TDRS-1 SINGLE EVENT UPSETS AND THE EFFECT OF THE SPACE ENVIRONMENT

Daniel C. Wilkinson, NOAA / National Geophysical Data Center, 325 Broadway, Boulder, CO 80303
Stuart C. Daughtridge, INTELSAT, 3400 International Dr. NW, Washington D.C. 20008-3098
John L. Stone, CONTEL Federal Systems, 1500 Conference Center Dr., Chantilly, VA 22021-0814
Herbert H. Sauer, NOAA / Space Environment Laboratory, 325 Broadway, Boulder, CO 80303
Phil Darling, CONTEL Federal Systems, P.O. Box 235, Las Cruces, NM 88004

Abstract

The systematic recording of Single Event Upsets on TDRS-1 from 1984 to 1990 allows correlations to be drawn between those upsets and the space environment. Ground based neutron monitor data are used to illustrate the long-term relationship between galactic cosmic rays and TDRS-1 upsets. The short-term effects of energetic solar particles are illustrated with space environment data from GOES-7.

A. Introduction

The Tracking and Data Relay Satellite System (TDRSS) was designed by NASA to provide communications and high data-rate transmissions for low Earth-orbiting satellites, such as the Space Shuttle, Hubble Space Telescope, Landsat, Cosmic Ray Background Explorer, etc., thereby eliminating the need for a cumbersome network of world-wide tracking stations.

The first satellite in the system, TDRS-1, was launched from the space shuttle, *Challenger*, in April 1983. A failure of the second stage of the Inertial Upper Stage left TDRS-1 short of geosynchronous orbit and the spacecraft's one-pound hydrazine station-keeping thrusters were then used to raise the spacecraft to a geosynchronous orbit (35,784 km altitude, 0° inclination) in July 1983 [1].

During the transfer orbit, the first anomalous responses were observed in the Attitude Control System (ACS), a problem that continues today. These anomalies were traced to state changes in the Random Access Memory (RAM) in the ACS [2]. Upsets of this kind are commonly referred to as Single Event Upsets (SEUs). The most serious ACS anomalies were considered mission-threatening because they could cause TDRS-1 to tumble and attentive ground control was required to maintain proper attitude. The late Don Vinson, an avid pilot, and one of those initially involved in TDRS-1 ground control, once exclaimed, "If this keeps up, TDRS will have to be equipped with a joy stick!"

SEUs are anomalous changes in the state of a memory device that are triggered by an energetic particle penetrating the device and depositing energy along its path. The charge deposition is proportional to Z/v^2, where Z is the atomic number of the particle and v is its speed [3]. Although single protons may not deposit sufficient energy to produce a SEU directly, protons with energies greater than 10-40 MeV (depending on the target device) can produce collisional products which can induce SEUs [4,5,6]. Figure 1 shows the energy deposition in Silicon for three energetic nuclei.

