GOES Solar Energetic Particle Observations During the Ground Level Enhancements 74-76 of 2024

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Outline

- GOES satellite status
- SEP instruments: SGPS and EHIS
- >500 MeV proton fluxes, 2017-2025
- GOES observations of GLEs 74, 75 and 76
- Helium and heavy ion fluxes
- Issues with fluxes
- Summary

- Data formats, URLs and references

GOES-R+ Satellite Series Overview

- Satellites status:
  - GOES-16 (R): launched 19 November 2016
    - GOES-East (75.2°W) since 18 December 2017
  - GOES-17 (S): launched 01 March 2018
    - Was GOES-West (137.2°W) from 12 February 2019 to 4 January 2023
    - In storage (104.7°W) since 14 March 2023
  - GOES-18 (T): launched 01 March 2022
    - GOES-West (137°W) since 4 January 2023
  - GOES-19 (U): launched 25 June 2024
    - Post-launch tests have been completed (89.5°W)
    - Will replace GOES-16 as GOES-East on 4 April 2025 (75.2°W)
- Each GOES-R+ series satellite carries a Space Environment In-Situ Suite (SEISS) of particle detecting instruments (Dichter+2015, Kress+2020):
  - Magnetospheric Particle Sensor – Low Energy (MPS-LO)
  - Magnetospheric Particle Sensor – High Energy (MPS-HI)
  - **Solar and Galactic Proton Sensors (SGPS) (2)**
  - **Energetic Heavy Ion Sensor (EHIS)**
- Processing of space weather data from the previous series has ceased:
  - GOES-13 data ceased on December 14, 2017
  - GOES-14 and -15 data ceased on March 4, 2020

On GOES 16-19, a new instrument (SGPS) has replaced the EPS and HEPAD instruments for monitoring solar energetic proton and alpha particle fluxes

GOES 16-19 Solar and Galactic Proton Sensor (SGPS)

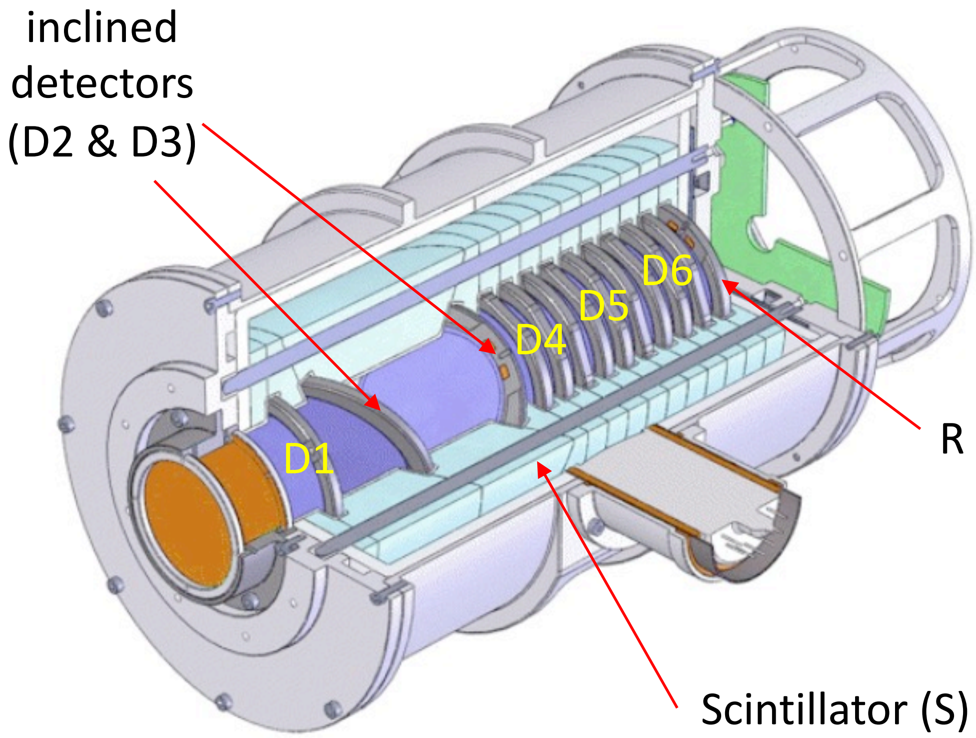
- 2 units, one looking east (+X) and one looking west (-X)
- Fluxes observed looking west are affected less by geomagnetic cutoffs, used by SWPC for Solar Radiation Storm alerts
- 3 solid state telescopes in each unit
  - FOVs: 60°, 60° and 90°
  - Passive tungsten shielding
- 1-500 MeV proton fluxes in 13 differential channels, plus >500 MeV integral channel
- 5-716 MeV alpha particle fluxes in 11 differential channels
- Data available at 1-s, 1-min and 5-min cadences (100% duty cycles)
- Integral fluxes *derived* from differential channels and >500 MeV integral channel, available at 1-min and 5-min cadence

Fig. 8. SGPS instrument. Telescope apertures are under the "Remove Before Flight" covers.

Table 1
GOES-R Series SGPS Proton Energy Channels by Telescope

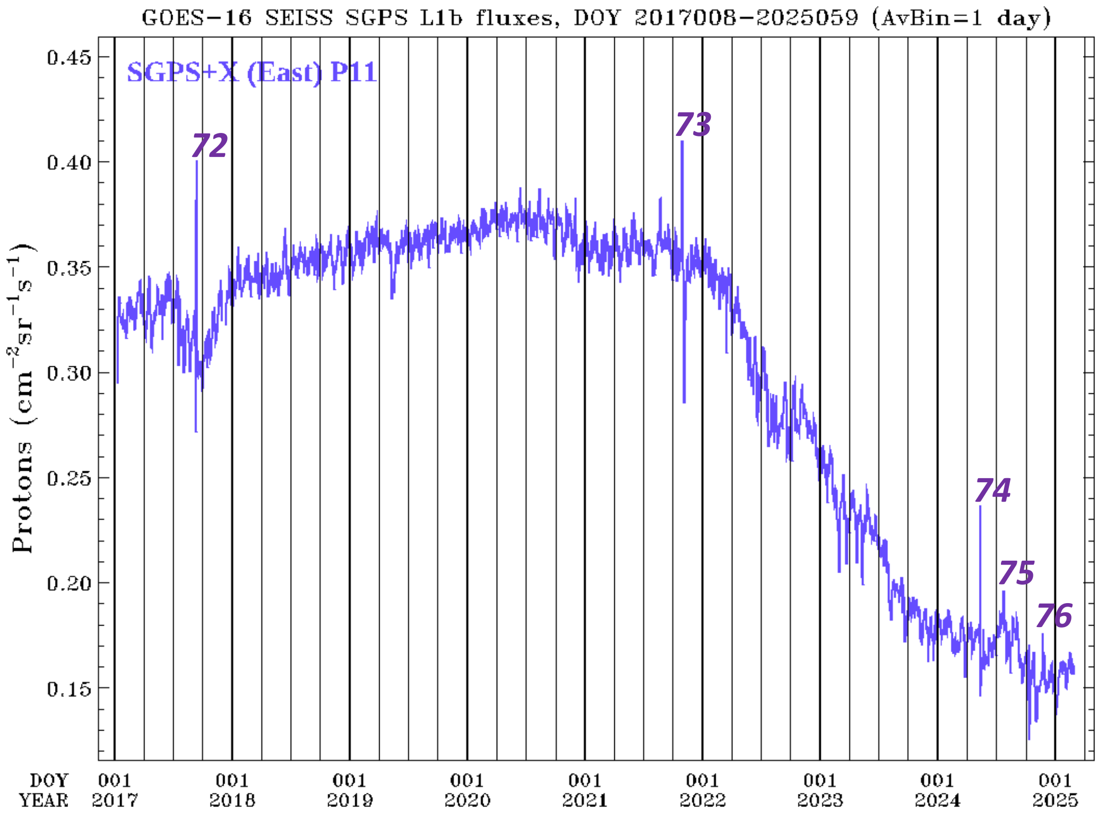
SGPS Tel. 1	SGPS Tel. 2	SGPS Tel. 3
P1: 1.0–1.9	P6: 25–40	P8A: 83–99
P2A: 1.9–2.3	P7: 40–80	P8B: 99–118
P2B: 2.3–3.4		P8C: 118–150
P3: 3.4–6.5		P9: 150–275
P4: 6.5–12	MeV	P10: 275–500
P5: 12–25		P11: >500

