Preparing for Human Exploration: Radiation Measurements on the Surface of Mars

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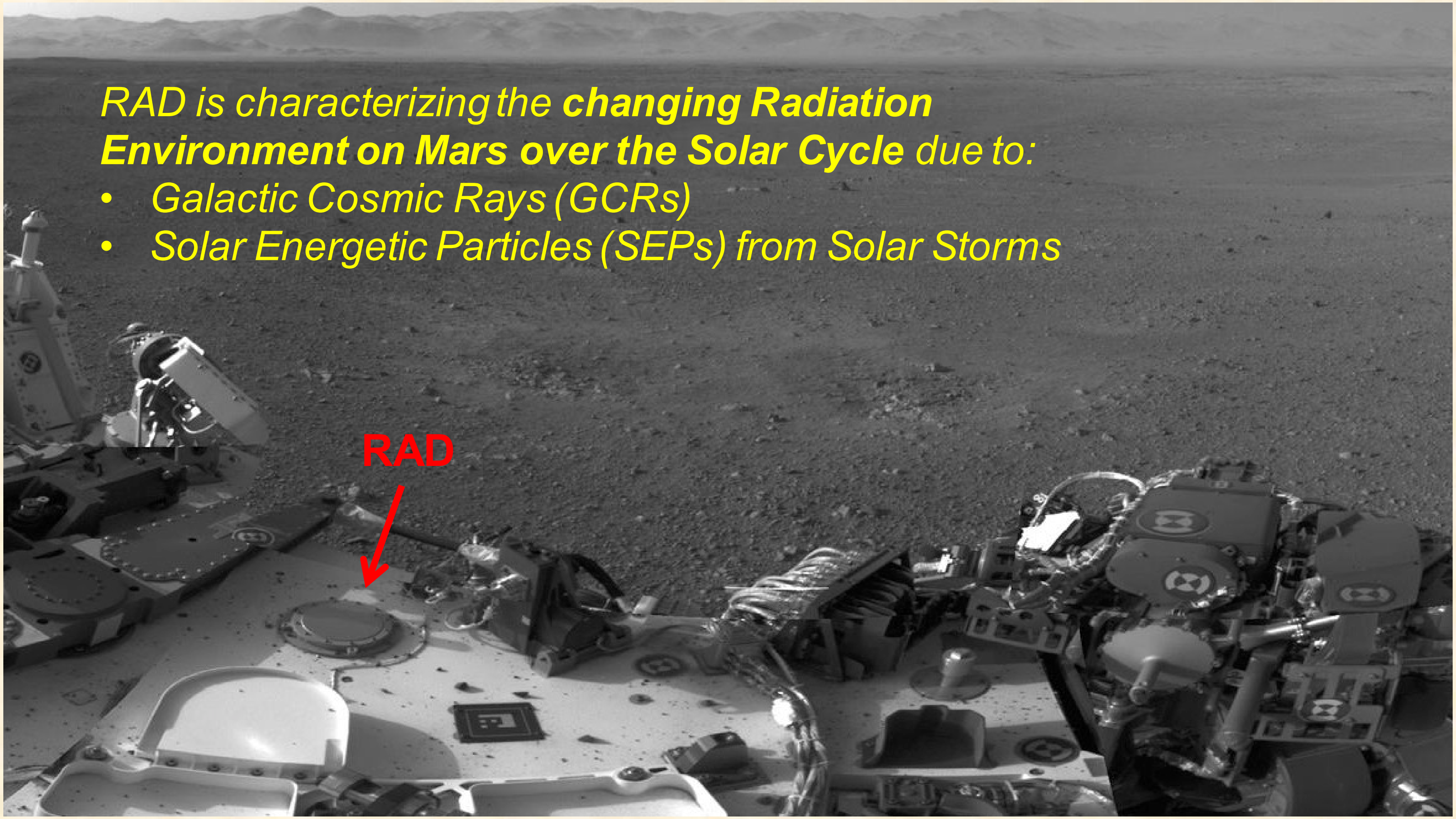
Artist's Concept. NASA/JPL-Caltech

The Radiation Assessment Detector (RAD) is a working asset on the Surface of Mars...

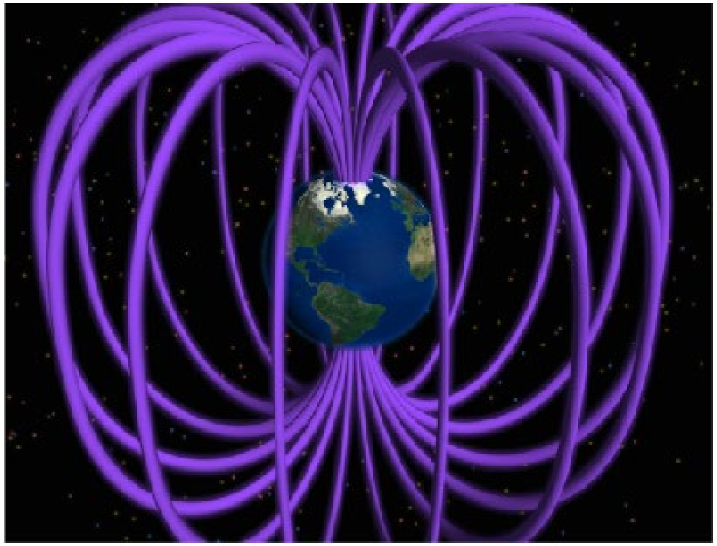
*RAD is characterizing the **changing Radiation Environment on Mars over the Solar Cycle** due to:*

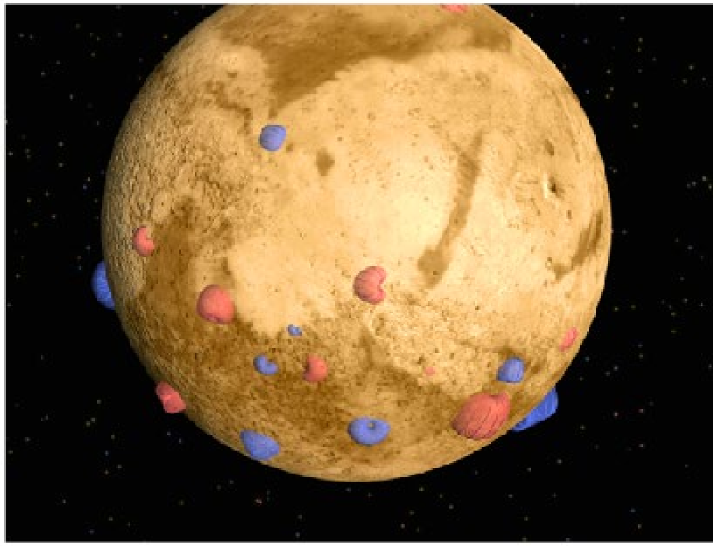
- *Galactic Cosmic Rays (GCRs)*
- *Solar Energetic Particles (SEPs) from Solar Storms*



RAD is a collaboration between NASA SMD (Heliophysics and Planetary Science Divisions), Human Exploration Mission Directorate (ESDMD), and internationally between the US (NASA) and Germany (DLR).

