The solar particle event on 10-13 September 2017 Spectral reconstruction and calculation of the radiation exposure in aviation and space

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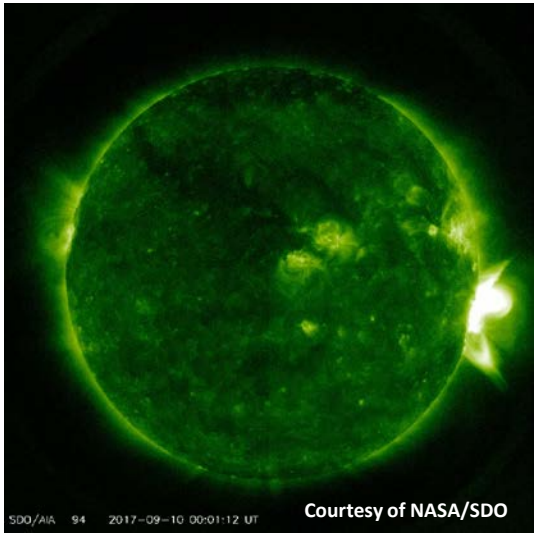
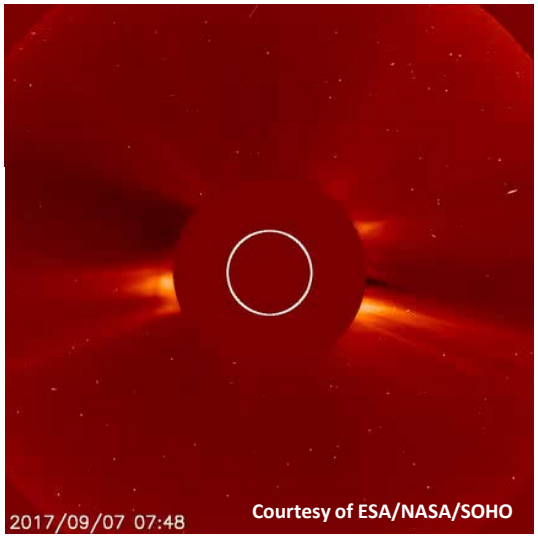
Background

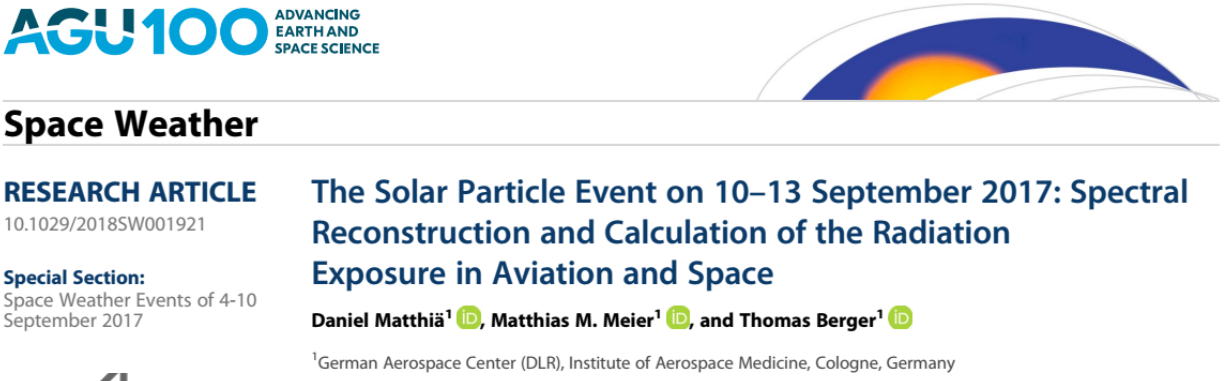
- Period of very active sun in Sep 2017
- Several X-class flares
- Ground level enhancement 10 Sep 2017
- Dose rate increase measured on the ISS (DOSTEL, ISS-RAD), lunar orbit (CRaTER), Mars (MSL-RAD)



