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Calibration of the GOES 6–16 high-energy proton detectors based on modelling of ground level enhancement energy spectra

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Abstract—For several decades, the Geostationary Operational Environmental Satellites (GOES) series have provided both real-time and historical data for radiation exposure estimation and solar proton radiation environment modelling. Recently, several groups conducted calibration studies that significantly reduced the uncertainties on the response of GOES proton detectors, thus improving the reliability of the spectral observations of solar energetic particle events. In this work, the long-established Band function fitting set for past ground level enhancements (GLEs) and their recent revision are used as references to estimate the best matching energies of proton channels of GOES 6–16, with emphasis on comparing with previous calibration studies on the high energetic proton measurements. The calculated energies for different missions in the same series (GOES 8, 10, 11) show overall consistency but with small variations, and differences among missions of different series are noticeable for measurements crossing the past three solar cycles, though the results are sensitive to the method used to subtract background fluxes. The discrepancy and agreement with previous calibration efforts are demonstrated with other independent analyses. It is verified that the integral channel P11 of GOES 6–16 can be reliably used as a differential proton channel with an effective energy of about 1 GeV. Therefore, the multi-decade in situ measurements of the GOES series can be utilized with more extensive energy coverage to improve space radiation environment models.

Keywords: solar energetic particle / modelling / space radiation environment / space weather

1 Introduction

Solar particle events (SPEs) occur following the approximate 11-year solar cycles but are highly episodic and almost unpredictable. While most events are small in scale, some large events involve fluxes of energetic protons elevated over a background by orders of magnitude for a period of several hours to a few days (Smart & Shea, 1985), which represent a major health threat to the crew of space exploration missions travelling beyond the protection of the Earth's geomagnetic field. Even for the current state-of-the-art crew vehicles such as the Orion multi-purpose crew vehicle (MPCV), particles with energies > 100 MeV are still of concern, as they can penetrate the thick shielding, induce energetic secondary particles, and deliver hazardous radiation doses to astronauts in a short time frame (Hu et al., 2020). To investigate the properties of these energetic particles and probe the possible mechanism of their origin, acceleration, and transport in interplanetary space, multiple instruments have been deployed at various locations in the

heliosphere, among which the series of Geostationary Operational Environmental Satellites (GOES) are widely used for radiation exposure estimation (Atwell et al., 2009; Hu et al., 2016) and solar proton radiation environment modelling (Xapsos et al., 2000, 2004; Jiggins et al., 2014). These multi-decade measurements provide a standard source of both real-time and historical information on the characteristics of SPEs (Sandberg et al., 2014).

Historically, the recorded GOES proton fluxes were used with fixed energies derived from ground laboratory calibrations (Smart & Shea, 1999), and with a delicate algorithm to remove the time-variant background and higher energy particle contamination in lower energy proton channels (Rodriguez et al., 2017). The processed data based on ground calibration involve uncertainties due to the implicit difference between in situ environment and ground particle beams. Because the GOES proton channels are broad in energy and relatively few, such uncertainties may have significant impacts on the past and ongoing investigations associated with the characterization of the solar proton radiation environment. In recent years, several groups conducted cross calibrations between GOES and other space-borne

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particle detectors. In the work of Sandberg et al. (2014) (hereafter referred to as S14), the energetic particle sensors (EPS) measurements of GOES 5, 7, 8, and 11 were compared with NASA IMP-8/Goddard medium energy (GME) experiment data set, and the proton energies derived for the P2–P7 channels (also known as solar energetic particle environment modelling (SEP-EM) energies) were significantly lower than the nominal energies obtained through ground calibration (Onsager et al., 1996). In a later work by Bruno (2017) (hereafter referred to as B17), using the high-energy particle measurements of the payload for antimatter matter exploration and light-nuclei astrophysics (PAMELA), a set of effective energies were determined for the proton channels of the P6, and P7 and the high energy proton and alpha detector (HEPAD) P8–P11 sensors onboard GOES 13 and 15. More recently, Raukunen et al. (2020) (hereafter referred to as R20) reported a comprehensive bowtie analysis of the HEPAD proton channel energy responses measured in an energetic proton beam. All these studies help reduce the uncertainties on the proton intensities provided by GOES instruments, greatly improving the reliability of the differential energy spectra measured during SPEs.

Among these recorded SPEs, there is a subset of events called ground level enhancements (GLEs), involving sufficiently high numbers of energetic particles reaching the atmosphere of the Earth and producing showers of secondary particles all the way to the ground-based level. Since 1942, 72 GLEs have been observed by ground detectors such as the worldwide neutron monitor (NM) network and documented in public station websites and online archives. Because only particles with energies higher than the geomagnetic rigidity cutoff can break through the earth-bound magnetic field and be detected at a specific location, the NM database can be used to derive the spectra of past GLEs (Tylka & Dietrich, 2009), which provide an alternative resource to verify the proposed effective energies of proton channels for GOES data. The combination of the NM data with multiple satellite measurements helps to extend the proton spectra of GLEs to energies ranging from 10 MeV to 10 GeV, well covering the energies of protons recorded by EPS and HEPAD of the multi-decade GOES missions (Raukunen et al., 2018). Recently, the high energy section (>1.5 GV, ≈ 831 MeV) of these spectra were refined by correcting the variable galactic cosmic rays (GCR) background and using an improved neutron-monitor yield function (Usoskin et al., 2020; Koldobskiy et al., 2021).

This work reports our investigation on the effective energies of both EPS and HEPAD proton channels of GOES 6–15 by comparing event-integrated spectra with GLE spectra fitted from NM data and multiple satellites data. With the same technique, the modelled spectra of the latest GLE (2017-09-10) are used to estimate the effective energies of the new GOES solar proton channel set for GOES 16 (including P11), which are substantially different from the detectors of GOES-15 and prior missions. In Section 2, we describe the formalism of the two modelling approaches. The GOES data used in this work are overviewed in Section 3, and the techniques to derive the

effective energies by using spectra of GLEs are summarized in Section 4. In Sections 5 and 6, these energies are reported and juxtaposed with those derived in the works of S14, B17 and R20, and possible reasons leading to the discrepancies are discussed.

2 GLEs spectra

Using NM data and data from multiple satellites, Tylka and colleagues derived event-integrated proton spectra for 59 of 67 GLEs occurring between 1956 and 2012 (Tylka & Dietrich, 2009; Raukunen et al., 2018). The other 8 events have too few NM counts to be reliable for fitting. The satellites utilized include IMP-8, ACE, GOES, SAMPEX, STEREO (Tylka & Dietrich, 2010), and the NM stations have cutoff rigidities ranging from 1 to 10 GV (≈ 433 MeV to 9.1 GeV) (Tylka & Dietrich, 2009). Raukunen et al. (2018) summarized the event list and the modelling parameters for a universal Band functional form:

See the Equation (1) bottom of the page

here $J(>R)$ is the omnidirectional event-integrated integral fluence in units of cm^{-2} , J_0 is an overall fluence normalization coefficient, γ_1 is the low rigidity power-law index, γ_2 the high rigidity power-law index and $(\gamma_2 - \gamma_1)R_0 \equiv R_b$ is the breakpoint rigidity. The Band function is constructed in such a way that both the function and its first derivative are continuous. This double power-law function has been shown to approximate well the proton and heavy-ion spectra of large SEP events measured by instruments on the ACE, SAMPEX, SOHO, and GOES spacecraft (Desai & Giacalone, 2016), and can be theoretically explained by shock acceleration (Desai & Giacalone, 2016) and interplanetary transport effects (Li & Lee, 2015; Zhao et al., 2016).

However, the assumption of a constant GCR background during GLE events is not always valid. A recent work (Usoskin et al., 2020) showed that, in addition to the relatively slow solar-cycle modulation, GCRs sometimes experience short-time variability due to interplanetary transients and local anisotropy. Applying a smooth temporal variability, they computed the detrended GCR intensity for each event and for each NM station (Usoskin et al., 2020). Combining with revised GOES proton fluences with rigidity below 1 GV and other data resources, Koldobskiy et al. (2021) obtained a new set of modelling parameters for historical GLEs with a modified Band function (MBF):

$$\begin{aligned} J(>R) &= J_1 R^{-\gamma_1} \exp\left(-\frac{R}{R_1}\right), & \text{if } R \leq (\gamma_2 - \gamma_1)R_0 \\ &= J_2 R^{-\gamma_2} \exp\left(-\frac{R}{R_2}\right), & \text{if } R > (\gamma_2 - \gamma_1)R_0 \end{aligned} \quad (2)$$

$$\begin{aligned} J(>R) &= J_0 R^{-\gamma_1} \exp\left(-\frac{R}{R_0}\right), & \text{if } R \leq (\gamma_2 - \gamma_1)R_0 \\ &= J_0 R^{-\gamma_2} \left\{ [(\gamma_2 - \gamma_1)R_0]^{(\gamma_2 - \gamma_1)} \exp(\gamma_2 - \gamma_1) \right\}, & \text{if } R > (\gamma_2 - \gamma_1)R_0 \end{aligned} \quad (1)$$

where parameters γ_1 , γ_2 , R_1 , R_2 , and J_2 are defined by fitting, and other parameters can be calculated as,

$$\begin{aligned} R_0 &= R_1 R_2 / (R_2 - R_1), \\ J_1 &= J_2 [(\gamma_2 - \gamma_1) R_0]^{(\gamma_2 - \gamma_1)} \exp(\gamma_2 - \gamma_1). \end{aligned} \quad (3)$$

This MBF keeps the feature that both the function and its first derivative are continuous but has a roll-off at higher energies than the original Band function (Koldobskiy et al., 2021). The major improvement of this revision is a 2–4 times increase in the integral fluences for most events in the rigidity range of 1.5–4 GV (kinetic energy 831 MeV–3.17 GeV) (Usoskin et al., 2020).

Table A.1 lists the GLE spectral parameters used in this work, as well as their onset time, duration, and the spacecraft that observed them. This is compiled from the works of Raukunen et al. (2018) and Koldobskiy et al. (2021). For Band function analysis, some events such as GLEs 42 and 43 were treated separately for their initial GLE and following energetic storm particle components (Raukunen et al., 2018), and two sets of parameters are presented in Table A.1. Some events such as GLE 54 are too weak to be analyzed through the MBF approach and are excluded in our analysis.

