REVIEW OF MARCH 1989 SOLAR ACTIVITY AND RESULTANT GEOMAGNETIC STORM

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Abstract

A large, complicated sunspot region rotated onto the visible disk of the sun on March 6, 1989, and raised solar activity to very high levels for 06-19 March. The region's output was intense, setting new records for the current solar cycle. In particular, the largest geomagnetic storm since 1960 occurred on March 13 and produced auroral sightings as far south as Florida and Texas. Numerous technical systems were affected by the activity including spacecraft operations, the space surveillance network, HF communications, VLF (such as LORAN) communication, and electrical power systems. More recent solar-geophysical activity in August-October 1989 has also been impressive, suggesting that a remarkable solar cycle is currently in progress. Real-time information and forecasting of the space environment is available from the Space Environment Services Center (SESC), a joint National Oceanic and Atmospheric Administration (NOAA) and U.S. Air Force operation.

The Space Environment Services Center (SESC)

SESC is jointly operated by the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Air Force and provides continuous real-time monitoring and predicting of solar-geophysical activity. The center also functions as the world warning agency for an international network of similar organizations. SESC issues a number of products including forecasts, warnings, and alerts of disturbances to a wide variety of users who are affected by the state of the space environment.

SESC collects solar-geophysical data from a worldwide network of ground based and spacecraft observatories. Observatories in Australia, Italy, Puerto Rico, Canada, New Mexico, Arizona, California, and Hawaii report solar optical and radio data to SESC. Measurements of geomagnetic field variations are made locally in Boulder and are received from many locations on various communication networks including an international communications network, and the Remote Geophysical Observing Network which covers much of Canada and parts of the U.S. Total solar x-ray output, the energetic particle environment, and the geomagnetic field at geostationary orbit are monitored by the NOAA Geostationary Operational Environmental Satellites (GOES). Additional particle data are received from the polar orbiting NOAA satellites.

The Solar Cycle

The discovery that sunspots follow a 10 to 11 year cycle was made in the 19th century by Schwabe (1844). Figure 1 is a plot of monthly sunspot numbers. Note that the cycles do show some variation in size and duration.