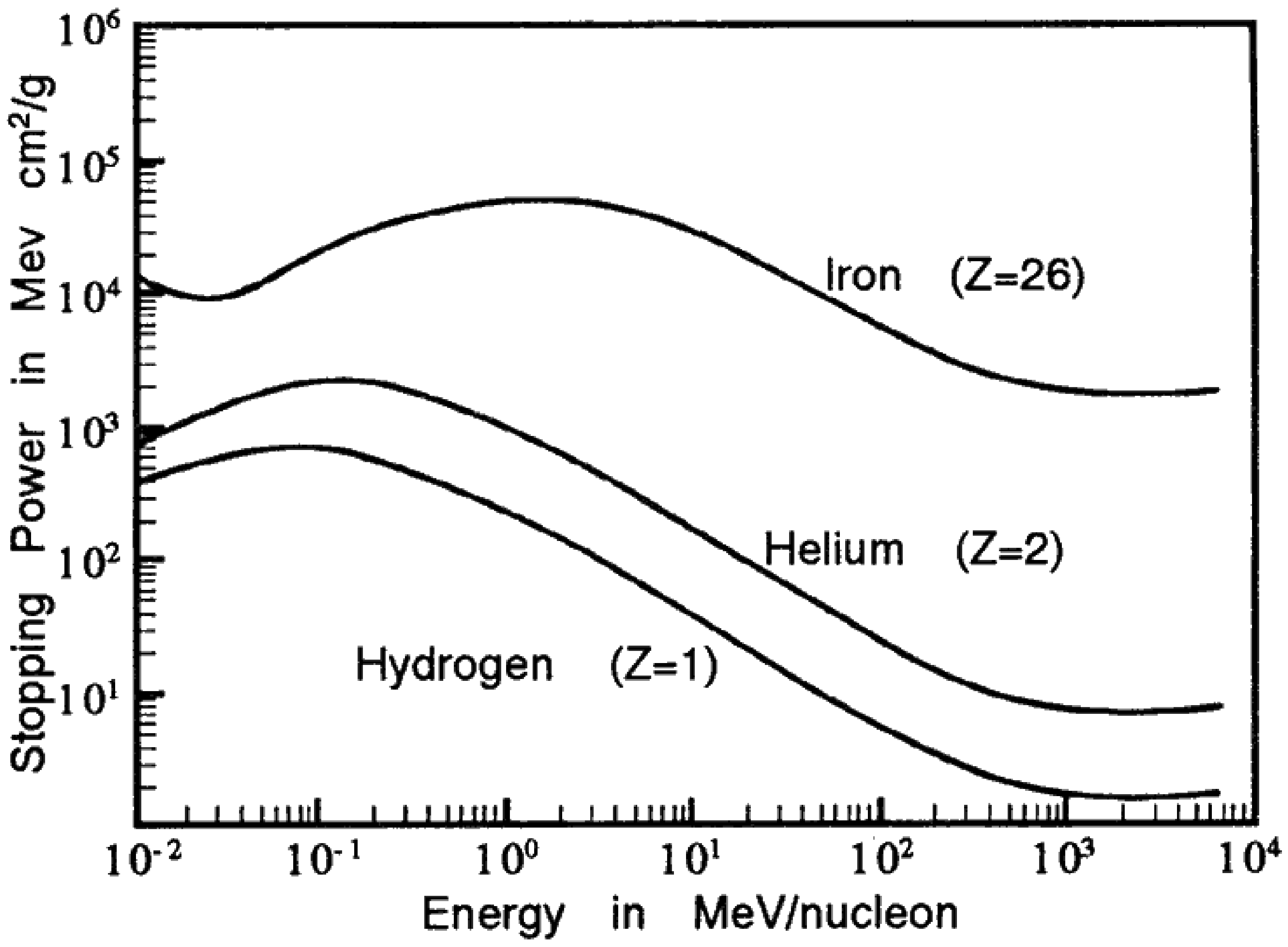

Figure 1. The stopping power in Silicon for Hydrogen, Helium, and Iron [7]. The stopping power for Iron above 10 MeV/nucleon is 1000 times higher than for Hydrogen, demonstrating the importance of heavy ions despite their relatively low abundance (Figure 2).