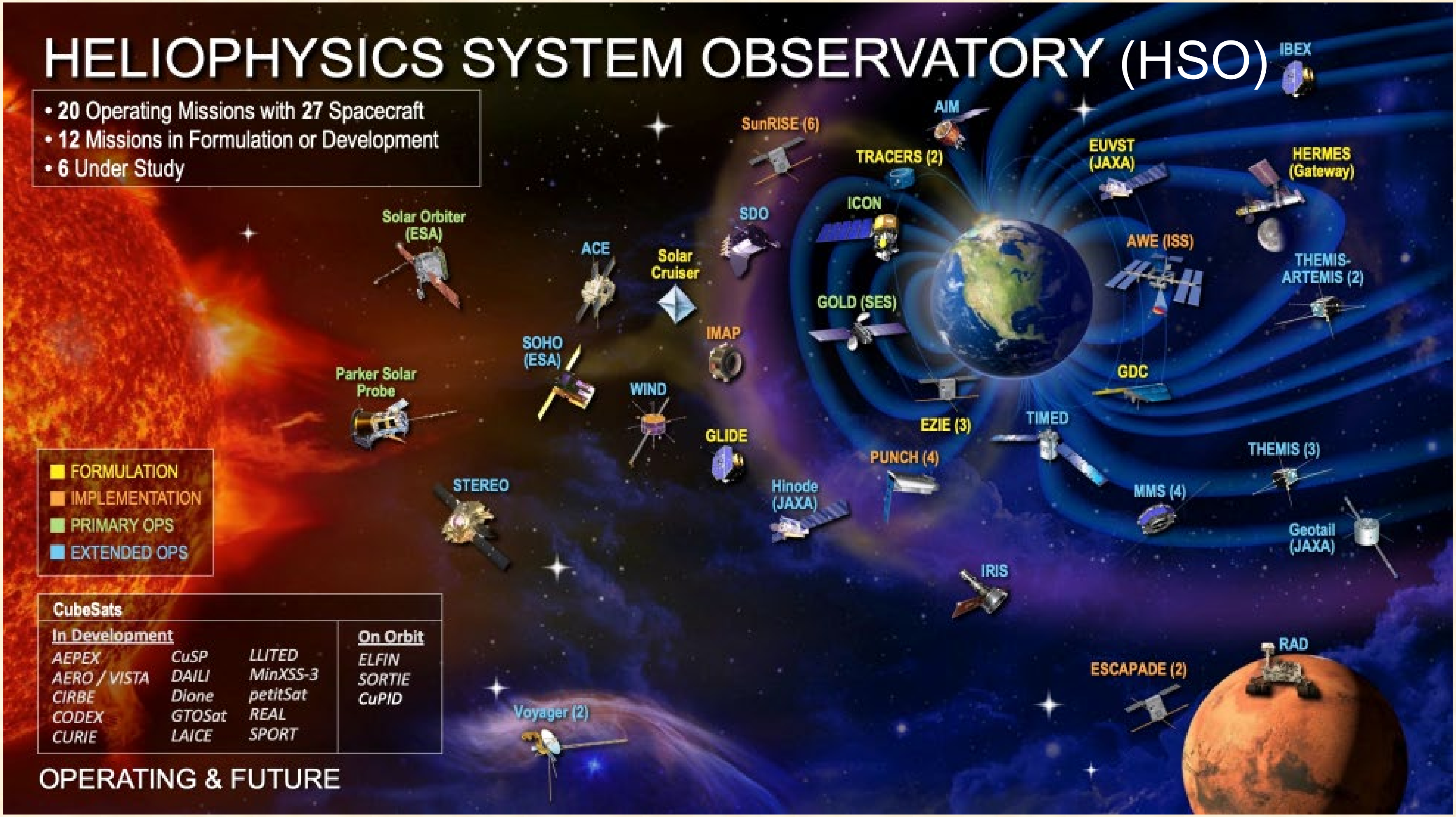
Unlike Earth, the Surface of Mars experiences DIRECTLY the effects of Space Weather...





- The surface of Mars is much more exposed to space radiation than is the surface of Earth, for two reasons:
  - Mars lacks a global planetary magnetic field (magnetosphere)
    - Only weak, local, remnant magnetic fields
  - Mars atmosphere is much thinner
    - ~1% of thickness of Earth’s atmosphere

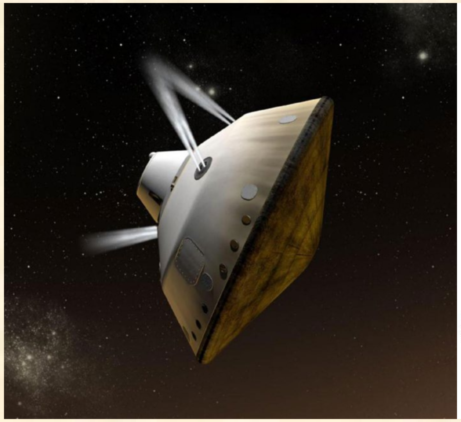
A Challenge for Deep Space Exploration: Interplanetary Space Weather



As we expand out into the solar system and to Mars, each mission will have a unique need to know when a solar storm will pass through its corner of space, and how dangerous it will be..

RAD Measurements During Cruise and on the Surface of Mars

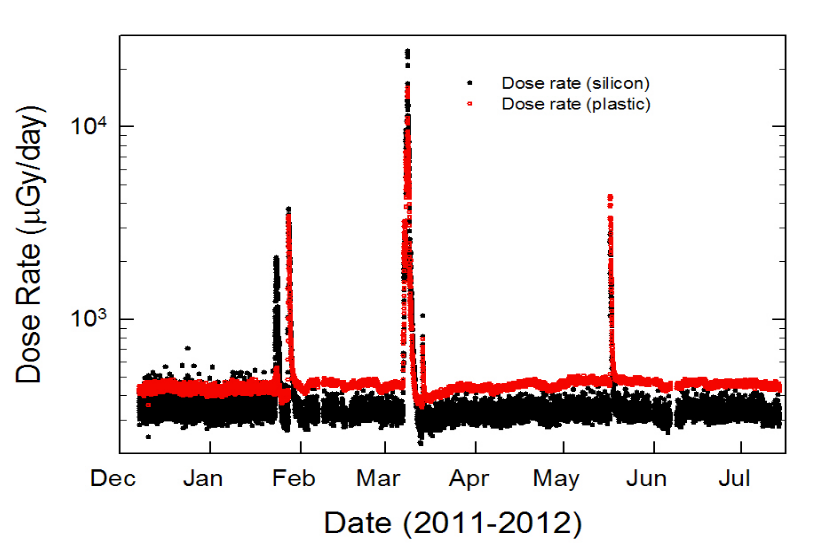
RAD Observations During Cruise to Mars...



