Challenges of Space Weather and Space Radiation Predictions for Human Explorations in Deep Space

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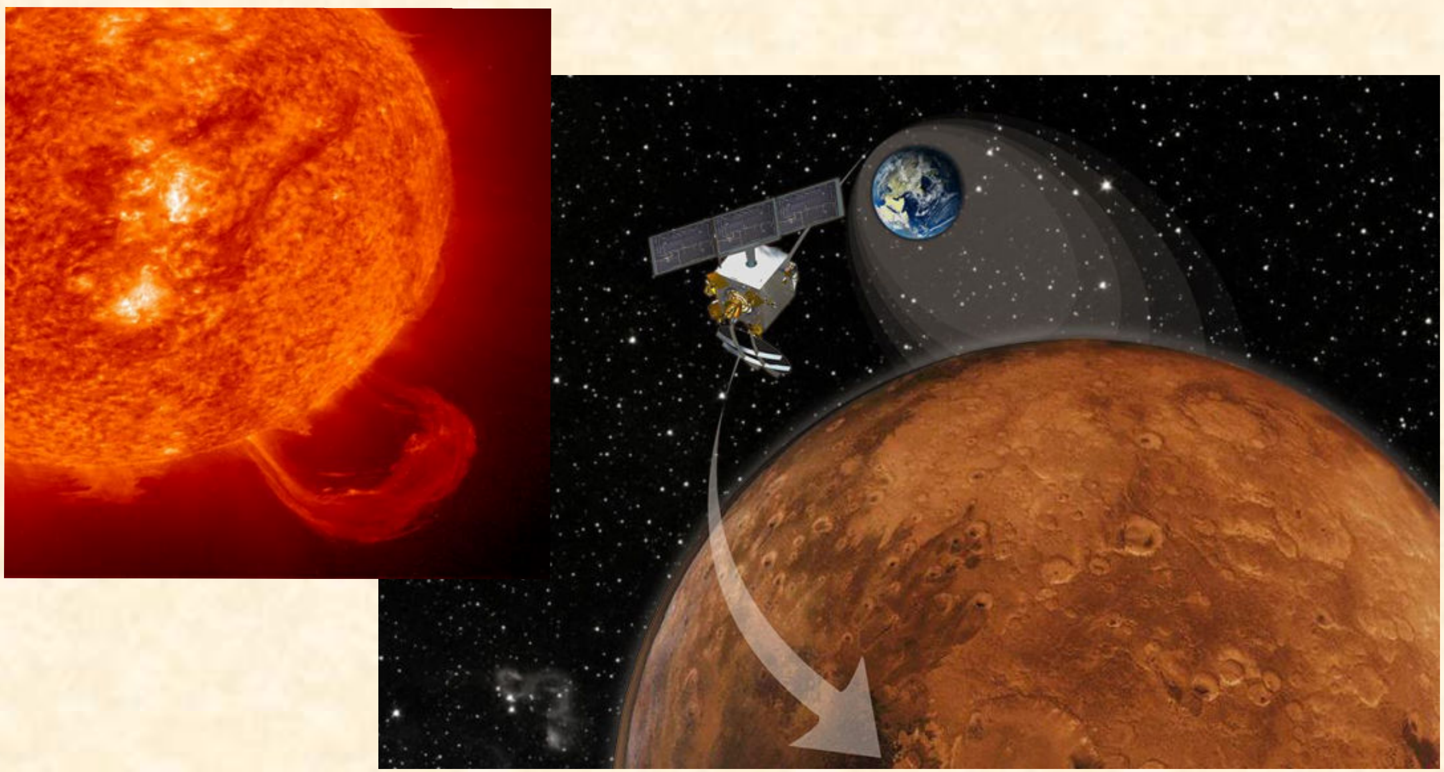
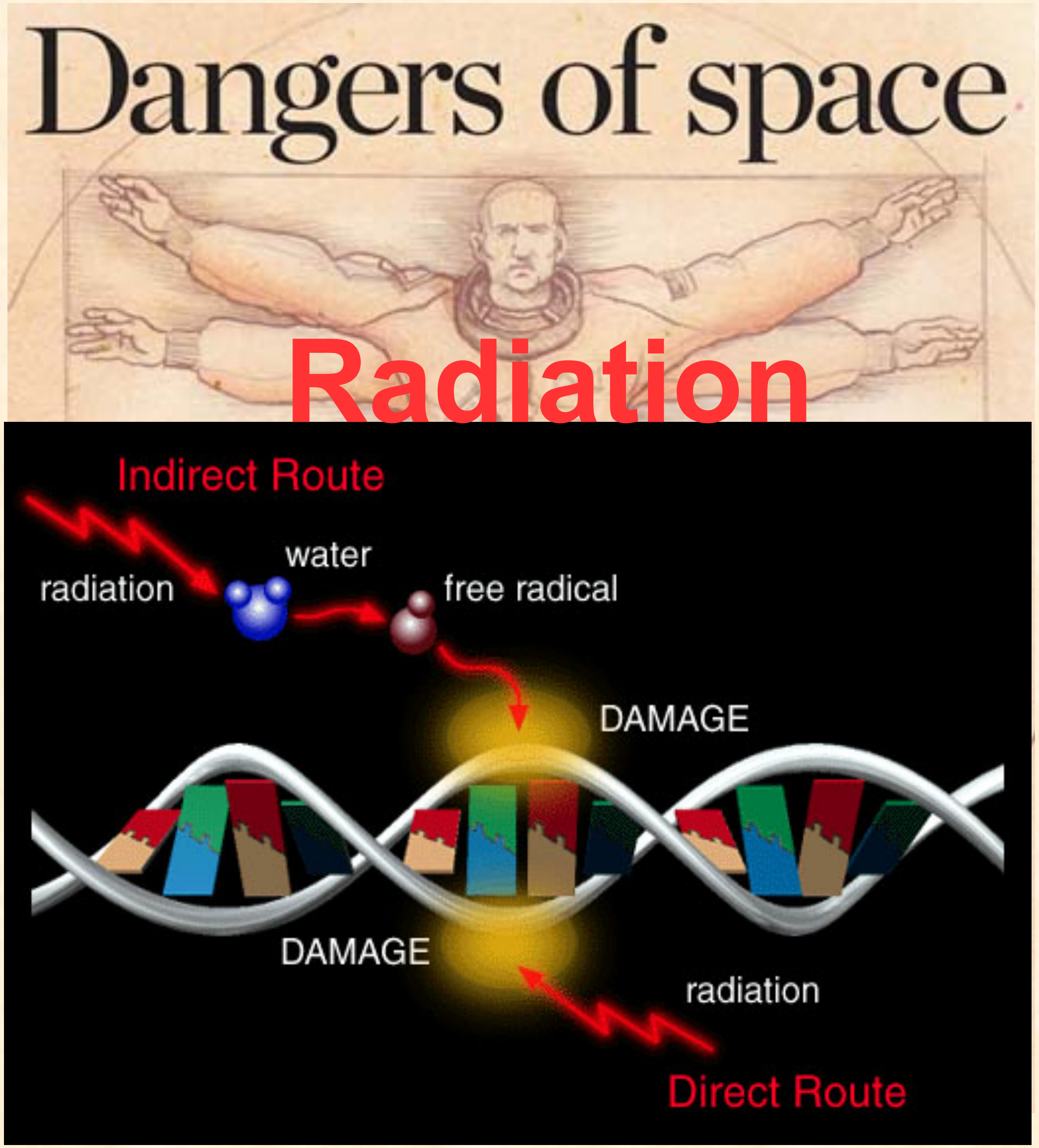


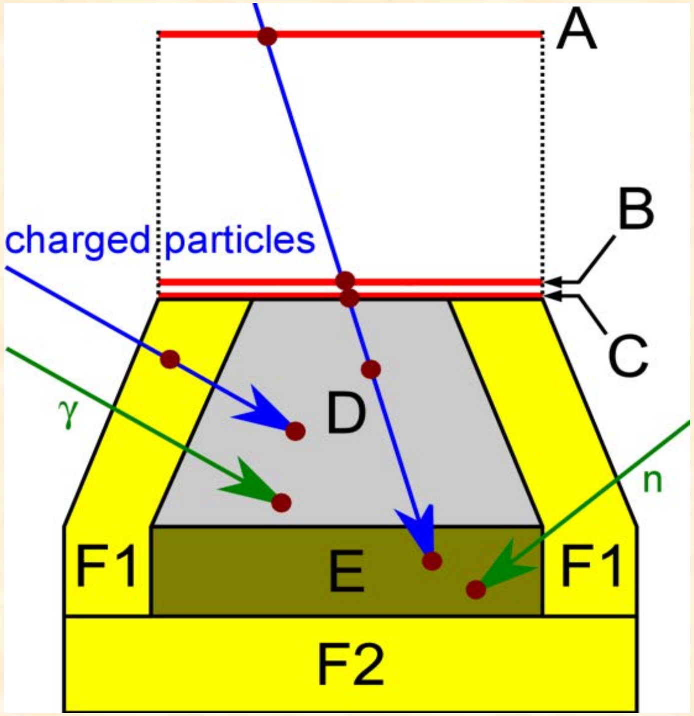
Radiation for Space missions



Space agencies such as ESA, NASA, the Chinese space agency and even private companies are launching new human deep space exploration programs to the Moon and **Mars**.