GOES 16-19 Energetic Heavy Ion Sensor (EHIS)



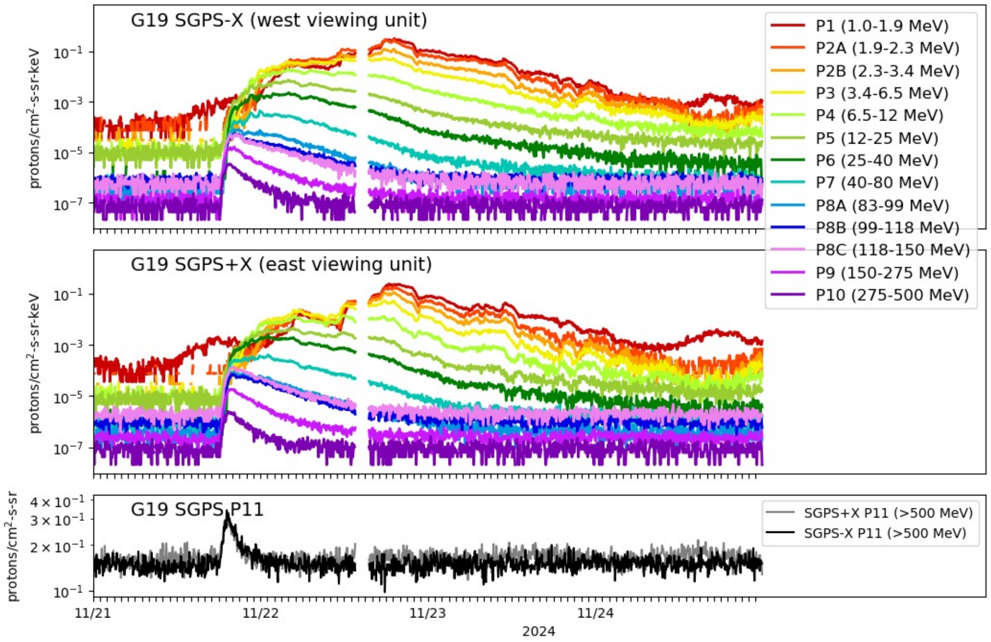
- Primary purpose: measure fluxes of solar energetic particles (SEPs) responsible for Single Event Effects (SEE) and dose damage
- Single solid-state telescope uses angle-detecting inclined sensor (ADIS, Connell+2001) system to discriminate heavy ions by atomic number (Z)
- Reports ion fluxes by Z in five energy channels whose energies vary with Z
  - 11-239 MeV for protons
  - 11-165 MeV/n for helium
  - 18-334 MeV/n for carbon
  - 38-826 MeV/n for iron
- Scintillator (S) provides active anti-coincidence shielding (.NOT.S, non-prime) but is taken out of the logic above a count rate threshold (NO S, prime)
- L1b cadence is 5 minutes (100% duty cycle)

GOES-16 SGPS >500 MeV proton fluxes since January 2017

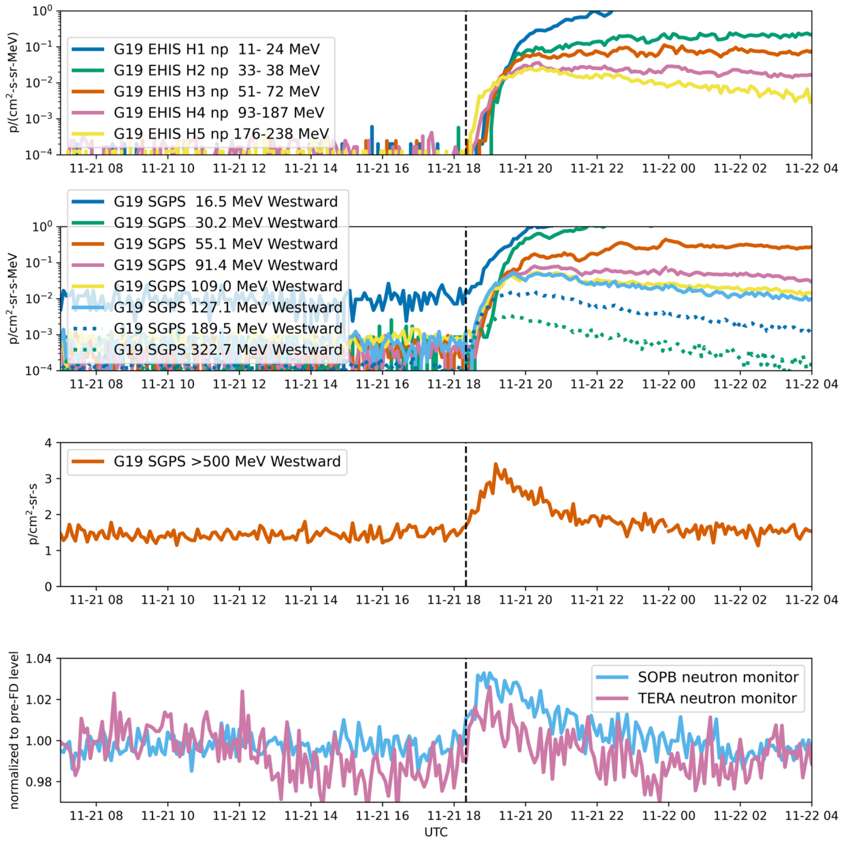


- The GOES-16 SGPS P11 (>500 MeV) fluxes are continuous since the instrument turned on in January 2017
- The fluxes exhibit characteristics of cosmic rays, including the solar cycle variation, Forbush decreases, and 27-day solar rotation modulation
- Signatures of SEP events corresponding to GLEs are indicated by '7's above the corresponding spikes in these one-day averages