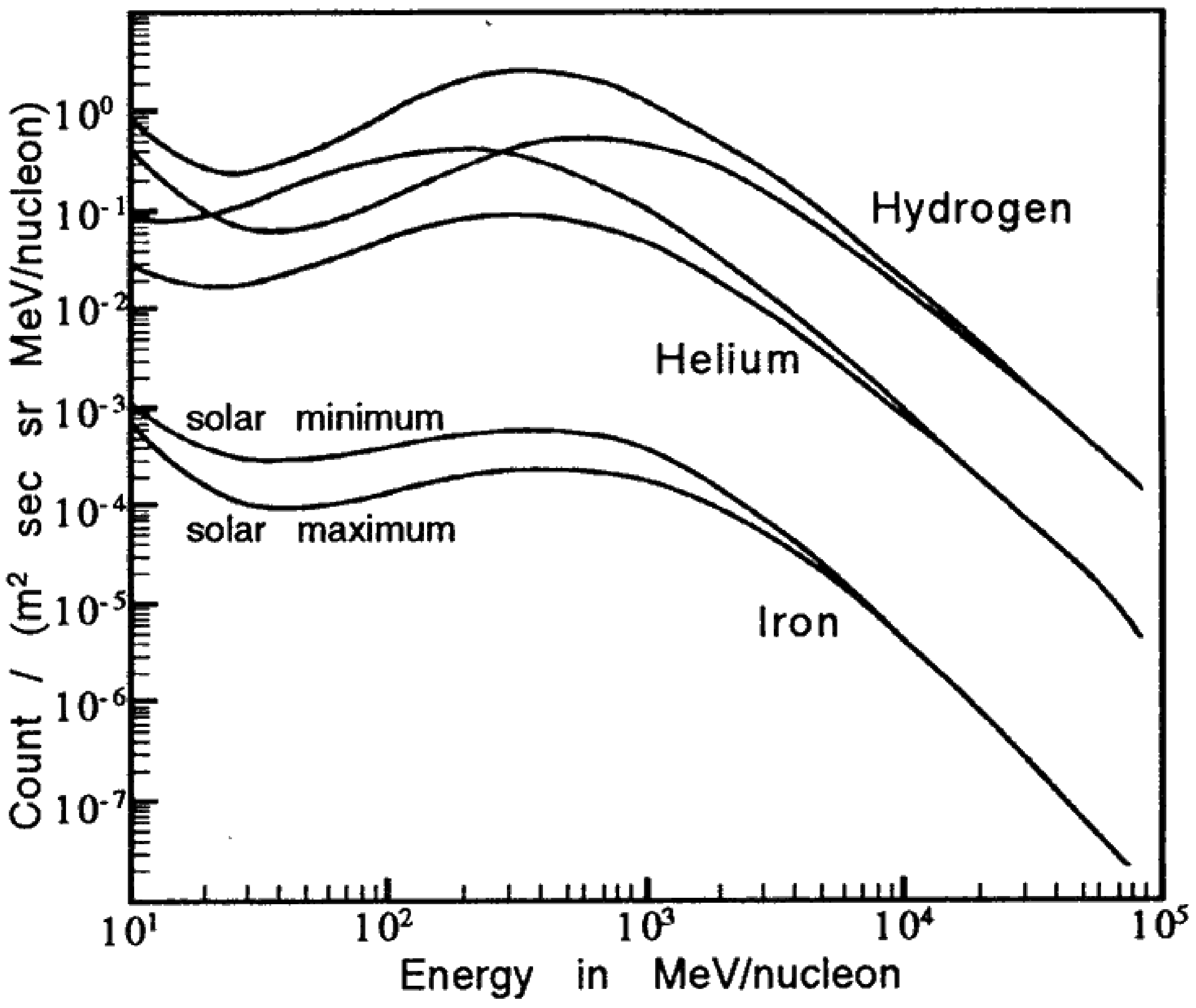

Figure 2. The galactic cosmic ray spectrum of Hydrogen, Helium, and Iron.

0018-9499/91/$01.00 ©1991 IEEE

B. Recording SEUs on TDRS-1

The ACS contains four pages of RAM, 256 bytes per page. Each page consists of two static bi-polar Fairchild 93L422 (256 x 4 bit) RAM chips. Half of the total RAM is in use (Table 1).

Table 1. ACS RAM Usage and SEU History

	Used	1984	1985	1986	1987	1988	1989	1990
Page 0	93%	10	17	22	24	23	14	5
Page 1	57%	71	102	157	131	106	114	57
Page 2	53%	83	254	277	269	258	266	101
Page 3	0%	174	262	302	269	200	259	94
Total	51%	338	635	758	693	587	653	257
SEUs/Chip/Day*		.238	.360	.414	.368	.274	.355	.129
Estimated Total*		696	1048	1208	1076	800	1036	376

*Based on Page 3 SEU count.

The wide discrepancy in the number of SEUs recorded in the four RAM pages is explained by the ability to detect them. The used portions of Pages 0 and 1 contain changing parameters, making SEU detection difficult. Only upsets causing noticeable changes in the ACS operation can be observed. The used portion of Page 2, however, contains static parameters, which are monitored for SEUs via a check-sum algorithm. SEUs in unused RAM are monitored by RAM dumps, which were performed infrequently before April 1986 and weekly thereafter.

The following statement summarizes the quantitative threat to the TDRS-1 mission: "In all 8 chips there are 42 bits in normal mode that will cause sun/earth pointing loss (tumble) if left unattended. Some must be answered in less than 90 seconds" [2].

C. Energetic Particles in Near-Earth Space

There are three primary sources of natural particle radiation in the space environment. 1) Galactic cosmic rays have their source outside the solar system. 2) Energetic solar particles are accelerated into the near-Earth environment by solar flares. 3) Energetic particles in the radiation belts are trapped by closed field lines in Earth's magnetosphere. The weakness of the magnetic field at geostationary altitude, however, prevents trapped radiation from having sufficient energy to be a source of TDRS-1 SEUs.