3 GOES data

The first GOES, after its two precursor spacecraft SMS1–2, was launched in October 1975, and the most recent one, GOES-17, in March 2018. While EPSs were on GOES 1–15 (it is called energetic proton, electron and alpha detector (EPEAD) on GOES 13 and 15), HEPAD flew only on GOES 4–15. Apart from the redesign of one detector for GOES 8 (launched on 13 April 1994), the EPS has not changed since GOES 4 (launched on 9 September 1980). Each EPS (or EPEAD) system comprises one telescope and three dome detectors, which together report seven proton channels with ground calibrated energies ranging from 0.74 to 900 MeV, as well as electron and alpha particle channels (Panametrics Inc., 1995). Each HEPAD system consists of two silicon detectors and a Cherenkov detector in a telescope configuration. It observes high energy protons in four energy channels above 350 MeV and alpha particles in two energy channels above 2560 MeV (Sellers & Hanser, 1996). On GOES 16 and 17, a pair of solar and galactic proton sensors (SGPS) measure 1–500 MeV proton fluxes in 13 logarithmically spaced differential channels (P1–P10) and >500 proton flux in a single integral channel (P11) (Kress et al., 2020).

All EPS and HEPAD proton fluxes are archived and publicly accessible at National Centers for Environmental Information website (<https://satdat.ngdc.noaa.gov/sem/goes/data/avg/>) in CSV and netCDF formats. There are two types of differential fluxes for each channel of EPS, one uncorrected (raw data) and one corrected with a Zwickl algorithm (Rodriguez et al., 2017). The main purpose of using this algorithm is to calculate integral flux from the channel fluxes, the energies of each having finite lower and upper bounds according to ground proton beam calibration. In addition, because the detectors are built with passive shielding (no anticoincidence system) and measurements are affected by significant side and rear-penetration effects, this

algorithm also corrects for high energy contamination of lower energy channels (Bruno, 2017). Although the HEPAD channels only have uncorrected data, there is guidance to remove the high energy proton contamination from out-of-acceptance particles (especially rear-penetration effects) (Smart & Shea, 1999). Particularly, the integral channel P11 (>700 MeV) data can be processed as a differential channel with energy integrated geometrical factor $\int G(E)dE = 1565 \text{ cm}^2 \text{ sr MeV}$ and effective energy of 1000 MeV (Smart & Shea, 1999; Hu et al., 2016). In this work, we follow the procedure of Bruno (2017), use both the uncorrected and corrected EPS proton fluxes and uncorrected HEPAD fluxes directly to derive the event-integrated spectra, and estimate the matching energies of each channel by comparing with the two sets of spectra of historical GLEs described in Section 2.

4 Data analysis

The first GLE observed by GOES HEPAD was GLE 39 (February 1984), and the most recent one was GLE 72 (September 2017), involving GOES 5–16. Since GOES 5 and 7 did not provide HEPAD data, and the measurements of GOES 9, 12, and 14 overlapped with other satellites, in this work, we focus on the analysis of proton data provided by GOES 6, 8, 10, 11, 13, 15, and 16. Combined with data recorded by EPS, HEPAD, and SGPS, a contiguous and uniform dataset of solar proton fluxes encompassing energies from several MeV to about 1 GeV can be developed for the time period of 1986–present if a consistent effective energy set can be determined and validated for the proton detectors onboard these spacecraft.

To get event-integrated spectra, it is important to choose the right timestamps for event onset and end. The onset times of these GLEs were reported in Raukunen et al. (2018), however, their durations were not well defined in the literature. To make the comparison with the two sets of GLE modelling consistent for this multi-decade data set, we used fluxes from channel P6 to define the end of an event by checking if it falls below the pre-event background for 24 h. The durations we determined for the GLEs analyzed in this work are reported in Table A.1. SPEs are known to involve many different physical processes to produce large amounts of charged particles in interplanetary space (Desai & Giacalone, 2016). Protons with higher energies usually arrive earlier than those with lower energies in the near-Earth environment, as they are faster than their lower energy counterparts and less affected by the interplanetary medium and heliomagnetic field (Miroshnichenko, 2018). They also fall back to the background earlier, as shown in Figure 1 for one typical GLE. Channel P6 was chosen because of its similar dynamical pattern to channels of higher energies protons (Fig. 1). If channels of lower energy protons such as P2 were chosen, the duration of this event would be much longer, and the integrated event fluence at higher energy channels may contain substantial uncertainties due to various effects, such as a Forbush decrease (FD), which is a sudden suppression of the GCR intensities caused by interplanetary transients like a coronal mass ejection driven interplanetary shock (Usoskin et al., 2020).

Because such FDs can cause a variable background flux, it is also tricky to select a period to calculate the background to be

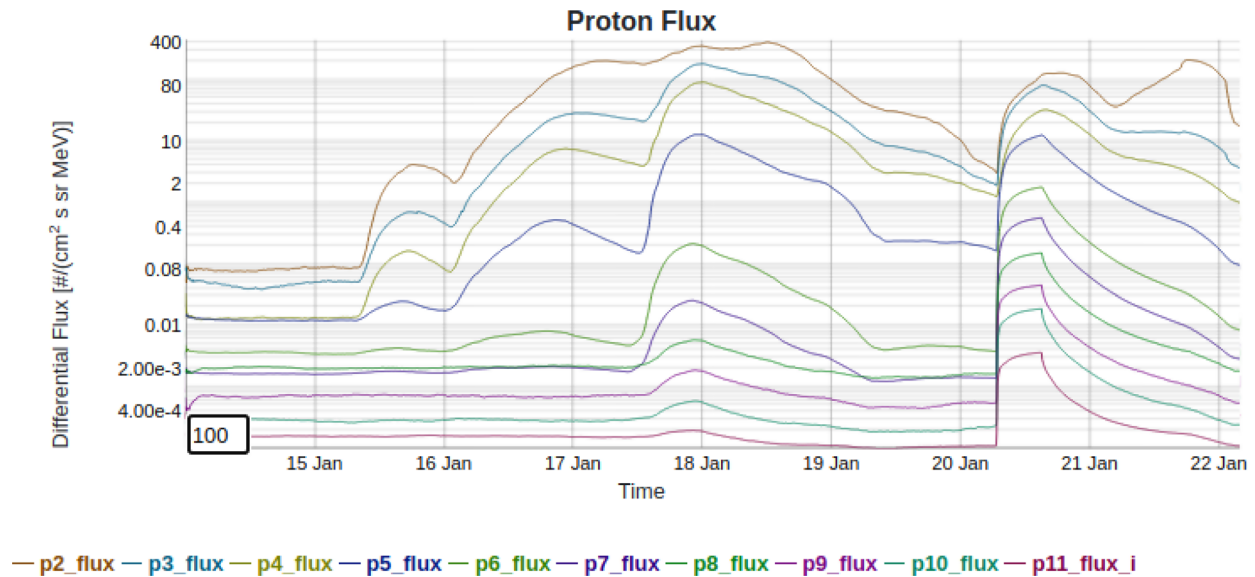


Fig. 1. Background proton fluxes are not constant – Forbush decrease observed by GOES 11 before the 2005-01-20 event. In the higher energy channels P8–11, the background fluxes on January 19 and the start of the 20th are suppressed compared to the background levels observed on January 17 and the days prior. Dygraph was used with a rolling average of 100 points from the uncorrected 5-min averaged flux.

removed from the event-integrated fluence, especially if the FDs occur in combination with one or more SPEs before a GLE. For the 2005-01-20 GLE depicted in Figure 1, before the onset on January 20, the fluxes of HEPAD channels were suppressed after the brief elevation in January 17–18, however, the fluxes of P2–P5 were still above the background before the pre-event starting on January 15. If a period before the pre-event is used, after subtracting the background, the event-integrated fluences of the HEPAD channels would be lower than those calculated with a background using a period just before the GLE (i.e., on January 19). Because, in most events, the fluences of these high energy channels are usually much lower than those of lower energy channels, such treatment would cause a significant reduction of the spectral index in this energy range and make the comparison with GLE modelling less accurate. In the development of two sets of GLE modelling described above, the Band functional set was based on the assumption of constant background, while the MBF set was based on variable background due to interplanetary transients and local anisotropy (Usoskin et al., 2020). Therefore, in this study, we chose a period of 24 h immediately before the onset of the GLE to calculate the background flux for each channel for the comparison with the MBF set and chose a period of 24 hours 7 days before the onset to get background flux for the comparison with the Band function set. If the fluxes at these times are still higher than the background due to the occurrence of one or more pre-events, the times used to calculate the background are pushed days earlier before the pre-events.

We used an in-house software WASPE (web app for solar particle events), to obtain background-subtracted event spectra for each GLE. All available 5-min averaged proton data from GOES 6 at NOAA SWPC website were downloaded and stored locally, which can be retrieved at any time from 1984 to the present. The plotting library dygraphs (<https://dygraphs.com/>) was used to visualize flux variation in time and rendered a spectrum of the selected period. This tool allows zooming the plots either

horizontally or vertically, which is useful to examine the details of the records and results. Another good feature of it is to display information of each data point by just hovering over it with the mouse cursor, which is very helpful to determine the onset and end of an event and to detect gaps of bad data and data spikes. For each data gap, we simply used the average flux of the two ends to fill the missing points; for spikes, we followed the algorithm described in Raukunen et al. (2020) to identify them and clean the data. After these processes, we applied a segmental spectrum approach (Hu et al., 2016) to get the hourly spectra of the selected data, and the event-integrated spectrum, with every data point subtracted by the calculated background 1 day or 7 days before the onset. Various effective energies for EPS and HEPAD channels can be applied to get the spectra. In this work, The SEPTEM effective energies for P2–P5 (Sandberg et al., 2014) and those identified by Bruno (2017) for P6–P11 were used for spectrum plotting and estimation.

