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)

Space Weather

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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 $\gamma$:

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

- Double power law in rigidity (Band function), parameters $J_0$, $\gamma_1$, $\gamma_2$, $R_0$:

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

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

Fit 1h averaged GOES data between 10 Sep 2017 1630 UTC and 12 Sep 2017 2230 UTC
Fit of primary particle spectra

- Initial phase
- Late phase
- Event average
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/cm²:**
  - Calculated dose in Si: 5.3 mGy and dose in skin 3.7 mGy / 8.3 mSv
- **1 g/cm²:**
  - 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)
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 rigidity $R_c$
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/cm² 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/cm² < 8.2 mSv (skin)
Event integrated doses

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Interplanetary space</th>
<th>Mars surface</th>
<th>Aviation integrated over first 10 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 g/cm²</td>
<td>30 g/cm²</td>
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<tr>
<td>Power law</td>
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<tr>
<td>Si mGy</td>
<td>6,136.0</td>
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<tr>
<td>Skin mGy</td>
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<td>Skin mSv</td>
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<tr>
<td>Double power law</td>
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<tr>
<td>Si mGy</td>
<td>1,622</td>
<td>5.3</td>
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<tr>
<td>Skin mGy</td>
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<tr>
<td>Skin mSv</td>
<td>917.6</td>
<td>8.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

|                  |                      |              | 40,000 ft                           |
| Si mGy           |                      |              |                                     |
| Skin mGy         |                      |              |                                     |
| Skin mSv         |                      |              |                                     |
| E (ICRP103) μSv  |                      |              | 24.8                                |
| E (ICRP103) μGy  |                      |              | 4.1                                 |

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

(a) Free Space
- 1 g/cm², skin, double power law
- 1 g/cm², Si, double power law
- 30 g/cm², skin, double power law
- 30 g/cm², Si, double power law

(b) Mars Surface
- skin, power law
- skin, double power law
- Si, power law
- Si, double power law

(c) Earth, 40000ft
- $dE_{103}/dt$, power law
- $dE_{103}/dt$, double power law
- $dD_{0}/dt$, power law
- $dD_{0}/dt$, double power law