Courtesy of NASA/SDO

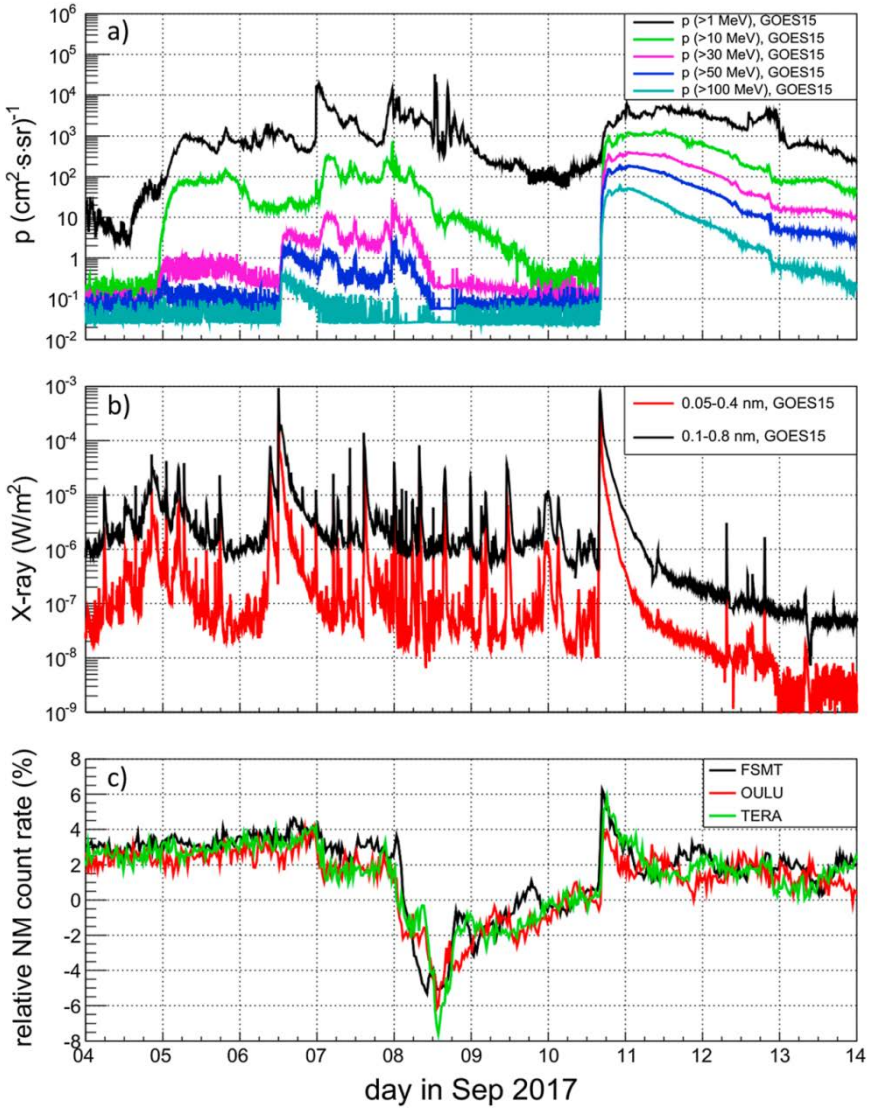


Courtesy of ESA/NASA/SOHO



The September 2017 events

- GOES-15 proton flux in Sep 2017
- GOES-15 X-ray flux
- Neutron monitor increase



Energy spectra

- Power law in rigidity, parameters J_0 and γ:

$$j(R) = J_0 \cdot \left(R / \left(\mathrm{GV} \cdot c^{-1}\right)\right)^{-\gamma}$$