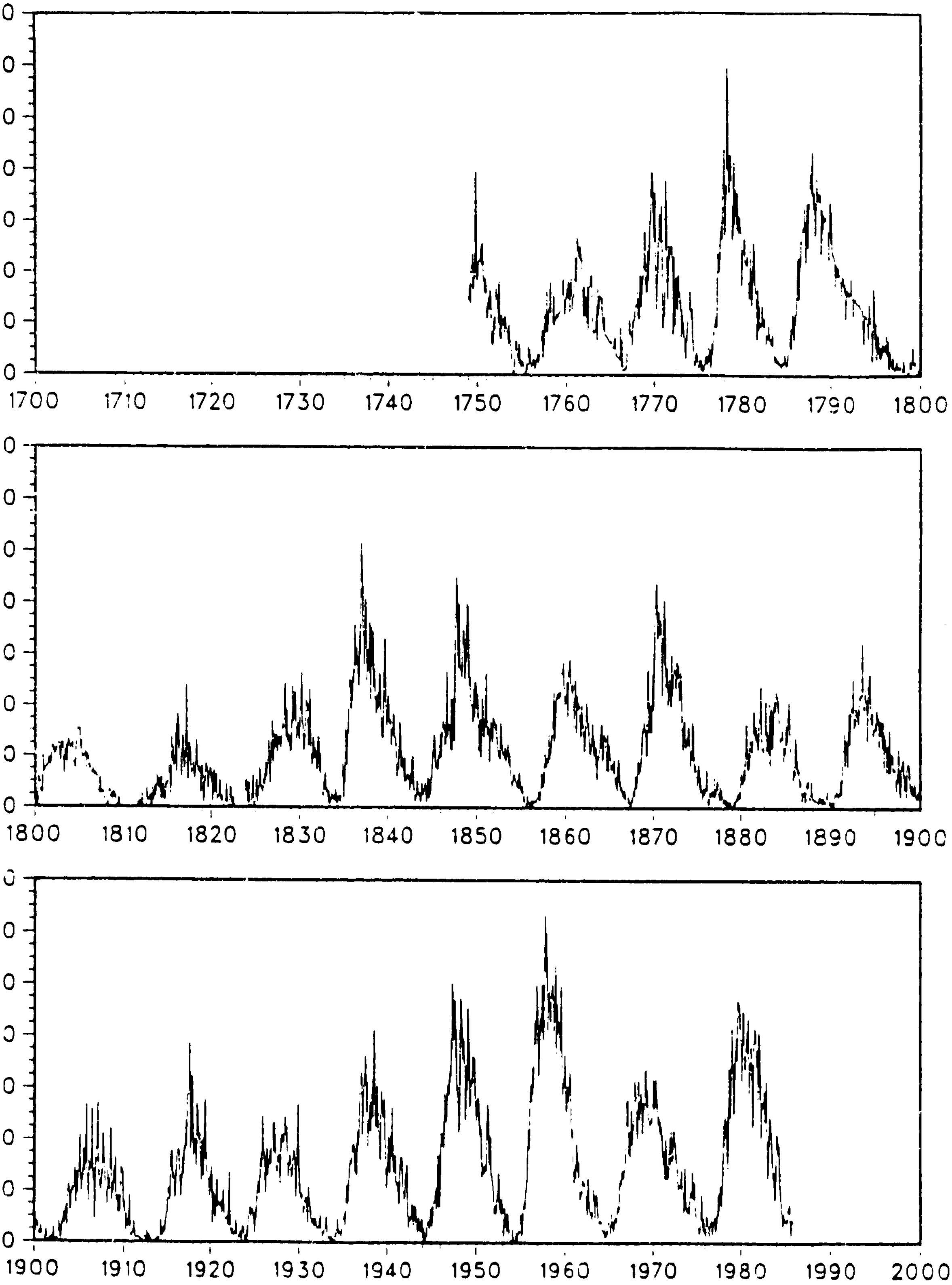

Figure 1. The sunspot cycle.

Associated with the sunspot cycle is the solar activity cycle which generally follows the sunspot cycle. One illustration of the solar activity cycle is the monthly totals for optical flares for solar cycles 20-22 as shown in Figure 2 . Optical flares are brightenings at visible wavelengths in sunspot regions as observed by special filters. Other indicators of solar activity

