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Comment on the use of GOES solar proton data and spectra in solar proton dose calculations

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Abstract

There is a need to understand the calibration and response of the GOES solar particle detectors since the GOES data are being used to evaluate high energy solar particle events. We share some of our experience in utilizing these data in the analysis of solar particle ground-level events (GLEs).

For the 29 September 1989 event, we have evaluated the solar proton and alpha particle spectral characteristics throughout the event. The results show that the solar cosmic ray spectrum is extremely hard at low energies with the magnitude of the slope increasing with increasing energy and with time. Published by Elsevier Science Ltd.

Keywords: Solar proton events; Solar proton detectors; GOES spacecraft; Alpha particle detector; Particle detector calibration

1. Introduction

The geosynchronous orbit position is a good place to monitor solar particle events since the magnetosphere will channel the particle flux to the spacecraft, even if the particle flux is highly anisotropic. As an example, consider the 22 October 1989 solar particle event shown in Figs. 1 and 2. The initial flux of this event was extremely anisotropic, centered in a direction 60 degrees out of the ecliptic plane (Cramp et al., 1997). The IMP 8 particle sensors (measuring flux in a spin plane in the ecliptic) did not record the initial onset of this extremely anisotropic particle event (T.P. Armstrong, private communication, 1990), but the particle sensors on all the geosynchronous spacecraft, specifically the NOAA GOES 6 and 7, and the three geosynchronous spacecraft on which the Los Alamos National Laboratory has energetic particle sensors (Nemzek et al., 1994), observed this extremely anisotropic particle onset.

2. The GOES particle sensors

The NOAA GOES spacecraft has become the primary real time solar energetic particle source available to the scientific community. Description of the particle sensors and energy ranges are given in the appendices. A recipe for converting the data on the NGDC CD-ROM to integral particle flux is given in Appendix C. These sensors have a wide dynamic range (Hanser, 1995) but are not calibrated to the precision achieved by "state of the art" sensors on NASA spacecraft. In the energy range between 1 and 100 MeV, Zwickl (1989) has developed a dynamic algorithm to correct for high energy particle penetration through the side of the detectors which has greatly improved the utility and reliability of these proton data during commonly occurring proton events. A comparison between the

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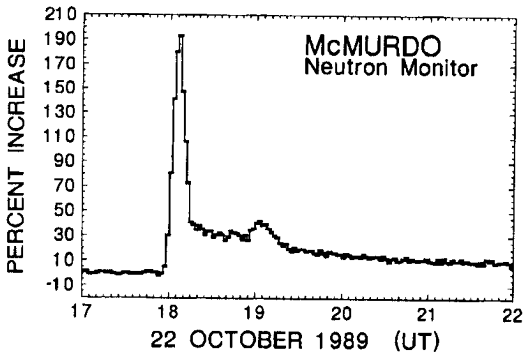

Fig. 1. The 22 October 1989 solar particle event as observed by the McMurdo, Antarctica neutron monitor. The initial onset was very anisotropic.

corrected GOES integral fluxes at energies of >10, >30 and >60 MeV and the IMP 8 measurements, shows a general agreement within a factor of two for most events (R. Zwickl and T.P. Armstrong, private communication, 1994). Sauer (1995) has been developing correction recipes for the high energy proton data (300 to ~1000 MeV) from the high energy proton detector (HEPD) on the GOES spacecraft (see Appendices). When using the Sauer (1995) conversion factors, the resulting integral data from the P8, P9 and P10 channels agreed well with the ground-level event (GLE) analysis of Smart et al. (1994) and Smart and Shea (1996). Fig. 3 is a comparison, during the GLE maximum, of the solar proton spectra derived from the analysis of the ground-level solar cosmic ray increase observed by the worldwide neutron monitor network and the high energy data from the GOES spacecraft for the 11 June 1991 GLE. (See the Appendices for a detailed discussion of the GOES particle sensors.)