MSL Spacecraft during Cruise

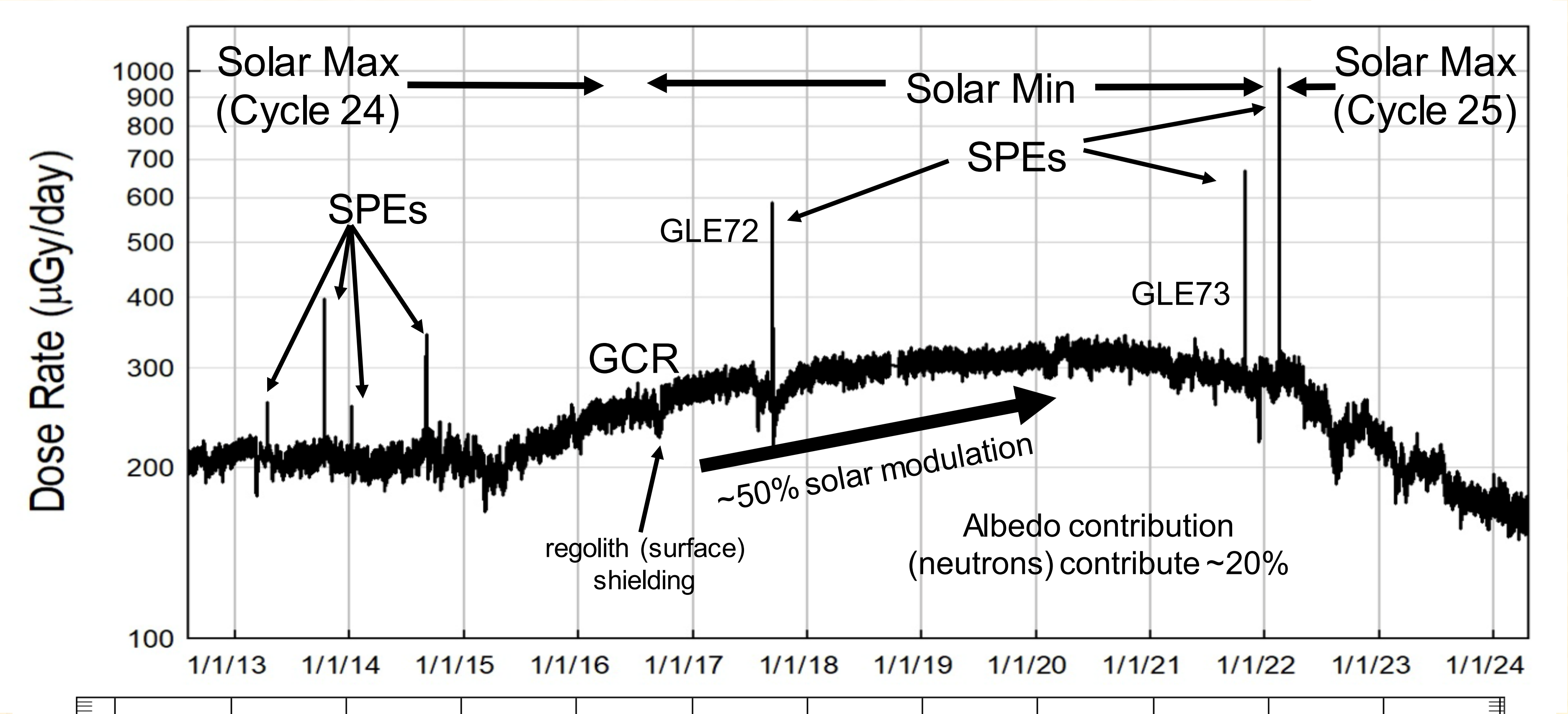
Manned Crew Exploration Vehicle (*Orion)*

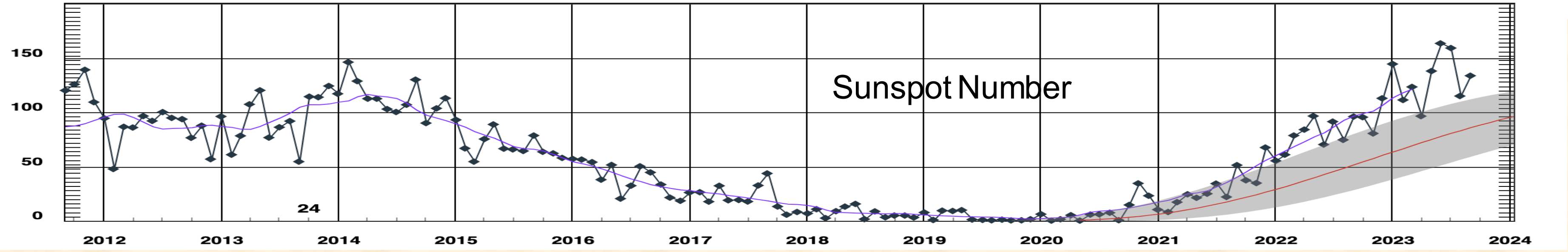
On its way to Mars, inside the MSL Spacecraft, RAD served as a proxy to help validate models of the radiation levels expected inside a spacecraft that future astronauts may experience…



During Cruise, SEP Events contributed ~5% to the Total Integrated Dose Equivalent.

A Solar Cycle of Radiation Measurements on the Surface of Mars with MSL/RAD





The September 10, 2017 Solar Particle Event (SPE) was seen at both Earth (GLE72) and Mars

Aurora seen on Mars from MAVEN

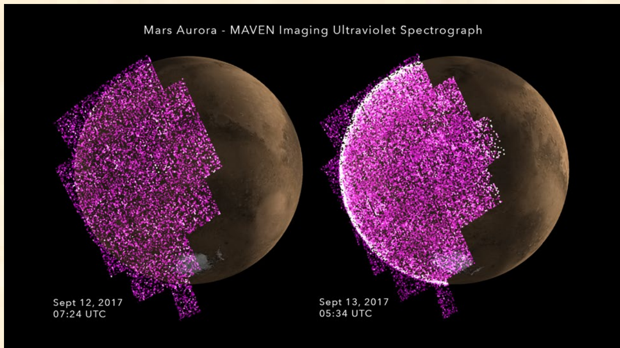


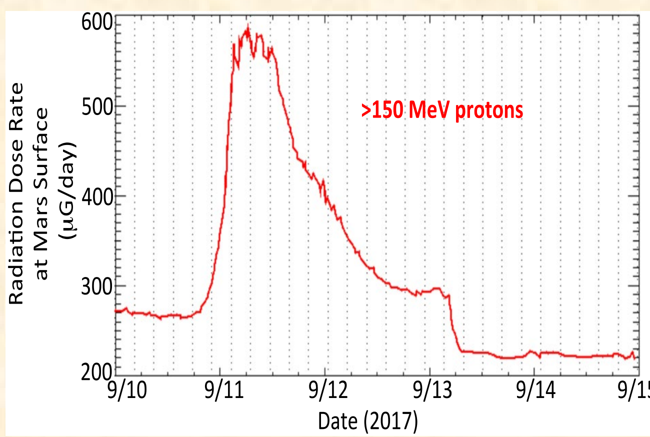
Image courtesy NASA/MAVEN

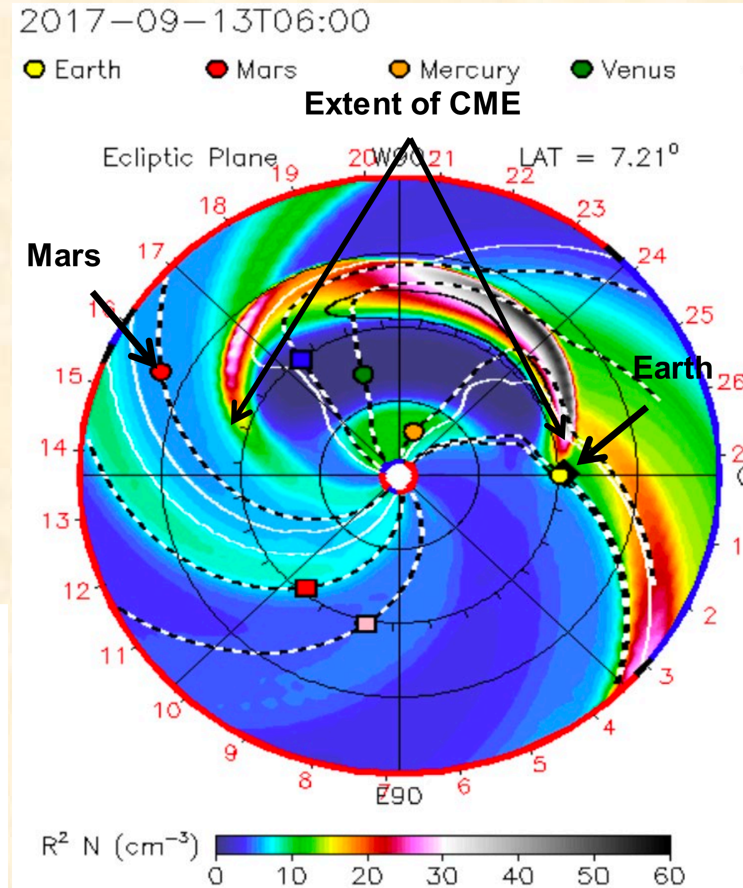
Aurora seen on Earth from Alaska

Image courtesy Lindsay Ohlert

All together, his event was seen…

- On the surface of Mars by RAD
- In Mars orbit by MAVEN
- In Earth orbit by GOES & ISS/RAD
- On the ground here on Earth by several Neutron Monitors