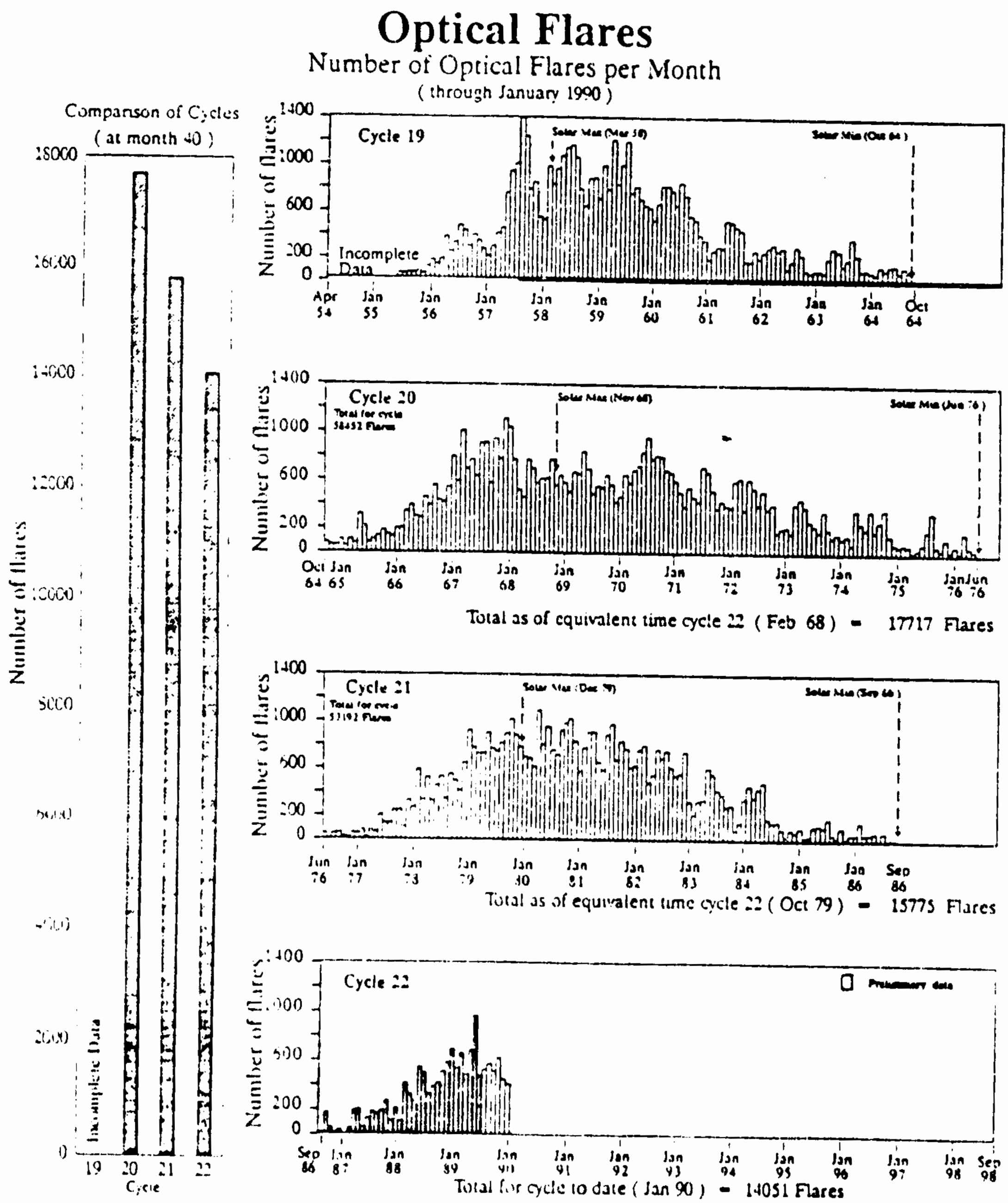

Figure 2.

Source: Preliminary Report and Forecast of Solar-Geophysical Activity, published weekly by SESC include x-ray flares, energetic particle events, and ground level events. X-ray flares are measurements of x-ray emission during a flare, and are classified according to the peak flux measurement of the event as shown in the table below.

Peak flux range $(W/m^2)(\varphi$ = peak flux)	X-ray flare Classification	Example
$\varphi >= 10^{-4}$	X	$\varphi = 3.2 \times 10^{-4}$ is X3.2
$10^{-4} > \varphi >= 10^{-5}$	M	$\varphi = 7.2 \times 10^{-5}$ is M7.2
$10^{-5} > \varphi >= 10^{-6}$	C	$\varphi = 5.9 \times 10^{-6}$ is C5.9

Energetic particle events are enhancements above background of the flux of measured particles. SESC defines an event as when the flux of energetic protons reaches or exceeds 10 protons/cm^2/s/steradian at greater than or equal to 10 MeV. Ground level events occur when very energetic particles from solar flares reach the earth in sufficient quantity that secondary emissions (neutrons) are measured with ground based instruments. An SESC defined ground level event is when the neutron counts exceed 5% of the background level.

Although long term predictions of the solar cycle are difficult to make, one can conclude from Figure 2 that the current solar cycle 22 is still young, and that we should be expecting high levels of activity to continue over the next 3-4 years.

Solar-Geophysical Activity for 6 - 19 March, 1989

The time period from 6 to 19 March was remarkable for solar-geophysical activity. In particular, the geomagnetic disturbance of 13-14 March was historically one of the largest on record. The usual method of measuring the level of disturbance of the earth's magnetic fields is by means of geomagnetic indices.

In this paper, reference will be made to the K-index and the A-index. The K-index is a 'quasi-logarithmic' index which is calculated every three hours by determining the difference between the actual magnetic field variation (in nanotesla) and what would be expected under quiet conditions. This difference is then converted to a K-index using a look-up table specific to each observatory. The A-index is a 24 hour index of the magnetic field disturbance and is derived from the K-indices. The method is as follows: for each K-index, there is an equivalent a_k (lowercase 'a') three hourly index known as the equivalent amplitude. The A-index is then calculated as the average of eight, three-hourly a_k indices and is a number ranging between 0 and 400. The distribution of the A-index as measured by an observatory in Fredericksburg Virginia is shown in Figure 3. This allows us to put the March 13-14 disturbance in proper perspective. The Fredericksburg A-index was determined to be 248, the largest observed since 1960.