3. Particle flux evolution and radiation dose

The possibility that a large, very energetic solar cosmic ray event could generate a significant radiation dose to astronauts in a short time interval is a matter of concern. Since the large transient increases in particle flux could often be associated with solar flares it was assumed that the solar flare process was the source of energetic particles observed in space. The presumed solar flare acceleration process was assumed to be of an "explosive" nature. Inherent in the early dose estimates was the assumption of "explosive" particle release from the sun and a subsequent "explosive" increase in dose from a very fast increase in high energy particle flux. This presumption led to large dose estimates early in the solar particle event. Papers written in the decades of the 1960s and 1970s reflect this assumption. Some of the original radiation dose estimates from the large energetic proton events of the 1950s and 1960s were many rads per hour (Keller and Pruett, 1965; Foelsche, 1965). However, more recent dose calculations for these same events (Wilson et al., 1991) are considerably lower. One of the reasons for these differences is the use of new standards for converting radiation types to dose (ICRP Report, 1991; ICRU Report, 1997). Another reason is a better definition of the solar particle spectra for the more recent events and a subsequent re-evaluation of the spectral characteristics of some of the earlier events (Wilson et al., 1991).

The spacecraft observations of the large energetic solar proton events of solar cycle 22 do not support the "explosive" particle release and flux increase scenario. Typically, in the 30 to several hundred MeV

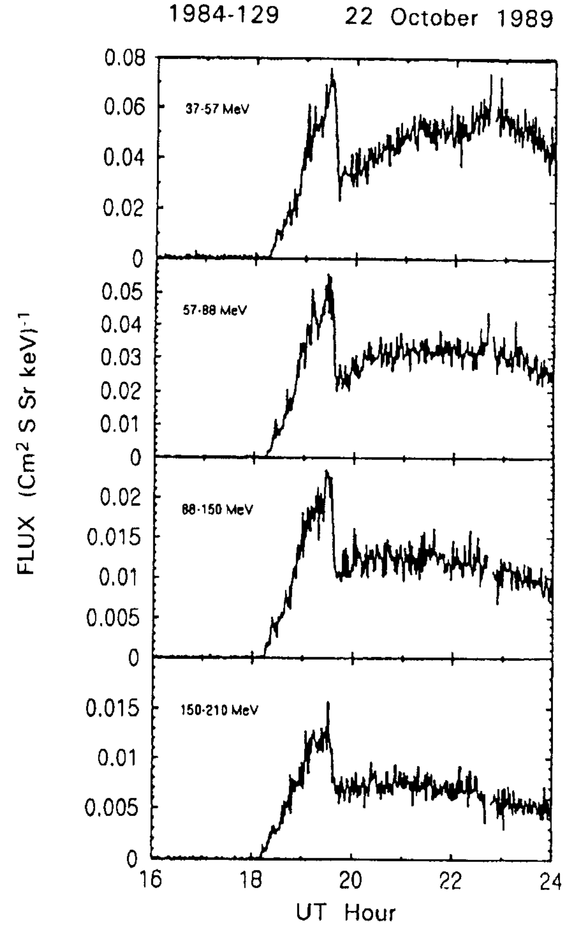

Fig. 2. The 22 October 1989 solar particle event as observed at geosynchronous orbit by the LANL particle sensors on spacecraft 1984–129. (Adapted from Nemzek et al., 1994.)

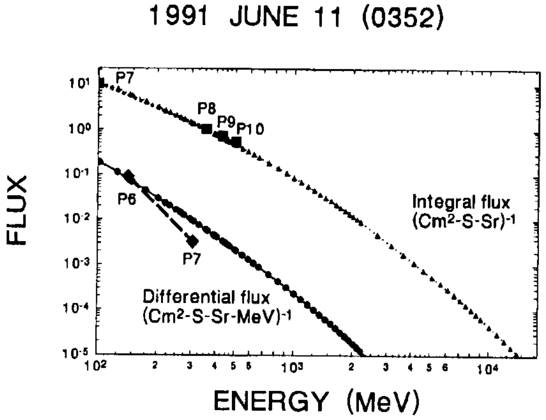

Fig. 3. Comparison of the GOES high energy proton fluxes with the spectrum derived for the 11 June 1991 solar cosmic ray ground-level event at GLE maximum. The top line represents the integral spectra derived from the analysis of the neutron monitor data, and the solid squares are the corrected integral flux derived from the GOES HEPD data (see Appendix C). The bottom line represents the differential energy spectra derived from the neutron monitor data, and the solid squares are the GOES (uncorrected) differential flux. The slope difference between the differential, P6 and P7 flux suggest a correction is needed in the upper limit energy response for P7.

energy range, the time scale of hours from particle onset to flux maximum was observed. This will be demonstrated in the following section with an analysis of the 29 September 1989 very energetic large solar cosmic ray event.