The total spectrum of each GLE was then used to compare with the two sets of modelled spectra fitted from ground NM data and satellite data and to estimate the best matching energies of each EPS and HEPAD channel. Figure 2 shows a schematic description of this procedure. First, the two sets of modelled spectra were converted from rigidity to kinetic energy in units of MeV and from integral spectra to differential spectra. Then a set of fluences were calculated according to the parameters of the models in the energy range of 0.1–2500.0 MeV, with a grid of 0.1 MeV. Finally, the fluence of each proton channel calculated by WASPE was compared with the set, fluence with 1-day background versus MBF while fluence with 7 days background versus Band function, and the best matching energy value in the grid was singled out for this GLE. In other words, the estimated effective energy is the value at which the observed fluence falls on the modelled curve. Because the detectors onboard each GOES have recorded multiple GLEs with almost the same configurations, the average of these best matching values in the energy grid can be considered as the approximate

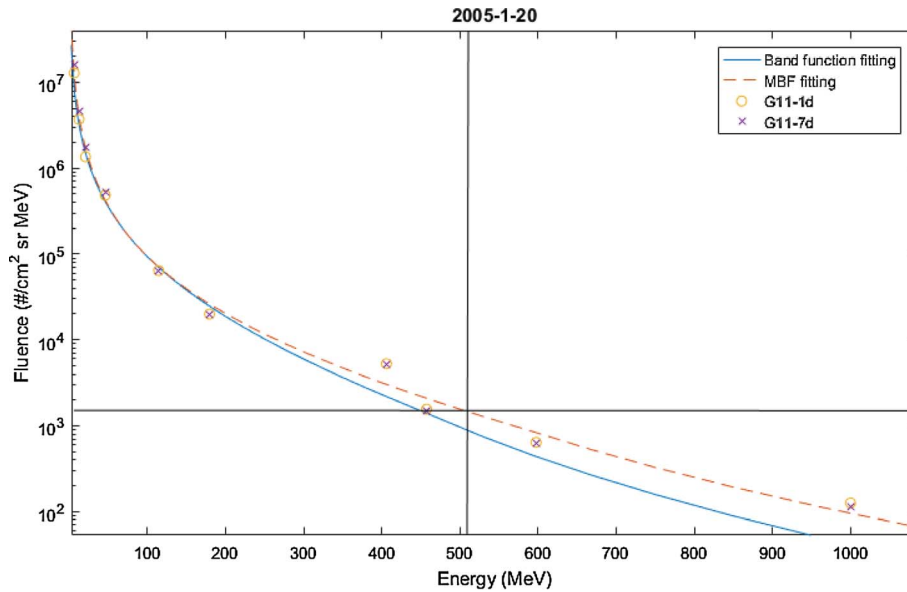


Fig. 2. Scheme of the algorithm to obtain effective energy of each proton channel by comparison with the two sets of GLE modelling. The solid and dash curves are converted differential spectra from rigidity to kinetic energy, based on the two fitting functions for the 2005-01-20 GLE, respectively, and symbols are fluences of GOES 11 proton channel P2–P11 for this event, calculated by subtracting background fluxes at different times (1 day and 7 days before the onset). The two crossed straight lines demonstrate the scheme to estimate the effective energy for P9. The horizontal line marks the measured fluence level. The vertical line indicates the effective energy at which the fluence best matches the MBF fitting of this event.

effective energies of EPS and HEPAD channels. In addition to simple numerical averages and their standard deviation (STD), we use the duration of each event (Table A.1) as a weight factor to get the weighted average for each GOES, to reflect the relatively higher contribution from events lasting longer.

5 Results

Among all missions up to date, GOES 6 observed the most GLEs (GLEs 40–54) during its service period of 1983–1994. However, during the two time periods observing GLEs 47–50 and 54, the background fluxes of HEPAD channels were elevated about 1000 times to those before and after the periods, and the fluences of these events at the high energy channels were significantly higher than those of EPS channels, resulting in non-monotonic spectra in energy that are incomparable to functional fitting models. In addition, there was a long duration event before GLE 51, making it difficult to choose a period to calculate background fluxes. The fluences of HEPAD channels of this GLE are incomparable with the modelled spectra, resulting in larger variations in the matching energies than in other events. Therefore these six GLEs were not used in this study.

Tables 1 and 2 list the best matching energies of GOES 6 proton channels compared with Band function and MBF fitting of GLEs, respectively. For HEPAD channels P8–11, the average matching energies obtained by comparing with MBF models (MBF energies hereafter) are consistently higher than those obtained by comparing with Band function models (Band energies hereafter), which agrees with previous study showing systematically higher fluences in the rigidity range 1.5–4 GV

after using the detrended NM data (Usoskin et al., 2020). Figure 2 of this work also shows this feature for the 2005-01-20 event. The MBF energy for P7 is about 15 MeV higher than its Band energy, while those for P6 are very close to each other. With uncorrected data, the MBF energies for P2–5 are consistently lower than Band energies, though for some events, no matching energies can be obtained by comparing fluences with MBF models (Table 2). The problem for P4 (Mottl & Nymmik, 2007) is obvious for both approaches, not only in their large variation for different events but also in the non-monotonic slope of the spectrum for several events, so we decided not to use the data of this channel in our later analysis. Such a non-monotonic feature appears only once for HEPAD channel P10 in the analysis of the 1989-09-29 event; the recorded higher fluence for P11 than that of P10 may be related to the strong anisotropic high energy protons during the initial stage of this event (Lovell et al., 1998), during which the pitch angles of high energy protons are significantly smaller than those of lower energy counterparts, but the data analysis may have assumed that they are the same.

Using NOAA corrected data, the matching energies for P2' and P3' are enhanced a bit, but those for P5'–7' are significantly decreased (Tables 1 and 2). This is different from the results obtained for EPS channels of other GOES missions, all of which show minor changes from the results using their uncorrected data (discussed in the following text). Both corrected and uncorrected data were used in the calibration study of GOES 13 and 15 to develop the effective energies B17 (Bruno, 2017), while only uncorrected data were used in developing S14 effective energies for EPS (Sandberg et al., 2014). Compared with S14 energies for P2–P5 of GOES 5 (6.3, 11.1, 17.9, 48.7 MeV) and GOES 7 (6.6, 11.2, 21.1, 50.5 MeV)

Table 1. Best matching energies (unit: MeV) of GOES 6 proton channels as compared with Band function fitting of GLEs. P2'–P7' refer to the results obtained by using corrected fluxes of NOAA data, and the rest are achieved from uncorrected fluxes. The row of Avg. refers to simple numerical averages, STD refers to their standard deviations, and W. Avg. are the weighted averages by using the duration of each event (Table A.1) as a weight factor.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
1989-07-25	752.2	693.0	386.0	338.5	284.1	134.6	47.0	49.5	10.6	6.6	194.2	113.9	42.3	62.1	21.9	9.8
1989-08-16	722.2	652.1	361.1	309.0	263.9	140.6	48.7	34.7	12.5	7.5	197.2	124.6	44.9	35.5	13.5	7.7
1989-09-29	724.5	744.3	369.6	302.5	245.9	126.6	46.6	29.4	10.6	4.9	179.1	107.7	42.4	30.7	16.1	6.3
1989-10-19	849.6	797.7	399.0	333.2	274.4	131.8	51.1	48.1	11.6	5.5	196.0	115.7	48.4	50.9	12.5	5.7
1989-10-22	690.6	636.0	376.5	317.8	257.0	133.5	46.9	47.4	13.1	8.4	195.3	118.2	50.4	43.6	15.2	9.1
1989-10-24	771.1	730.6	344.1	308.9	264.5	130.2	49.4	52.2	12.2	7.5	180.4	113.0	45.3	59.9	13.8	7.8
1989-11-15	819.6	716.3	388.4	340.1	269.1	118.9	40.4	66.3	9.9	5.0	178.8	101.1	36.9	120.3	16.3	5.8
1991-06-15	766.6	689.5	391.8	331.2	273.4	141.8	50.9	52.0	14.7	9.3	197.9	124.6	47.1	55.1	16.1	9.6
1992-06-25	762.1	687.9	394.7	326.3	271.7	142.8	51.7	46.1	14.2	9.3	199.1	127.0	48.1	47.4	14.7	9.4
Avg.	762.1	705.3	379.0	323.1	267.1	133.4	48.1	47.3	12.2	7.1	190.9	116.2	45.1	56.2	15.6	7.9
STD	49.1	48.9	18.0	14.0	11.0	7.8	3.5	10.6	1.7	1.7	8.7	8.5	4.1	26.2	2.7	1.7
W. Avg.	754.6	715.2	371.2	316.0	262.5	132.3	48.2	43.5	11.9	6.8	187.4	114.8	44.5	49.9	15.3	7.6

Table 2. Best matching energies (unit: MeV) of GOES 6 proton channels as compared with MBF fitting of GLEs. Empty cells indicate no matching energies can be obtained by comparing the event fluence with the fitting models.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
1989-07-25	815.8	727.2	429.8	384.1	318.3	149.8	41.3	45.1			218.3	125.2	35.2	61.0	11.1	
1989-08-16	864.3	777.4	399.4	332.4	272.2	126.4	37.8	26.2	9.0	5.3	189.9	109.8	34.6	26.8	9.7	5.5
1989-09-29	922.2	950.6	417.6	327.5	254.7	113.6					173.3	93.2				
1989-10-19	791.4	743.3	358.3	294.5	242.9	97.2					172.1	75.8				
1989-10-22	815.9	749.2	417.9	345.2	278.2	142.1	41.7	42.1	6.9	3.5	212.9	124.4	45.5	37.9	8.7	3.9
1989-10-24	902.2	842.6	356.4	317.4	270.0	132.5	36.9	42.7			182.9	115.6		56.2		
1989-11-15	933.9	797.9	421.9	367.5	302.4	147.2		65.8			221.1	122.6		147.3		
1991-06-15	886.1	791.5	430.9	360.5	298.5	143.2	40.2	41.4	7.5	3.9	209.5	122.9	36.4	44.7	8.6	4.1
1992-06-25	899.3	807.4	437.8	362.1	297.4	144.0	42.8	37.1	8.6	5.1	209.9	125.5	39.2	38.4	9.0	5.2
Avg.	870.1	798.6	407.8	343.5	281.6	132.9	40.1	42.9	8.0	4.5	198.9	112.8	38.2	58.9	9.4	4.7
STD	51.3	67.3	30.6	28.1	24.4	17.7	2.3	11.9	1.0	0.9	19.4	17.4	4.5	40.7	1.0	0.8
W. Avg.	887.5	837.5	402.3	336.1	274.2	128.5	39.1	41.1	8.3	4.7	190.5	109.0	37.1	54.6	9.5	4.9

(Sandberg et al., 2014), the Band energies of GOES 6 in this work are quite close to them, while the MBF energies are rather variable, which is not a surprise as the MBF fitting was conducted using GOES proton fluxes with energies > 30 MeV (Koldobskiy et al., 2021). If uncorrected data are used, both Band and MBF energies for P6 and P7 of GOES6 are higher than their S14 energies of GOES 5 (114 and 218 MeV) and GOES 7 (114 and 243 MeV) (Sandberg et al., 2014). The effective energies R20 of HEPAD channels P8–11 by the bow-tie analysis were reported as 405, 473, 622, and 780 MeV (Raukunen et al., 2020), very different from those we obtained. However, these sets of energies were developed not for direct usage but requiring scaling of the corresponding fluxes with a set of correction factors (Raukunen et al., 2020). We will compare them to our results in the following Section 6.