GLE 76: GOES-19



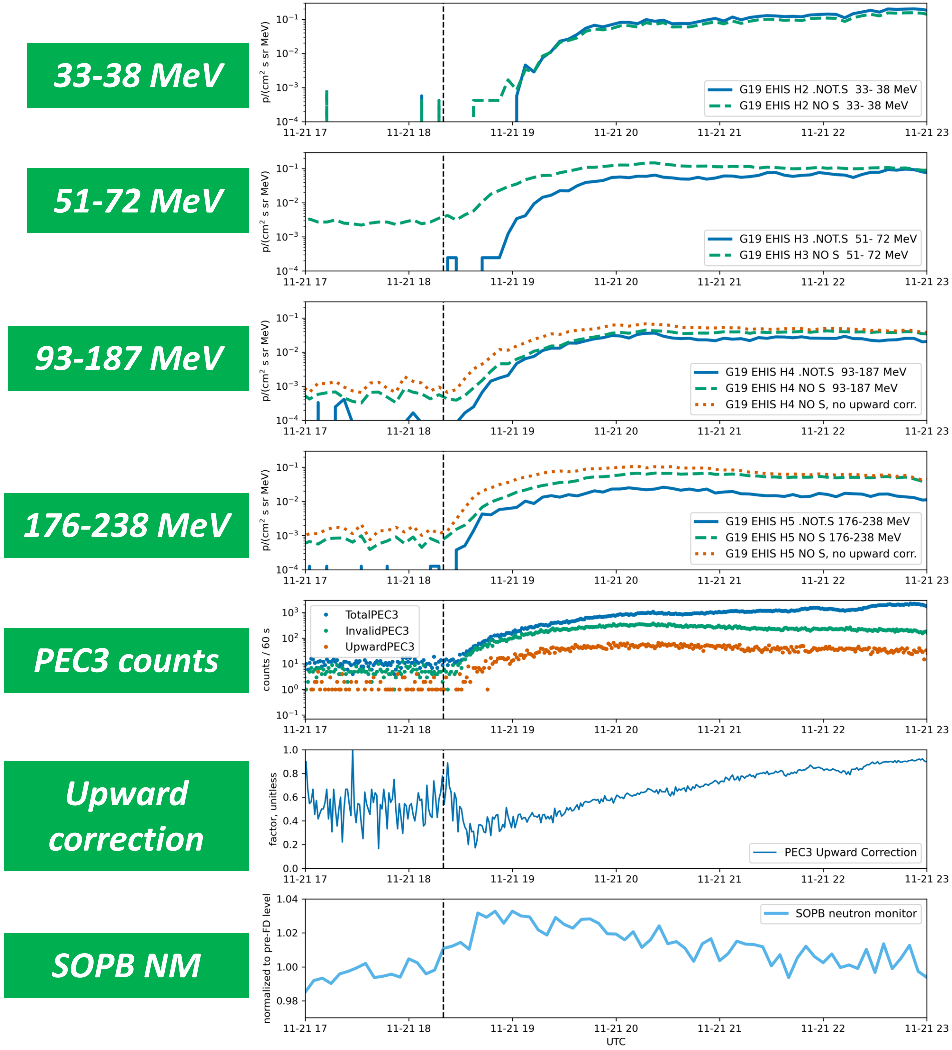
GOES-19 SGPS protons 21-24 Nov 2024



GOES-19 p+, TERA and SOPB NM rates, 21 Nov 7UT - 22 Nov 4UT

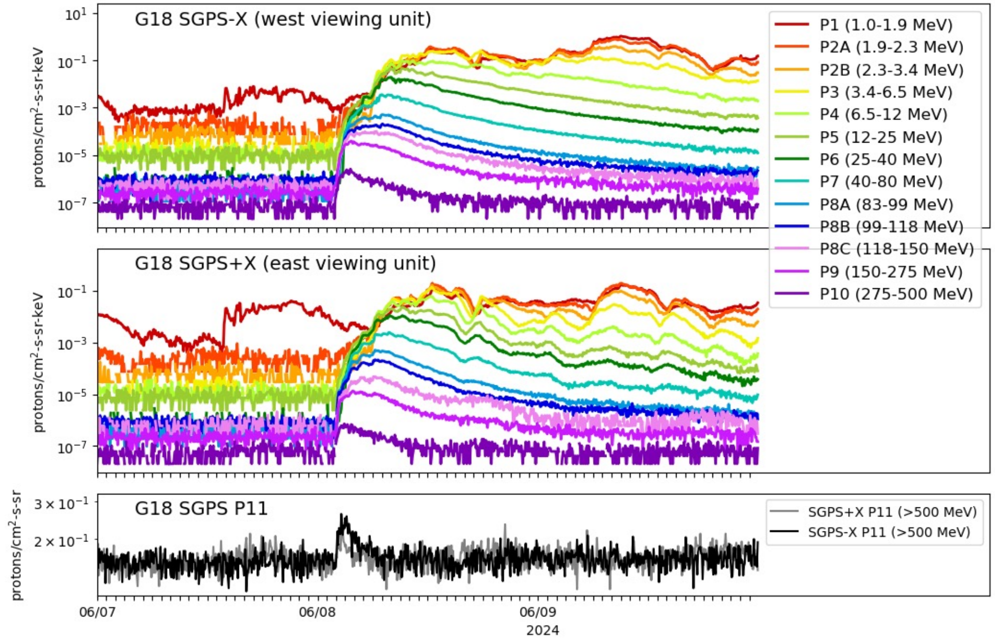
GLE 76 onset
(G19 EHIS, SOPB NM)

- EHIS pulse-height analysis event counts (PEC) include total, invalid, and upward (rear-entry, part of invalid)
- These are used to calculate an 'upward' correction to the H4 and H5 prime (NO S) fluxes: (total-invalid)/total
- The 'upward' multiplicative correction is smallest at the event onset
- This correction does not in general match the benefit of the anti-coincidence scintillator in the circuit (.NOT.S, non-prime)
- The .NOT.S fluxes exhibit more accurate proton event onsets