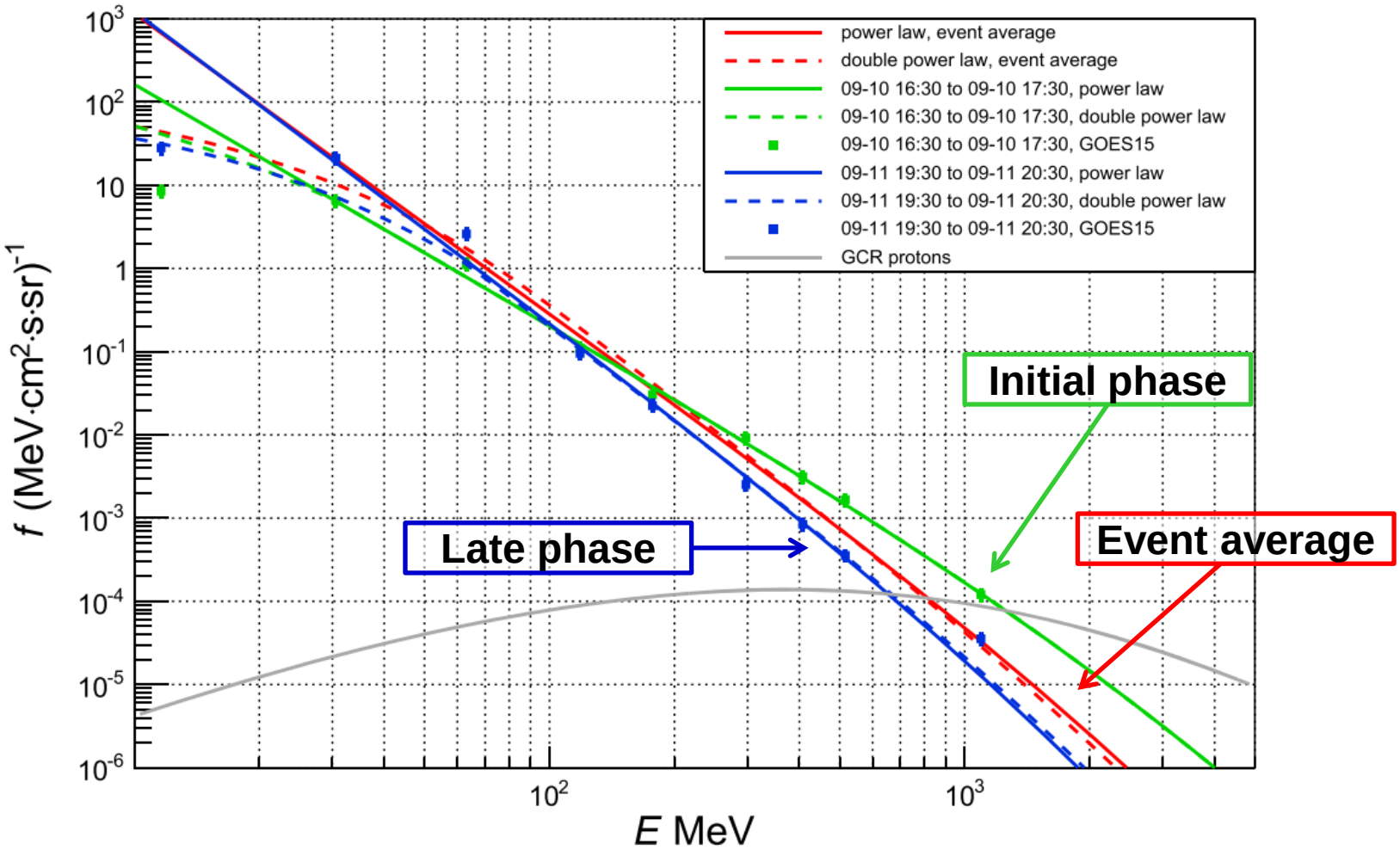
- Double power law in rigidity (Band function), parameters J_0, γ_1 , γ_2 , R_0 :

$$J(>R) = J_0 \cdot \left(\frac{R}{GV \cdot c^{-1}}\right)^{-\tilde{\gamma}_1} \exp\left(-\frac{R}{R_0}\right) \qquad \text{for } R \leq (\tilde{\gamma}_2 - \tilde{\gamma}_1) R_0$$

$$J(>R) = J_0 \cdot \left(\frac{R}{GV \cdot c^{-1}}\right)^{-\tilde{\gamma}_2} \left(\frac{(\tilde{\gamma}_2 - \tilde{\gamma}_1) R_0}{GV \cdot c^{-1}}\right)^{(\tilde{\gamma}_2 - \tilde{\gamma}_1)} \exp(\tilde{\gamma}_2 - \tilde{\gamma}_1) \qquad \text{for } R > (\tilde{\gamma}_2 - \tilde{\gamma}_1) R_0$$