Radiation is one of the most important long-term risks to such missions.

In preparation, this requires a very timely and thorough study to better understand the space weather conditions and their effects as a baseline for the development of mitigation strategies against radiation risks.



The Radiation Assessment Detector (RAD)

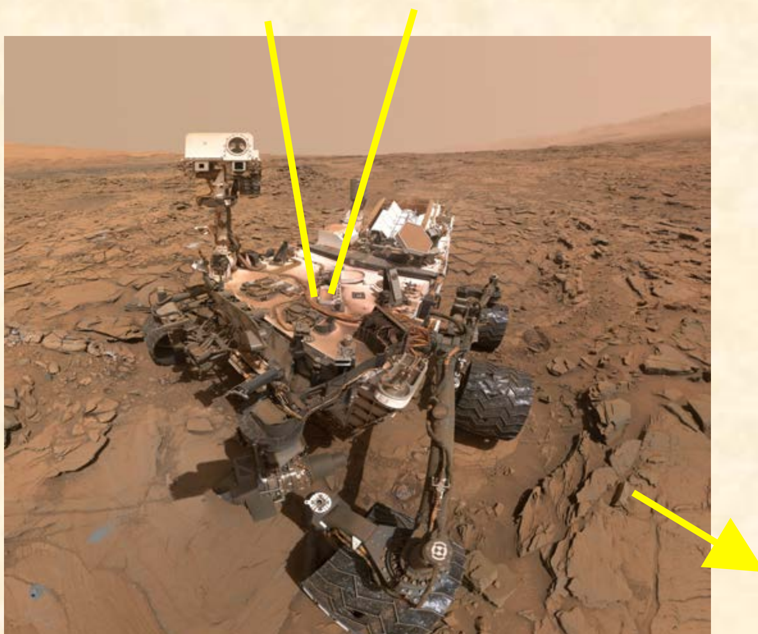
RAD (**Hassler et al 2012**) is an energetic particle detector measuring **galactic cosmic rays**, **solar energetic particles**, and their secondary particles generated in the Martian atmosphere.

λRAD contains 6 detectors, **A, B, and C** are **silicon diodes** (each 300 um thick) arranged as a telescope.

The other three (**D, E, and F**) are **scintillators**.

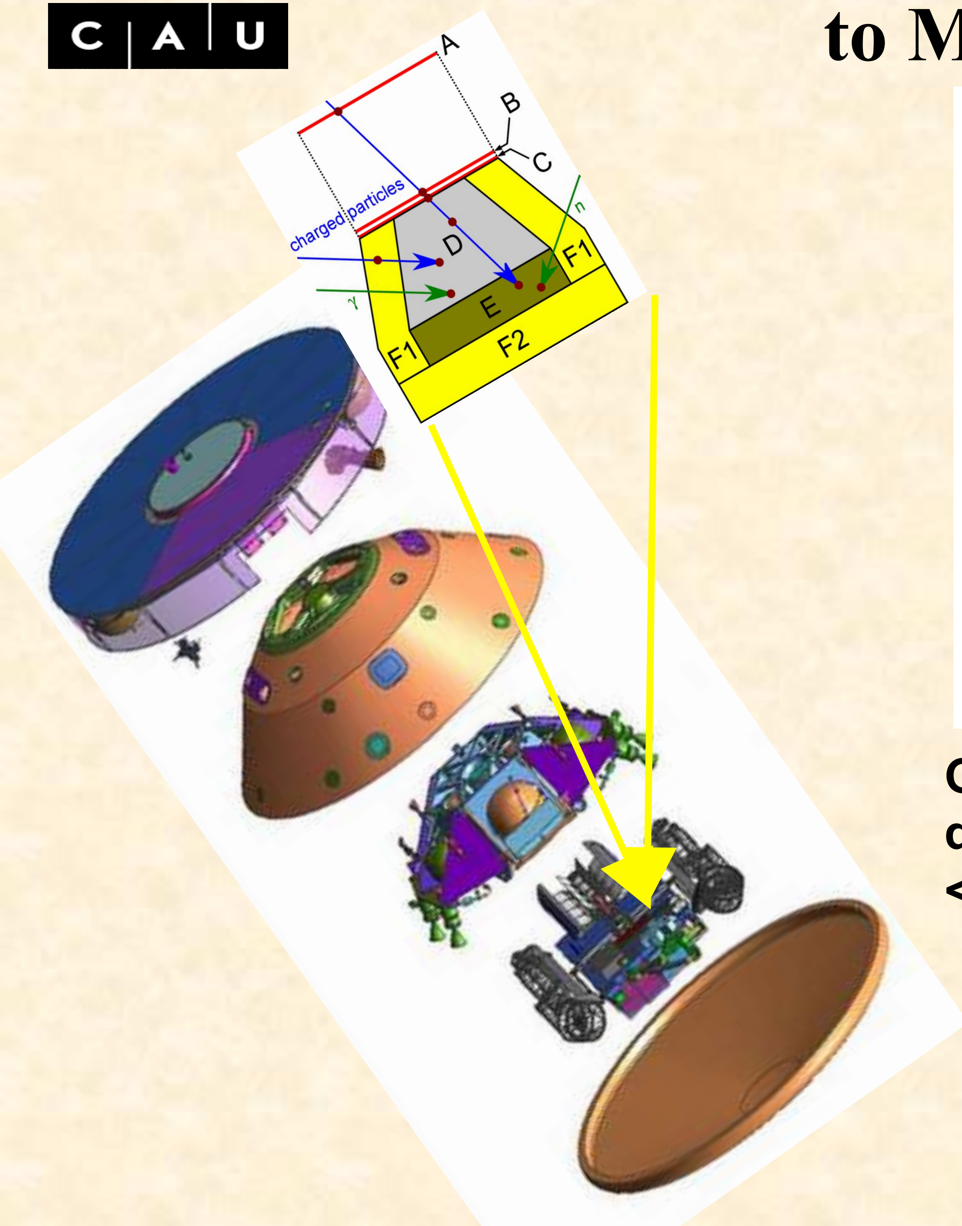
- -**D**: 2.8 cm thick CSI
- -**E**: 1.8 cm thick hydrogen-rich plastic,
- -Both D and E are efficient for **neutral particles**
- -**F**: 1.2 cm thick plastic; **anti-coincidence**

Dose rates (deposited energy by particles) are measured in both silicon and plastic detectors.

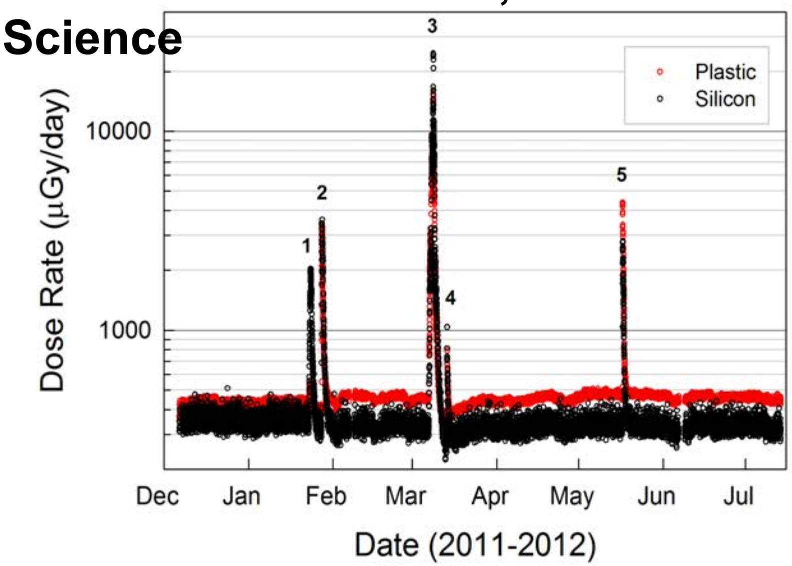


A selfi of the curiosity rover on Mars.