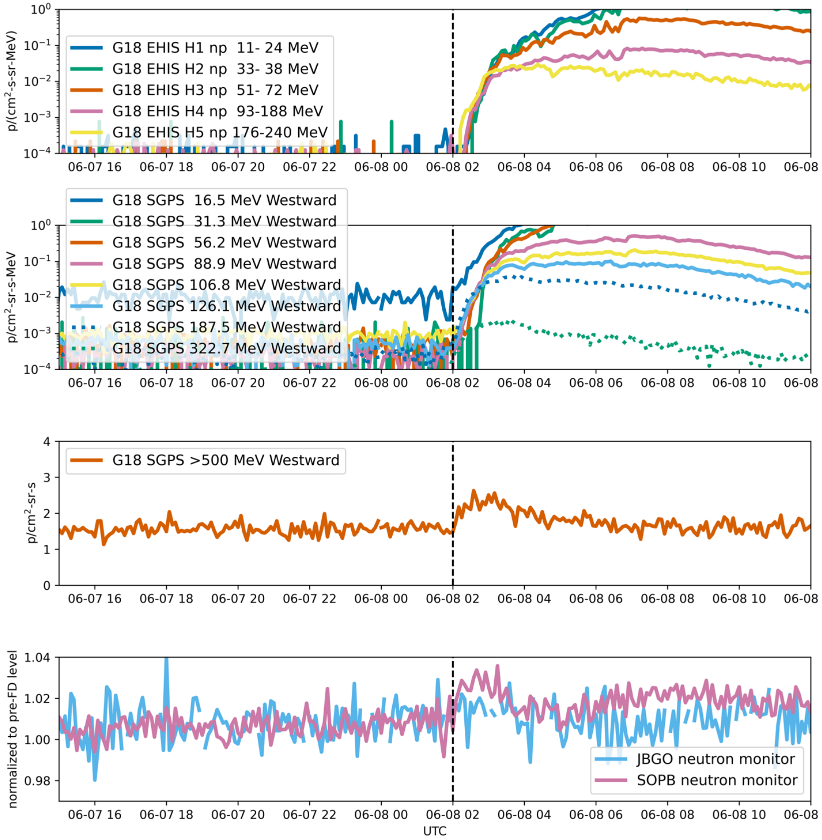


GLE 75: GOES-18

CIRES



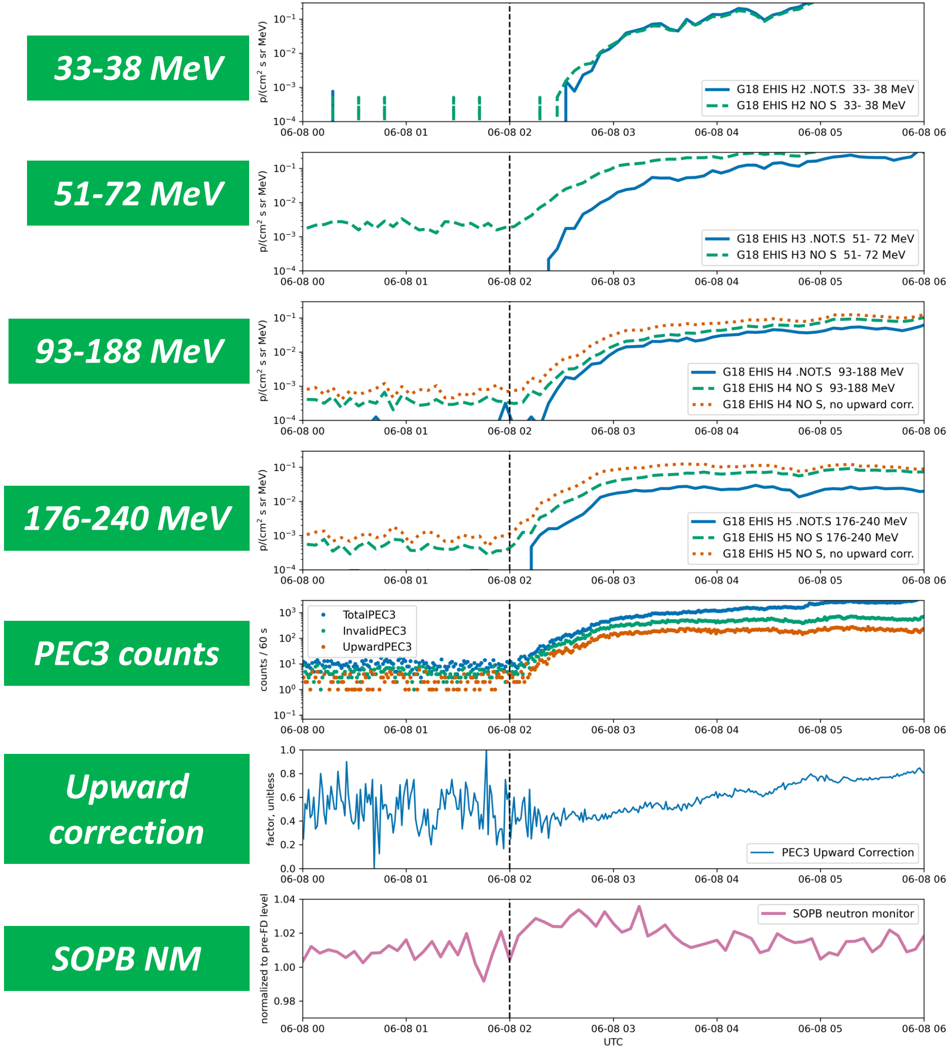
GOES-18 SGPS protons 07-09 June 2024



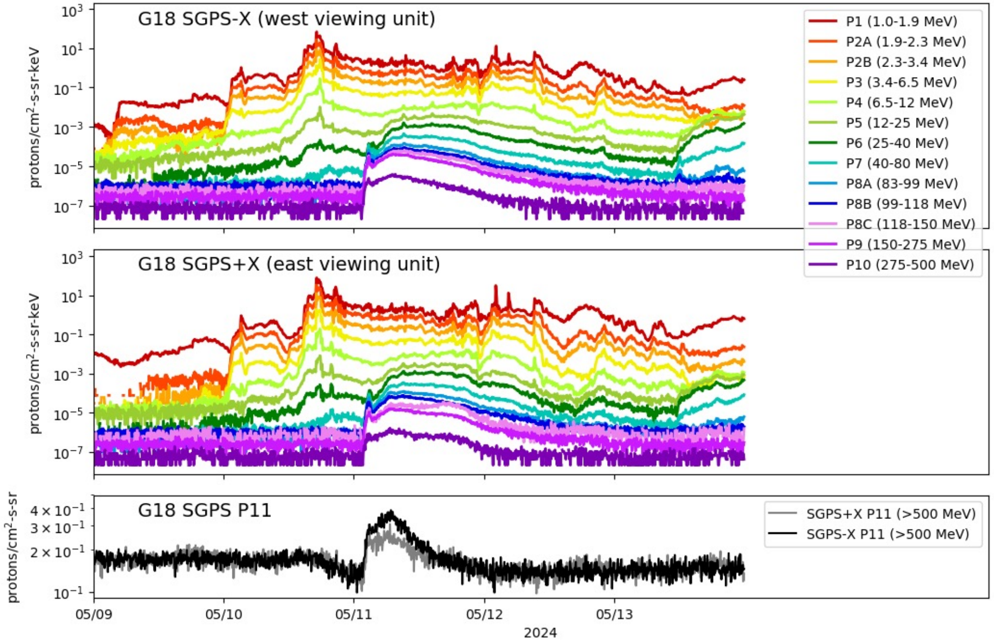
GOES-18 p+, JBGO and SOPB NM rates, 07 Jun 15UT - 08 Jun 12UT

GLE 75 onset
(G18 EHIS, SOPB NM)

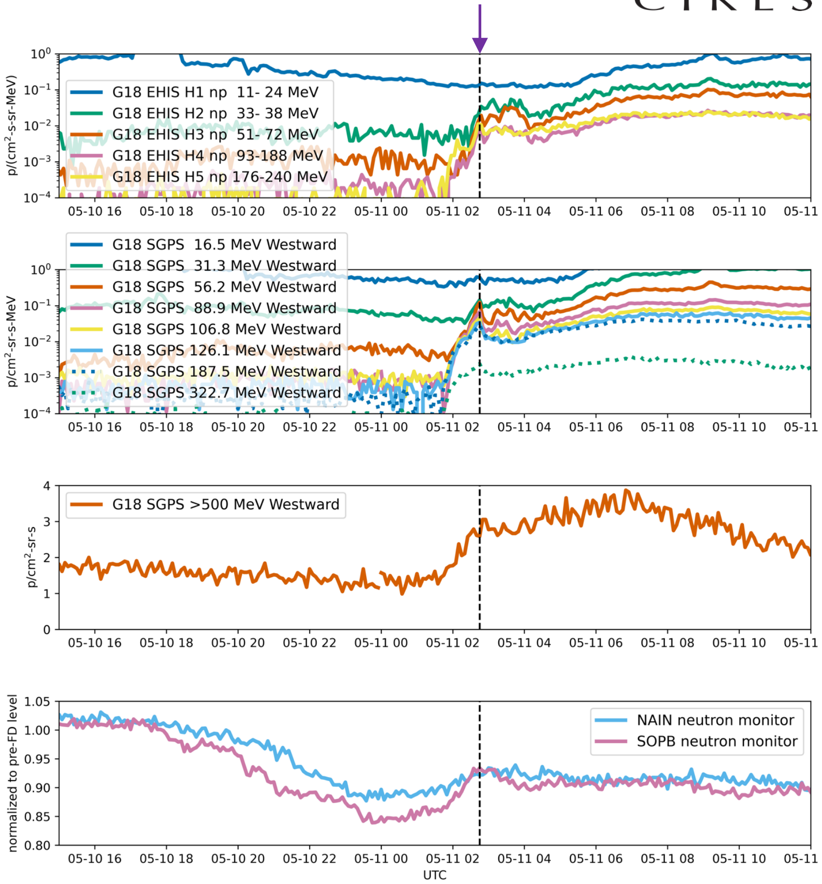
- Similar onset to GLE 76
- Pulse-height analysis event counts (PEC) include total, invalid, and upward (rear-entry, part of invalid)
- These are used to calculate an ‘upward’ correction to the H4 and H5 prime (NO S) fluxes: (total-invalid)/total
- The ‘upward’ multiplicative correction is smallest at the event onset
- This correction does not in general match the benefit of the anti-coincidence scintillator in the circuit (.NOT.S, non-prime)
- The .NOT.S fluxes exhibit more accurate proton event onsets