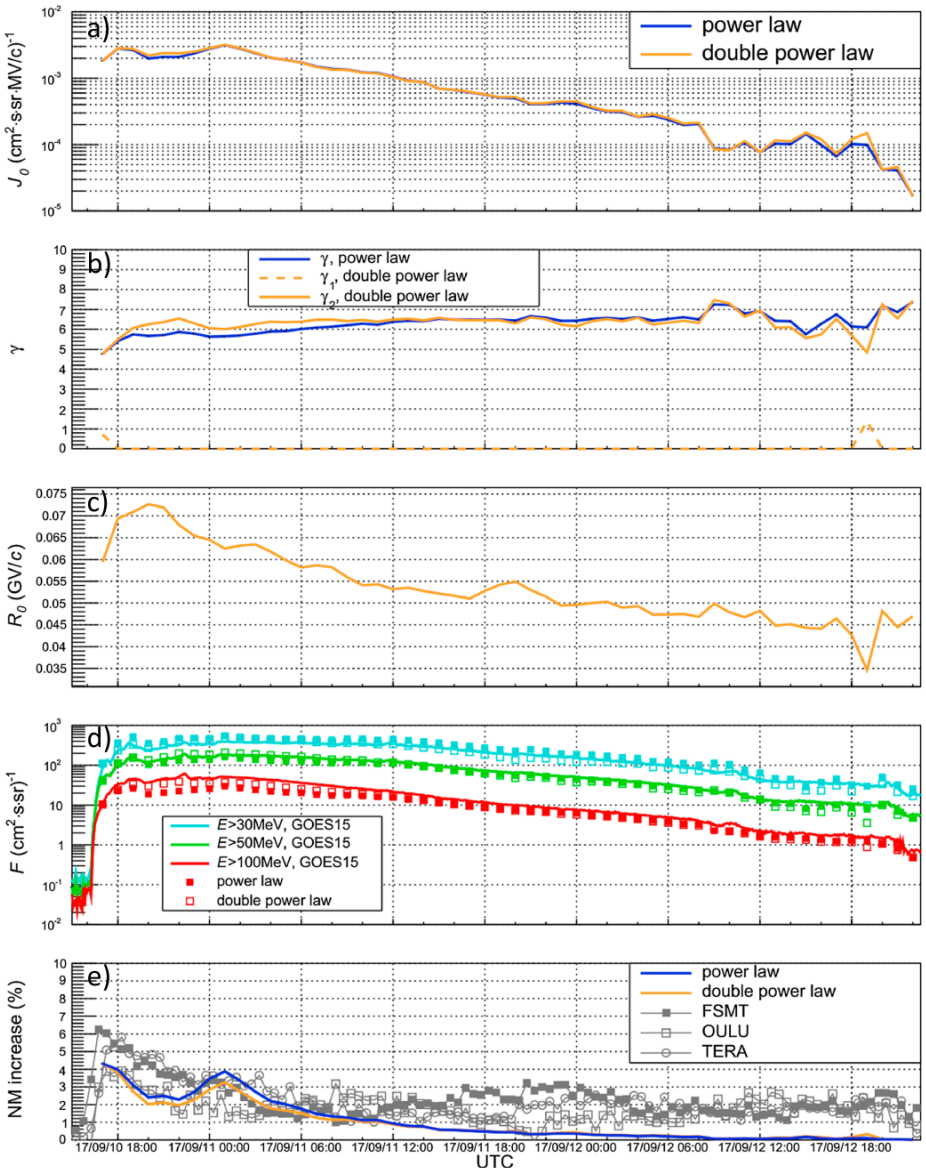
Fit 1h averaged GOES data between 10 Sep 2017 1630 UTC and 12 Sep 2017 2230 UTC

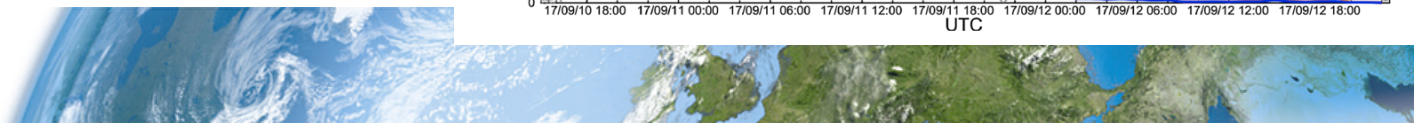
Fit of primary particle spectra



Spectral parameters during the event

- Absolute intensity
- Spectral index
- Turn over rigidity/energy
- Modelled and measured integral proton flux
- Modelled and measured neutron monitor count rate increase