Radiation inside a spacecraft in deep space measured during **the cruise phase to Mars**



From **Zeitlin et al 2013, Science**



GCR-induced dose rate: ~0.481 uGy/ day

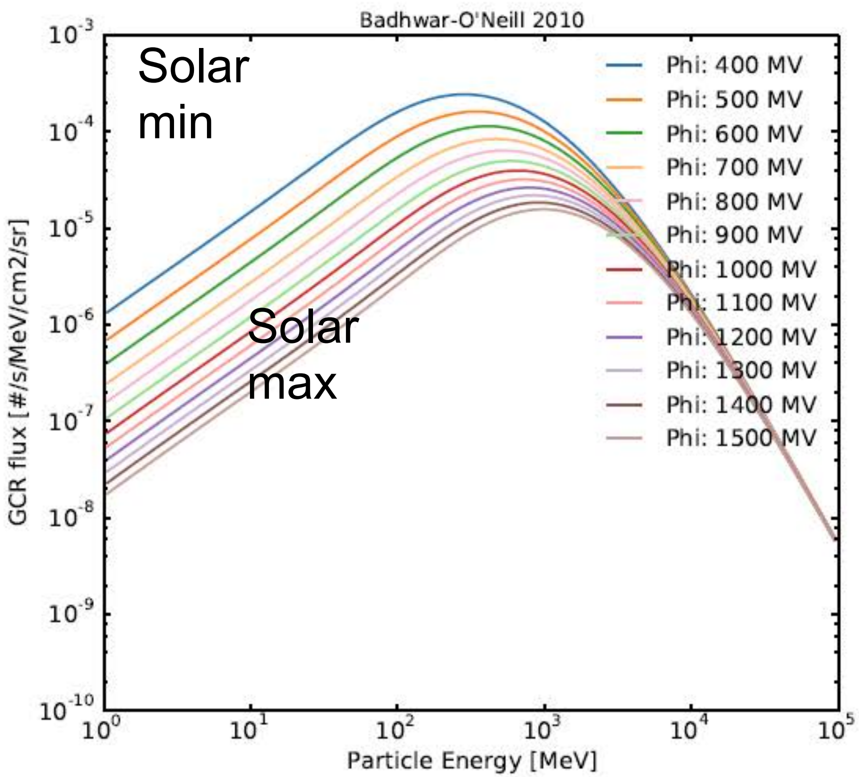
<Q> :

SEP events.

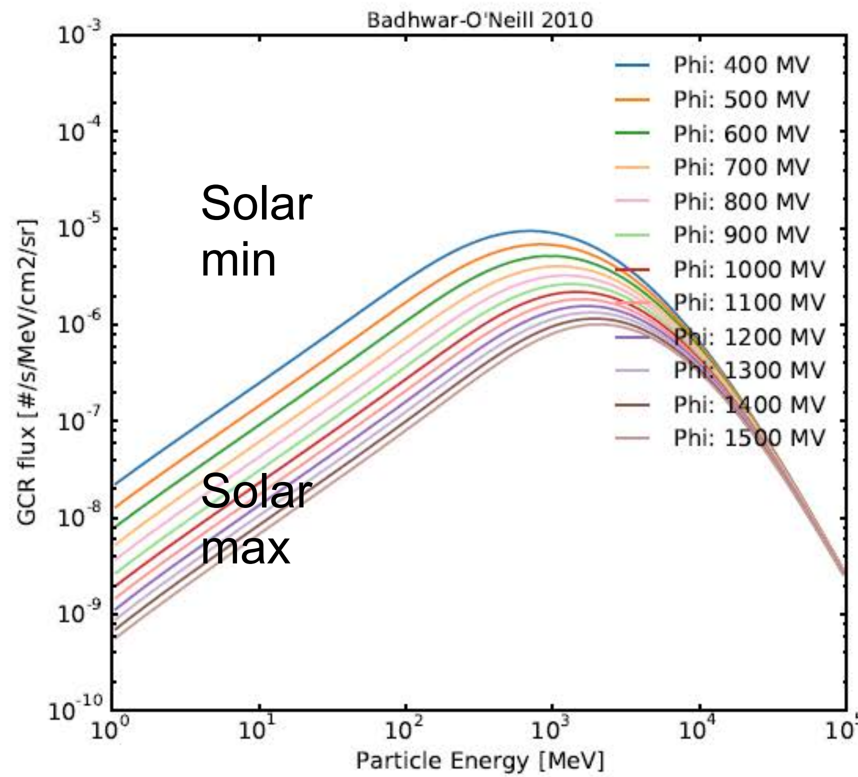
Time period (2012)	Integrated dose equivalent (mSv)
23 to 29 January	4.0
7 to 15 March	19.5
17 to 18 May	1.2
Cruise SEP Total	24.7

How about the radiation under other solar modulation conditions?

protons

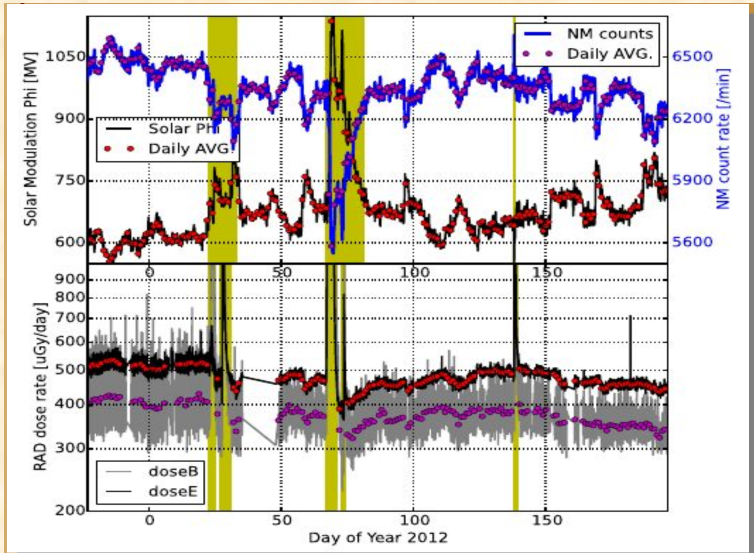


4He particles

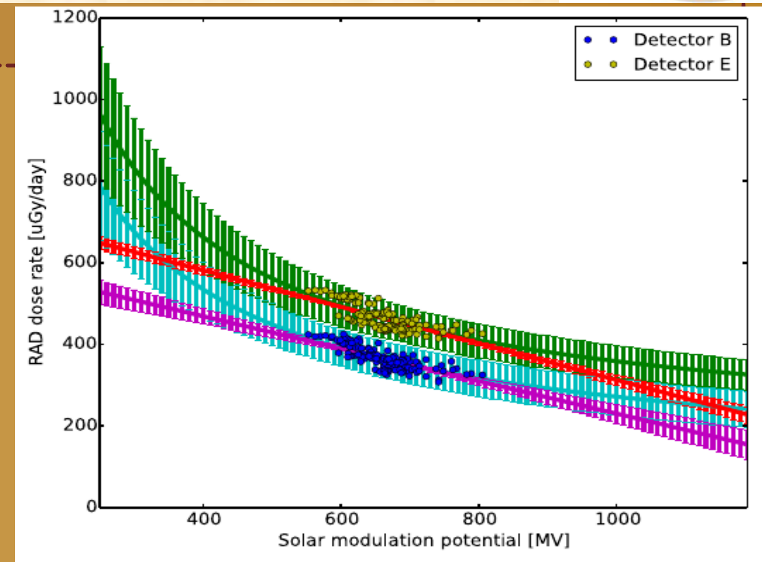


Badwahr O' Neil 2011 model

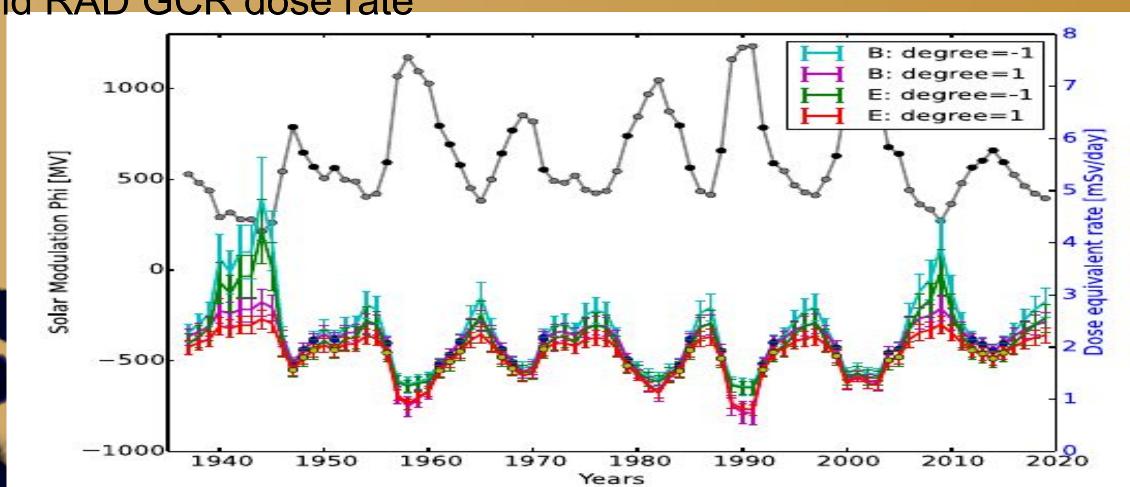
Empirical Predictions of GCR radiation during Cruise Phase under Different Solar Modulation Conditions