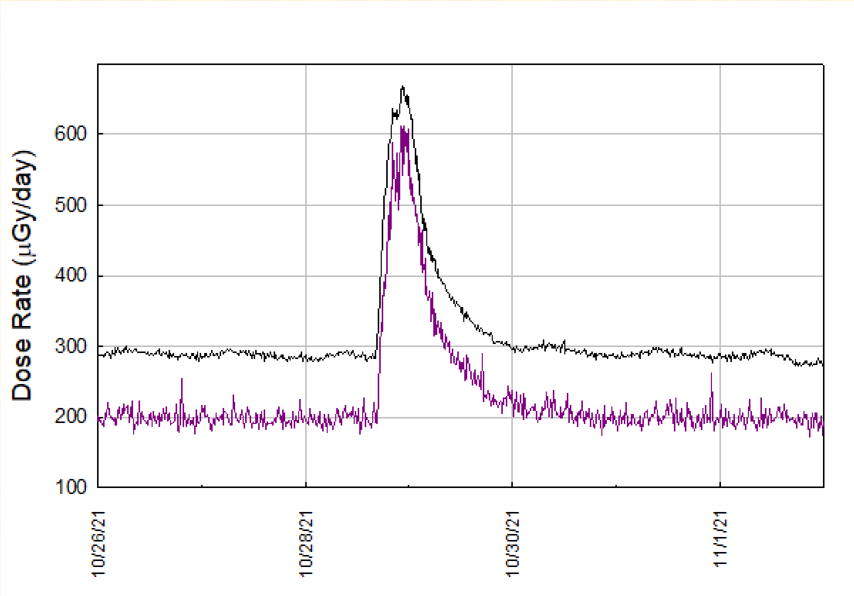


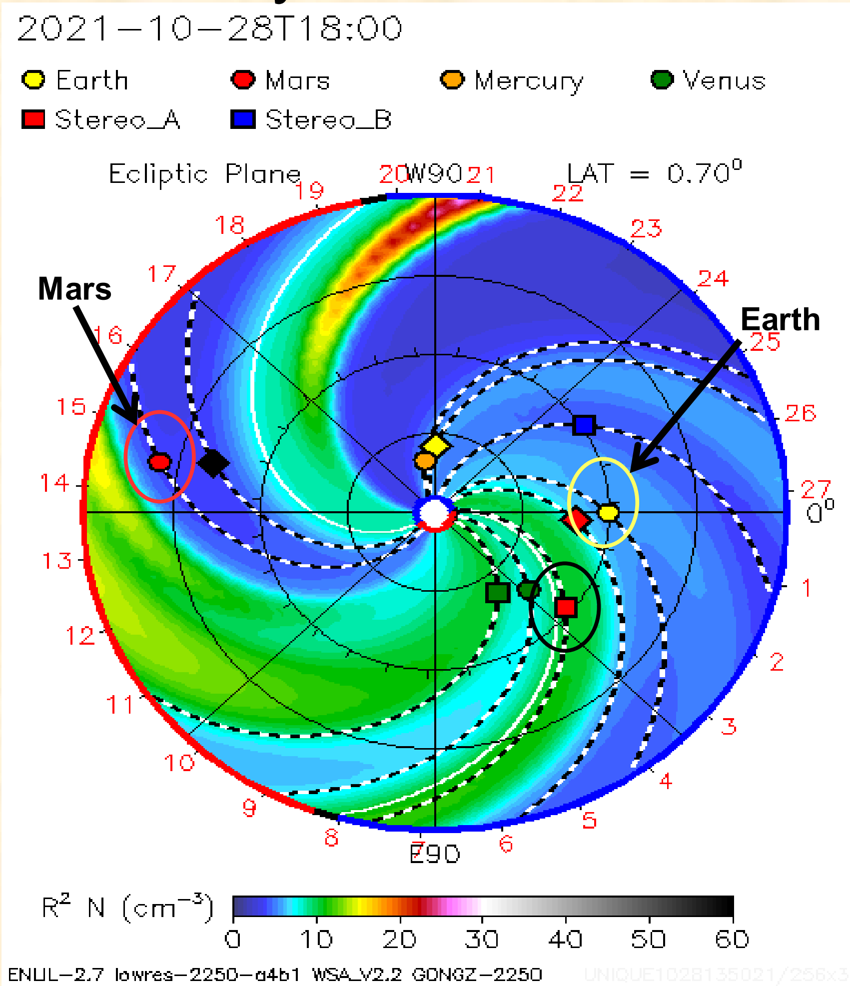


ENLIL Solar Wind Model showing propagation of the CME through the inner solar system.

The October 28, 2021 SPE Event (GLE73)

The Oct. 28, 2021 event corresponds with the first observed X-class flare of the new solar cycle!