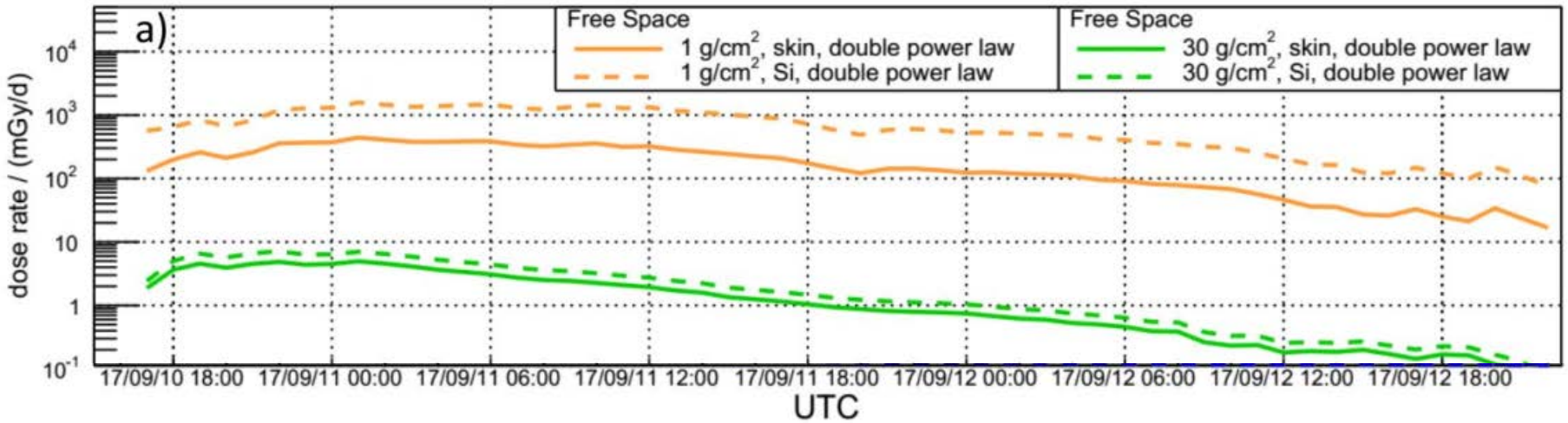




Calculation of doses during the event

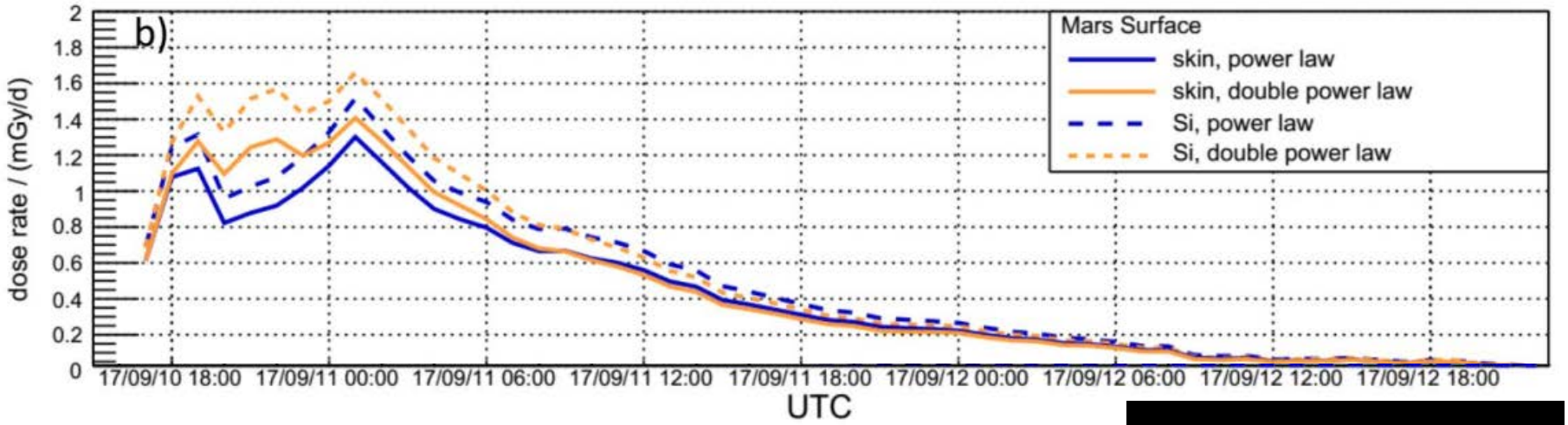
- Interplanetary space (no magnetic shielding):
  - 1 g/cm^2 and 30 g/cm^2 spherical shielding
  - Dose in Si, organ doses
- Mars surface (vertical column depth 23 g/cm^2)
  - Dose in Si, organ doses
- Aviation altitude (high latitude/no magnetic shielding, 40 kft, PANDOCA model)
  - Effective dose, dose in Si
- ISS, Columbus/DOSTEL shielding (credit: N. Stoffle, K. Lee, SRAG)
  - Dose in Si