Anti-correlation of solar modulation and RAD GCR dose rate



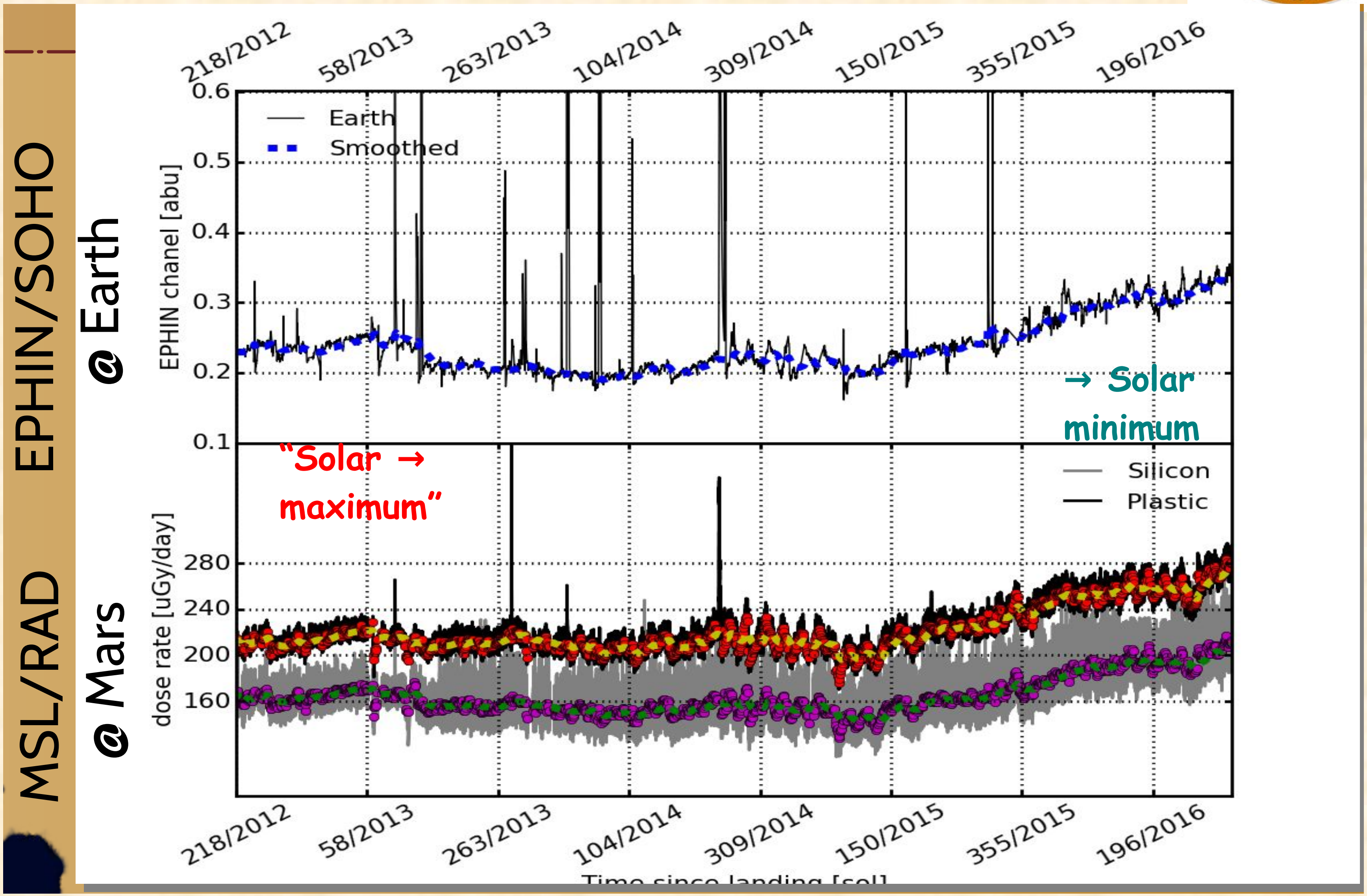
Quantify and extrapolate this correlation



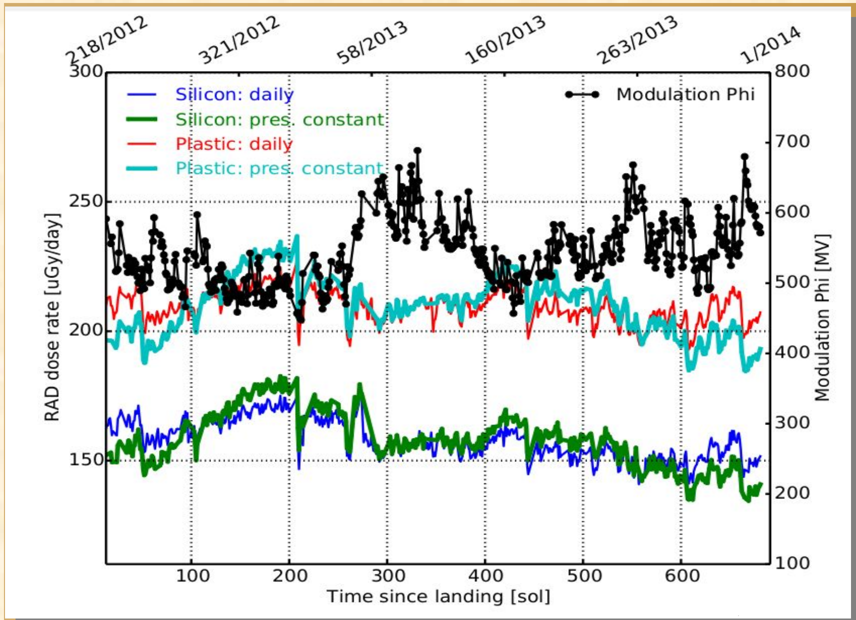
Empirical model of the dose rate during different solar modulation conditions

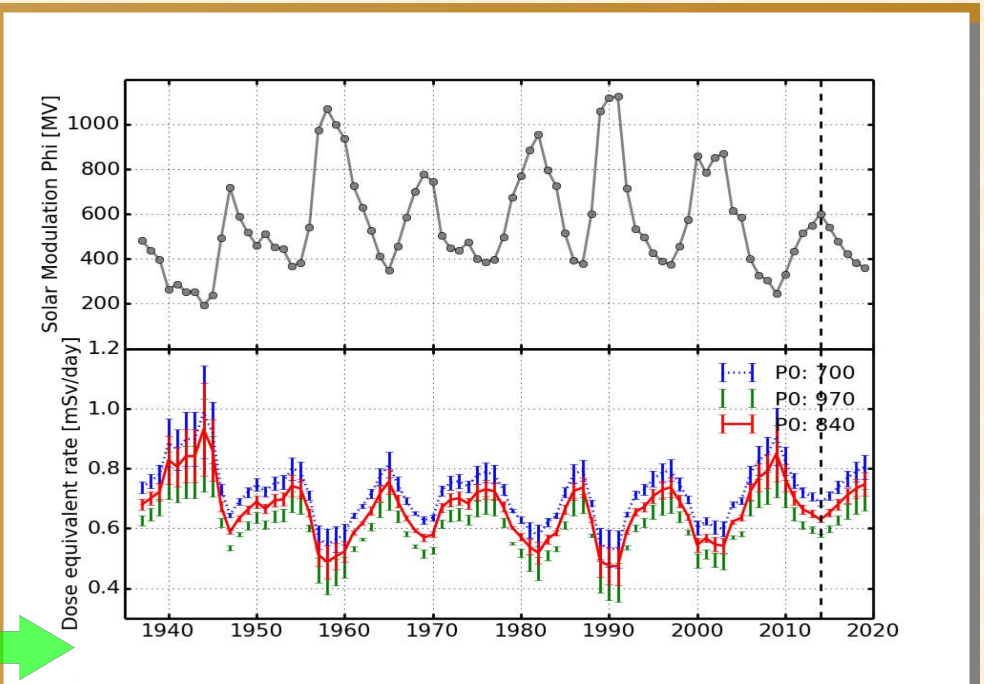
Guo et al 2015 A&A

On the Surface of Mars, GCR radiation is also modulated by solar activity and has been increasing as solar activity decreases



Empirical predictions of GCR radiation on the Surface of Mars under Different Solar Modulation Conditions