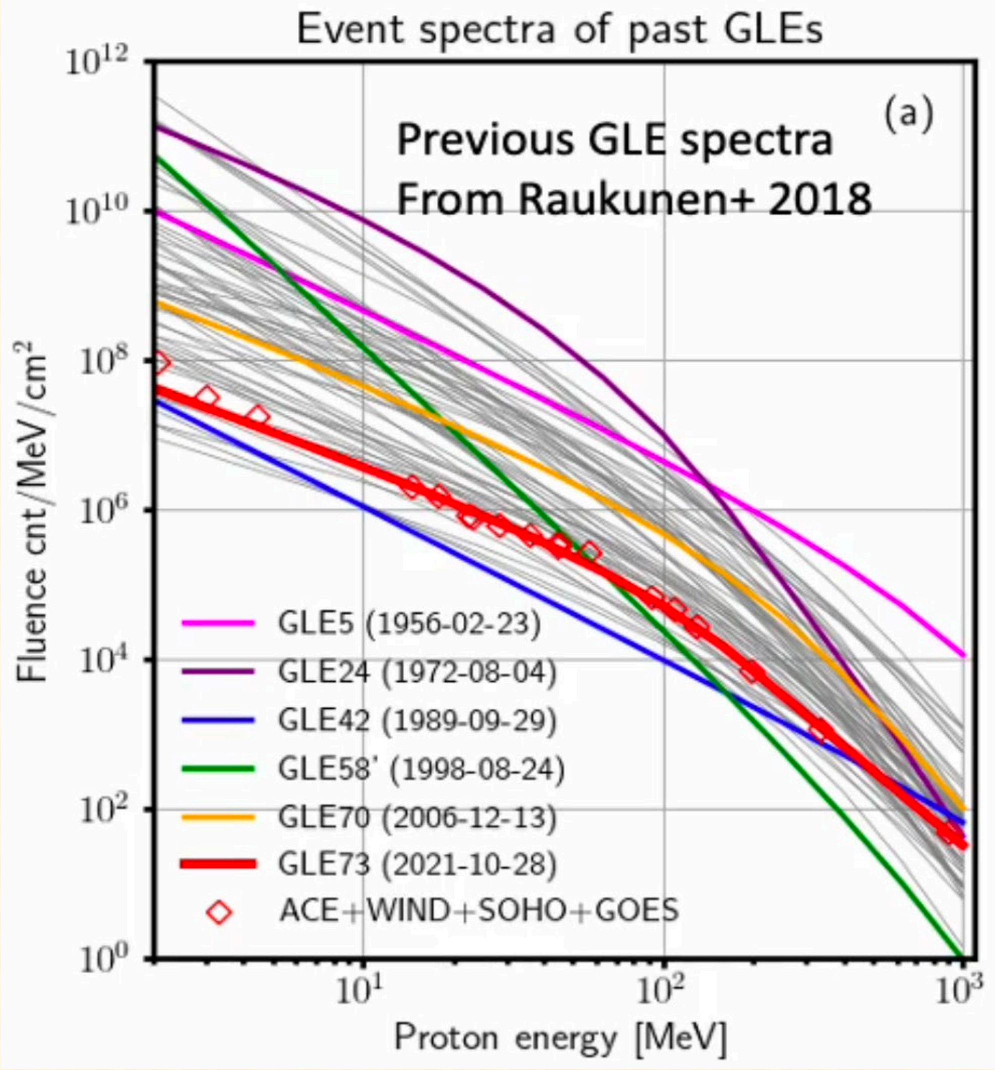




Mars & Earth were magnetically well separated at the time (~ 180°) … yet the event was still seen at both locations.

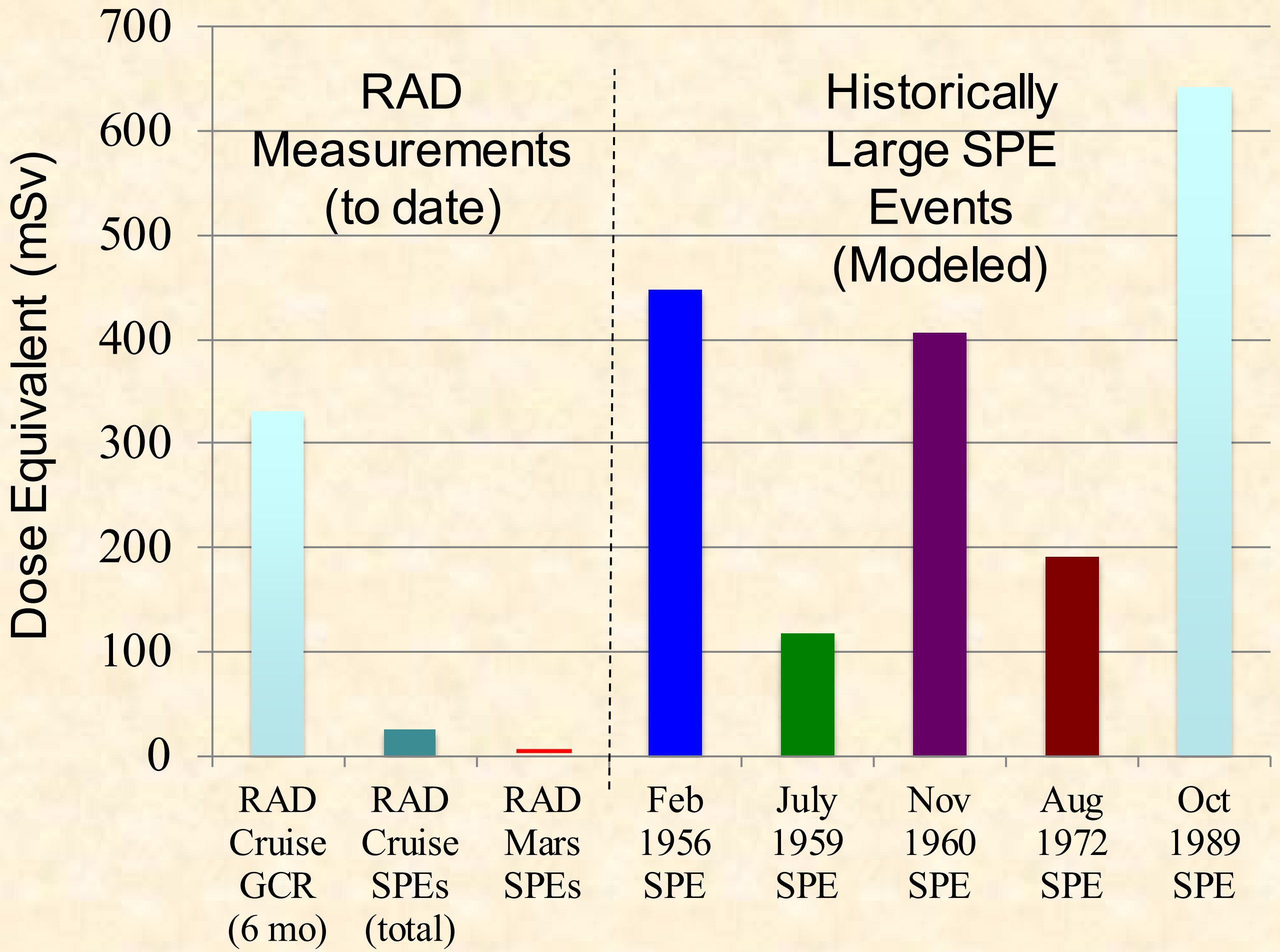
Comparison of the October 28, 2021 SPE (GLE73) to "historically large" events seen since the beginning of the Space Age

Comparison of Ground Level Event (GLE) 73 (Oct. 28, 2021) observed by several assets (ACE, WIND, SOHO & GOES) in the Heliophysics System Observatory (HSO) to other "historically large" events seen since the beginning of the space age.



How do the events observed by RAD compare with other "historically large" Solar particle events?

What might we expect from a Carrington Event or Super-Storm?



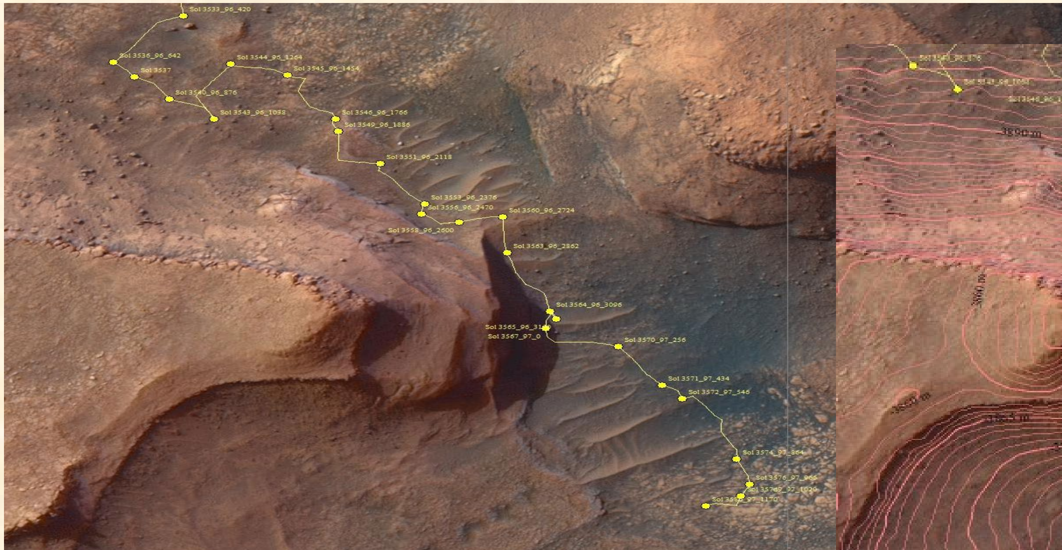
*SPE Dose Equivalent values modeled behind 5 g/cm2 Aluminum by M.-H. Kim, F. Cucinotta, et al. (AGU, 2012).