GOES 8 had the best combination of longevity and data quality of the detectors in the GOES 8–12 series (Rodriguez et al., 2014). Its service time (1995–2003) overlapped with GOES 10 and 11, and several GLEs they observed provide an opportunity for inter-calibration as reported in a recent work (Rodriguez et al., 2017). Compared with the results of GOES 6, the effective energies for P11 are significantly increased, while those for P10 and P7 are significantly decreased (Table 3 and 4).

Like GOES 6, the MBF energies for HEPAD channels are higher than the Band energies (except for P8), but unlike GOES 6, they are lower than the latter for P6 and P7 by about 10 MeV. Both energies for P6 and P7 are higher than S14 energies (107 and 153 MeV) (Sandberg et al., 2014). The Band energies for P2–5 are close to S14 energies (6.05, 10.6, 19.0, 47.8 MeV), and the difference of the MBF energies for these channels are not as large as for GOES 6. Unlike GOES 6, using corrected fluxes only results in minor changes for all EPS channels (Tables 3 and 4).

The detectors on GOES 10 are the only ones in the series of GOES 8–12 that faced eastwardly (Rodriguez et al., 2014), therefore, for events with east–west anisotropic particles, the recorded flux should be different from those that faced westwardly. Nevertheless, the effective energies obtained by the two approaches are very close to the corresponding sets for GOES 8, with seven same events in the analysis list (Tables 5 and 6 vs. Tables 3 and 4), with the largest differences for P11 (20 MeV and 24 MeV, respectively). The measurement of this channel is known to be subjected to large uncertainties as the fluxes of protons in this high energy range are usually rather small, and the event-integrated fluence is highly dependent upon the choice of background for subtraction. For all

Table 3. Best matching energies (unit: MeV) of GOES 8 proton channels as compared with Band function fitting of GLEs. Empty cell indicates no matching energies can be obtained between the event fluence and the fitting model.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
1997-11-06	914.0	522.3	404.2	298.8	188.4	126.8	50.4	18.7	9.5	4.6	188.2	129.0	56.4	19.3	11.8	5.1
1998-05-02	1172.0	581.2	468.5	345.1	201.7	128.1	48.3	19.8	12.5	7.5	202.0	131.1	53.5	20.2	14.5	8.0
1998-08-24		636.8	480.9	338.8	194.1	132.9	49.5	19.7	12.5	8.3	191.8	134.5	50.7	19.7	12.5	8.3
2000-07-14	821.0	556.3	444.9	343.9	213.6	136.6	44.4	20.4	16.7	13.7	213.6	138.4	45.5	20.5	17.6	14.2
2001-04-15	863.7	513.4	400.7	284.2	181.6	118.9	50.4	19.4	10.0	5.9	181.4	121.6	59.4	19.9	11.1	6.1
2001-04-18	888.6	485.9	388.3	292.6	189.1	127.2	52.2	19.6	11.9	7.8	187.8	129.1	57.3	19.8	12.8	8.1
2001-11-04	846.2	564.3	442.3	337.8	213.7	138.9	45.7	20.7	15.3	12.0	213.7	140.3	46.4	20.7	15.8	12.3
2001-12-26	923.7	559.6	455.0	346.3	201.5	130.7	48.8	20.5	11.8	7.8	201.4	132.9	51.5	20.7	12.5	8.0
2002-08-24	892.6	516.5	417.4	310.2	189.5	126.1	53.2	19.9	11.1	7.0	189.8	128.2	56.8	20.0	11.4	7.1
Avg.	915.2	548.5	433.6	322.0	197.0	129.6	49.2	19.9	12.4	8.3	196.6	131.7	53.1	20.1	13.3	8.6
STD	109.2	44.9	32.4	25.3	11.4	6.0	2.8	0.6	2.3	2.9	11.6	5.7	4.9	0.5	2.2	2.9
W. Avg.	895.1	549.5	432.7	322.4	198.4	130.6	48.7	19.8	12.7	8.7	198.1	132.6	52.2	20.1	13.7	9.0

Table 4. Best matching energies (unit: MeV) of GOES 8 proton channels as compared with MBF fitting of GLEs.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
1997-11-06	1139.6	621.7	463.2	329.0	194.1	121.8	43.6	16.4	9.1	5.3	193.9	124.2	49.2	16.8	11.1	5.8
1998-05-02	1152.7	570.9	438.9	317.9	190.7	121.1	46.7	20.2	13.4	8.8	193.2	124.9	51.7	20.6	15.5	9.4
1998-08-24	1119.9	572.0	444.4	299.6	174.3	106.7	33.4	11.6	6.9	4.3	177.5	111.0	34.5	11.6	6.9	4.3
2000-07-14	913.7	589.4	453.9	334.7	193.7	119.4	37.5	16.7	13.5	10.9	193.7	121.1	38.4	16.7	14.2	11.3
2001-04-15	1027.1	591.5	457.0	313.0	190.4	116.9	42.8	14.0	6.4	3.5	190.6	120.2	52.0	14.4	7.3	3.7
2001-04-18	1027.3	562.4	430.8	301.6	187.0	120.1	47.6	18.4	11.6	7.9	187.5	123.1	52.4	18.6	12.4	8.2
2001-11-04	1035.2	570.3	417.6	293.4	162.9	97.3	30.8	14.9	11.4	9.3	162.9	98.4	31.2	14.9	11.8	9.5
2001-12-26	1174.2	615.5	483.5	349.7	198.6	128.1	49.5	22.4	13.7	9.5	198.7	130.2	52.0	22.6	14.4	9.7
2002-08-24	1031.4	613.2	478.4	338.7	201.2	127.5	48.6	16.2	8.5	5.2	201.1	129.7	52.3	16.3	8.7	5.2
Avg.	1069.0	589.7	452.0	319.7	188.1	117.7	42.3	16.8	10.5	7.2	188.8	120.3	46.0	16.9	11.4	7.5
STD	83.5	22.5	21.5	19.5	12.2	9.9	6.9	3.2	2.9	2.6	11.8	10.0	8.7	3.3	3.1	2.7
W. Avg.	1056.7	591.9	451.4	320.2	187.5	116.8	40.9	16.3	10.5	7.3	188.1	119.2	44.2	16.4	11.4	7.6

Table 5. Best matching energies (unit: MeV) of GOES 10 proton channels as compared with Band function fitting of GLEs. Empty cell indicates no matching energies can be obtained between the event fluence and the fitting model.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
1998-08-24		637.4	486.4	357.9	199.4	132.8	53.8	22.6	15.4	9.5	196.6	133.9	55.5	22.7	15.5	9.5
2000-07-14	843.2	557.8	442.1	342.1	218.6	137.5	46.4	21.9	18.2	14.0	218.5	139.2	47.7	22.0	19.3	14.5
2001-04-15	920.4	513.8	397.1	283.5	187.1	120.1	57.7	33.5	21.4	14.4	186.9	122.8	72.0	36.2	32.5	17.4
2001-04-18	1009.0	502.8	397.7	296.3	194.5	128.7	55.6	23.6	16.5	10.5	192.9	130.6	61.7	24.0	19.0	11.1
2001-11-04	831.2	547.0	429.3	328.0	214.8	136.4	48.2	21.9	17.0	12.3	214.8	137.8	49.1	21.9	17.7	12.6
2001-12-26	967.9	573.1	461.8	360.8	212.5	135.2	57.4	28.4	21.2	14.2	212.6	137.3	61.8	28.8	24.6	15.2
2002-08-24	979.6	522.0	414.5	316.1	195.1	129.0	59.3	28.1	19.9	12.8	196.1	130.9	64.7	28.5	21.9	13.2
2003-10-28	876.7	568.1	457.9	352.8	224.6	139.0	45.7	20.9	16.7	11.7	224.6	140.4	46.6	20.9	17.6	12.0
2003-10-29	908.8	591.5	468.8	356.0	215.5	133.9	52.4	22.1	15.0	8.6	215.4	135.9	55.6	22.3	16.1	8.8
2003-11-02	951.7	532.5	413.5	312.6	197.2	131.0	52.6	23.2	17.8	11.3	196.8	132.7	54.3	23.3	18.4	11.4
2005-01-20	989.6	539.3	414.1	301.6			54.0	31.6	17.4	7.3			70.0	35.3	31.6	8.4
2006-12-13	1015.9	559.5	440.7	334.9			54.4	31.1	18.1	6.9			62.5	32.7	24.5	7.4
Avg.	935.8	553.7	435.3	328.6	205.9	132.4	53.1	25.7	17.9	11.1	205.5	134.2	58.5	26.6	21.6	11.8
STD	64.7	36.9	29.1	26.4	12.7	5.5	4.4	4.5	2.1	2.6	13.0	5.2	8.4	5.6	5.7	3.0
W. Avg.	926.2	556.2	436.5	329.5	185.8	119.0	52.6	25.5	17.7	11.1	185.4	120.5	57.8	26.4	21.4	11.7

other channels, the corresponding energies are just about several MeV apart away from GOES 8, with those of GOES 10 higher in overall. The trends discussed above for GOES 8 are kept the same, i.e., enhanced MBF energies than Band energies, and minor changes if corrected data were used. S14 energies do not include GOES 10 in calibration; compared with GOES 8 and 11 (Sandberg et al., 2014), the P2–5 energies are several

MeV higher in general, while P6 and P7 are significantly higher, the same trend as for GOES 8.