From the analysis of the large events that occurred in the 22nd solar cycle we have learned it is a serious mistake to use one simple value to characterize the spectral characteristics of a large high energy solar cosmic ray event. This is perhaps one of the major reasons that such high dose values were calculated for the events in the 19th solar cycle. Lacking accurate measurements at a number of energies, the early dose calculations were made using one spectral slope determined from the known energies (usually either very high in the GeV range or in the low MeV range), and extrapolating this spectral slope to all other energies. This method typically results in a considerable overestimate of the flux at the other end of the energy spectra thus leading to higher dose calculations. When the 29 September 1989 event occurred, the NOAA Space Environment Center radiation dose prediction was significantly larger than the actual measurement on the Concorde or by subsequent calculation by a number of researchers (O'Brien et al., 1996a,b, 1998; Wilson et al., 1991; Wilson and Nealy, 1992). The most likely reasons for these differences were the utilization of an outdated radiation transport model and the use of an unrealistic exponential model of the solar particle spectrum to extrapolate from low to high energies.

4. The flux and spectral evolution of the 29 September 1989 event

The 29 September 1989 solar cosmic ray ground-level event was large and significant by every measurement; Smart and Shea (1991) evaluated this as the third largest high energy solar proton event since the first ground-level solar cosmic ray event was identified in 1942. Particles with energies >20 GeV were present

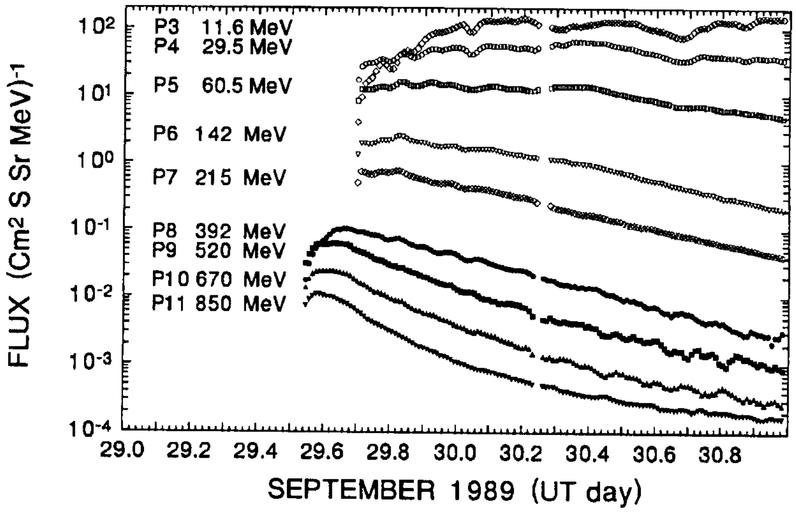

Fig. 4. The 29 September 1989 solar proton flux from 11 to 850 MeV as observed by the GOES 6 and 7 spacecraft.

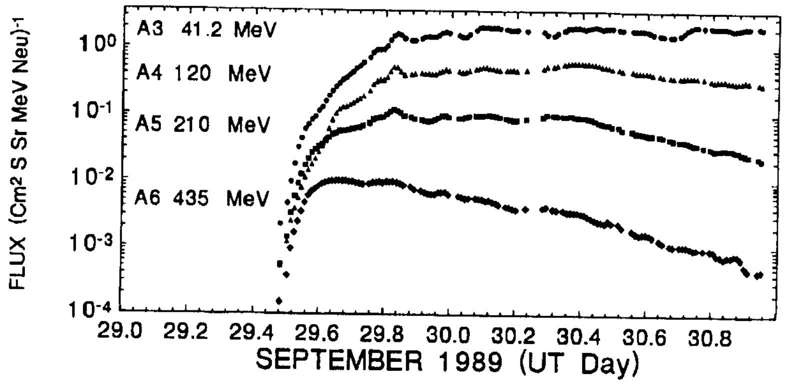

Fig. 5. The 29 September 1989 solar alpha particle flux from 41 to 435 MeV/Nucleon as observed by the GOES 7 spacecraft.