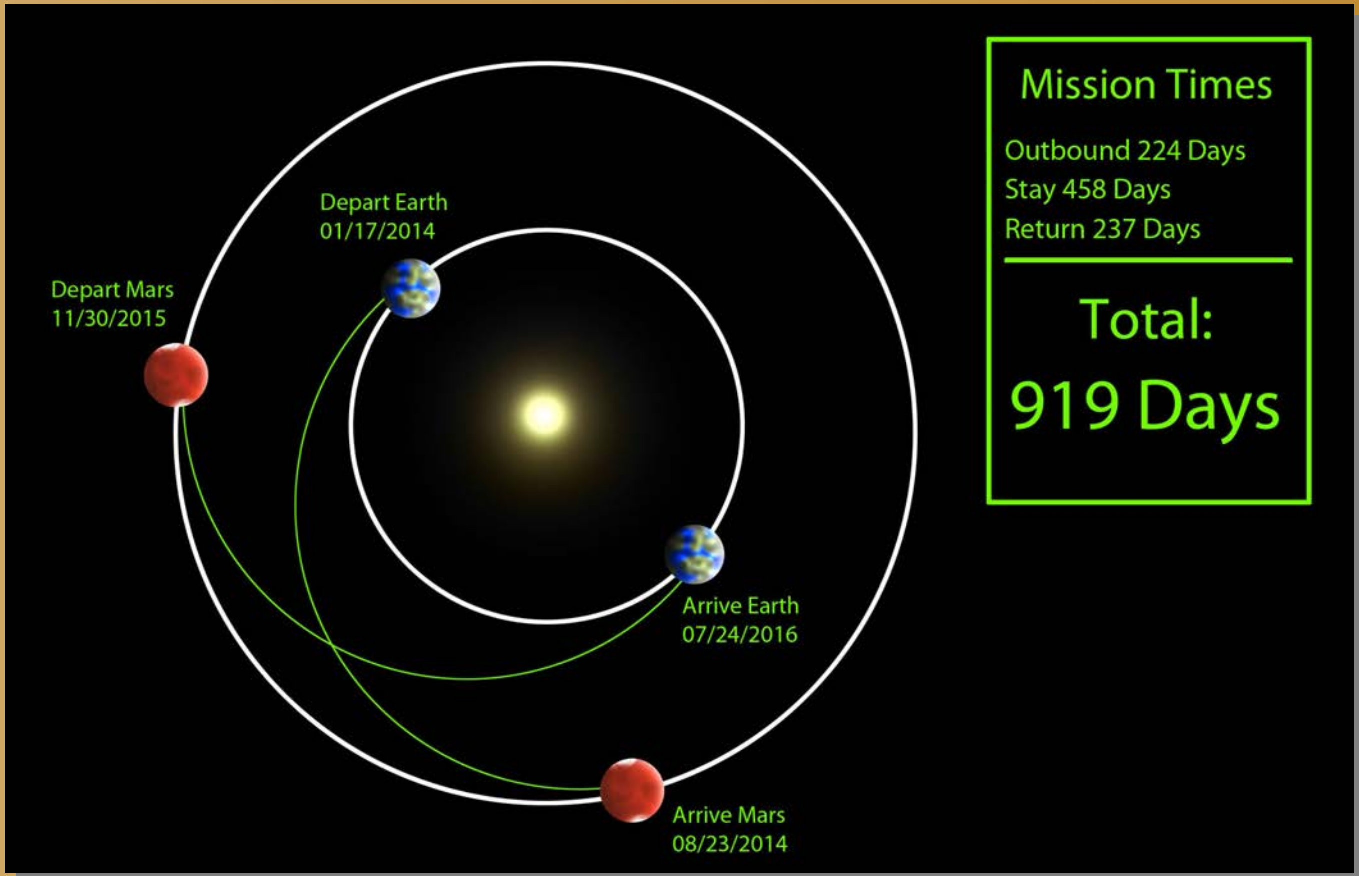
The long-term heliospheric modulation of the surface radiation is isolated by subtracting the variation induced by seasonal pressure changes.
(Guo et al 2015b, ApJ)

Based on the modulation-dose rate correlation, we can 'predict' the Martian surface radiation under different solar modulation conditions.

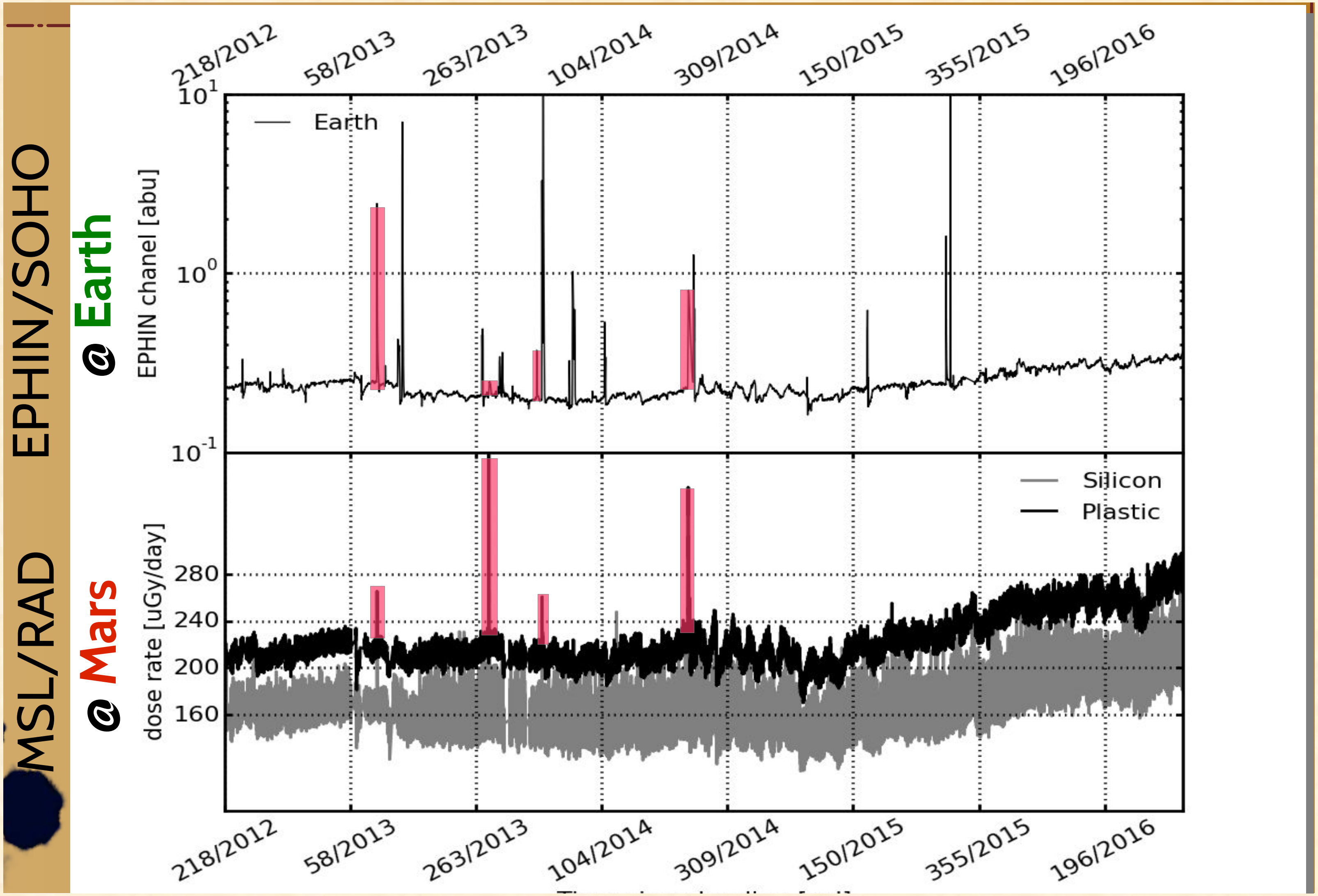
Model-derived GCR radiation levels for a typical Mission to Mars

Solar minimum: cruise (224+237)*3 + Mars (458*0.8) ~ **1.75 Sv**

Solar maximum: cruise(224+237)*1.2 + Mars (458*0.5) ~ **0.78 Sv**



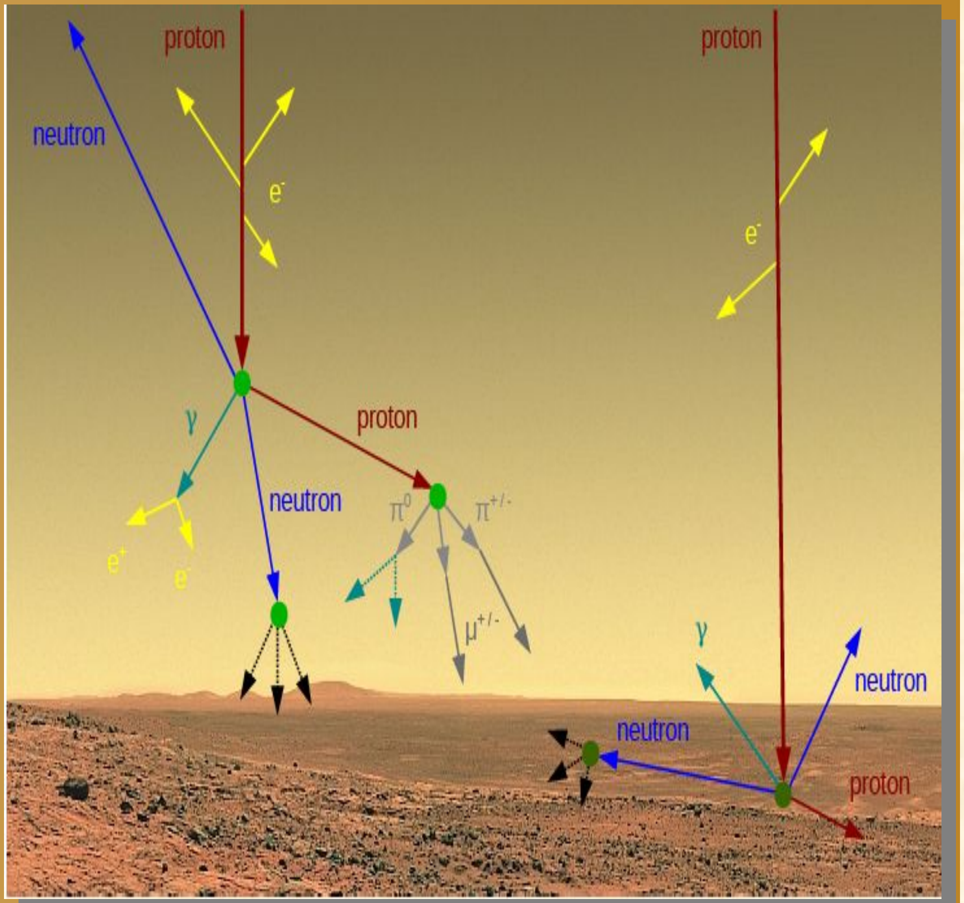
We also need to consider SEP induced radiation! SEPs seen on the surface of Mars by MSL/RAD (2012-2016)



