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Solar Proton Transport to Earth

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ABSTRACT. Since 1976 the USA weather satellites named GOES, followed by a sequence number, have continuously monitored the Sun for proton emissions. The monitoring data is a valuable resource available online, but it is not being fully utilized. To encourage use, procedures are detailed for downloading GOES data to a Windows 10 computer with Excel software. Excel makes easy the calculation of proton velocity, pace, and rigidity given energy, which GOES registers in eleven channels from 2.5 to >700 MeV. Plots of pace versus time protons arrive at GOES are linear, zero pace is emission time, and line slope is proton path length. Proton flux at GOES is an indicator of neutron flux at commercial aircraft on polar routes, and dose to aircraft occupants is calculable from flux. January 2014 is chosen to demonstrate some uses of GOES data. Proton emission started on January 6 around 7:30, flux of 100 MeV protons began a sharp increase coincident with neutron monitor count rate increases causing GLE 72, and the emission continued for four days with several emission bursts. The January 8 burst (25-hr width at half max) is shown to cause >6 milli-Sievert dose at high-latitude flight levels. For perspective, Germany requires air crewmembers be grounded by that dose and have medical follow-up. In conclusion, GOES data cover 270 proton events during which there were 41 GLE, so January 2014 is a tip of the iceberg.

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1. Introduction

Satellites named GOES, followed by a sequence number, are a resource of the USA National Oceanic and Atmospheric Administration (NOAA) for monitoring space and terrestrial weather. Only GOES 13 and 15 are currently operational, but GOES have continuously monitored the Sun for proton emissions since 1976. The NOAA Space Weather Prediction Center (SWPC) evaluates GOES data and reports a solar proton event (SPE) when proton flux is significant. From 1976 to 2017 there were 270 SPE that caused 35 ground level enhancements (GLE). (Six more GLE had no reported association with SPE.)

GOES registers protons in 11 energy channels P1 at 2.5 MeV to P11 at >700 MeV. The data is a valuable resource for solar physics studies and air travel radiation safety, but it has not been fully utilized or understood. For example, Thakur et al. [1] say a P11 flux increase is typical of GLE, it increased 67% at GOES 13 on 6 January 2014 confirming the observation of GLE 72 at neutron monitor (NM) station SOPO, and flux was greater at GOES 13 than 15 at high energies.

GOES data say otherwise. The GLE started around 8:00, and from 7:15 to 9:15 the P11 flux did not exceed background plus 2σ at GOES 15 and only from 8:30 to 8:45 at GOES 13. Flux decreased with channel number from the maximum at P1 to P11 which was 200,000 times smaller. The GOES 15/GOES 13 fluxes averaged 1.06 ± 0.17 for all channels other than P2. But, 100 MeV proton fluxes at GOES 13 and 15 began increasing at the GLE start time, and that GOES data confirms the GLE 72 on 6 January 2014.

Polar-route flights have become common since starting in 2001. The USA Federal Aviation Administration (FAA) defines them as having any time beyond 78° N or 60° S, and it requires airlines flying those routes to mitigate dose during solar flare activity [2]. It reports estimated dose from galactic cosmic rays (GCR) for representative domestic and international flights [3], but not from SPE, and it has not changed the representatives since the first in 1990.

SPE proton create neutrons in air, and 72 kPa of air at NM SOPO did not shield tne NM from neutrons that caused GLE 72. Commercial planes cruise in air at 20 kPa, so some polar-route flights received a neutron dose on 6 January 2014.

Section 2 makes using GOES data easy by telling how to download it to a personal computer, Section 3 has characteristics of the solar protons transported to GOES, Section 4 demonstrates a GOES data use, and Section 5 concludes GOES data is valuable for solar physics, air travel radiation safety, and the understanding of GLE.

2. GOES Data

Space weather by GOES is at www.swpc.noaa.gov with charts of solar proton flux and more, but chart data is at http://satdat.ngdc.noaa.gov. Get data by selecting *GOES SEM Data Files→ new-avg,* pick a year, month, GOES number, and *csv* to display data files. Click a file name with *epead* for channels 1-7 or *hepad* for channels 8-11; e.g., *epead_p17ew_5m* or *hepad_ap_5m*. A file with *1m* or *5m* has data at 1-min or 5-min intervals, *ap* has alpha and proton flux, and *xrs* has X ray flux. Clicked files go to the computer download directory.