(Swinson and Shea, 1990); the event was observed at every operating cosmic ray detector on the surface of the Earth. The 29 September 1989 event occurred in the "modern" spacecraft era, and there are direct spacecraft measurements of the particle flux up to energies of about 800 MeV. The particle spectrum of this event is complex and not described by simple parameters.

The initial reports of particle energy spectra for this event appeared to be inconsistent. Mathews and Venkatesan (1990) determined the spectral slope at the mean response of the high energy detectors (5–7 GeV) whereas Humble et al. (1991) and Smart et al. (1991) determined the spectral slope at 1 GV rigidity. Subsequent analyses of this event (e.g., Cramp et al., 1993) show that the spectral slope is a function of energy and time. The slope is extremely hard at low energies; the magnitude of the slope increases (i.e., becomes "softer") with increasing energy and time. An intensity–time plot of the GOES spacecraft data obtained for the 29 September 1989 event, after additional corrections and adjustment described in the appendices, is presented in Fig. 4 (protons) and Fig. 5 (alpha particles). (The GOES proton detectors have a serious side penetration problem whereby the high energy protons register in the low energy proton channels. Error flags and corrections for this problem removed the early part of the event for protons below 200 MeV.)

5. The time-evolving proton spectra observed by the GOES spacecraft

The use of the Sauer (1995) correction recipes for the high energy proton data still does not satisfactorily resolve the different energy slope and high energy flux between the HEPD data and the lower GOES energy data. In the analysis of the 29 September 1989 high energy solar proton event (Kahler et al., 1997), the spectra derived from the unmodified GOES data at various times in the event have "kinks" which lead us to strongly suspect that there needs to be further adjustment(s) to the energy ranges of the high energy data. One "kink" is in the P7 energy range (see Fig. 6). Adjustment of the high energy range of the dome detector (P7), by changing the upper energy limit from 500 to 400 MeV for this proton sensor as described in the last part of Appendix A seems to remove this "kink". Appendixes A and B describe the adjustments to the energy levels and conversion factors we have used in this analysis of the higher energy solar proton data from the GOES spacecraft. This includes the correction in the P8 and P9 data for the side penetration developed by Sauer (1995). The Sauer recipe for side penetration correction may be too large for the very large high flux events such as the 29 September 1989 data illustrated here. (See the Appendices and the first panel of Fig. 7.)

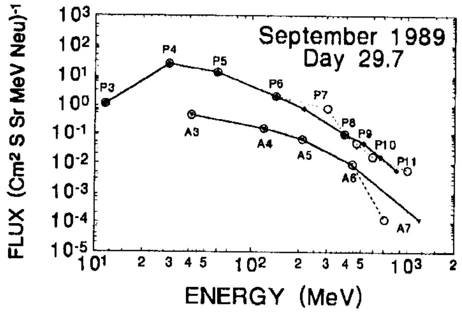

Fig. 6. The 29 September 1989 solar energetic proton and alpha particle data observed by the GOES 6 and 7 spacecraft instrumentation. The open circles (connected by doted lines for protons and dashed lines for alpha particles) indicate the Sauer (1995) corrections to the mid-point energy response for each detector channel. The solid diamonds (protons) and triangles (alphas) indicate our adjustment to make what we consider more consistent flux spectra plots. (See the Appendices for more details.)