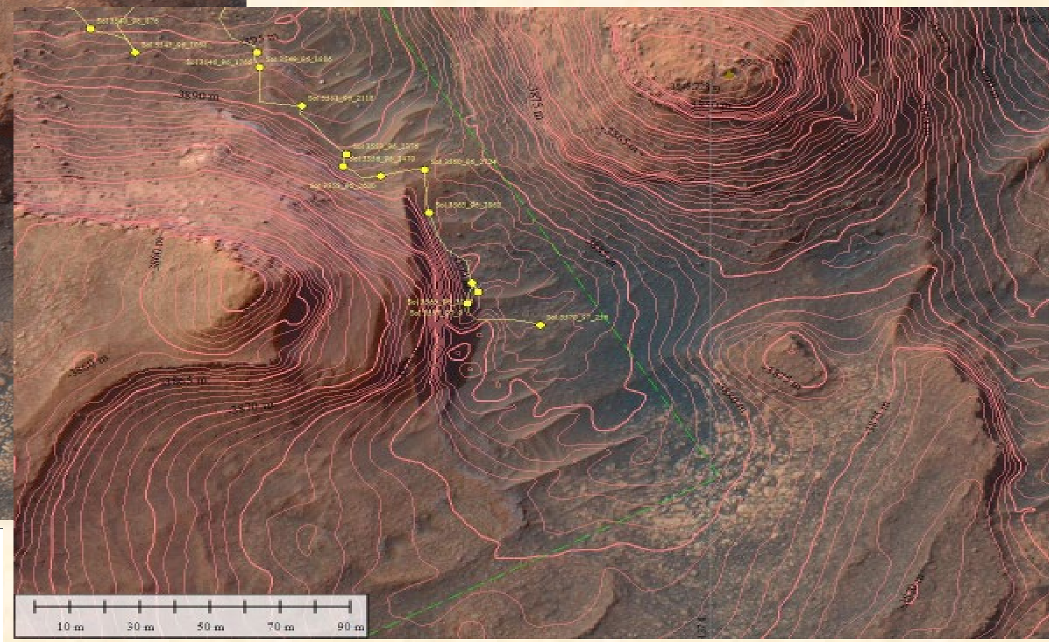
RAD cruise measurements from Jan-July 2012.

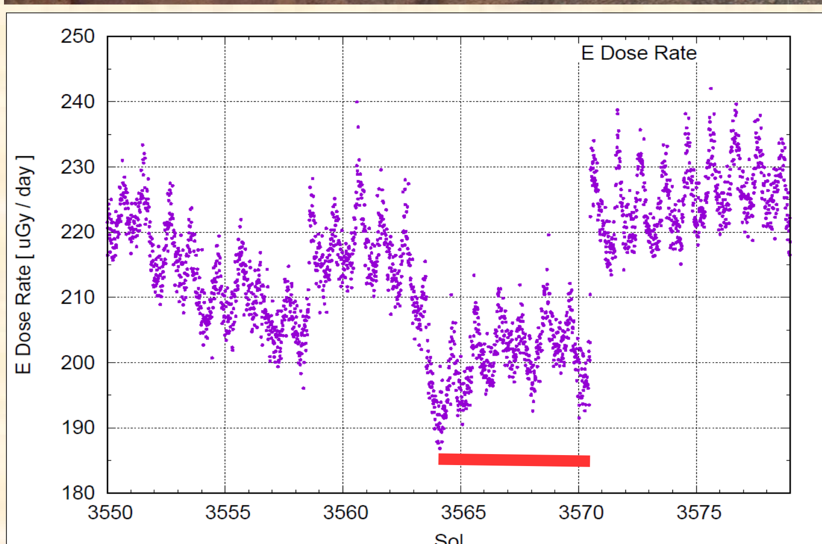
Nov. 1960 SPE includes contributions from 2 events.

Oct. 1989 SPE includes contributions from 5 events over 1 month.

Surface (Regolith) Shielding at Paraitepuy Pass







RAD measured a distinct decrease in dose rate (~10-12%) during the drive through Paraitepuy Pass due to the radiation shielding from the cliff walls.

In-situ shielding could be an important element of radiation storm shelter design to reduce mass/cost for future Mars missions

Implications for Human Exploration of Mars

Mars Radiation Environment Summary

RAD Measurement[1]	Cruise[2]	Mars Surface[3] (Solar Min)	Mars Surface[3] (Solar Max)	
Charged Particle Flux	0.64	0.90	0.43	particles cm^{-2} s^{-1} sr^{-1}
Fluence (B)	3.98	2.10	1.35	cm^{-2} s^{-1}
Dose Rate	431 +/- 40	317 +/- 25	163 +/- 10	μGy/day
Avg. Quality Factor <Q>	3.7 +/- 0.5	2.3 +/- 0.2	2.7 +/- 0.3	(dimensionless)
Dose Equivalent Rate	**1.6 +/- 0.2**	**0.74 +/- 0.10**	**0.44 +/- 0.07**	**mSv/day**

[1]Contributions from Curiosity's RTG have been subtracted from all measured quantities.
[2]Cruise took place in between solar min and solar max. Fluence was higher in cruise due to 4π vs. 2π irradiation.
[3]Surface measurements are affected by seasonal atmospheric pressure variations in addition to solar cycle effects.

Representative Radiation Dose Rates in Other Environments

- Natural Bkg Radiation (Earth) ~0.01 mSv/day
- Chest X-Ray ~0.06 mSv
- DOE Limit for Radiation Workers ~0.14 mSv/day
- International Space Station (ISS) 0.4 - 1.0 mSv/day

Implication for Manned Mission

NASA "Design Reference" Mission
(based on RAD observations to date)

Mission Phase	**Dose Equivalent**	**Notes**
Astronaut Career Limit*	**~0.6-1.0 Sv**	**Depends on age, gender, etc.**
Cruise to Mars (180 days)	~300 mSv	near Solar Max
Mars Surface Mission (600 days)	~300 mSv	Solar Max
Return to Earth (180 days)	~300 mSv	near Solar Max
Total Mission Dose Equivalent (600 days on Mars)	**~0.9 Sv**	600 day stay @ Max

*Astronaut Career Limits vary by Space Agency. NASA Astronaut Career Limits are based on 3% excess career fatal cancer risk, and vary by age, gender, etc.

Solar minimum conditions → factor of ~ 1.5 to 2 larger dose equivalents

What is the Risk of 1 Sv Dose Equivalent ?