D. Galactic Cosmic Rays and TDRS-1 SEUs

The energy spectrum of galactic cosmic rays extends from several MeV to energies exceeding 10^{14} MeV, and consists of approximately 84% protons (Hydrogen), 15% alpha-particles (Helium), and less than 1% of heavier nuclei [8]. Figure 2 illustrates the galactic cosmic ray spectrum for Hydrogen, Helium, and Iron for solar minimum and maximum conditions. Galactic cosmic radiation has an approximate 11-year solar cycle variation, in which the flux is maximum at solar minimum and minimum at solar maximum. Long-term data on galactic cosmic rays are available from ground-based neutron monitors--instruments that indirectly detect cosmic rays by measuring the neutron flux that results from a cascade of nuclear collisions that occurs when relativistic (>400 MeV/nucleon) particles strike atmospheric constituents [9].

Neutron monitor data from Deep River, Canada (Figure 3) illustrate the inverse relationship with the solar cycle. This relationship results from the effect that solar activity has on the interplanetary medium. As solar activity increases, as indicated by an increasing sunspot number, the interplanetary medium becomes more disturbed and increases the shielding of galactic cosmic rays. Galactic cosmic rays in the low end of the energy spectrum can vary by as much as 400% between solar minimum and solar maximum (Figure 2). The Deep River neutron monitor varies only 15% - 20% over a solar cycle because geomagnetic and atmospheric shielding limits ground based measurements to only the higher energies--energies that vary only slightly over a solar cycle (Figure 2).

Figure 4 is an expanded view of the SEU interval in Figure 3. The TDRS-1 weekly SEU count shown in these figures begins in April 1986 to take advantage of the systematic SEU monitoring that began at that time and includes all observed SEUs. Since some SEUs go unobserved, the SEU rate shown in this plot is a minimum. See Table 1 for an estimation of the actual SEU rate. The envelope of the TDRS-1 SEUs clearly follows the solar-cycle modulation of the galactic cosmic rays. The spikes in August, September and October 1989 are responses to solar flares. The off- scale responses in September and October are for weekly SEU totals of 88 and 157 respectively.

There are two kinds of solar-terrestrial events that impose short-term variations on the energetic particle flux. Depressions in the galactic cosmic ray flux, termed Forbush Decreases, last from hours to days, and result from outwardly propagating interplanetary disturbances produced by impulsive solar events (i.e., solar flares, coronal mass ejections, or high speed streams) [10]. Further, some solar flares produce energetic particles that can enhance the near-earth energetic particle populations by five orders of magnitude. Enhancements in a neutron monitor count due to energetic solar particles, termed Gound Level Events (GLEs), occur when solar particles with sufficient energy (>400 MeV/nucleon), strike the upper atmosphere and initiate a nuclear cascade that reaches Earth's surface. The neutron monitor data in