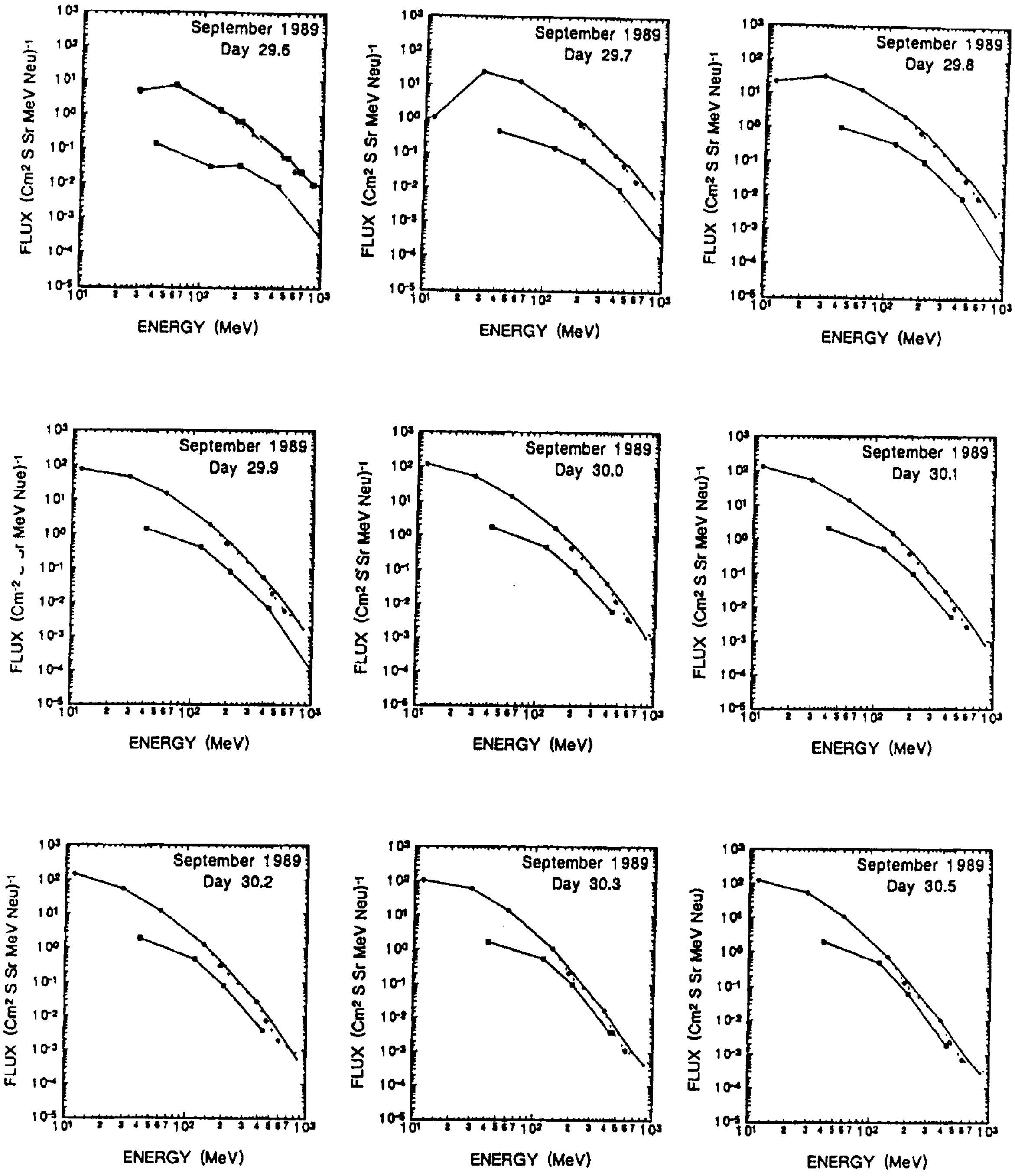

Fig. 7. The spectral evolution of the 29 September 1989 solar cosmic ray event as observed by the GOES 6 and 7 spacecraft instrumentation. The top line in each insert indicates the proton flux. The bottom line in each inset indicates the alpha particle flux. See the Fig. 6 caption and the Appendices for detail on the energies.

We have compared simultaneous spectra derived from the GOES high energy detectors with the spectra derived from the analysis of the neutron monitor data during solar cosmic ray ground-level events of 22 October 1989 and the 11 and 15 June 1991 GLEs. We have used the derived GLE (ground-level event) spectra as a normalization spectra. Then we found adjustments for the GOES high energy particle detector midpoint energies so the spectra were consistent. (See the Appendices for more details.) The criteria used were that the spectral form should be relatively self-consistent, and there should be no "kinks" in the spectra. Fig. 6 displays the proton and alpha spectra derived from the GOES 6 and 7 energetic particle sensors on 29 September during the interval 1630–1645 UT. Fig. 7 illustrates representative high energy proton and alpha particle spectra during 29 and 30 September 1989.

It is interesting to note that even 2 h after the event onset, the fluxes at energies less than 100 MeV/Nucleon have not yet maximized. The long times-to-maximum flux for large flux events are typical of the observations throughout the 22nd solar cycle. These data do not support the "explosive" release particle flux and dose scenarios.