GLE 74: GOES-18



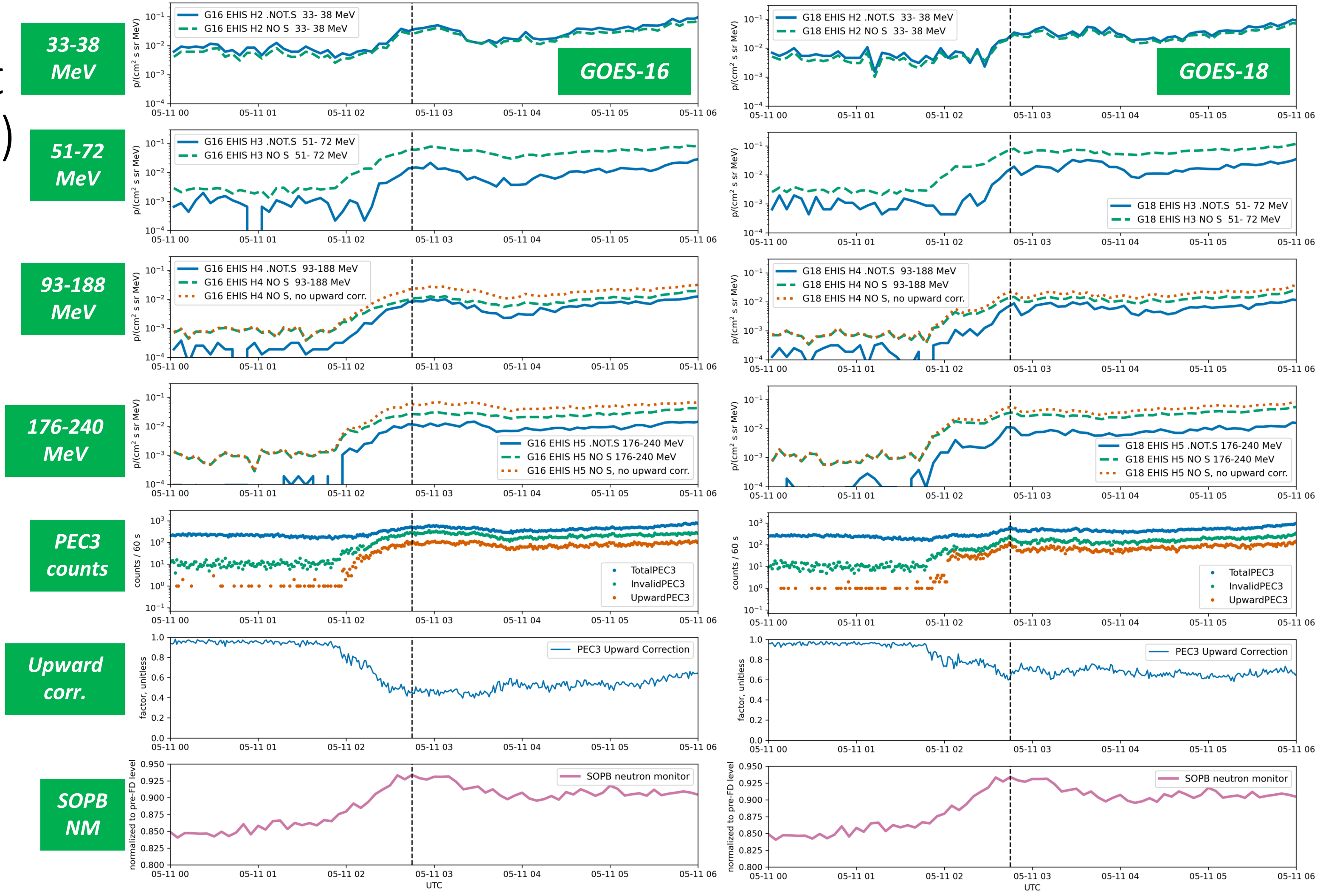
GOES-18 SGPS protons 09-13 May 2024



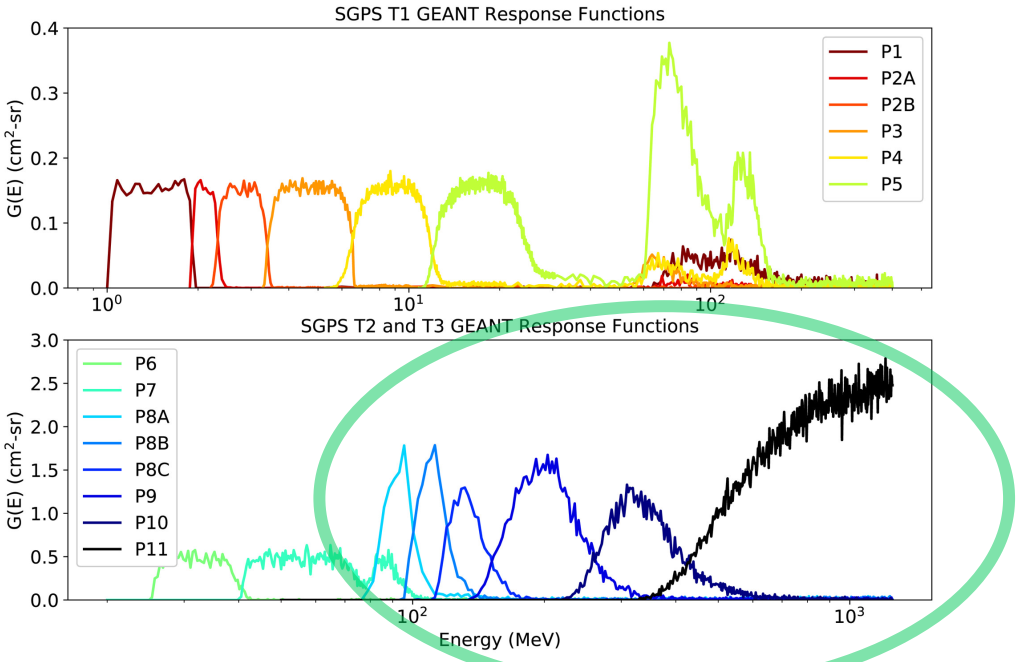
GOES-18 p+, NAIN and SOPB NM rates, 10 May 15UT - 11 May 12UT

GLE 74 onset (GOES, SOPB)

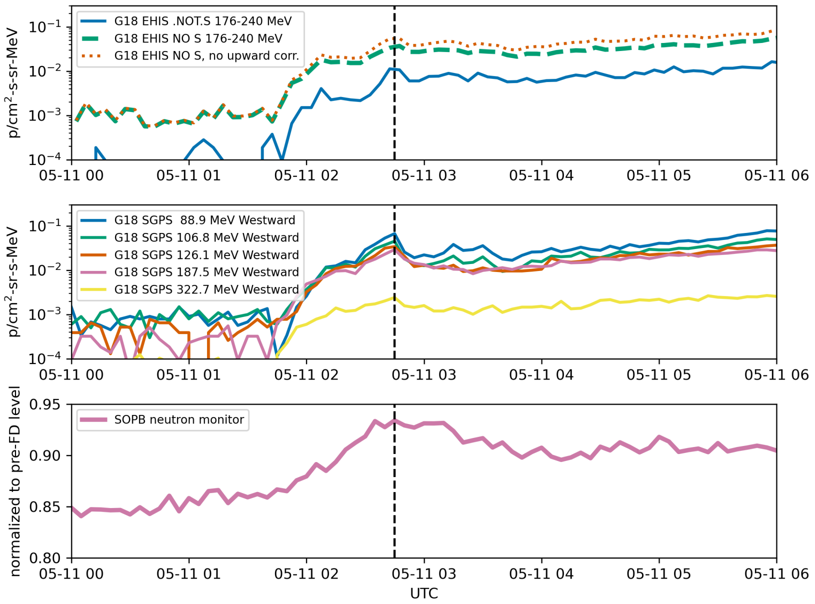
- Event onset more complicated than GLEs 75 and 76
- Initial maximum corresponding to SOPB GLE is present in GOES-16 and -18 .NOT.S fluxes -> in-band
- Presence of ‘spike’ in GOES-18 .NOT.S fluxes at 11 May 0245 UT during GLE suggests that it is in-band
- GOES-18 flux ‘spike’ is not evident at GOES-16: longitudinal difference?