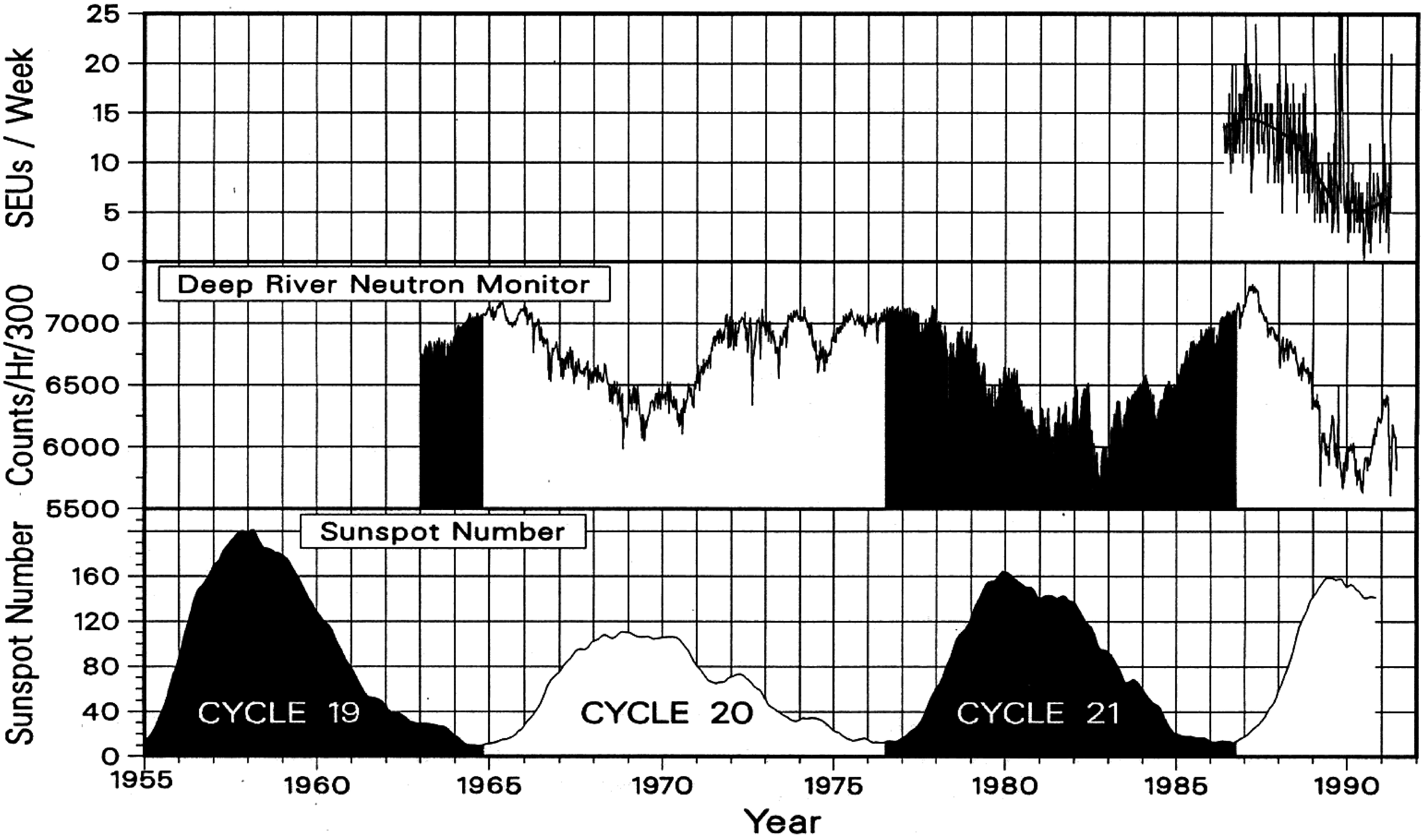

Figure 3. Illustration of the inverse relationship between galactic cosmic rays, represented by neutron monitor data, and the solar cycle, represented by the sunspot number. The neutron monitor data are weekly averages of hourly counts. The sunspot numbers are smoothed monthly values.