6. Summary

The GOES solar particle data are very useful monitors for high energy solar particle events. There is a need to understand the calibration and response of the GOES solar particle detectors to high energy solar particle events. We have used these data to evaluate the solar proton spectral characteristics for the 29 September 1989 event illustrating extremely hard spectra at low energies with the magnitude of the slope increasing with increasing energy and with time. These spectra cannot be modeled with simple functions. The intensity–time profile of this very energetic, very large relativistic solar particle event does not support the "explosive release concept" of particle flux or high initial radiation dose scenarios.

Appendix A. The GOES energetic proton detectors

The proton data are in 11 different energy ranges from three different sensor systems. The energy ranges of the proton data channels are listed below. There is some controversy over the actual sensitivity of the proton instruments, especially the Cerenkov detector (see Rinehart, 1978 for an initial description), which provides data for proton channels 8 through 11. (Data source: NGDC CD-ROM, "GOES Space Environmental Monitor".)

Proton sensor data description

Solid state telescope assembly: P1–P3:

Proton energy identifier	P1	P2	P3
Low energy threshold	0.60	4.20	8.70
High energy limit	4.20	8.70	14.50
Mid point energy	2.40	6.45	11.60

Dome solid state detector assembly: P4–P7:

Proton energy identifier	P4	P5	P6	P7
Low energy threshold	15.0	39.0	84.0	110.0
High energy limit	44.0	82.0	200.0	500.0
Mid point energy	29.5	60.5	142.0	305.0

High energy (HEPD) Cerenkov detectors assembly; P8–P11

Original HEPD energy identifier	P8	P9	P10	P11
Original low energy limit	370.0	480.0	640.0	> 850.0
Original high energy limit	480.0	640.0	850.0	
Original mid point energy	425.0	560.0	745.0	

Calibration

There have been attempts to do "in-flight" calibration of the sensors during actual solar particle events (Hanser, 1985). There has been additional work by comparing the response from these instruments to the data obtained from the NASA IMP spacecraft (Zwickl, 1989) and by comparing the HEPD data to the analysis of high energy solar proton ground-level event (GLE) data (Sauer, 1993). The greatest unresolved problem is the response of the HEPD instrument. The threshold energy adjustment and the geometric factor adjustments proposed by Sauer (1995) are a good first step. These are very helpful in resolving some of the discrepancies in the P8, P9 and P10 data.

Sauer (1995) recommended energy levels for HEPD data P8–P11 Cerenkov detectors assembly. The P11 midpoint is based on the work of Hanser (1985).

Adjusted HEPD energy identifiers	P8	P9	P10	P11
Adjusted low energy limit	355.0	430.0	505.0	685.0
Adjusted high energy limit	430.0	505.0	685.0	1315.0
Adjusted mid point energy	392.5	467.5	595.0	1000.0

The use of these adjustments still leaves discrepancies in the HEPD flux slope data that are difficult to resolve. It is our opinion that there is definitely a serious discrepancy in the P11 data. The P11 data channel is simply inconsistent with all of the other data. When using the Sauer (1995) energy thresholds and conversion factors, the resulting integral flux data (see Appendix C) from the P8, P9 and P10 channels agreed well with the GLE analysis of Smart et al. (1994) and Smart and Shea (1996). The use of these data still does not satisfactorily resolve the different energy slope and high energy flux between the HEPD data and the lower GOES energy data. We are currently using the following energy levels for our analysis of the higher energy solar proton data from the GOES spacecraft.

Dome solid state detector assembly P5–P7

Modified proton energy identifier	P5	P6	P7
Modified low energy limit	39.0	84.0	110.0
Modified high energy limit	82.0	200.0	400.0
Modified mid point energy	60.5	142.0	255.0[a]

[a] For the 29 September GLE we used 215 MeV, probably to compensate for the side and rear penetration of the detector by the extreme flux of high energy penetrating particles.

Modified HEPD energy identifier	P8	P9	P10	P11
Modified integral threshold energy	355.0	430.0	485.0	545.0
Modified mid point energy	392.5	490.0	705.0	985.0

Using these conversion factors, the integral HEPD flux seems to agree with the analysis of the solar cosmic ray GLE data. However, when the differential energy flux is converted to differential rigidity flux, the values obtained are not consistent with the GLE analysis. The reasons for this may be that we do not have the correct geometric factors for the instrument. Dr H. Sauer has been developing a new detector area — angular response specification. Our adjustments have been restricted to energy thresholds.