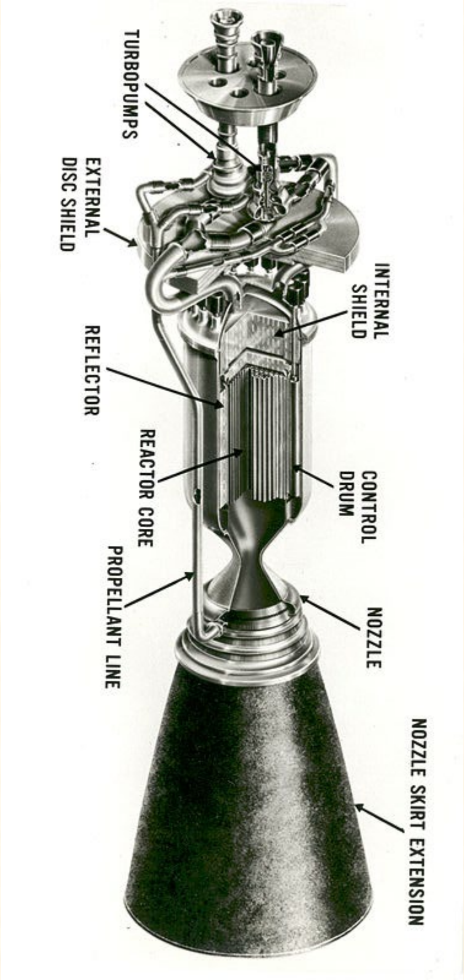
- Radiation exposure increases **cancer risk**.
  - Understanding of this has remained elusive, even after decades of research.

- Radiation also causes **central nervous system (CNS)** and **cardiovascular damage**.
  - Not yet accounted for in space radiation protection. (not fully understood…no current framework exists to quantify this risk).

- **Knowledge of risk** comes mostly from long-term studies of Japanese **A-bomb survivors**.
  - Many questions remain about risk transfer between cohort populations
  - ***Population Health***: A-bomb survivors were under-nourished, astronauts expected to be healthy, well-nourished, non-smokers
  - ***Dose Rate***: A-bomb exposure was instantaneous, astronaut exposure will be protracted
  - ***Exposure Type***: A-bomb exposure mostly γ-rays, astronaut exposure mix of protons, heavy ions & neutrons

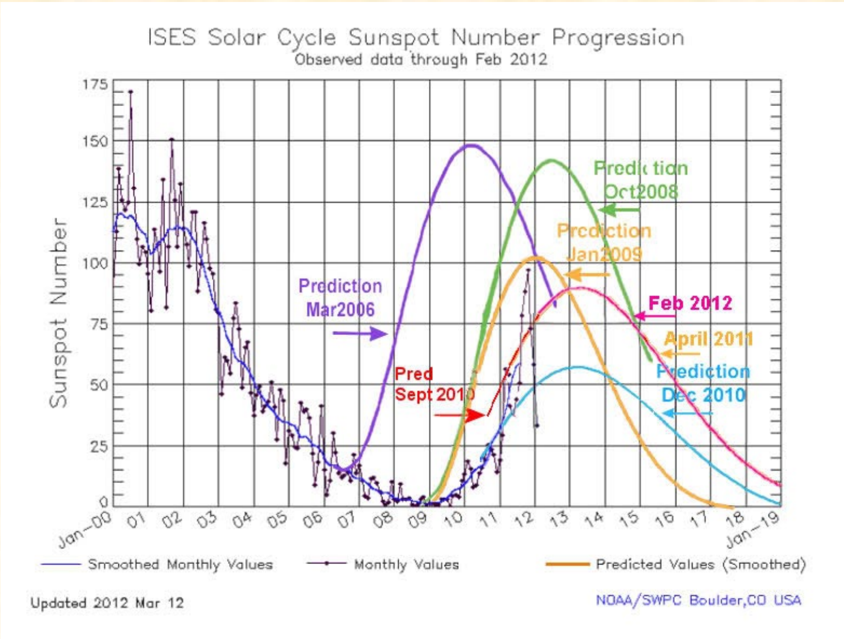
So How Do We Get Humans to Mars?

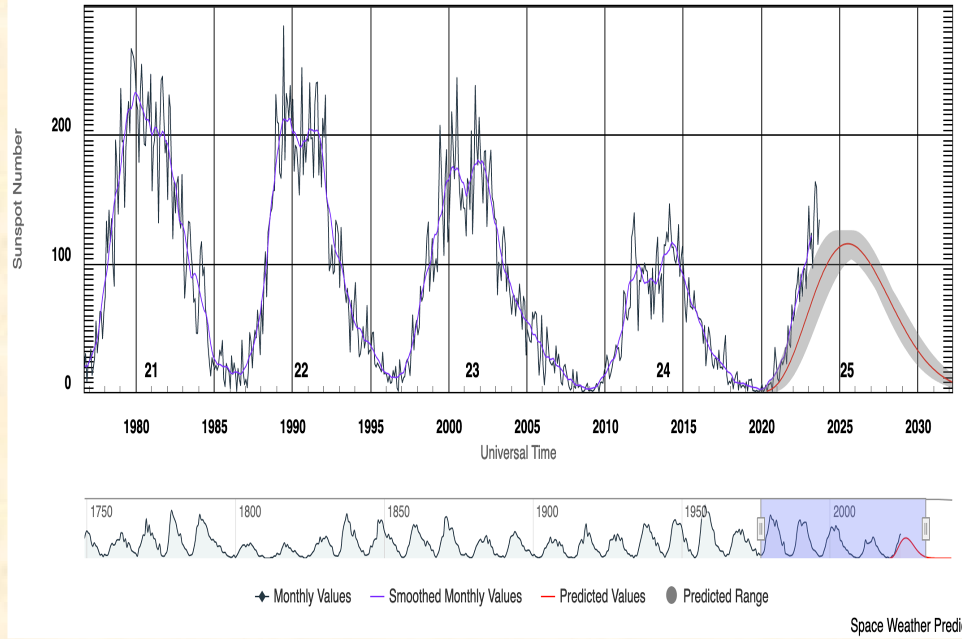
- Ideally, reduce days in space!
  - **Go really fast!!!**
- Optimize shielding
  - Crew shelters during cruise & on Mars
  - Biological mitigation techniques (diet?)
- Continue to understand better the radiation environment & challenges
  - Establish & maintain heliosphere-wide (e.g. HSO) network of observations to improve understanding of space weather events
  - Improve predictive capability to inform mission design and give crews sufficient warning to seek shelter