GOES 11 was in storage mode from 2000 to 2005, and the data quality suffers bias due to satellite spinning (Rodriguez et al., 2014). This is evident for the matching energies of P10 and P11 for the 2003 Halloween events, which are significantly higher than the results of other GLEs documented

Table 6. Best matching energies (unit: MeV) of GOES 10 proton channels as compared with MBF fitting of GLEs. Empty cell indicates no matching energies can be obtained between the event fluence and the fitting model.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
1998-08-24	1174.3	581.6	443.1	300.0	180.2	106.3	36.8	13.6	8.7	5.0	183.0	110.4	38.3	13.6	8.8	5.0
2000-07-14	939.1	590.9	451.5	332.5	198.7	120.1	39.3	17.9	14.8	11.2	198.7	121.8	40.4	18.0	15.7	11.6
2001-04-15	1095.1	591.2	451.7	311.3	196.9	118.2	50.2	26.6	15.7	9.9	197.3	121.6	65.2	29.0	25.4	12.3
2001-04-18	1118.5	582.7	436.4	300.5	192.3	121.5	50.7	21.9	15.7	10.3	192.9	124.5	56.5	22.3	17.9	10.8
2001-11-04	991.6	544.4	400.1	282.6	164.0	95.4	32.4	15.7	12.5	9.5	164.0	96.5	33.0	15.7	13.0	9.7
2001-12-26	1211.1	636.2	483.1	366.2	209.4	132.5	57.7	30.0	23.0	16.1	209.3	134.5	61.8	30.4	26.4	17.1
2002-08-24	1130.2	623.6	477.4	351.0	208.2	130.8	54.8	23.8	16.2	9.9	208.1	133.1	60.1	24.1	18.0	10.3
2003-10-28	1277.9	618.7	453.1	319.9	187.4	113.5	46.8	27.6	23.8	19.0	187.4	114.6	47.5	27.6	24.7	19.3
2003-10-29	887.6	576.7	456.8	342.5	202.4	121.4	43.0	16.2	10.4	5.5	202.4	123.4	45.9	16.3	11.3	5.6
2003-11-02	983.6	558.7	424.8	311.3	198.2	128.2	49.3	21.3	16.3	10.3	199.0	130.3	51.0	21.4	16.8	10.4
2005-01-20	1139.4	621.0	456.4	321.6			57.1	41.7	23.2	10.7			75.0	48.7	47.8	12.4
2006-12-13	1176.7	595.0	447.7	316.4			55.7	32.3	17.4	4.4			64.2	34.4	26.6	4.9
Avg.	1093.8	593.4	448.5	321.3	193.8	118.8	47.8	24.1	16.5	10.2	194.2	121.1	53.2	25.1	21.0	10.8
STD	118.3	27.5	21.9	23.5	13.7	11.4	8.3	8.1	4.9	4.2	13.4	11.5	12.6	9.8	10.4	4.4
W. Avg.	1070.8	590.8	447.0	320.3	192.5	117.2	46.3	23.3	15.7	9.5	192.9	119.4	51.7	24.4	20.5	10.1

Table 7. Best matching energies (unit: MeV) of GOES 11 proton channels as compared with Band function fitting of GLEs.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
2000-07-14	742.1	541.8	444.3	337.2	219.2	138.7	43.8	21.8	17.1	13.0	219.1	140.5	44.7	21.8	18.0	13.5
2001-04-15	760.8	532.4	427.2	287.8	184.3	118.6	48.5	23.3	12.7	7.2	184.4	121.4	56.4	24.2	15.3	7.7
2001-04-18	800.5	519.2	411.3	285.5	191.9	127.6	50.0	21.4	13.1	7.9	190.7	129.6	54.3	21.6	14.5	8.2
2003-10-28	1179.6	605.1	463.3	359.8	225.7	139.3	43.4	20.9	15.7	11.0	225.6	140.7	44.2	20.9	16.4	11.3
2003-10-29	1085.6	625.5	460.8	360.6	214.1	132.6	47.3	20.6	13.2	7.5	214.0	134.5	49.5	20.8	14.1	7.7
2003-11-02	1516.1	641.4	431.5	330.3	203.5	132.5	48.7	19.9	13.0	8.2	202.8	134.1	49.9	19.9	13.2	8.2
2005-01-20	804.1	552.2	449.7	314.5	195.5	119.0	40.1	19.0	9.9	4.1	195.5	121.9	47.0	20.1	14.6	4.6
2006-12-13	927.5	578.6	468.9	341.4	210.0	129.5	43.9	20.2	10.5	4.1	210.1	131.9	47.8	20.7	12.2	4.3
Avg.	977.0	574.5	444.6	327.1	205.5	129.7	45.7	20.9	13.2	7.9	205.3	131.8	49.2	21.3	14.8	8.2
STD	269.6	45.4	20.0	29.1	14.3	7.9	3.4	1.3	2.4	3.1	14.4	7.4	4.3	1.4	1.8	3.1
W. Avg.	916.1	568.0	445.9	328.3	206.6	130.0	45.1	20.9	13.3	8.1	206.4	132.2	48.6	21.3	15.1	8.4

(Tables 7 and 8) and higher than the results of the same events calculated for GOES 10 (Tables 5 and 6). If these three events were taken off the list, the averaged energies would be close to those for GOES 8 and 10. For the only event that was recorded outside the storage mode (2006-12-13 event), the matching energies are close to the effective energies obtained for GOES 8 and 10, using either uncorrected or corrected data. This demonstrates similarity in proton measurements among this series of missions (Rodriguez et al., 2014). The energies obtained from both approaches for P6 and P7 are again higher than S14 energies (104 and 148 MeV), but both sets of energies for P2–5 are close to S14 energies (6.4, 12.5, 20.8, 46.1 MeV) (Sandberg et al., 2014).

GOES 13 and 15 only documented 2 GLEs during their service time (Tables 9 and 10). One of them, the 2012-05-17 event, is the last GLE that utilizes satellite data and NM data to get a Band function form (Raukunen et al., 2018). To make the comparison complete, we adopted a Band-ER (Ellison & Ramaty) function model for GLE 72 (Bruno et al., 2019; A. Bruno, pers. commun.) to calculate the matching energies (Table 9). The Band-ER formalism was found to be more accurate than the Band function to describe SPEs recorded by PAMELA (Bruno et al., 2019), which included a higher energy rollover than the Band function, and used a set of effective energies for GOES 13 and 15 calibrated with high-quality data

of PAMELA to get the fitting parameters (Bruno, 2017; Bruno et al., 2019). Though no NM data were used for the GLE 72 modelling (Bruno et al., 2019), the matching energies of P10 and P11 obtained for this event are close to those obtained for GLE 71 through Band function modelling (Table 9). Nevertheless, the Band-ER energies for GLE 72 P6–9 are consistently lower than Band energies for GLE 71, either with GOES 13 or 15 data. Compared with Band energies for P6–11 obtained for GOES 8, 10, and 11 (Tables 3, 5, and 7), the Band energies for GOES 13 and 15 are consistently much higher, with P11 about 200 MeV higher. The reasons for this discrepancy might be the small size of this event compared with other typical GLEs, especially for the fluence of P11, and its initial anisotropic particle stream (Adriani et al., 2015; Bruno et al., 2016), which was not considered in Band function fitting (Tylka & Dietrich, 2009). Compared with S14 energies for GOES 8 and 11 (Sandberg et al., 2014), the P2–5 energies for GOES 13 are several MeV higher, and those for GOES 15 energies are close, while P6 and P7 for both are significantly higher, the same trend as for GOES 8, 10, and 11.

Even with the same MBF formalism, the matching energies for HEPAD channels P8–11 obtained from GLE 71 are consistently higher than those obtained from GLE 72 for both GOES 13 and 15 (Table 10). Compared with their energies for GOES 8, 10, and 11 in Tables 2, 4, and 6, the average energy for

Table 8. Best matching energies (unit: MeV) of GOES 11 proton channels as compared with MBF fitting of GLEs.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
2000-07-14	818.9	571.6	453.4	327.0	199.3	121.3	37.0	17.8	13.8	10.4	199.3	123.0	37.8	17.9	14.6	10.8
2001-04-15	901.3	613.7	490.7	316.9	193.6	116.5	40.9	17.3	8.5	4.4	194.0	119.9	48.9	18.1	10.6	4.8
2001-04-18	923.9	591.4	458.0	292.4	189.4	120.4	45.6	20.0	12.7	7.9	190.1	123.4	49.7	20.2	13.9	8.2
2003-10-28	1917.0	673.8	460.1	328.8	188.4	113.7	45.2	27.6	22.9	18.2	188.4	114.9	45.7	27.6	23.6	18.5
2003-10-29	1056.5	609.7	448.6	347.7	201.0	120.0	38.3	15.0	9.1	4.8	201.1	122.0	40.4	15.1	9.8	4.9
2003-11-02	1322.9	614.2	439.8	326.5	204.8	129.7	45.6	18.2	11.9	7.4	205.8	131.8	46.7	18.2	12.0	7.5
2005-01-20	938.3	636.9	499.9	336.3	201.3	119.8	42.9	24.1	13.4	6.4	201.5	122.9	50.2	25.6	20.6	7.1
2006-12-13	1062.1	621.7	480.4	323.0	194.0	124.8	44.5	18.7	7.9	1.9	194.8	127.0	48.7	19.3	10.0	2.0
Avg.	1117.6	616.6	466.4	324.8	196.5	120.8	42.5	19.8	12.5	7.7	196.9	123.1	46.0	20.3	14.4	8.0
STD	357.3	30.3	21.4	16.0	6.0	4.9	3.4	4.1	4.8	5.0	6.0	4.9	4.6	4.2	5.1	5.0
W. Avg.	1021.5	608.9	467.1	326.4	197.4	121.0	41.5	19.3	12.0	7.2	197.8	123.4	45.0	19.7	14.1	7.5

Table 9. Best matching energies (unit: MeV) of GOES 13 and 15 proton channels as compared with Band and Band-ER function fitting of GLEs.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
2012-05-17	1223.4	580.4	471.0	393.8	210.7	129.4	50.1	22.0	14.2	6.6	206.2	129.1	55.5	22.3	17.2	6.9
2017-09-10	1174.1	585.4	433.1	346.8	178.2	115.1	52.4	23.8	17.5	8.7	176.0	115.7	55.0	24.1	21.2	9.4
Avg.	1198.8	582.9	452.1	370.3	194.5	122.3	51.3	22.9	15.9	7.7	191.1	122.4	55.3	23.2	19.2	8.2
STD	34.9	3.5	26.8	33.2	23.0	10.1	1.6	1.3	2.3	1.5	21.4	9.5	0.4	1.3	2.8	1.8
W. Avg. (G13)	1193.7	583.4	448.1	365.5	191.1	120.8	51.5	23.1	16.2	7.9	188.0	121.0	55.2	23.4	19.6	8.4
2012-05-17	1117.7	566.5	480.2	368.2	219.2	146.7	48.6	18.9	10.5	4.6	212.8	145.9	51.6	19.0	11.5	4.7
2017-09-10	1156.8	553.4	420.2	309.7	174.2	117.9	50.7	21.6	12.9	6.4	172.0	118.7	52.8	21.8	14.6	6.8
Avg.	1137.3	560.0	450.2	339.0	196.7	132.3	49.7	20.3	11.7	5.5	192.4	132.3	52.2	20.4	13.1	5.8
STD	27.6	9.3	42.4	41.4	31.8	20.4	1.5	1.9	1.7	1.3	28.8	19.2	0.8	2.0	2.2	1.5
W. Avg. (G15)	1141.3	558.6	444.0	332.9	192.1	129.3	49.9	20.5	11.9	5.7	188.2	129.5	52.3	20.7	13.4	6.0

Table 10. Best matching energies (unit: MeV) of GOES 13 and 15 proton channels as compared with MBF fitting of GLEs.