Calculated doses during the event Interplanetary space

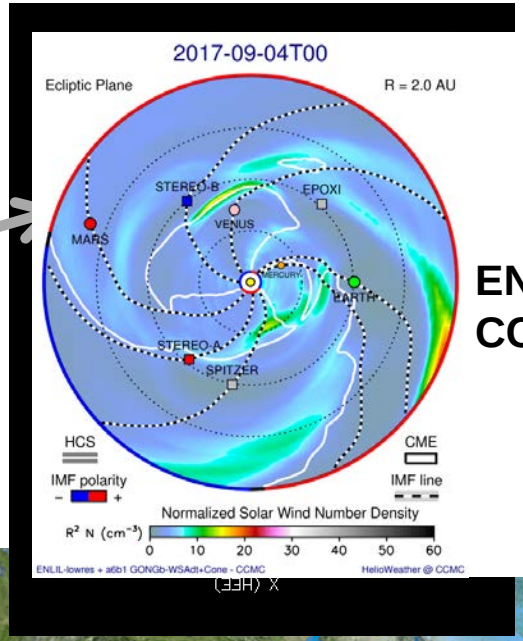


- 30 g/cm^2:
  - Calculated dose in Si: 5.3 mGy and dose in skin 3.7 mGy / 8.3 mSv
- 1 g/cm^2:
  - Calculated dose in Si: 1.6 Gy and dose in skin 0.42 Gy / 0.9 Sv
- CRaTER, lunar surface : 0.8–0.9 Gy; skin dose 1.5 Gy-Eq (*Schwadron et al., 2018, Space Weather*)

Calculated doses during the event Mars surface (for Earth event)

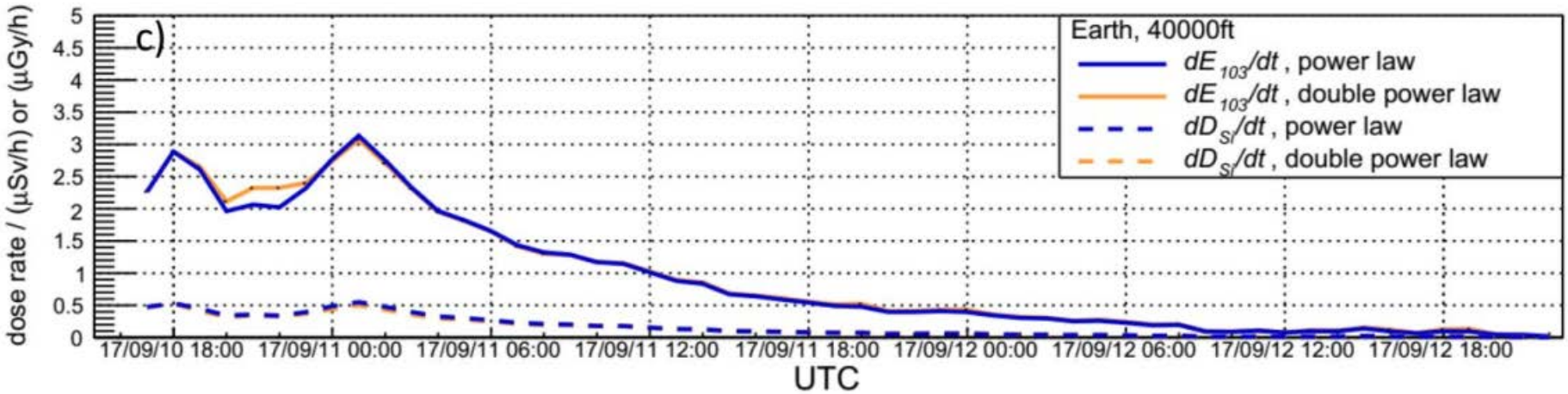


- Calculated dose in Si 1.1 to 1.2 mGy, skin: 2.2 to 2.3 mSv
- MSL-RAD 418 µGy (*Zeitlin et al, 2018, GRL*)