MSL/RAD SEP Measurements

RAD observed several solar particle events (**SPEs**) during the cruise phase and on the surface of Mars. Their onset times and spectra are different from those observed at near Earth due to:

- the atomic and nuclear **interaction** of particles with the Martian **atmosphere**
- different **magnetic connection** to the particle acceleration sites (at the flares, and/or CMEs and shocks)
- **Cross-field transportation effects** on particles as they propagate through the heliosphere



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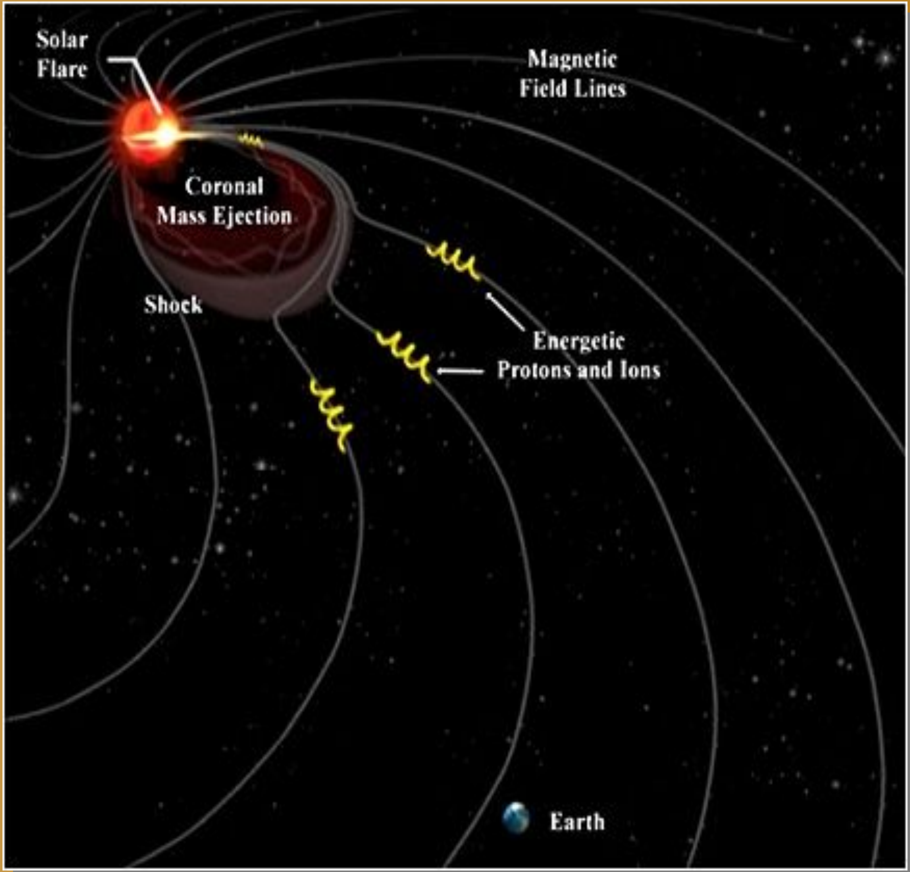
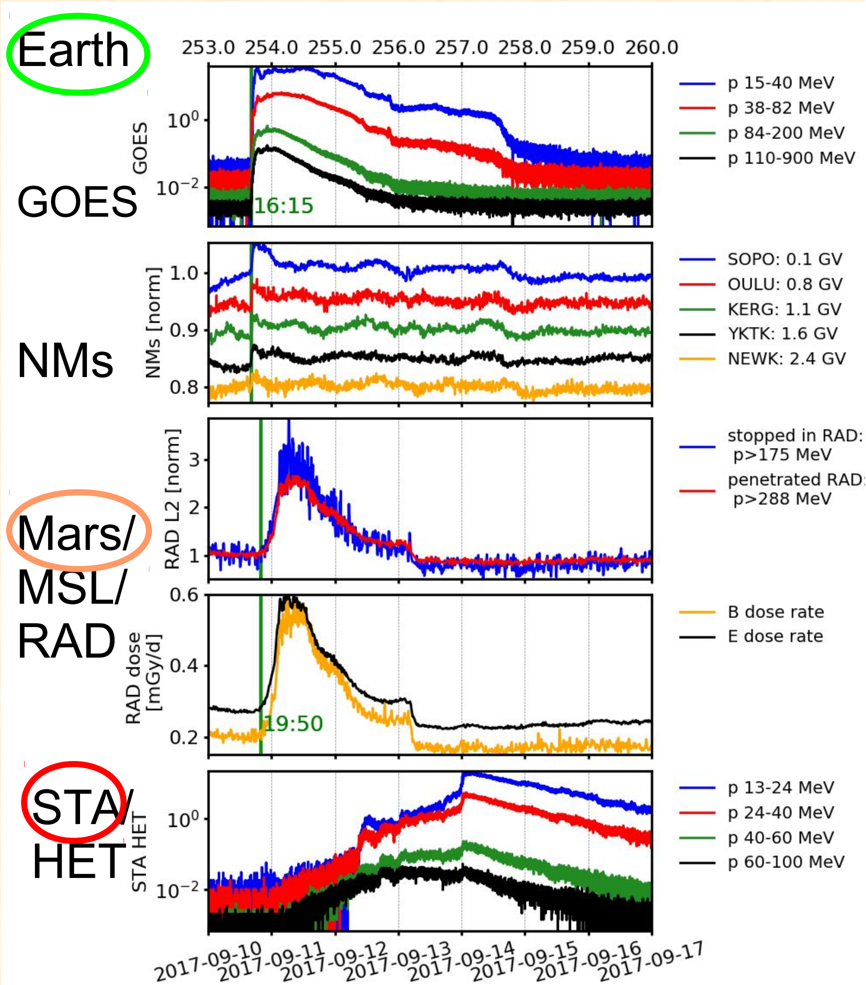


10 Sept. 2017 SEP Event arriving at Earth, Mars & STEREO-A



Earth

- The onset of protons > 100 MeV seen by GOES at Earth is at about **16:15** on 2017-09-10.
- SEPs were also registered as a ground level enhancement (GLE) seen by multiple neutron monitors with cutoff rigidities up to about 3 GV (~2 GeV protons)

Mars

- Mars magnetic foot point is ~150 degrees from the flare.
- The earliest onset at Mars is about **19:50** and this has been the biggest GLE at Mars seen by the Radiation Assessment Detector (RAD) since the landing of the Curiosity rover.
- Considering protons needs ~175 MeV to penetrate through the Martian atmosphere and an extra 113 MeV to penetrate through the RAD instrument, particles with >300 MeV arrived Mars. We are working on retrieving the SEP spectra at Mars on top of the atmosphere from surface measurement.

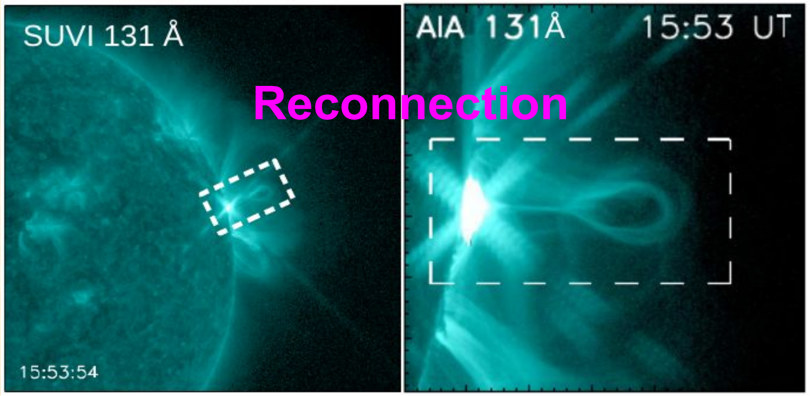
STEREO-A

- STA foot point is >~200 degrees away from flare and still detected particles ~ 100 MeV.
- The SEPs arriving at STA are likely transported there across Interplanetary Magnetic Field (IMF) lines via diffusion and scattering as STA was at the back side of the flare and CME shock.