GLEs	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P7'	P6'	P5'	P4'	P3'	P2'
2012-05-17	1304.4	599.5	468.4	381.9	194.9	119.3	49.4	24.2	16.7	9.0	190.9	119.0	54.0	24.5	19.7	9.4
2017-09-10	1016.8	562.9	437.4	364.6	199.8	122.7	44.6	19.4	14.8	8.5	198.0	123.8	47.4	19.6	17.4	9.0
Avg.	1160.6	581.2	452.9	373.3	197.4	121.0	47.0	21.8	15.8	8.8	194.5	121.4	50.7	22.1	18.6	9.2
STD	203.4	25.9	21.9	12.2	3.5	2.4	3.4	3.4	1.3	0.4	5.0	3.4	4.7	3.5	1.6	0.3
W. Avg. (G13)	1130.9	577.4	449.7	371.5	197.9	121.4	46.5	21.3	15.6	8.7	195.2	121.9	50.0	21.5	18.3	9.2
2012-05-17	1209.4	587.0	482.7	351.9	202.9	134.9	48.0	21.3	13.1	6.7	196.9	134.2	50.6	21.5	14.1	6.8
2017-09-10	985.2	536.5	428.4	331.9	194.9	126.3	42.9	17.8	11.5	6.8	193.3	127.6	45.1	17.9	12.7	7.1
Avg.	1097.3	561.8	455.6	341.9	198.9	130.6	45.5	19.6	12.3	6.8	195.1	130.9	47.9	19.7	13.4	7.0
STD	158.5	35.7	38.4	14.1	5.7	6.1	3.6	2.5	1.1	0.1	2.5	4.7	3.9	2.5	1.0	0.2
W. Avg. (G15)	1074.2	556.5	449.9	339.8	198.1	129.7	44.9	19.2	12.1	6.8	194.7	130.2	47.3	19.3	13.3	7.0

GOES 15 P10 seems to be underestimated, while those for P8 of both GOES 13 and 15 are overestimated. Nevertheless, the overall discrepancy from previous missions is much smaller than values obtained from the Band and Band-ER models, and the results for GLE 72 are more consistent than GLE 71. Though the fitting was conducted with GOES protons with energies > 30 MeV, the energies obtained for P2–5 agree with S14 energies for GOES 8 and 11 (Sandberg et al., 2014), while P6 and P7 are significantly higher, a trend the same as GOES 8, 10, and 11. This MBF formalism was found to be in good agreement with B17 energies calibrated for GOES 13 and 15 with PAMELA records (Koldobskiy et al., 2021). Compared with B17 P6–11 energies for GOES 13 (114.4, 179.6, 337.3, 407.1, 508.8, 1002.4 MeV) and GOES 15 (120.0, 178.6,

297.3, 407.4, 516.0, 1094.7 MeV) (Bruno, 2017), the energies of this work are consistently higher, but the spectral shape is similar for any individual event.

The first satellite of the GOES-R series, GOES 16, which was launched in November 2016, happened to record the proton fluxes of GLE 72 (Kress et al., 2021). The new GOES solar proton channel set starting with GOES 16 (including P11) is substantially different from the GOES-15 and prior channel set, which has persisted for decades. The SGPS record of this mission was retrieved (ftp://ftp.ngdc.noaa.gov/STP/goesr/solar_proton_events/sgps_sep2017_event_data/) to calculate the event-integrated fluence and to compare with Band-ER and MBF models (Bruno et al., 2018; Koldobskiy et al., 2021). Like P11 of previous missions, the SGPS P11 was treated as a

Table 11. Matching energies (unit: MeV) of GOES 16 SGPS proton channels obtained from MBF and Band-ER models of 2017-09-10 event, with a comparison of nominal energies reported in Kress et al. (2021). P11 was treated as a differential channel, with each data point divided by a factor of 10^6 to convert a unit from $\#/(cm^2 sr)$ to $\#/(cm^2 sr MeV)$.

Models	P11	P10	P9	P8C	P8B	P8A	P7	P6	P5	P4	P3	P2B	P2A	P1
MBF	854.1	421.1	234.7	137.4	109.9	92.2	59.7	31.3	20.2	12.8	6.8	4.7	2.9	2.2
Band-ER	909.0	404.8	208.1	126.5	104.9	91.2	65.9	38.5	24.9	14.8	6.3	3.7	1.9	1.2
Nominal range	>500	275–500	150–275	118–150	99–118	83–99	40–80	25–40	12–25	6.5–12	3.4–6.5	2.3–3.4	1.9–2.3	1.0–1.9
Mean of nominal		370.8	203.1	133	108.1	90.6	56.6	31.6	17.3	8.8	4.7	2.8	2.1	1.4

differential channel, with each data point divided by a factor of 10^6 (converting the unit from $\#/(cm^2 sr)$ to $\#/(cm^2 sr MeV)$). The best matching energies are listed in Table 11, with a comparison of ground calibrated nominal energy ranges and their geometric means (Dichter et al., 2015; Kress et al., 2021). These obtained energies are quite close to the calibrated mean energies, with those of P5–10 all in the nominal range (Table 11). The Band-ER energy for P11 is about 200 MeV lower than GOES 13 and 15, and its MBF energy is close to those obtained for GOES 6 (Table 2), but is about 200 MeV lower than other missions (Tables 4, 6, 8 and 10).

6 Discussion

As mentioned above, the SEPTEM group used NASA IMP-8/GME data set as reference obtained a set of effective energies for proton channels P2–P7 of GOES 5, 7, 8, and 11 (Sandberg et al., 2014), which were significantly lower than those currently used by the NOAA SWPC to calculate solar proton integral fluxes from GOES rates. Compared with high-resolution observations by the STEREO low-energy telescope (LET) and high-energy telescope (HET) during the December 2006 solar proton events, the following study indicated the cross-calibrated GOES effective energies should be considered more accurate than the current NOAA product (Rodriguez et al., 2017). Recently, the SEPTEM data set was expanded to include HEPAD P8–P10 data by utilizing the bowtie analysis results (Raukunen et al., 2020) and extended proton fluxes to the energy of 727.4 MeV (SEPTEM RDSv3 (beta) <https://spitfire.estec.esa.int/hapi/>). This cross-calibrated data set has been very useful for the investigation of solar energetic particles and associated radiation environment models (Raukunen et al., 2020, and references therein). Because the set of lower effective energies for GOES proton channels leads to systematically lower integral fluxes and lower event-integrated fluences, it would be interesting to see if the expansion of SEPTEM data to higher energies can be further validated by independent measurement and/or modelling. If so, the impacts of many historical large events may have been overestimated in previous literature, and the habitats requirement can be relaxed for current and future human missions beyond LEO to mitigate biological effects due to severe SPEs (Townsend et al., 2018).

The high precision data collected by the PAMELA mission provides such an opportunity, as it contains about 30 large SPEs between 2006 July and 2014 September, with accurate proton fluxes between ~ 80 MeV and a few GeV (Bruno et al., 2018). The spectra of these events bridge the gap between the

low-energy observations of in situ space-based instruments and GLE data from the worldwide network of NMs, which are ideal for making a detailed comparison of the effective energies that the SEPTEM group used to derive the data set and those of this work. We chose four events from the list with significant proton records at around 1000 MeV and used their reported spectra (Bruno et al., 2018) to compare with the event-integrated fluences obtained from SEPTEM RDSv3 (beta) data set as well as those directly from GOES data with the effective energies of this work. Because the PAMELA data were evaluated with a 48-min time resolution corresponding to spacecraft semi-orbits, the reported spectra were not exactly the event fluences integrated from the onset to the end of the events (Bruno et al., 2018). To make the comparison consistent, we chose the closest timestamps to the reported start and end times in Bruno et al. (2018) for the 5-min average fluxes of SEPTEM data and GOES data to do integration, and removed background calculated the same way as we did above for GLEs by referring to the onset of the events.

Figure 3 depicts the Ellison & Ramaty (ER) spectra of the 4 PAMELA documented SPEs (Bruno et al., 2018), along with their background-subtracted fluences derived from SEPTEM V3 and GOES 10, 11, 13 and 15. The background fluxes were calculated at different times, as given in the legends, before the onsets of the corresponding SPEs. The SEPTEM data set has already removed the pre-event background, so the fluences are the same after subtracting the background calculated at two different times. For GOES data, the differences are not recognizable for the records of the 2014-01-06 event but are noticeable for most channels in three other events (Fig. 3). It can be noted that SEPTEM's fluences are evenly separated in log scale; that is because the combined EPS/P2–P7 and HEPAD/P9–P10 of GOES data for each timestamp were re-binned into a set of 14 logarithmically spaced proton energy channels. For the GOES fluences, we used the MBF effective energies of this work for the specific spacecraft.