Appendix B. The GOES energetic alpha particle detectors

The energetic alpha particle data are in three different energy ranges from three different sensor systems. The energy ranges of the alpha data channels are listed below. (Data source: NGDC CD-ROM, "GOES Space Environmental Monitor".)

Solid state telescope assembly: A1–A3

Alpha energy identifier	A1	A2	A3
Low energy threshold	3.80	9.90	21.30
High energy limit	9.90	21.30	61.00
Mid point energy	6.85	15.60	41.15

Dome solid state detector assembly: A4–A6

Alpha energy identifier	A4	A5	A6
Low energy threshold	60.0	160.0	330.0
High energy threshold	180.0	260.0	500.0
Mid point energy	120.0	210.0	415.0

High energy (HEPD) Cerenkov detectors assembly; A7–A8

Original HEPD energy identifier	A7	A8
Original low energy limit	630.0	> 850.0
Original high energy limit	850.0	
Original mid point energy	740.0	

Sauer (1995) recommended energy levels for the alpha particle data A3–A8

Adjusted Alpha energy identifiers	A3	A4	A5	A6
Adjusted low energy limit	21.3	60.0	160.0	330.0
Adjusted high energy limit	61.0	180.0	260.0	550.0
Adjusted mid point energy	41.1	120.0	210.0	440.0

Adjusted Alpha energy identifiers	A7	A8
Adjusted low energy limit	625.0	> 800
Adjusted high energy limit	800.0	
Adjusted mid point energy	712.5	

The use of these adjustments still leaves discrepancies in the spectral plots derived from the high energy alpha energy channels. We are currently using the following energy levels for our analysis of the higher energy solar alpha particle data from the GOES spacecraft during ground level solar cosmic ray events Kahler et al. (1997).

Modified alpha energy identifier	A4	A5	A6	A7
Modified mid point alpha energy	120	210.0	435	1020.0[a]

[a] Probable maximum energy dependent response.

Appendix C. Conversion from CD-ROM high energy proton flux data to corrected proton flux developed by Sauer (1995).

Procedure: convert data back to counts, correct for side penetration and apply new geometric factors to obtain corrected flux.

1. Convert data back to counts

   The geometric factors originally applied were:

   A-omega (P8) = 77 cm^2-sr-MeV
   A-omega (P9) = 48 cm^2-sr-MeV
   A-omega (P10) = 369 cm^2-sr-MeV
   A-omega (P11) = 1310 cm^2-sr-MeV

2. Next, make a correction for the pre-event background.
3. Then, correct for side and back penetration.
4. And, convert back to flux.

HEPD corrections from Sauer (1995)

1. Convert back to counts

   P8 data × 77 = c/s
   P9 data × 48 = c/s
   P10 data × 369 = c/s
   P11 data × 1310 = c/s

2. Remove the pre-event background
3. Correct the side and back penetration

   P8 (counts)-0.74 × P11 (counts)
   P9 (counts)-0.11 × P11 (counts)

4. Reconvert to differential flux (change 13 August 1996)

   The geometric factors applied are:

   A-omega (P8) = 67.5 cm^2-sr-MeV
   A-omega (P9) = 67.5 cm^2-s-r-MeV
   A-omega (P10) = 162 cm^2-sr-MeV
   A-omega (P11) = 1565 cm^2-sr-MeV[1]

   P8 (corrected counts)/67.5 = d*j*/d*e* at 293 MeV
   P9 (corrected counts)/67.5 = d*j*/d*e* at 460 MeV
   P10 (corrected counts)/162 = d*j*/d*e* at 595 MeV
   P11 (corrected counts)/1565 = d*j*/d*e*at 1000 MeV

5. Convert to integral flux.

   After correcting P8 and P9 as detailed above, then

   $> 355 = P8 + P9 + P10 + P11$
   $> 430 = P9 + P10 + P11$
   $> 505 = P10 + P11$
   $> 685 = P11$[2]

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[1] The estimated differential geometric factor for interpreting the P11 channel counting rate as the differential flux at 1000 MeV.

[2] The P11 integral flux is inconsistent with the lower energy integral flux values. (NOTE: the derived differential fluxes (d*j*/d*e*) are inconsistent with the $> E$ integral flux.)

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