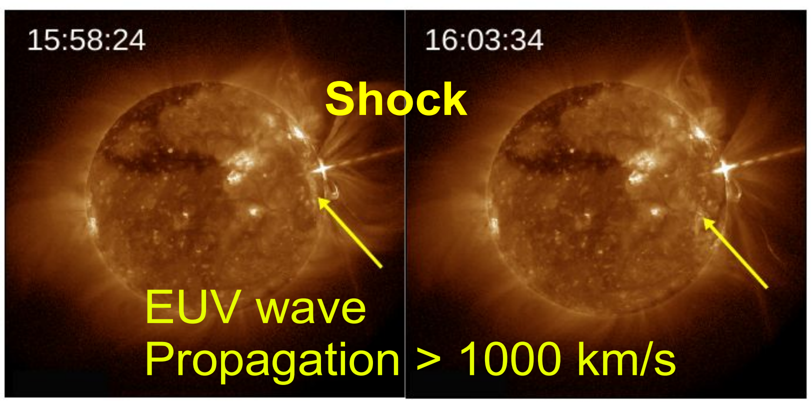
Guo et al. 2018 GRL, submitted.

The acceleration of energetic particles (protons > 2 GeV) are likely related to the **Current Sheet Reconnection & Global Shock** driven by the extremely fast CME (>~2600 km/s)

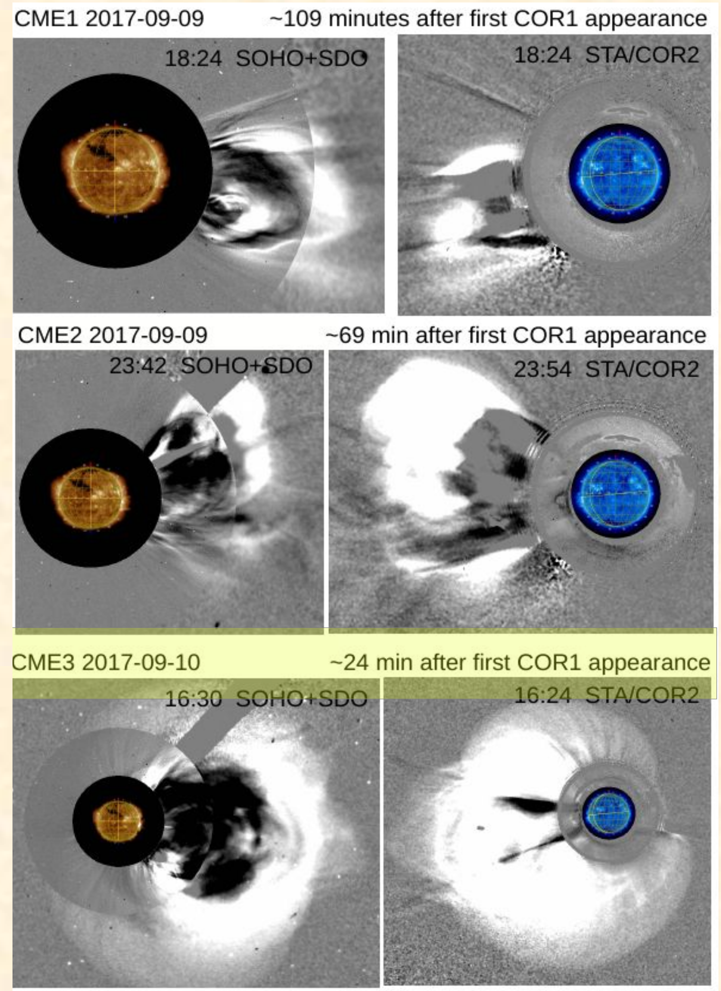
(a) Flare, current sheet and the MFR ~10/09 15:53



(b) EUV wave in SUVI's 195Å pass-band ~10/09

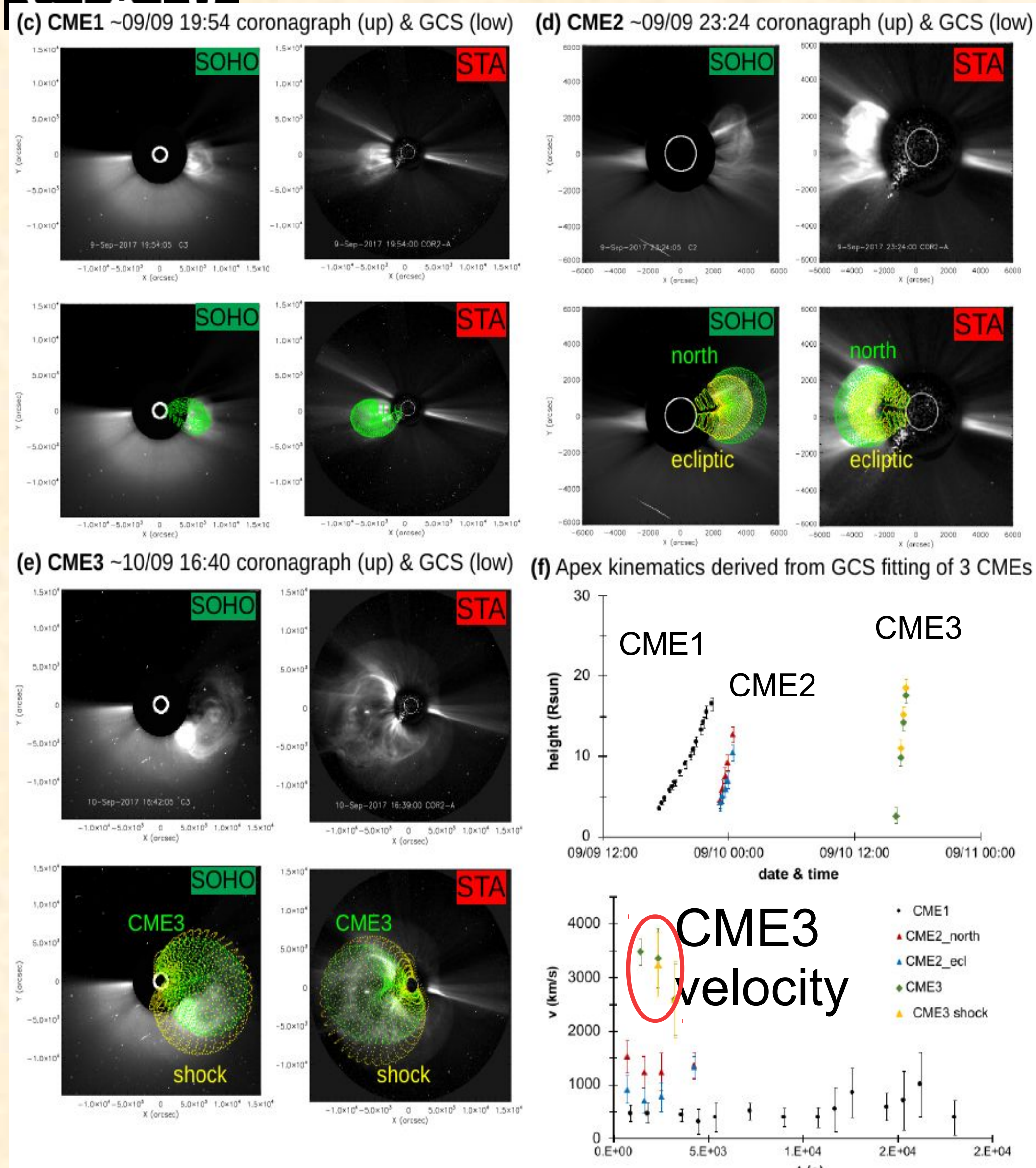


Seaton and Darnel , 2018; Warren et al., 2017; Li et al., 2018; Guo et al 2018 GRL,

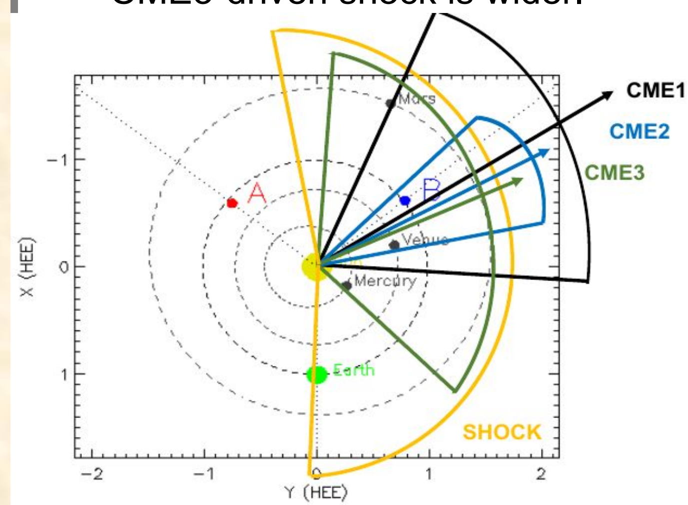


SOHO Coronagraph observations show the launch of 2 other CMEs ½ day before this event