For these four events, the SEPTEM's fluences of the first 9 channels (with energies < 115.0 MeV) are in good agreement with the fitted spectra from PAMELA data, except for the channels 1 and 2 for the 2012-01-27 event (Fig. 3). The SEPTEM's fluences of 2006-12-14 event for channels 10–14 are zeros; for the other three events, those for channels 13 and 14 (with energies 503.0 and 727.4 MeV, respectively) are in line with PAMELA spectra, but those for channels 10–12 (with energies 166.3, 244.2, and 347.8 MeV, respectively) are significantly lower (Fig. 3). This is not unexpected as the cross-calibrated SEPTEM effective energies for P6, and P7 of GOES 11–13 are 103.7 and 154.6 MeV, respectively, which are lower than those calibrated with PAMELA data for GOES 13 and 15

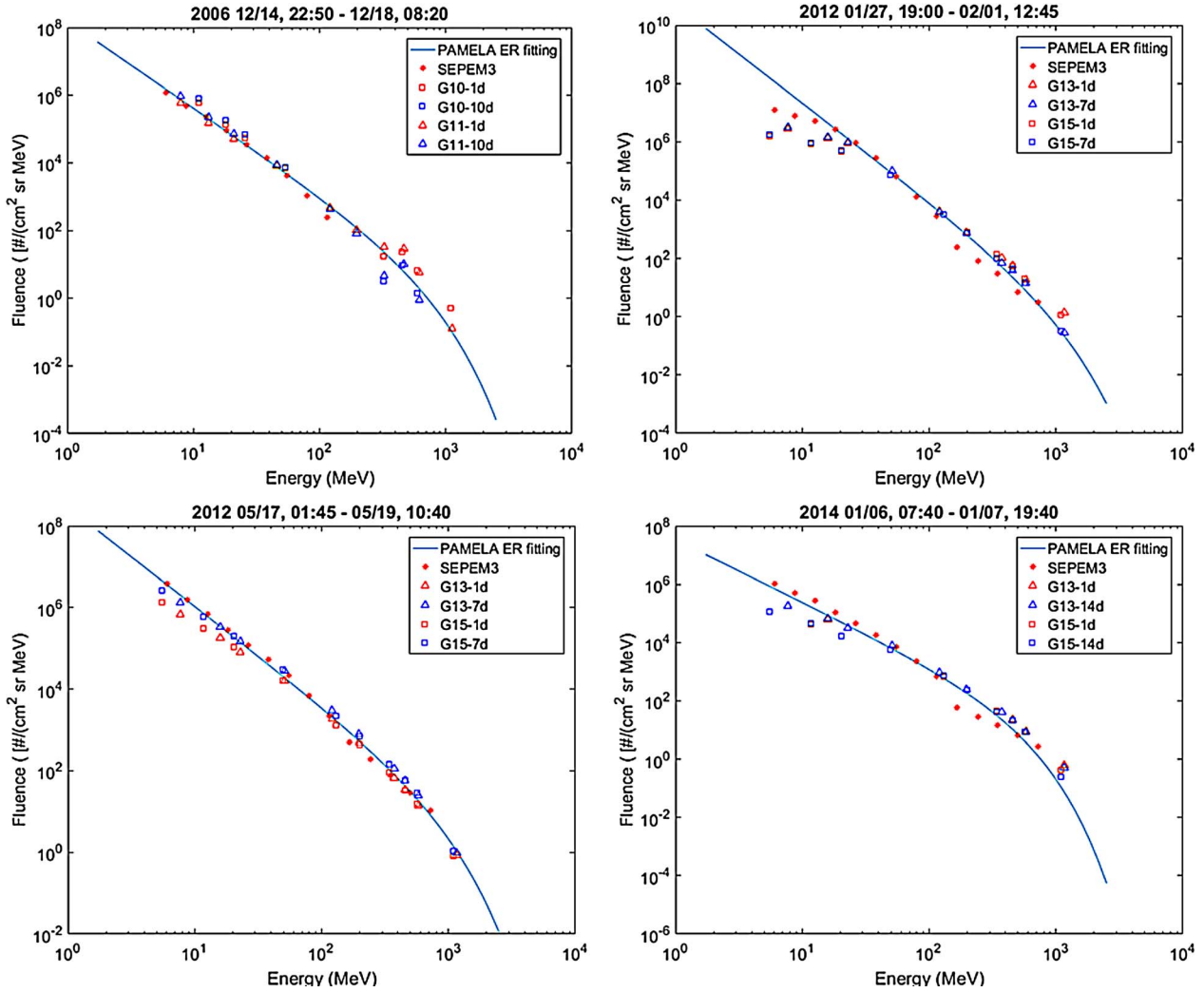


Fig. 3. GOES fluences of 4 PAMELA documented SPEs plotted at MBF effective energies of this work, compared with SEPEM V3 fluences and ER spectra fitted with PAMELA data. Red symbols represent fluences derived by subtracting background 1 day before the onset of the events (not the starting time showing in the figures), and blue symbols denote fluences derived by subtracting background 7 days or more (due to pre-events) before the onset of the events. SEPEM V3 data has removed background flux, so the fluences of each event obtained with different backgrounds are the same.

(113–120 and 178–181 MeV, respectively) (Bruno, 2017). This just demonstrates that a set of lower effective energies for GOES data result in a lower event-integrated spectrum, as we discussed above.

For these four events, the fluences obtained directly from GOES data plotted at MBF energies are in good agreement with the PAMELA spectra except those with energies < 30 MeV (Fig. 3). This is consistent with the scheme to derive MBF parameters by using the GOES integral fluxes with energies > 30 MeV (Koldobskiy et al., 2021). The P5, P6, and P7 fluences are among the best matching with the PAMELA spectra for all four GOES mission, processed with either background immediately before the onsets or days before the onsets (Fig. 3). For the 2006-12-14 event, the P8 fluences are lower than the P9 fluences for GOES 10 and 11, i.e., not following the monotonic trend in energy, and some are quite different from the PAMELA spectrum; nevertheless, the overall spectra in energy are close to that of PAMELA's. For the other

three events, the spectra shapes of all HEPAD channels are rather close to those of PAMELA's, though most of the fluences are higher than those from the PAMELA spectra. This overestimation reflects the higher effective energies through the MBF approach compared with B17 energies, which is discussed above. Because Band energies for GOES 13 and 15 are very close to their MBF energies (see Tables 9 and 10), the comparison of fluences from these three events with Band energies should be similar to those in Figure 3. For the 2006-12-14 event, however, if Band energies were used, the points representing the fluences of HEPAD channels would shift to the left by varying amounts; For P11, this is about 100–160 MeV (see Tables 5–8). This comparison indicates MBF energies are more consistent with independent measurements for GOES 10 and 11 than Band energies, which is probably true for other earlier missions.

The bowtie energies R20 were not developed for direct usage but require scaling the corresponding fluxes with a set

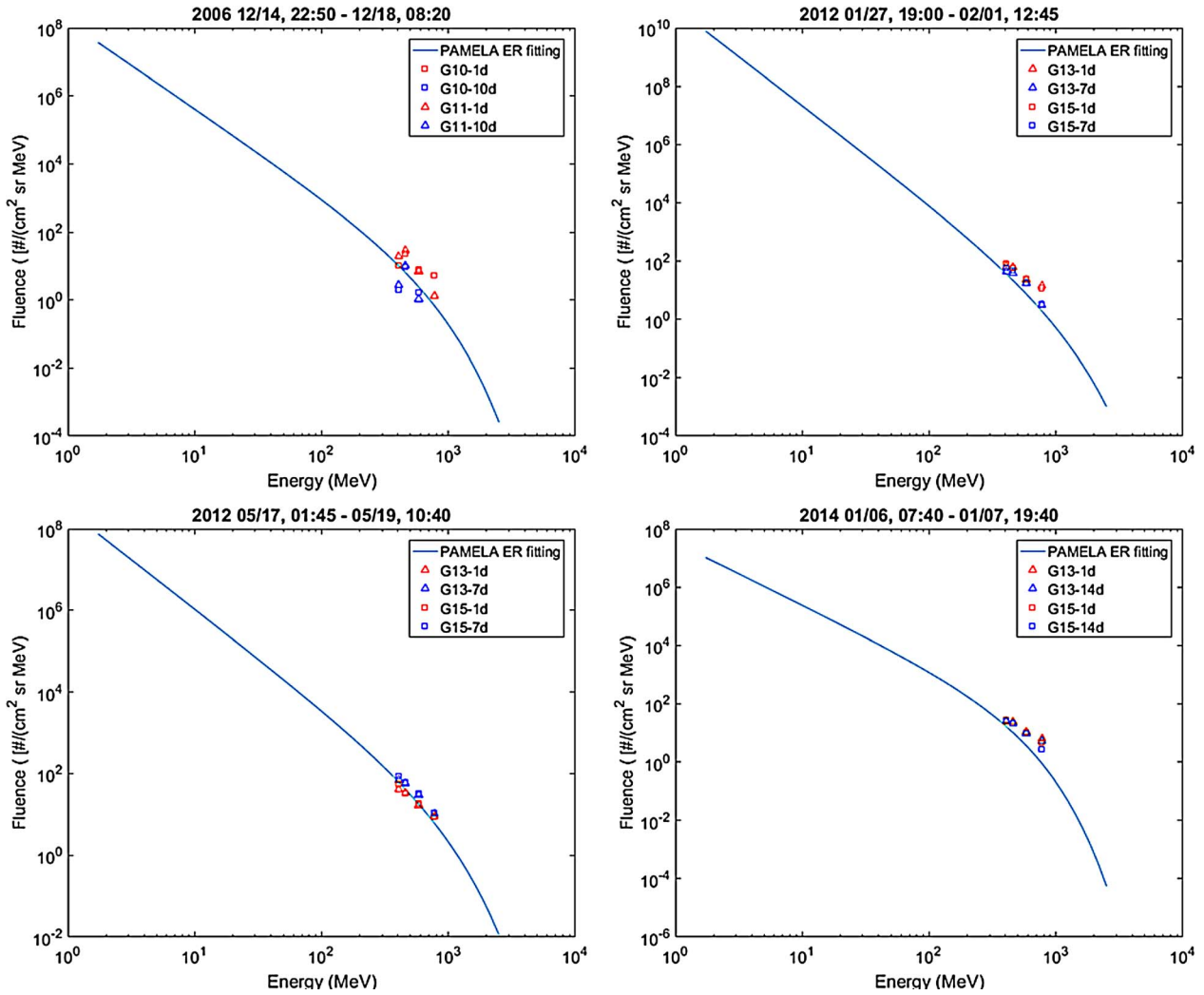


Fig. 4. GOES fluences of four PAMELA documented SPEs plotted at the bowtie energies for four HEPAD channels, compared with ER spectra fitted from PAMELA data. The fluences were scaled with correction factors of 0.614, 1.02, 1.19, and 10.50, respectively, for P8–P11. Symbols in different colours represent fluences derived by subtracting backgrounds at different times, as in Figure 3.

of correction factors (Raukunen et al., 2020). Figure 4 plots the fluences scaled with these factors at the bowtie energies for the same four events as in Figure 3. If one compares these two figures (Figs. 3 and 4), it is clear the alignments of the two sets of fluences with respect to the PAMELA spectra are very similar. The bowtie energies were obtained with techniques without any GLE analysis (Raukunen et al., 2020), and the PAMELA spectra were derived from completely independent sources (Bruno et al., 2018), so the results described in Figures 3 and 4 well demonstrate the reliability of our analysis technique as well as the results. In particular, this work proved again that the integral channel P11 of all GOES data can be used as a differential flux channel as suggested before (Smart & Shea, 1999), either by converting the fluxes/fluences with a factor of 10.50 at its bowtie energy 775 MeV, or directly using GOES fluxes/fluences at MBF energies about 1100 MeV for GOES 8–15 (Tables 4, 6, 8, and 10), with background properly subtracted. Though no independent sources are available to check the energies obtained for GOES 6, it is simple to verify the agreement of the bowtie energies and the MBF energies

with any documented events. It is noted that, in expanding the SEP/EM data set to include bowtie calibrated HEPAD data, the P8 channel was not used as it does not properly line up with the P7 and P9 channels (<https://spitfire.estec.esa.int/hapi/>). This disagreement may relate to the lower effective energies for P6 and P7 of S14 as compared with B17 as well as those in this work.