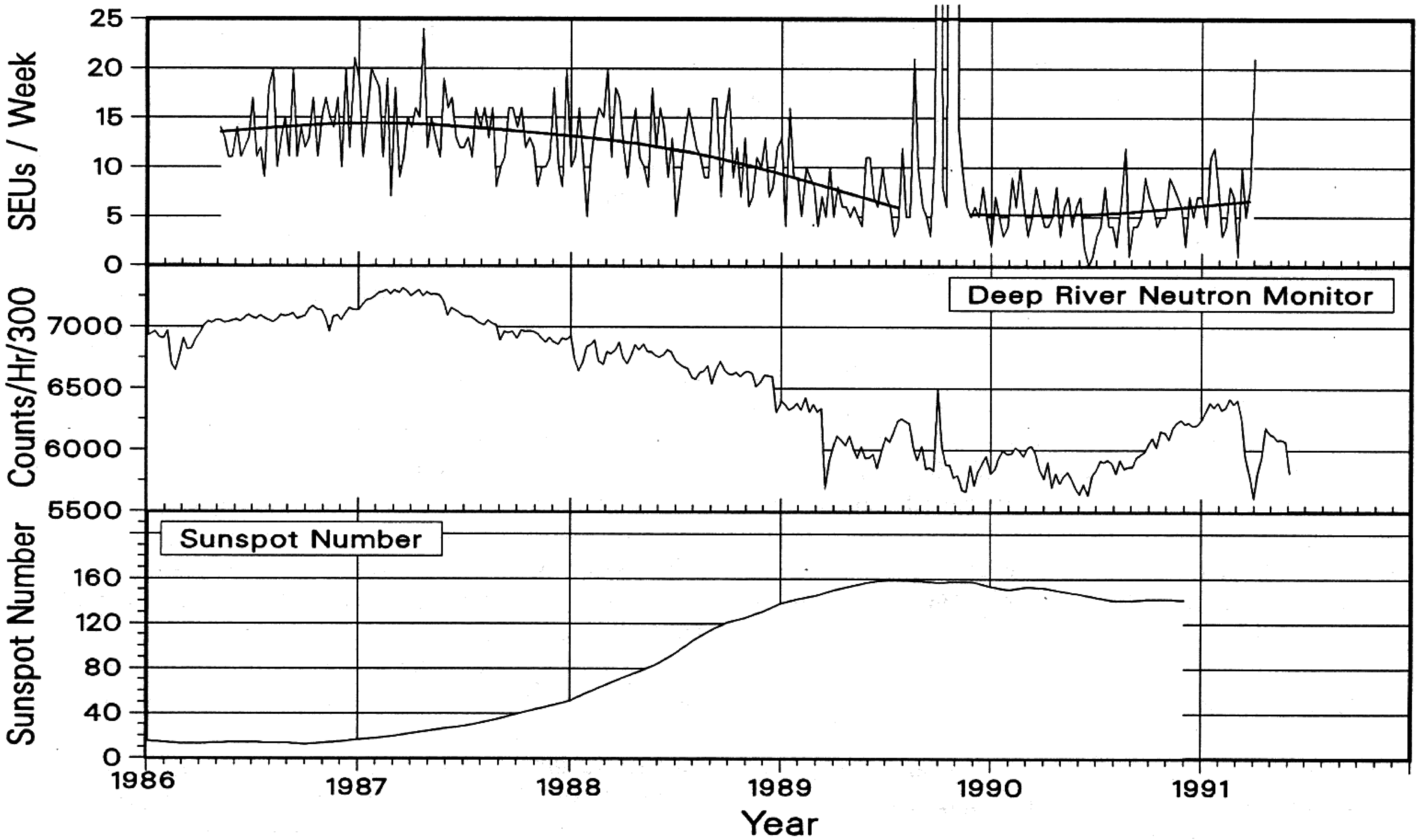

Figure 4. Expanded view of the SEUs plotted in Figure 3. showing that the envelope of the TDRS-1 SEUs clearly follows the modulation of the galactic cosmic rays. The smoothed line through the TDRS data was created by using a cubic spline function. The spikes in September and October 1989 reach 88 and 157 SEUs per week respectively.

Figure 4 shows several Forbush Decreases, the most notable in March 1989 and March 1991. Figure 4 also shows the extraordinary GLE that occurred near the end of September 1989--the second largest ever recorded [11].

E. Energetic Solar Particles and TDRS-1 SEUs

The series of large solar flares in August, September, and October of 1989 caused a substantial response in the TDRS-1 SEU rate. These flares were associated with particle events that produced five GLEs during this period, indicating an extremely high-energy component to the total flux. During these three solar activity intervals, August 12-17, September 29-October 1, and October 19-25, TDRS-1 recorded 23, 91, and 249 SEUs respectively.

Figure 5 shows the effect of the October 19, 1989, solar flare on the near-Earth space environment as recorded by the Geostationary Operational Environmental Satellite (GOES-7). The 1-8 Angstrom X-ray detector shows the flux going off-scale at 1300 UT. An estimation of the peak flux resulted in an X13 classification.

The proton panel of Figure 5 shows the very steep onset of a solar particle event as measured by GOES-7. During energetic particle events, the GOES particle sensors overestimate the true flux by high-energy particles entering lower energy detectors. However, even after correction, the total fluence of this event is comparable to that of August 1972, the largest of the satellite era [12]. The second enhancement of the proton flux that occurred on the 20th was due to the arrival of an interplanetary shock. The mass spectrum of energetic solar particles consists of 87% protons, 12% alpha-particles, and less than 1% of all heavier nuclei [10]. The proton component has been shown by Normand and Stapor [13] to be the primary cause of TDRS-1 SEUs during solar flares.

The Deep River neutron monitor panel shows the signature of a GLE. This observation, together with others,

