

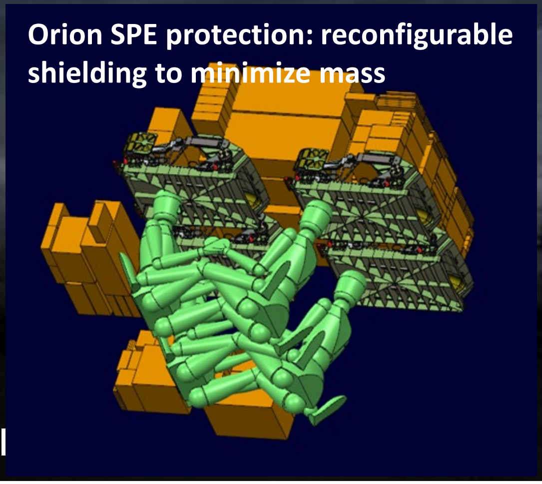
Supports Optimization and Validation of Radiation Mitigations Strategies

- Predict dose rates for human missions
- Risk Model updates and calculation of Permissible Exposure Limits
- Shield Optimization & Verification of Exposure Requirements
- Definition of GCR Simulator requirements for ground-based radiation health research
- Validation of biological countermeasures

Science Data

- Impact of radiation hazards on indigenous Martian life forms - similar to terrestrial?
- radiation or oxidizing chemistry will determine the minimum depth needed to drill to look for extant life on Mars today
- How deep life would have to be today for natural shielding to be sufficient
- radiation contributes significantly to the unique chemistry of the Martian surface

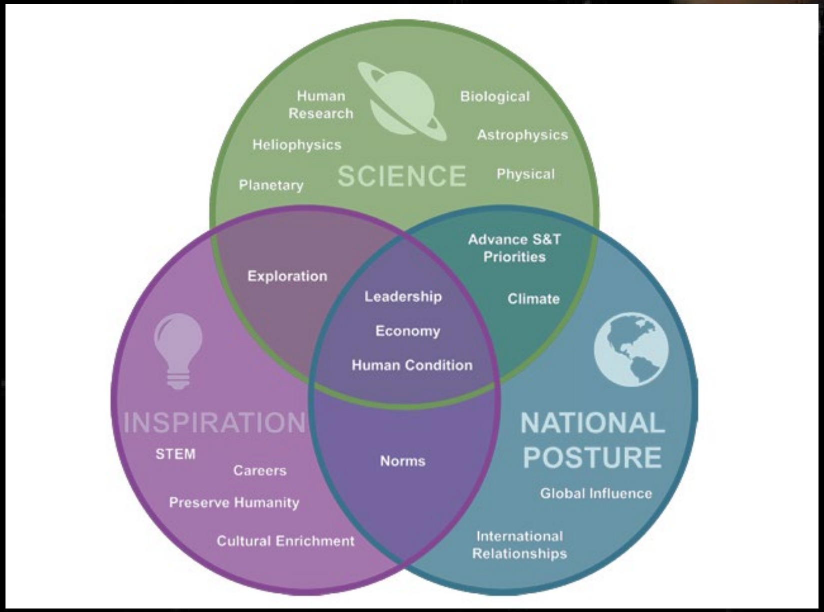




Influence of the space radiation environment and M2M science objectives

Characterizing the Mars Radiation environment

Moon2Mars Architecture Objectives



- Advance the understanding of how biological systems and humans responds to the environment of the moon, Mars, and deep space (Human and Biological Science 1, 2, 3)
- Utilize robotic and human missions to improve our understanding of space weather phenomena (HS 1)
- Determine the history of the Sun as recorded in lunar & Martian regolith (HS 2) – regolith contains the scientific record of the history of solar activity
- Advance our understanding of the origin of life in our solar system (LPS-4) – how did radiation affect prebiotic chemistry?
- Understand and mitigate impacts of the space & planetary environments on crew health and performance to support the first human mission to Mars (OP 6, 7)
- Return Crew safely to Earth and mitigate adverse impacts to their health (RT-3) – inspire our next generation


Questions?