The recent analysis of the 2017-09-10 event (GLE 72) with GOES 13, 15, and 16 data also demonstrated the underestimation of P6 and P7 energies for GOES 13 and 15 (Kress et al., 2021). The average fluxes of this event were calculated with SEP/EM energies for GOES 13 and 15 and with GOES 16 ground-calibrated energies for GOES 16. An ordinary least squares fit to the EPS versus SGPS fluxes indicated that, in the energy range of 83–500 MeV, the ratios of average fluxes between GOES 13 and GOES 16 are about 0.442–0.560, and between GOES 15 and GOES 16 are about 0.397–0.846 (Kress et al., 2021). This study, along with the calibration study of Bruno et al. (2018) and our results in this work, indicate that simply using the calibrated energies of GOES 11 EPS for

GOES 13 and 15 may significantly underestimate the effective energies of the proton channels of these two recent missions. Moreover, the reference IMP-8 GME data used by the SEP-EM analysis (Sandberg et al., 2014) may experience performance degradation along its service time from 1973 to 2001, as we notice the SEP-EM P6 and P7 energies for GOES 5 (114 and 218 MeV) and for GOES 7 (114 and 243 MeV) are closer to our results for GOES 6 during 1986–1994, while those for GOES 8 (107 and 153 MeV) and for GOES 11 (104 and 148 MeV) are much lower than our analysis on data between 1995 and 2010. This study, along with other recent analyses, indicates that the historical large SPEs such as 1989-10-19 events are not overestimated, but just a conservative estimation (Townsend et al., 2018), and the habitats requirement for current and future human missions beyond LEO need to be considered more thoroughly to mitigate the potential hazards due to severe SPEs (Hu et al., 2020).

7 Summary and conclusions

The Band function models of past GLEs are based on multiple satellite measurements and Earth surface neutron measurements to ensure that the high energy components of the events are accurately represented. The recent revision of these spectra using variable GCR background and an improved neutron-monitor yield function leads to a set of MBF models, providing about 2–4 times enhancement of integral fluences for most events in the energy range of 831 MeV–3.17 GeV. These two sets of GLE models are used as references to estimate the effective energies of EPS and HEPAD proton channels of GOES data recorded over the past 35 years, and those of SGPS detectors of the GOES R series recently launched into orbits. The calculated energies for different missions in the same series (GOES 8, 10, 11) show overall consistency but with small variations, and the differences among missions of different series are noticeable for the measurements crossing the past three solar cycles. The energies of the HEPAD proton channels are slightly higher than the recently calibrated energies for GOES 13 and 15 detectors with PAMELA data but are consistent with the results of independent bowtie analysis and PAMELA measurements. The major discrepancies with previous calibration efforts by the SEP-EM group are the energies for EPS channels P6 and P7, which is rather large for Band energies and slightly smaller for MBF energies.

As many past and ongoing space radiation physical models, climatology models, forecast models, radiation hazard alert services, and radiation effect standards are based on GOES data, improved characterization of these multi-decade measurements may have a significant impact to the space research and operational communities. This work reports a systematic comparative study of GOES data with the long-established models and recent refinement of the GLE spectra, with results indicating the previous recognized worst case 1989-10-19 event was not overestimated but just a conservative estimation. The high-energy particles in such severe SPEs can penetrate the thick shielding even for the current state-of-the-art crew vehicles such as the Orion MPCV and deliver hazardous radiation doses to astronauts in a short time frame. It is verified that the integral channel P11 of GOES 6–16 can be reliably used as a differential proton channel with an effective energy of about 1 GeV (for

GOES 16, the fluxes need to be divided by a conversion factor of 10^6), therefore the multi-decade in situ measurements of the GOES series can be utilized with more extensive energy coverage to improve the space radiation environment models, and to provide more accurate guidelines for designing the spacecraft to operate through any event encountered during a mission.

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Appendix

Table A.1. Spectral parameters of GLEs since 1986 as compiled from the works of [Raukunen et al. \(2018\)](#) and [Koldobskiy et al. \(2021\)](#).

GLE	Onset time	Duration (h)	Band function parameters				MBF parameters					Recorded spacecraft
			J_0	γ_1	γ_2	R_0	γ_1	R_1	J_2	γ_2	R_2	
40	1989-07-25 0850	80	1.29E+7	0.54	6.60	1.82E−1	−0.24	0.154	7.33E+4	6.18	+∞	GOES 6
41	1989-08-16 0145	150	7.27E+7	1.91	5.86	1.85E−1	2.10	0.315	1.65E+6	4.25	1.375	GOES 6
42	1989-09-29 1135	340	1.80E+5, 2.03E+10	2.06, −0.11	2.63, 4.58	3.66E+0, 9.45E−2	−1.95	0.069	9.89E+6	3.39	5.935	GOES 6
43	1989-10-19 1310	77	1.22E+9, 9.09E+9	0.53, 0.91	5.81, 4.43	1.62E−1, 8.44E−2	−1.21	0.109	6.59E+6	4.44	2.960	GOES 6
44	1989-10-22 1810	48	1.09E+9	1.23	7.25	1.35E−1	0.35	0.122	1.84E+6	6.07	5.807	GOES 6
45	1989-10-24 1820	264	4.42E+7	2.18	5.65	3.85E−1	−1.77	0.077	1.19E+7	2.95	1.131	GOES 6
46	1989-11-15 0705	72	3.85E+6	0.97	5.53	2.20E−1	−1.16	0.117	5.58E+4	4.97	+∞	GOES 6
47	1990-05-21 2230	70	1.13E+8	0.55	4.31	1.37E−1	−1.55	0.088	2.85E+5	4.06	+∞	GOES 6
48	1990-05-24 2110	47	5.58E+7	0.80	4.91	1.83E−1	−0.95	0.137	6.14E+5	4.08	7.501	GOES 6
49	1990-05-26 2055	37	4.69E+7	0.33	5.72	1.83E−1	−1.03	0.131	2.80E+5	4.51	+∞	GOES 6
50	1990-05-28 0600	120	7.66E+7	0.42	4.98	1.43E−1	−0.80	0.142	1.67E+5	5.51	+∞	GOES 6
51	1991-06-11 0230	102	8.36E+8	0.97	5.14	1.05E−1	−2.31	0.059	1.55E+5	4.87	+∞	GOES 6
52	1991-06-15 0730	100	2.52E+7	2.18	5.98	1.43E−1	1.13	0.200	8.92E+5	5.02	2.883	GOES 6
53	1992-06-25 2035	100	8.62E+5	3.12	6.12	3.50E−1	2.12	0.297	8.89E+4	5.28	+∞	GOES 6
54	1992-11-02 0350	100	1.97E+9	0.46	6.91	9.51E−2						GOES 6
55	1997-11-06 1210	153	8.15E+8	0.28	5.38	1.16E−1	0.75	0.165	9.66E+5	4.23	3.077	GOES 8
56	1998-05-02 1345	52	8.98E+6	1.31	6.51	1.96E−1	1.57	0.221	6.26E+4	5.01	+∞	GOES 8
57	1998-05-06 0815	35	1.64E+6	1.92	7.46	2.02E−1						GOES 8
58	1998-08-24 2215	91	2.10E+5, 1.63E+4	2.98, 5.29	5.27, 7.74	6.77E−1, 9.83E−1	4.60	−0.277	1.55E+6	1.65	0.300	GOES 8, 10,
59	2000-07-14 1015	149	2.94E+9, 6.01E+7	0.51, 3.24	7.46, 7.85	1.23E−1, 2.26E−1	2.80	0.276	3.46E+6	5.85	2.191	GOES 8, 10, 11
60	2001-04-15 1400	60	5.22E+7	1.39	5.69	2.60E−1	1.02	0.290	2.90E+6	4.57	3.321	GOES 8, 10, 11
61	2001-04-18 0235	60	8.39E+6	1.85	5.02	2.37E−1	2.37	0.547	3.68E+5	4.01	5.172	GOES 8, 10, 11
62	2001-11-04 1630	106	2.14E+9, 4.78E+8	0.24, 2.36	6.67, 11.2	9.34E−2, 1.29E−1	3.70	0.311	3.08E+5	6.63	+∞	GOES 8, 10, 11
63	2001-12-26 0530	48	2.17E+7	1.81	7.86	1.80E−1	2.45	0.245	5.79E+5	4.11	0.673	GOES 8, 10, 11
64	2002-08-24 0120	77	5.06E6	2.36	6.70	2.25E−1	2.09	0.281	1.69E+5	7.00	+∞	GOES 8, 10, 11
65	2003-10-28 1105	34	8.44E+9, 1.12E+8	0.01, 2.81	6.48, 8.92	8.88E−2, 1.71E−1	6.49	−0.525	5.31E+6	0.01	0.447	GOES 10, 11
66	2003-10-29 2105	84	7.62E+7	2.04	6.86	2.06E−1	1.56	0.188	5.19E+5	6.85	+∞	GOES 10, 11
67	2003-11-02 1730	48	2.27E+6	3.50	7.01	3.21E−1	3.62	0.541	1.81E+5	5.40	+∞	GOES 10, 11
68	2005-01-17 0955	42	3.51E+7	2.65	8.29	1.62E−1						GOES 10, 11
69	2005-01-20 0630	96	3.80E+8	0.72	5.78	2.04E−1	1.16	0.295	8.03E+6	4.73	2.392	GOES 10, 11
70	2006-12-13 0245	84	1.33E+8	1.05	5.80	1.77E−1	0.18	0.114	1.46E+6	3.77	1.449	GOES 10, 11
71	2012-05-17 0140	100	1.03E+7	1.36	6.96	2.19E−1	2.23	0.372	2.60E+5	7.03	24.488	GOES 13, 15
72	2017-09-10 1605	152					1.46	0.164	4.59E+5	6.31	+∞	GOES 13, 15, 16