G18 SGPS at GLE74 onset



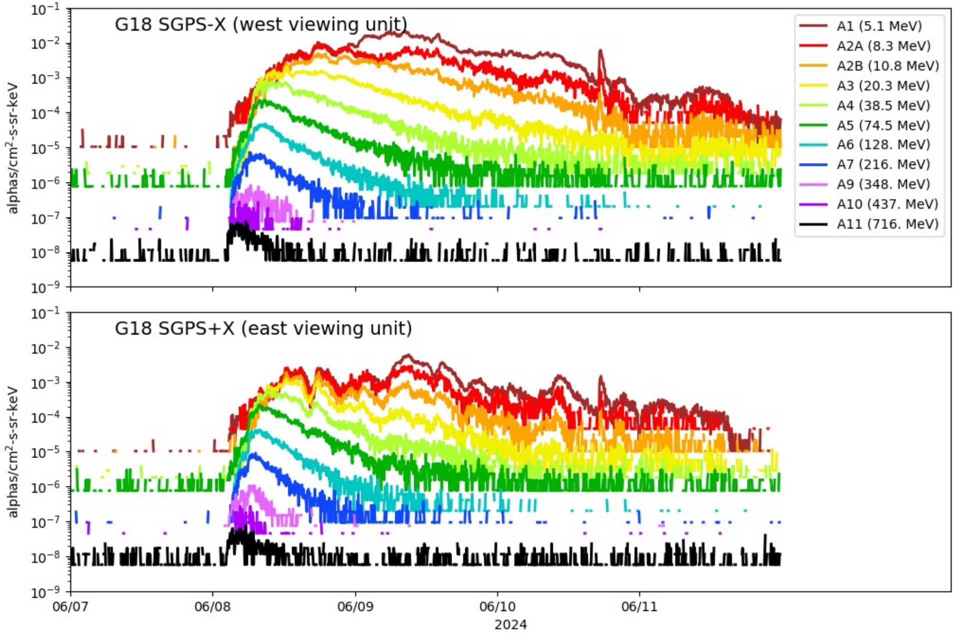
Kress et al., Space Weather, Volume: 19, Issue: 12, First published: 17 July 2021, DOI: (10.1029/2021SW002750)

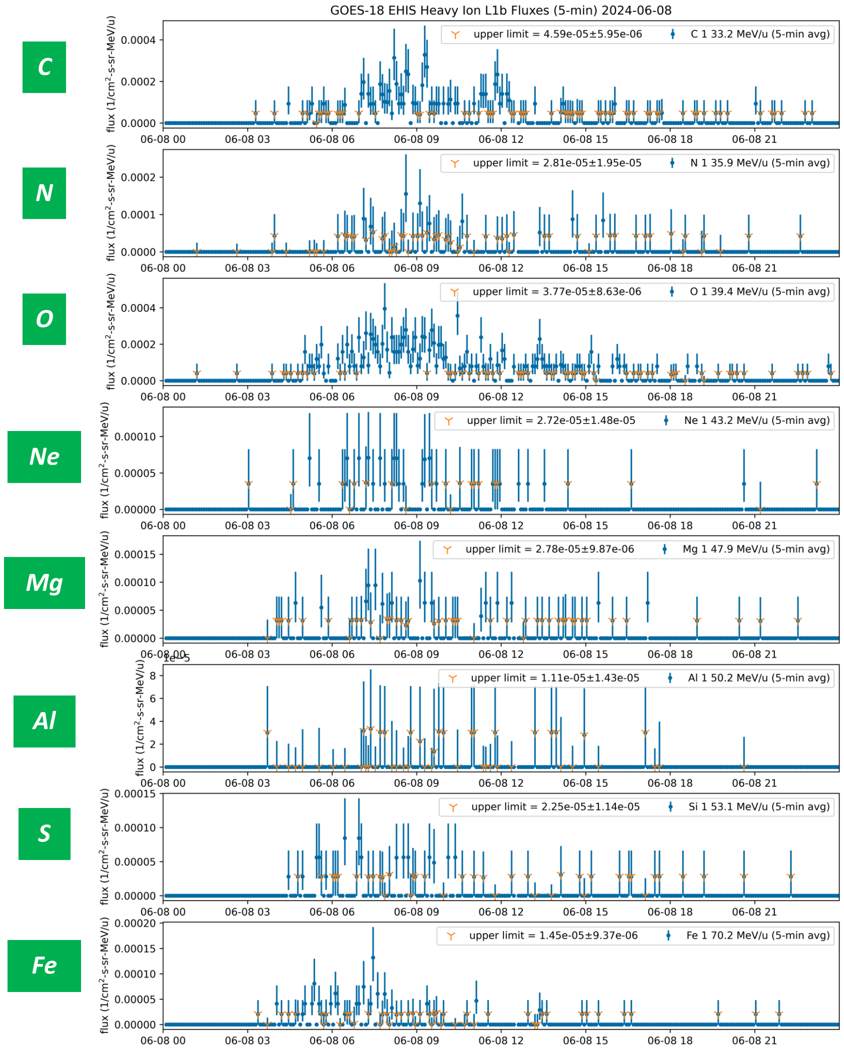


- P8A-P10 have very low out-of-band response up to 1 GeV
- This suggests that the ‘spike’ observed by GOES-18 P8A-P10 during the GLE is in-band, at least in part