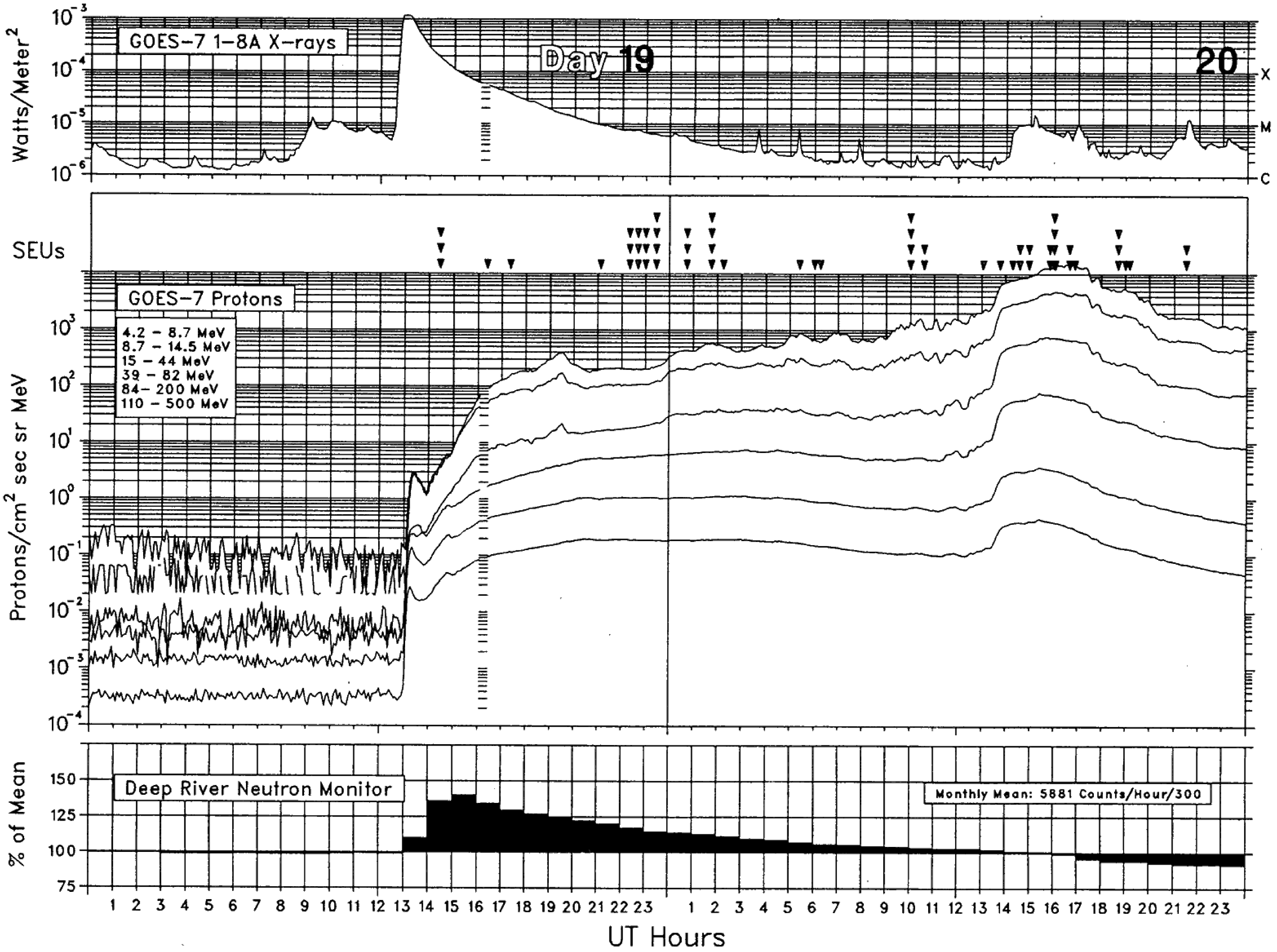

Figure 5. Effects of the October 19, 1989 solar flare on the near-Earth space environment as recorded by GOES-7 and the Deep River neutron monitor. The SEU panel shows upsets from either operational anomalies or Page 2 check-sum errors. The indication of multiple upsets is due to the way the SEU reports were recorded rather than the occurrence of legitimate multiple hits. Each arrow represents one SEU.

indicates that the solar particle spectrum extended well beyond 1000 MeV/nucleon.

The SEU panel shows upsets that resulted in either operational anomalies or Page 2 check-sum errors. The indication of multiple upsets is due to the way the SEU reports were recorded rather than the occurrence of legitimate multiple hits. SEUs found in dumps of unused RAM are not included because they lack sufficient time information.

F. SEUs on Subsequent TDRS

Experience with the high SEU rate on TDRS-1 prompted changes to be made in the ACS design on TDRS-3 and TDRS-4. TDRS-2 was lost with *Challenger*. The Fairchild static bi-polar 93L422 RAMs were upgraded to the hardened RCA CMM5114 CMOS/SOS. Using the October 1989 solar cosmic ray interval for comparison, we consider the upgraded RAM to be an unqualified success. During this period, TDRS-3 and TDRS-4 recorded no known SEUs in the upgraded ACS while TDRS-1 recorded 249!