ENLIL CCMC

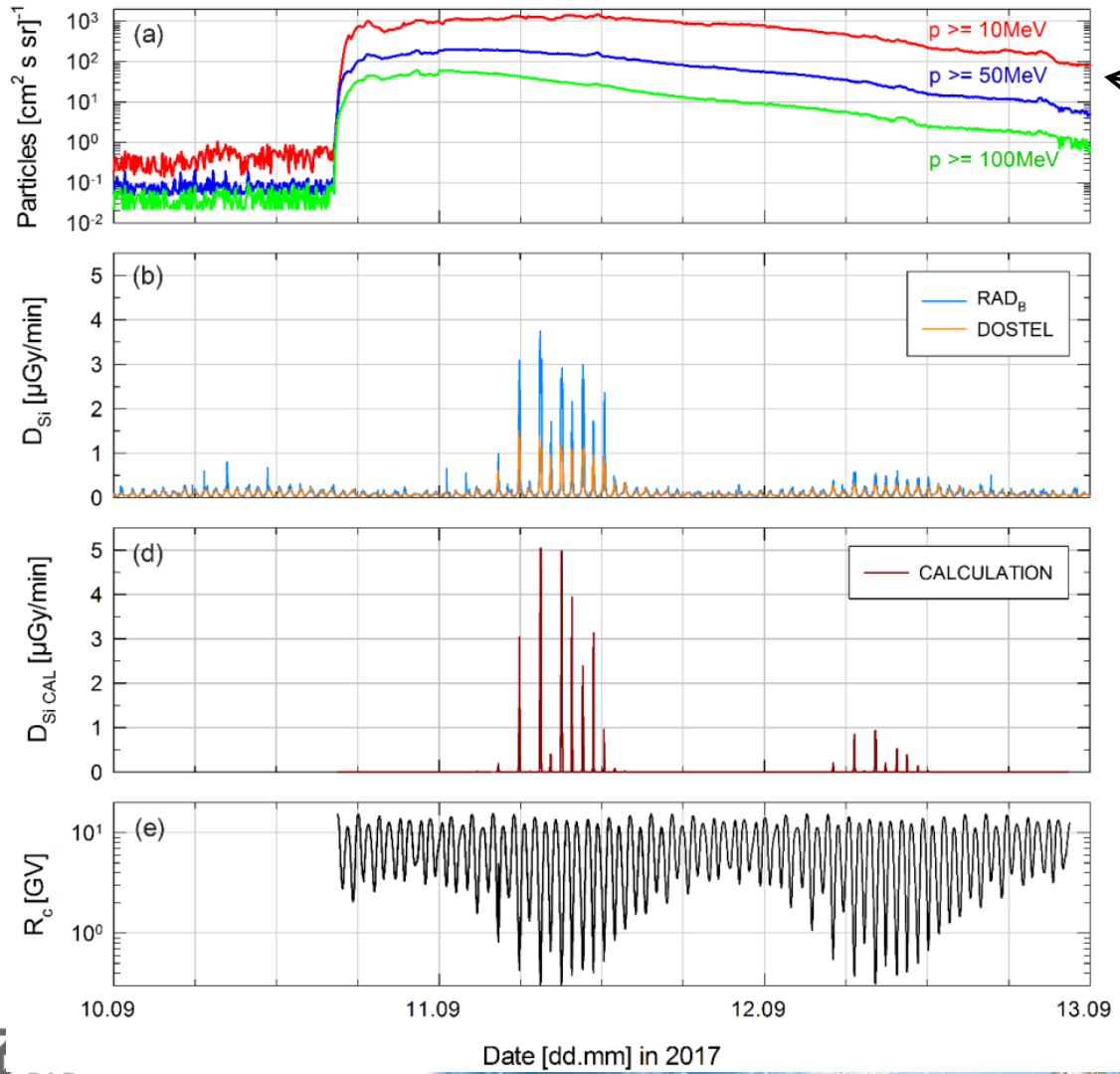
Calculated doses during the event
Aviation altitude



- Dose in Si ≤0.5 µGy/h, effective dose ≤3 µSv/h (40% GCR background)
- *Kataoka et al. (2018), Space Weather* have estimated a maximum rate of the effective dose of approximately 3 µSv/h at 12 km (≈39,000 ft)
- 10 h at 40 kft: 25 µSv (~ 35% of the GCR background, 72 µSv)
- see also *Copeland et al. (2018), Space Weather*