To work a download, open a new Excel file, select *Data→ Get External Data→ From Text*. Find downloads, highlight a GOES file there, click *Import→ Delimited→ Next→ Comma→ Next→ Finish*, and *Put Data in Existing Worksheet→ OK*. Create a folder named *GOES Data* and save the file to it using the file name in cell A1, but for easy retrieval, name it by year, month, GOES number, data type, and count time. For example, 2014 01 g15 hepad 5 min.

The first few hundred rows of column A have important descriptive information, and below them is the header *time-tag* for 288 or 1,440 rows at each day in the month. Data headers are on the time-tag row typically with four columns for each proton channel. Copy header row and rows for days of interest to a new sheet. Find any rows with −9999 for missing data and remove the −9999s. Insert scatter chart of time and "corrected flux" columns for an overview. Copy columns of interest with time-tag and headers to new sheets for analysis using more scatter charts.

3. Solar Protons at GOES

Energy (E) of an atomic particle is related to its mass (m) by the expression $E = (\gamma - 1)mc^2$ where γ is the Lorentz factor and c is light speed. Table 1 is an Excel sheet with solutions to the expression in cells E7- H17 for the characteristics of protons with E of the GOES channels. To help others, A7-A14 have text versions of formulas in E7-H7 that use constants in B1-B3.

	A	B	C	D	E	F	G	H
1	Light Speed	299,792.46	km s^{-1}					
2	Astrnomical Unit	149,597,870.70	km					
3	Proton Mass	938	MeV					
4								
5			Channel	Energy	Velocity	Pace	Rigidity	Lorentz
6				(MeV)	(km/s)	(min/AU)	(GV)	
7	**Velocity**		P1	2.5	21,844	114	0.07	1.003
8	=SQRT((1-($B$3/($B$3+D7))^2))*$B$1		P2	6.5	35,111	71.0	0.11	1.007
9	**Pace**		P3	11.6	46,716	53.4	0.15	1.012
10	=$B$2/E7/60		P4	30.6	74,760	33.4	0.24	1.033
11	**Rigidity**		P5	63.1	104,751	23.8	0.35	1.067
12	=SQRT(H7^2-1)*$B$3/1000		P6	165	157,728	15.8	0.58	1.18
13	**Lorentz**		P7	433	218,645	11.4	1.00	1.46
14	=1/SQRT(1-E7^2/$B$1^2)		P8	375	209,778	11.9	0.92	1.40
15			P9	465	222,941	11.2	1.04	1.50
16			P10	605	238,038	10.5	1.23	1.64
17			P11	700	245,770	10.1	1.34	1.75

Table 1. Excel sheet with characteristics of solar protons transported to GOES channels P1-P11. A7-A14 have text versions of formulas at E7-H7 that use constants at B1-B3 to calculate the characteristics at E7-H17..

The E in Table 1 are from early calibrations made at ground level that gave channels with varying widths plus a representative E for each channel. Channels P1-P7 on operational GOES were calibrated recently relative to proton detectors on other satellites [4]. The calibrations are named here as Eg for ground and Es for space. The Es P1-P7 values are 2.5, 6.0, 11.6, 24.5, 56.6,115, and 287 MeV. NOAA has not endorsed the Es.

4. Using GOES Data

January 2014 is picked to demonstrate GOES data use. Figure 1 plots NM SOPO count rates and GOES 13 and 15 channels P5 and P6 fluxes on January 6. Only P5 and P6 had flux increases near the GLE start. All data are at 5-min intervals, and backgrounds were made the average rate or flux from 2:00 to 6:00. The NM count rate rose above background plus 2σ at 8:10 and remained continuously above until 10:35. Significant flux increases began for GOES 13 and 15 P5 at 8:10 and 8:15, respectively, and P6 at 8:05. GOES data support the reality of GLE 72 and with an 8:10 start time.