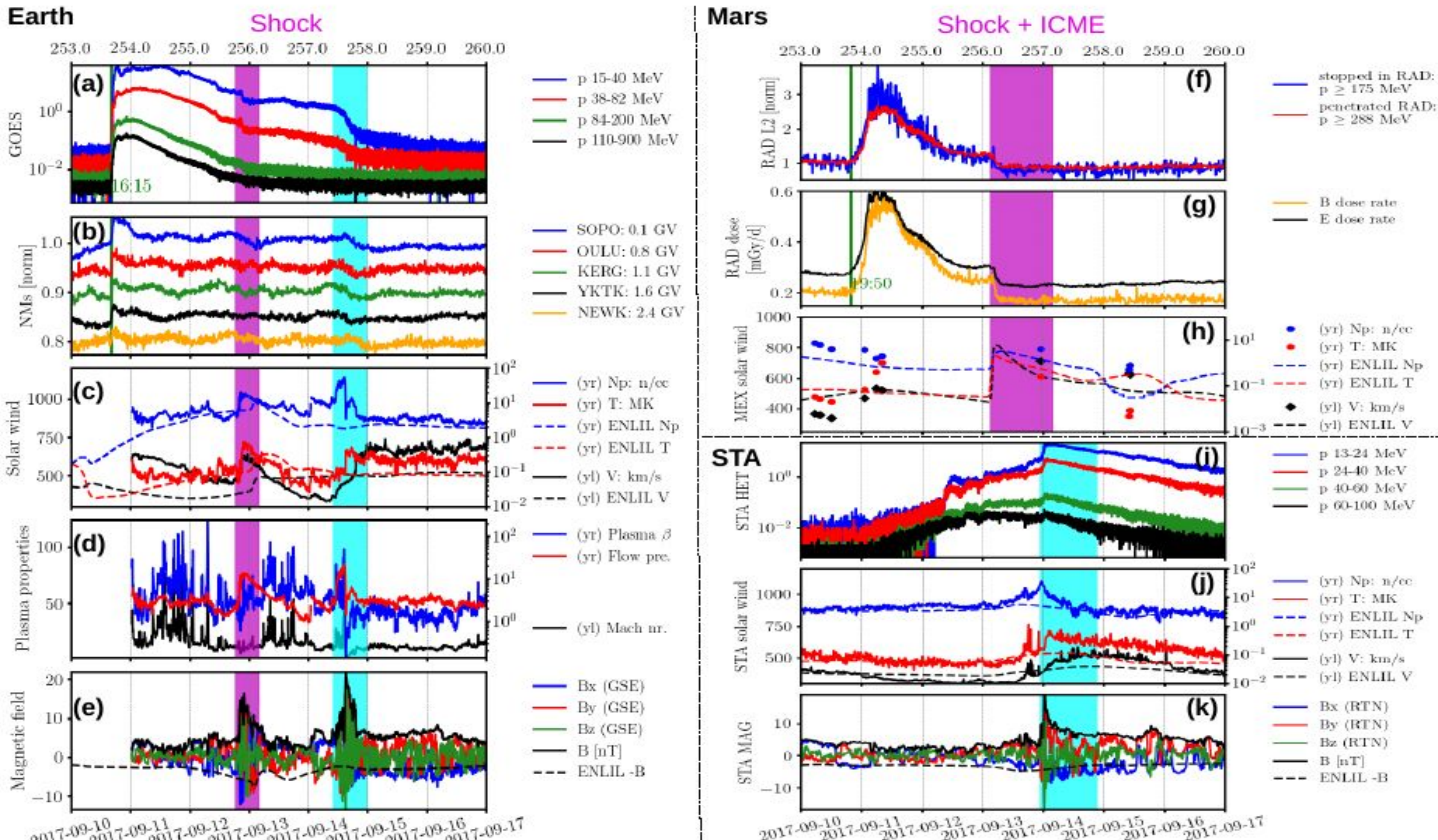
Kinematic Reconstruction of 3 CMEs



- The initial 3D geometry and kinematics of the CMEs have been constructed using graduated cylindrical shell (GCS) model [Thernisien et al., 2009; Thernisien, 2011] based on both STA and SOHO coronagraph observations.
- V _CME3 > 2600 km/s at the apex.
- Given V_cme3 >> V_cme2 > V_cme1, the later CMEs were likely catching up and interacting with the earlier ones.
- CME3-driven shock is wider.

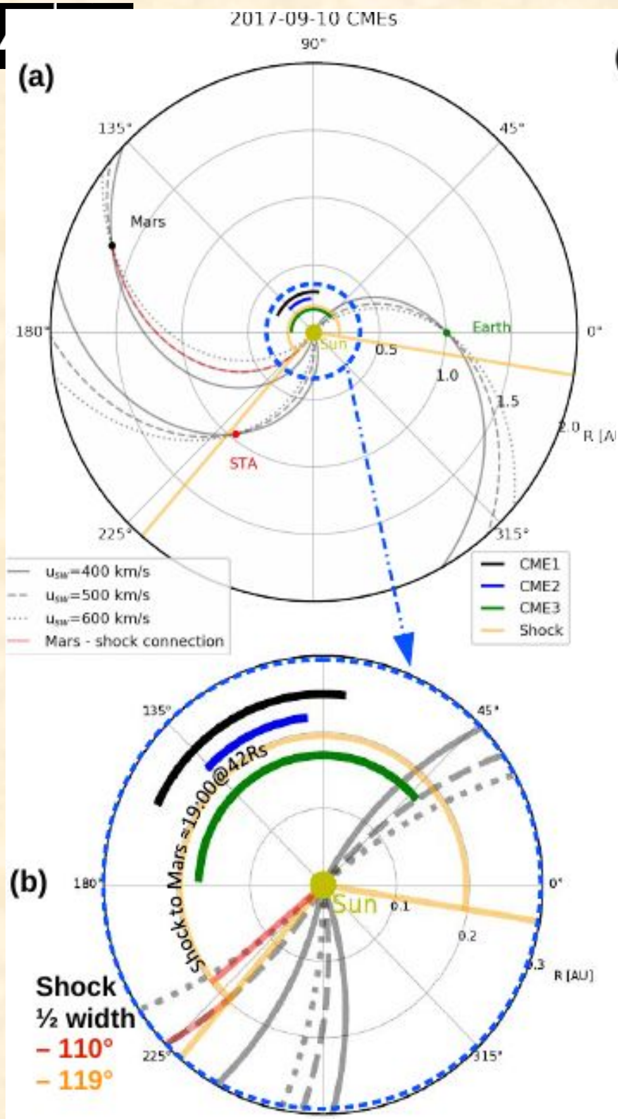


The remote sensing observations, combined with in-situ data at Earth, Mars and STEREO-A have been used to Interpret the CME's launch, propagation, interaction and transport of particles

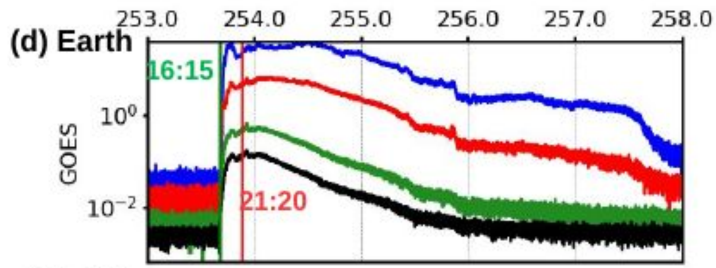


Guo et al 2018, GRL, submitted

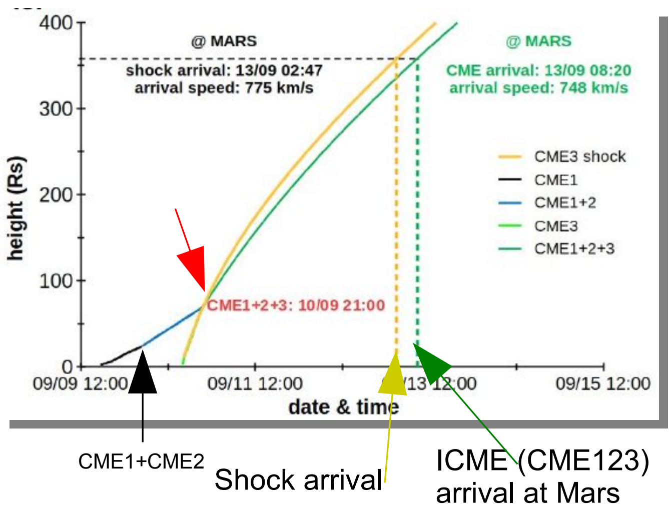
CME & Shock Arrival at Mars



Upon the SEP onset at Mars, the modeled shock front is close to the Parker spiral connecting to Mars.



Modeling results of the propagation and interaction of the 3 CMEs using the drag-based model (DBM)



- During the collision, CME mass merged as an entity and the two colliding bodies continued their propagation further with the momentum conserved [Temmer et al., 2012]
- The drag force decreases for 3 subsequent CMEs.
- As the change of CME kinematics due to collisions is much stronger, solar wind speed is kept the same before and after the CME interaction.
- Merging may be contributing to the second peak (~21:20) of particle injection as observed insitu.

Helping better Understand & Forecast Extreme Space Weather at Mars

The combined Analysis of the Measurements & Modeling of the Sept. 2017 Event is helping us better understand and therefore better forecast Extreme Space Weather Conditions at Mars!

To forecast SEP events, it is important and necessary to consider:

•The **acceleration and injection** of the particles at the Sun and the continuous acceleration by the ICME driven shock in the interplanetary (IP) space.

•The heliospheric position of the spacecraft and its **connection** to the injection site.

•Possible cross-field transport of particles in the IP space.

•The **shielding** configuration of the local environment, e.g., the spacecraft material or the planet atmosphere shielding.

Thank you!

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