GOES-18 Helium and Heavy Ion Fluxes, June 2024

GOES-18 SGPS helium-4 fluxes (5.1-716 MeV), 07-11 June 2024



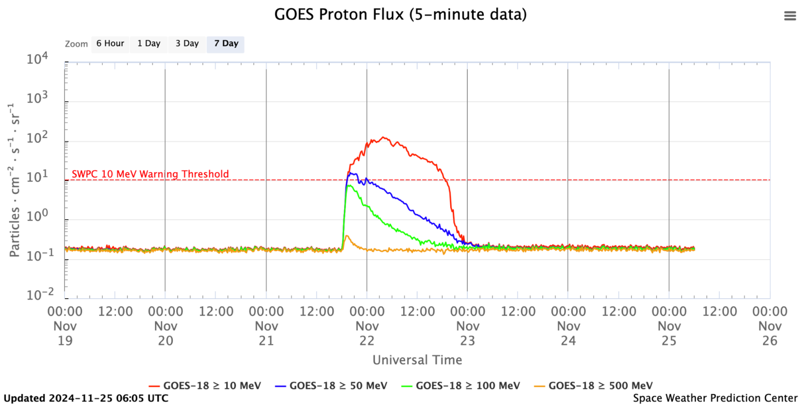


Issues in SGPS and EHIS data

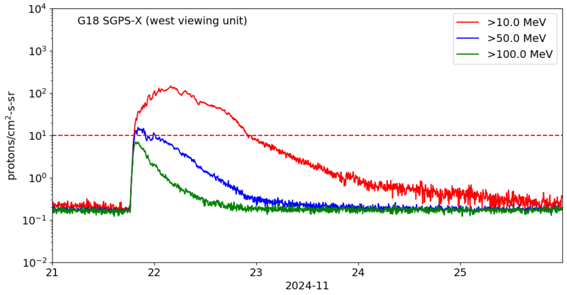
- SGPS anomalous channels
  - Temperature dependent channels
    - G16 SGPS-X P2A-P5, P8C-P11
    - G18 SGPS+X P8C-P11
  - Reporting low/high ($\gtrsim$ factor of 2)
    - G16 SGPS-X P4 reporting high
    - G17 SGPS+X P8C reporting high
    - G18 SGPS-X P8C and P9 reporting high
    - G18 SGPS+X P8C and P10 reporting low
    - G19 SGPS+X P8C reporting high
- EHIS anomalous channels
  - Proton and helium fluxes are low/high with respect to SGPS
    - EHIS to SGPS ratios: 0.15-3.5, energy & species dependent
    - Against our recommendations, HE1 and HE2 data are replaced with interpolated SGPS fluxes,
  - Some geometric factors need refinement (broad 'differential' flux channels)
  - Almost no .NOT.S (non-prime) real-time data (scintillator lit up by radiation belt electrons)
- SGPS alpha particle fluxes and EHIS data not yet available in real time
  - Planned to be released by NOAA SWPC in real time later this year

Problem with Proton Integral Fluxes in 2024

Operational integral fluxes from NOAA SWPC:



Corrected version, using NCEI in-house science/prototype code



- Due to an unexpected interaction between the integral flux calculation code and a too-long validity period (20 min) for L1b data arriving late, background removal function removed SEP fluxes
- Fixes in work:
  - *Retrospective:* Improved code developed to reprocess the integral fluxes at NCEI
  - *Real-time:* Shortened validity period and improved integral flux code currently under test at SWPC

Summary

- During 2024, three ground level enhancements (GLEs) were observed, with onsets on 11 May, 8 June, and 21 November.
- GOES-16 and -18 SGPS and EHIS observed proton fluxes during all three GLEs, and additionally GOES-19 (launched 25 June 2024) made observations during GLE 76.
- Onsets of GLEs 75 and 76 were similar in GOES proton fluxes
- Onset of GLE 74 was more complex - longitudinal structure was evident from comparisons of GOES-16 and -18
- EHIS active-anticoincidence scintillator shielding provides accurate observations of event onsets - this mode requires retrospective processing of raw proton counts
- SGPS alpha particle fluxes and EHIS heavy ion fluxes (C-Fe) are planned to be released by NOAA SWPC in real time later this year

Acknowledgments

- This work was supported by the NOAA Cooperative Agreement with CIRES, NA22OAR4320151
- We acknowledge the NMDB database (www.nmdb.eu) founded under the European Union's FP7 programme (contract no. 213 007), and the PIs of individual neutron monitors: Nain (University of Delaware Department of Physics and Astronomy and the Bartol Research Institute, USA), JangBogo (Chonnam National University, Department of Earth Science Education, South Korea), South Pole Bare (University of Wisconsin, River Falls, USA), Terre Adelie (Observatoire de Paris and the French Polar Institute IPEV, France)

GOES 16-19 SGPS Data Sources

- Real-time:
  - Plots: https://www.swpc.noaa.gov/products/goes-proton-flux
  - JSON format: https://services.swpc.noaa.gov/json/goes/
  - Alpha particle and heavy ion fluxes available soon from SWPC testbed
- Archive:
  - NetCDF4 format
  - Daily files of 1-s, 1-min and 5-min data
  - https://www.ncei.noaa.gov/products/satellite/goes-r

Selected contents of netCDF4 archive files:

```
netcdf sci_sgps-l2-avg5m_g17_d20220614_v3-0-0 {
dimensions:
        time = UNLIMITED ; // (288 currently)
        diff_channels = 13 ;
        sensor_units = 2 ;
        diff_alpha_channels = 11 ;
variables:
        double time(time) ;
                time:long_name = "Time stamp at the start of the
averaging period, in seconds since the J2000 epoch" ;
                time:units = "seconds since 2000-01-01 12:00:00" ;
                time:_FillValue = -1.e+31 ;
        float AvgDiffProtonFlux(time, sensor_units, diff_channels) ;
                AvgDiffProtonFlux:long_name = "Time-averaged proton
fluxes in several differential channels between 1 and 500 MeV." ;
                AvgDiffProtonFlux:units = "protons/(cm^2 sr keV s)" ;
                AvgDiffProtonFlux:_FillValue = -1.e+31f ;
                AvgDiffProtonFlux:valid_min = 0.f ;
                AvgDiffProtonFlux:valid_max = 8000.f ;
        float AvgIntProtonFlux(time, sensor_units) ;
                AvgIntProtonFlux:long_name = "Time-averaged proton
fluxes in the P11 >500 MeV integral channel" ;
                AvgIntProtonFlux:units = "protons/(cm^2 sr s)" ;
                AvgIntProtonFlux:_FillValue = -1.e+31f ;
                AvgIntProtonFlux:valid_min = 0.f ;
                AvgIntProtonFlux:valid_max = 6000.f ;
        float DiffProtonLowerEnergy(sensor_units, diff_channels) ;
        ...
        float DiffProtonUpperEnergy(sensor_units, diff_channels) ;
        ...
        float IntegralProtonEffectiveEnergy(sensor_units) ;
        ...
}
```

Data Access URLs and References

Reviews of GOES 16-19 cross-calibrations (PS-PVRs) [links at left: go to ‘SEISS’ tab]: https://www.noaasis.noaa.gov/GOES/product_quality.html

Archive of GOES 16-19 data: https://www.ncei.noaa.gov/products/satellite/goes-r

Reprocessed GOES 16 ‘GLE 72’ solar proton data (see also Kress+ 2021): https://www.ngdc.noaa.gov/stp/space-weather/satellite-data/satellite-systems/goesr/solar_proton_events/sgps_sep2017_event_data/.

Data questions: ncei.info@noaa.gov (please cc this address when communicating with the authors about data)

Connell, J. J., Lopate, C., & McKibben, R. B. (2001). The angle detecting inclined sensors (ADIS) system: measuring particle angles of incidence without position sensing detectors. Nuclear Instruments and Methods in Physics Research A, 457, 220-229. https://doi.org/10.1016/S0168-9002(00)00709-9

Dichter, B. K., Galica, G. E., McGarity, J. O., Tsui, S., Golightly, M. J., Lopate, C., & Connell, J. J. (2015). Specification design and calibration of the space weather suite of instruments on the NOAA GOES-R program spacecraft. IEEE Transactions on Nuclear Science, 62(6),2776–2783. https://doi.org/10.1109/TNS.2015.2477997