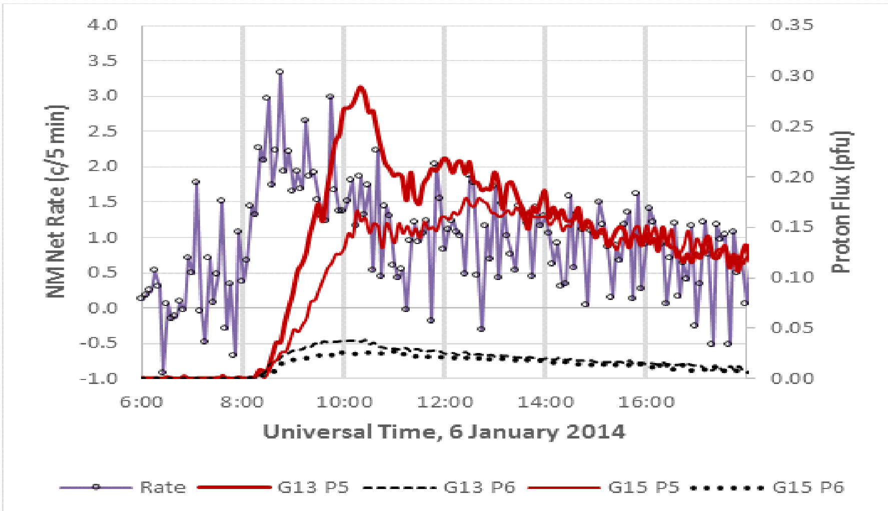

Figure 1. Count rates at NM station SOPO and proton fluxes at GOES 13 and 15. The NM and GOES 13 P5 registered significant increases at 8:10; at 8:15 for GOES 15 P5 and 8:05 for both GOES P6. GLE 72 is real and with an 8:10 start by 5-min data.

The Eg and Es for channel P5 is 63.1 and 56.6 MeV; for P6 it is 165 and 115 MeV. The range is 56.6 to 165 MeV, so "100 MeV" is adopted to represent the solar protons of Figure 1. There is <1 sec time difference between the arrival of protons at GOES and neutrons >10 MeV at NM. By flux and counts at 5-min intervals, GLE 72 started at 8:10 due to neutrons created by 100 MeV solar protons.

SWPC reported a GOES detection of SPE protons on 6 January 2014 when the sum of fluxes from all channels >10 MeV exceeded 10 pfu. (A pfu is proton flux unit and is 1 proton/cm²/s.) The flux increase started at 9:15, reached a maximum of 42 pfu at 16:00, decreased but remained above 10 pfu, and rose to a second maximum of 1,033 pfu at 3:40 on January 9. SWPC does not report SPE durations but says they end when the integral flux drops below 10 pfu. Time from start to first and second maxima were 6.8 and 66.3 hours.

The GOES differential energy data tell a different story. Each proton channel had one or more flux peaks of different start time and magnitude, and they indicate two overlapping SPE with different start and end times. Plots of flux vs. time give peak maximum flux, full width at half maximum (FWHM), and time of maximum. SPE 1 duration from its start to the start of SPE 2 was 36 hours, and SPE 2 lasted more than 50 hours .

Table 2 has characteristics of SPE 1 to the left and SPE 2 to the right. Channels P8-P11 are excluded as their fluxes were too small to yield meaningful measures. The SPE 1 and 2 average FWHM are 10 and 16 hours; their total fluxes are 57 and 2,258 pfu. SPE 2 was 40 times more intense based on flux.

Channel (P#)	FWHM (hr)	Peak Time (m/d/y h:m)	Flux (pfu)	FWHM (hr)	Peak Time (m/d/y/ h:m)	Flux (pfu)
P1	12	186810 20:00	50	22	1/10/14 0:05	1600
P2	11	1/6/14 16:00	3	10	1/9/14 7:00	500
P3	8	1/6/14 15:00	2.5	25	1/8/14 21:15	120
P4	18	1/6/14 19:00	1.2	26	1/8/14 16:00	35
P5	12	1/6/14 15:20	0.18	8	1/8/14 3:00	2.5
P6	8.6	1/6/14 13:00	0.028	11	1/8/14 2:25	0.045
P7	4.4	1/6/14 11:00	0.009	8.3	1/8/14 1:15	0.01

Table 2. Features of proton flux peaks at GOES energy channels P1 to P7 during SPE in January 2014. SPE 1 are columns 2-4 and SPE 2 are columns 5-7.