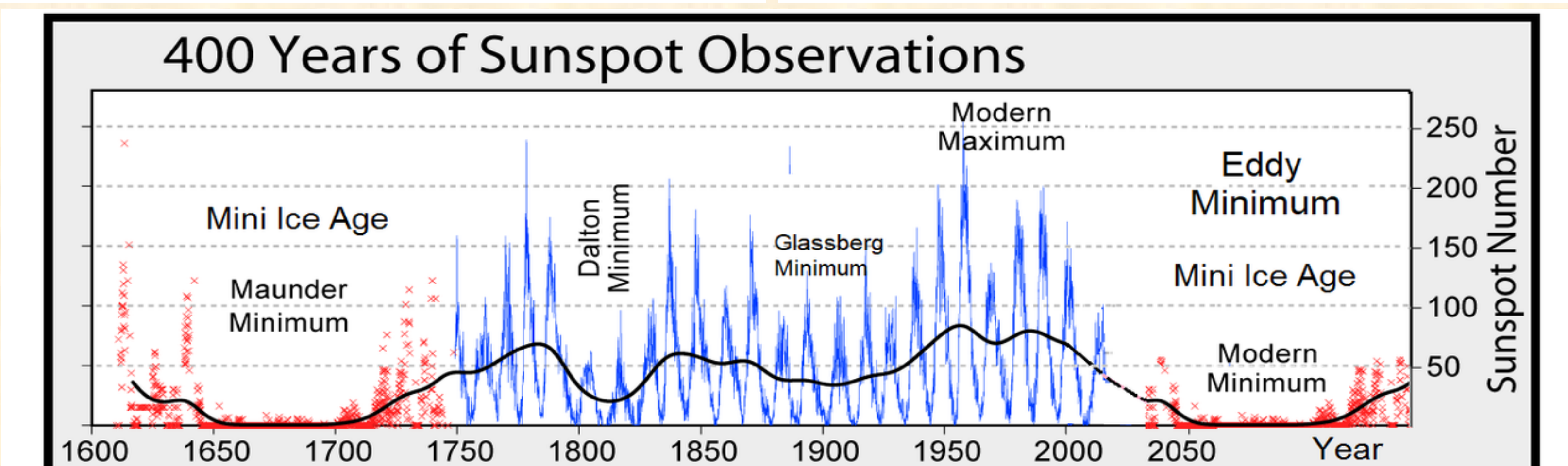


Prospects for the Next Solar Cycle

Predicting the Solar Cycle… is difficult!







Space Weather Effects Occur at All Phases of the Solar Cycle

(From Guhathakurta, 2015)

Solar La Niña (Minimum) (low sunspot number)

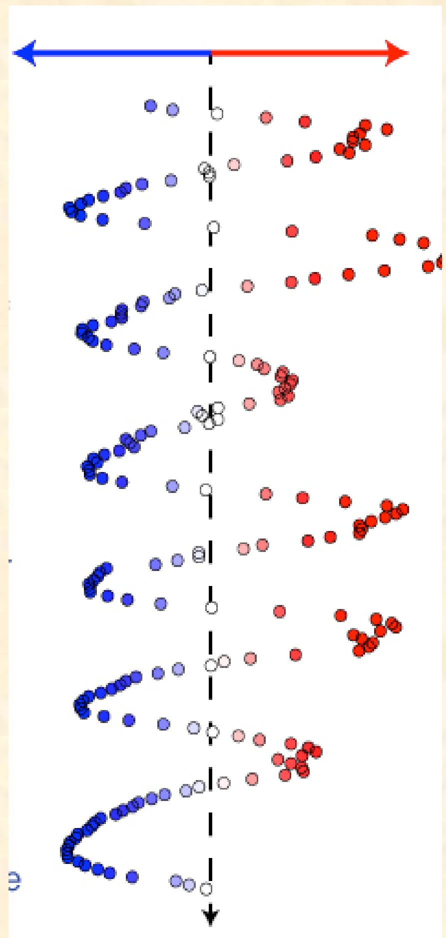
- Increased galactic cosmic rays

- Total solar irradiance changes

- Contraction of the heliosphere

- Collapse of the upper atmosphere

- Increased lifetime of space debris



Solar El Niño (Maximum) (high sunspot number)

- Decreased galactic cosmic rays

- Solar flares and coronal mass ejections

- Solar “cosmic rays” (energetic particles)

- Radio blackouts

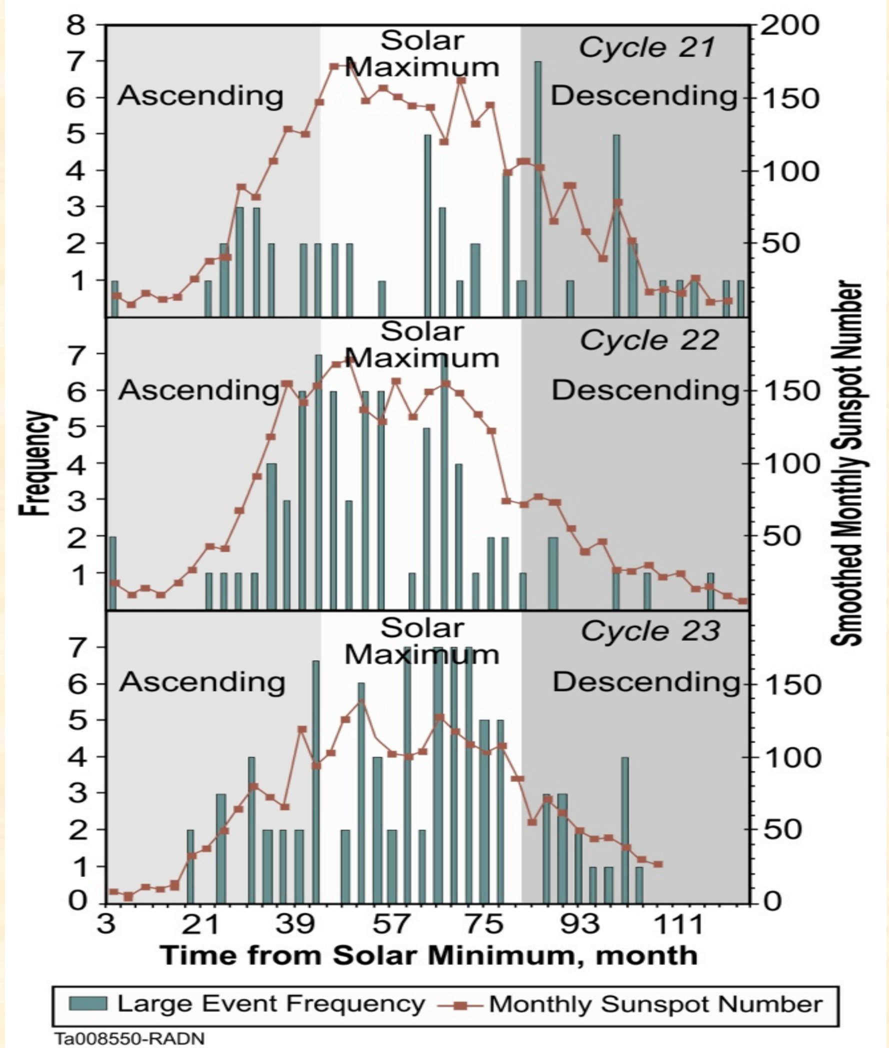
- Geomagnetic storms

- Disrupted power grid transformers = power blackouts

- Solar wind streams hit Earth

Large Solar Particle Events (SPEs) are seen throughout the Solar Cycle

- The 3 largest SPEs of this past cycle were during Solar Min or the early rising phase of the next solar max. (NOT Solar Max…maybe the next big one is coming?)
- These SPEs also had very ***wide longitudinal extent***…~180 deg!
- Improved understanding of the ***structure and propagation*** of these solar storms will ***improve*** *space weather prediction at earth, Mars, and throughout the heliosphere*!



Histogram of large SPEs vs time

Take-Away Points...
Characterizing Extreme Conditions throughout the Solar Cycle

- Solar Cycle Predictions are difficult!
- Extreme variations in the past 2 solar cycles have shown that ***current models clearly lack sufficient predictive capability***.
- We need to characterize these Extreme Conditions…
  - 1) Extreme Cycle variations (not just solar max, but solar min)
  - 2) Extreme SPEs (X-Class flares, GLEs, "Super-Events"…)
- To ***support human exploration to Mars and beyond***, we will need to provide ***heliosphere-wide space weather monitoring***, prediction & early warning for these missions.

Thank you!

- RAD is supported by NASA (SMD/Heliophysics) under JPL subcontract #1273039 to SwRI.
- ...and by DLR in Germany under contract with Christian-Albrechts-Universitat (CAU).

RAD data is available to the community via SPDF and PDS.