Ground tests of the Fairchild 93L422 and the RCA CMM5114 CMOS/SOS verify the on-orbit experience with these two memory devices [14]. The test results, shown in Table 2, provides two indicators of SEU sensitivity. High values for effective Linear Energy Transfer (LET) threshold represents low SEU sensitivity. High values for the device upset cross section indicate high SEU sensitivity.

Table 2. SEU Ground Tests

Device	Mfr	Bits	LET*	Cross Section**
CMM 514 CMOS/SOS	RCA	4K	58.0	No Upsets
93L422 bi-polar	Fairchild	1K	1.6	.02

*Effective LET threshold in MeV/(mg/cm^2). Threshold is condition for no upsets for fluence >= 10^6 ions/cm^2.

**Device upset cross section in upsets/fluence for 120-200 MeV Krypton ions at normal incidence, having an LET = 37 MeV/(mg/cm^2).

G. Conclusion

The high susceptibility of the TDRS-1 Attitude Control System to Single Event Upsets and the systematic long-term recording of those upsets have provided convincing evidence of their source. The solar-cycle modulation of galactic cosmic rays can be used in conjunction with such a SEU history to correlate SEU rate with galactic cosmic rays. Also, space environment monitors, like those on GOES-7, can be used effectively to correlate energetic solar particle events with increased SEU rates in geosynchronous orbit.

H. References

[1] J. Schmeichel and B.J. Ehlers, "In-Flight Rescue of Stranded TDRS-1 Spacecraft," AAS Annual Rocky Mountain Guidance and Control Conference, Keystone, Colorado, February 1984.

[2] D. Vinson, "TDRSS Anomalies," Proceeding - Spacecraft Anomalies Conference, Edited by V.G. Patterson and J.S. Schleher, in Colorado Springs, Colorado, October 30-31, 1984, pp. 94-109.

[3] M.W. Friedlander, Cosmic Rays, (Harvard Univ Press, Cambridge, MA, 1989), pp. 13, 61-62.

[4] P.J. McNulty, G.E. Farrel, R.C. Wyatt, P.L. Rothwell, R.C. Filz, and J.N. Bradford, "Upset Phenomena Induced by Energetic Protons and Electrons," IEEE Trans. on Nucl. Sci. NS-27 No. 6, 1980, pp. 1516-1522.

[5] W.L. Bendel and E.L. Petersen, "Proton Upsets in Orbit", IEEE Trans. on Nucl. Sci., NS-30 No.6, December 1983, p. 4481.

[6] Y. Takami, F. Shiraishi, T. Goka, Y. Shimano, M. Sekiguchi, K. Shida, N. Kishida, H. Kadotani, T. Kikuchi, N. Hoshino, S. Murakami, H. Anayama, and A. Morio, "Investigation of Single Event Upset Subject to Protons of Intermediate Energy Range", IEEE Trans. on Nucl. Sci., NS-37 No.6, December 1990, p. 1953.

[7] J.H. Adams, Jr., Cosmic Ray Effects on Microelectronics, Part IV, NRL Memorandum Report 5901, December 1987, p. 25.

[8] B. Rossi and S. Olbert, Introduction to the Physics of Space, (McGraw Hill, New York, 1970), p. 206.

[9] B. Rossi and S. Olbert, Introduction to the Physics of Space, (McGraw Hill, New York, 1970), pp. 83-120.

[10] M.W. Friedlander, Cosmic Rays, (Harvard Univ Press, Cambridge, Mass, 1989), pp. 41-52.

[11] M.A. Shea, "Solar Cosmic Rays, 1960-1989", 21st International Cosmic Ray Conference, Conference Papers, Vol. 12, Melbourne, Australia, January 1990, pp. 196-204.

[12] H.H. Sauer, R.D. Zwickl and M.J. Ness, Summary data for the Solar Energetic Particle Events of August through December 1989, NOAA Space Environment Laboratory Report, Boulder, Colorado, 1990.

[13] E. Normand and W.J. Stapor, "Variation in Proton-Induced Upsets Rates from Large Solar Flares Using an Improved SEU Model," IEEE Trans. on Nucl. Sci., NS-37 No.6, December 1990, p. 1947.

[14] D.K. Nichols, W.W. Price, W.A. Kolasinski, R. Koga, J.C. Pickel, J.T. Blandford, Jr, and A.E. Waskiewicz, "Trends in Parts Susceptibility to Single Event Upset from Heavy Ions," IEEE Trans. on Nucl. Sci., NS-32 No.6, December 1985, p. 4189.