Charts were made of pace vs. time-of-day when SPE 1 protons first reached GOES 13 and 15, and separately for Eg and Es. Channels P1 and P11 were not included as P1 had too many peaks and P11 had none. The charts say solar emission time was 7:33 (Eg) and 7:23 (Es) by GOES 13 and 7:36 (Eg) and 7:27 (Es) by GOES 15. The average is 7:30 ± 5.2 min. Path lengths were 1.40, 1.47, 2.25, and 2.34 AU. Similar charts were made for SPE 2 and GOES 15 channels P1-P7. Emission started January 7 at 18:25 (Eg) or 18:20 (Es) with path lengths 3.73 or 3.80 AU. SPE 1 ended on January 7 around 19:25 to 20:15 when SPE 2 began.

SPE proton emission times are important for solar physics, but other SPE features like energy, flux, and duration are of concern to air travel radiation safety. The potential for highest doses lies with long-lived high flux SPE and long-haul high-latitude flights such as New York-Shanghai and New York-Beijing. One USA airline operates those flights daily in both directions with flight times around 13 to 15 hours.

Dose estimates can be the product of exposure time, flux, and a fluence-to-dose coefficient. Exposure could be 10 hours on 8 January 2014 as flight times and flux FWHM are much longer, but some of the flight time is at lower latitudes and flight levels. A 5-hr exposure is adopted here for dose estimates, and those hours are from 11:00 to 16:00.

Dose estimates normally employ coefficients for an anterior-to-posterior (A-P) exposure geometry [5], but an isotropic geometry is recommended with GCR at flight levels [6]. By digitizing plots in those references, neutron dose coefficients with pSv cm^2 units are 470 ± 3% (A-P) and 345 ± 6% (isotropic) from 10 to 165 MeV. (The relative errors are by the mean of 13 samples and 1σ uncertainty.) Arguments can be made for and against both coefficients, so both coefficients are used and two estimates are given.

Neutron flux at polar flight levels derives from solar proton flux above the polar atmosphere. GOES channels P3-P6 (10 to 165 MeV) are chosen to represent the proton flux. Other channels are neglected because of low energy or low flux. No evidence is given for the polar flux to equal the P3-P6 flux, and it would be larger if GOES registers protons of rigidity >0 GV. As a single dose coefficient applies for the energy range, fluxes at channels P3-P6 are summed without weights. The neutron flux must be less than proton flux, and it is set at 20% of the P3-P6 sum for flight levels. No evidence is given for this percentage, but, neutrons from SPE 1 caused GLE 72, and proton flux was 40 times greater with SPE 2.

The two dose estimates are 10 and 7.3 mS for high latitude commercial flights on 8 January 2014, using P3-P6 fluxes averaged for GOES 13 and 15 and other factors stated above. Significantly, the main dose contributor was P3, then P4, and so on as that is the order of decreasing flux, and the dose coefficients were constant over the P3-P6 energy range. But, dose coefficients rise sharply with further energy increases, so the contribution from channels >P6 may be significant with other SPE. Surprisingly, dose was not due to GeV protons.

5. Conclusion

Protons have been transported from the Sun, on 270 occasions since 1976, to the GOES satellites where their energy and flux are measured, or they proceed into the atmosphere and create neutrons that cause radiation dose at flight levels or GLE at NM. The proton data accumulated at GOES is online and easily downloaded to a personal computer with spreadsheet software. GOES X ray data can be included to associate with the proton data. Proton pace is a parameter first used here to determine solar proton emission time and proton path length. GOES and NM data were combined to confirm the reality of a very weak GLE, and more importantly, specific proton energy channels were associated with NM count history. There are 35 SPE-GLE connections, and the approach could be applied with them to learn more about GLE. The example GOES data use had two SPE, and by creating multiple spreadsheet scatter charts for all GOES channels, new SPE features emerge, including arrival times, flux peaks, FWHM, maximum fluxes, and SPE durations. One of the two SPE was intense throughout January 8 and may have caused dose >6 mSv to aircraft on long-haul high latitude flights. GOES data could be used to reconstruct doses for many of the SPE, but a key factor that needs resolution is neutron flux at flight levels and NM relative to proton flux at GOES. Ultimately, SWPC might generate dose estimates as SPE are occurring for the benefit of air travelers.

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