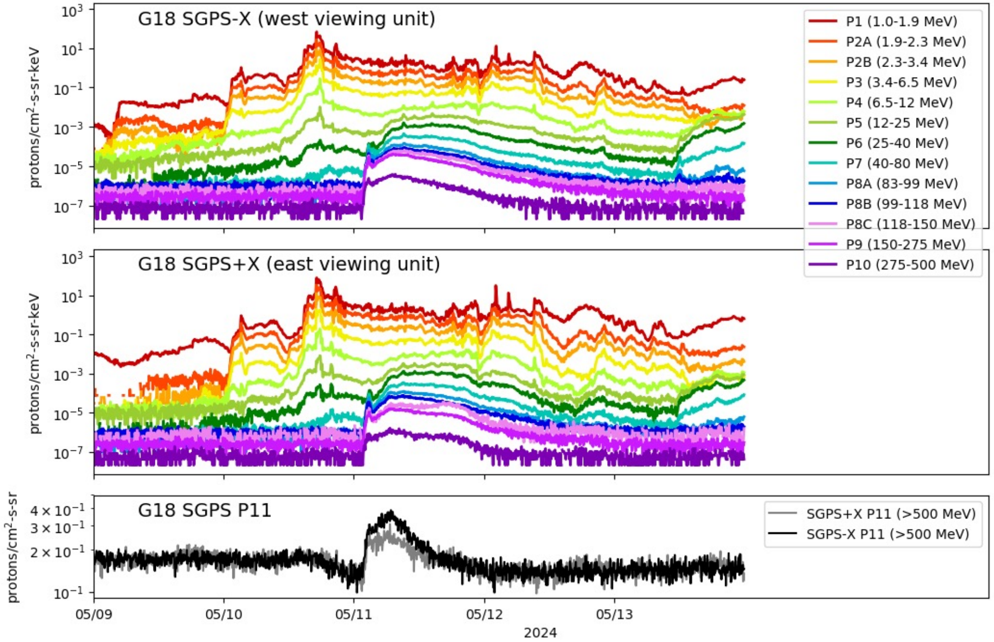
Kress, B.T., Rodriguez, J.V. & Onsager, T.G. (2020). The GOES-R space environment in situ suite (SEISS): Measurement of energetic particles in geospace. In *The GOES-R Series* (pp. 243-250). Elsevier.

Kress, B. T., Rodriguez, J. V., Boudouridis, A., Onsager, T. G., Dichter, B. K., Galica, G. E., & Tsui, S. (2021). Observations from NOAA's newest solar proton sensor. Space Weather, 19, e2021SW002750. https://doi.org/10.1029/2021SW002750

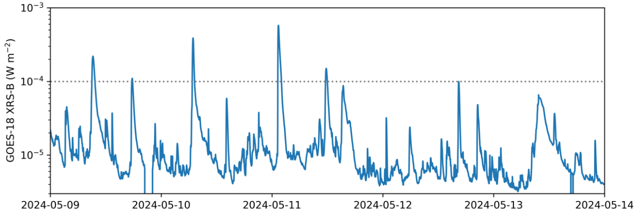
Plots in Response to Audience Questions

9-13 May 2024: solar X-ray irradiance, interplanetary magnetic field (IMF), solar wind dynamic pressure, and SYM-H geomagnetic storm index

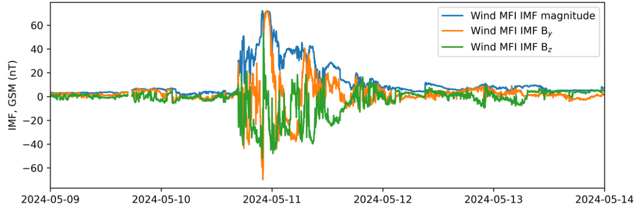
five X-class flares (>=1 x 10^{-4} W m^{-2})



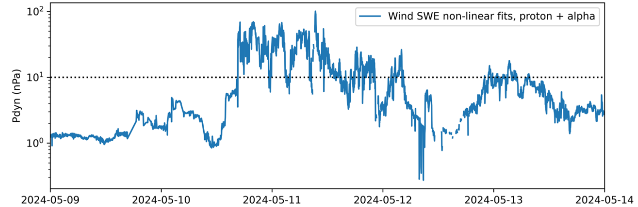
GOES-18 SGPS protons 09-13 May 2024



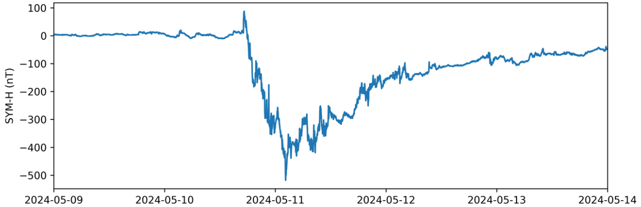
GOES-18 solar X-ray (0.1-0.8 nm) irradiance, 1-min averages



Wind IMF, GSM coordinate system



Wind solar wind dynamic pressure



SYM-H geomagnetic index

GOES-16 and -18 EHIS C, N, O, Fe Observations, 09-12 May 2024

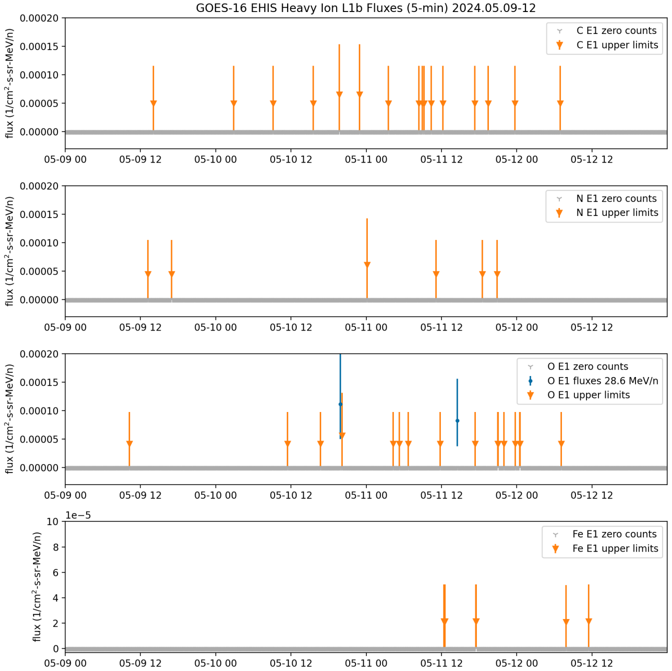
Almost all 5-min heavy ion observations during this event are 'upper bounds'

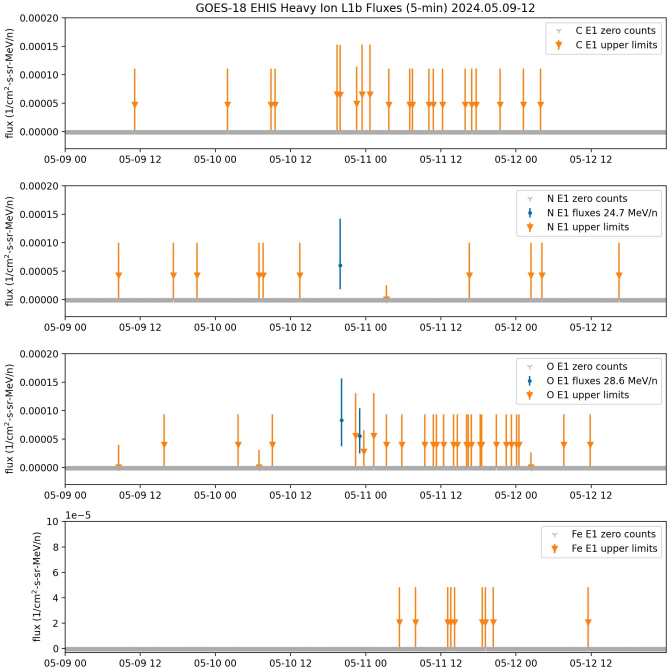
_C_

_N_

_O_

_Fe_





20.2 MeV/n

24.7 MeV/n

28.6 MeV/n

64.3 MeV/n

Iron fluxes were observed after GLE onset on 11 May c. 0200 UT at both GOES-16 and -18