At ISS, Columbus shielding

adapted from *Berger et al.(2018), Space Weather*



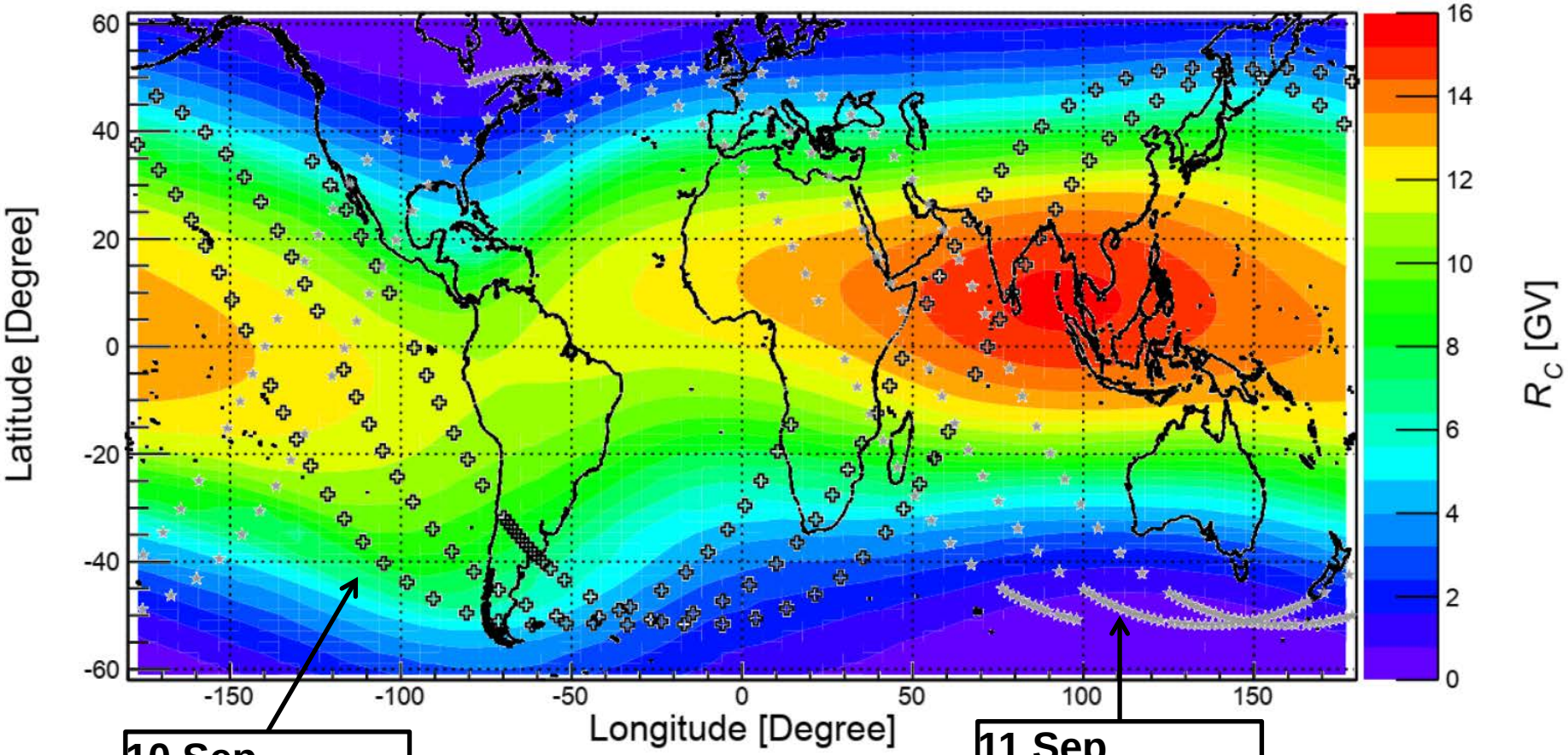
GOES proton flux

RAD/**DOSTEL** dose rate
68 µGy /**146 µGy**

Calculated dose rate
110 µGy

Cut-off rigidigy R_C

Magnetic shielding/cut-off rigidity along the ISS trajectory



10 Sep ~1730UTC to 2100UTC

11 Sep ~0530UTC to 0900UTC

Summary

- Excellent opportunity for model validation
- 10 Sep 2017 event is well described by a double power law in rigidity
- Insignificant event integrated doses
  - Except for interplanetary space 1 g/cm^2 shielding (~0.9 Sv skin dose) → unrealistic scenario
  - Aviation < 25 µSv (*E*)
  - ISS, Columbus < 110 µGy (Si)
  - Mars < 2.3 mSv (skin)
  - Interplanetary, 30 g/cm^2 < 8.2 mSv (skin)

Event integrated doses

Table 1
Event Integrated Dose Values Calculated for Interplanetary Space, Mars Surface, and Aviation Altitudes

			Interplanetary space		Mars surface	Aviation integrated over first 10 hr		
			1 g/cm^2	30 g/cm^2				40,000 ft
Power law	Si	mGy	6,136.0	4.7	1.1	Si	µGy	4.4
	Skin	mGy	1,070.0	3.5	1.0	*E* (ICRP103)	µSv	24.8
	Skin	mSv	3,128.0	8.7	2.2			
Double power law	Si	mGy	1,622	5.3	1.2	Si	µGy	4.1
	Skin	mGy	419.5	3.7	1.0	*E* (ICRP103)	µSv	25.5
	Skin	mSv	917.6	8.3	2.3			

Note. For interplanetary space and Mars, the dose rates were integrated between 10 September 2017 16:30 UTC and 12 September 2017 22:30 UTC for a silicon slab (Si) and for the skin dose using the ICRP 123 (ICRP, 2013) conversion coefficients. For aviation the integration was restricted to the first 10 hr of the event. *E* is the effective dose after ICRP 103 (ICRP, 2007).

Calculated doses during the event