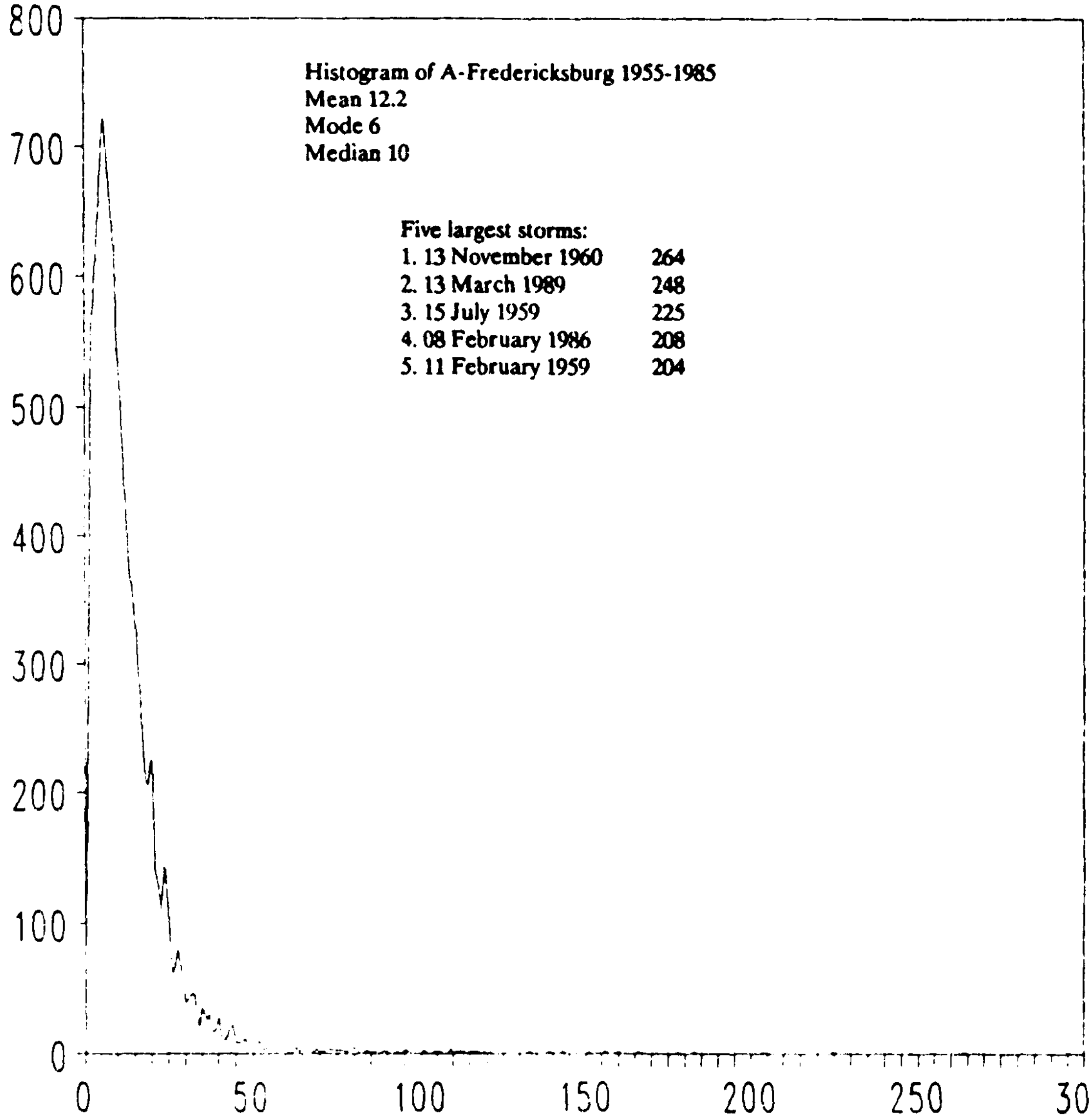

Figure 3. Histogram of the Fredericksburg A-index

Figure 4 is a composite panel of solar x-ray output, measurements of the 9-14 MeV proton fluxes, and the pseudo-Kp index (a real-time estimate of the planetary K-index) during the period. The region's x-ray flare emission consisted of 11 X-class events and 48 M-class events. Of these, three were particularly interesting: the estimated X15 (15×10^{-4} watts/m^2) on the 6th, which saturated the GOES x-ray sensors, the X4/4B flare on the 9th which attained the maximum of possible optical classifications (4B), and the X4/3B of 10 March, which was of long duration and was most likely the source of the great 13 March storm.

The particle panel shows the measured proton flux during the period. These proton events did not have large fluxes of extremely energetic protons.

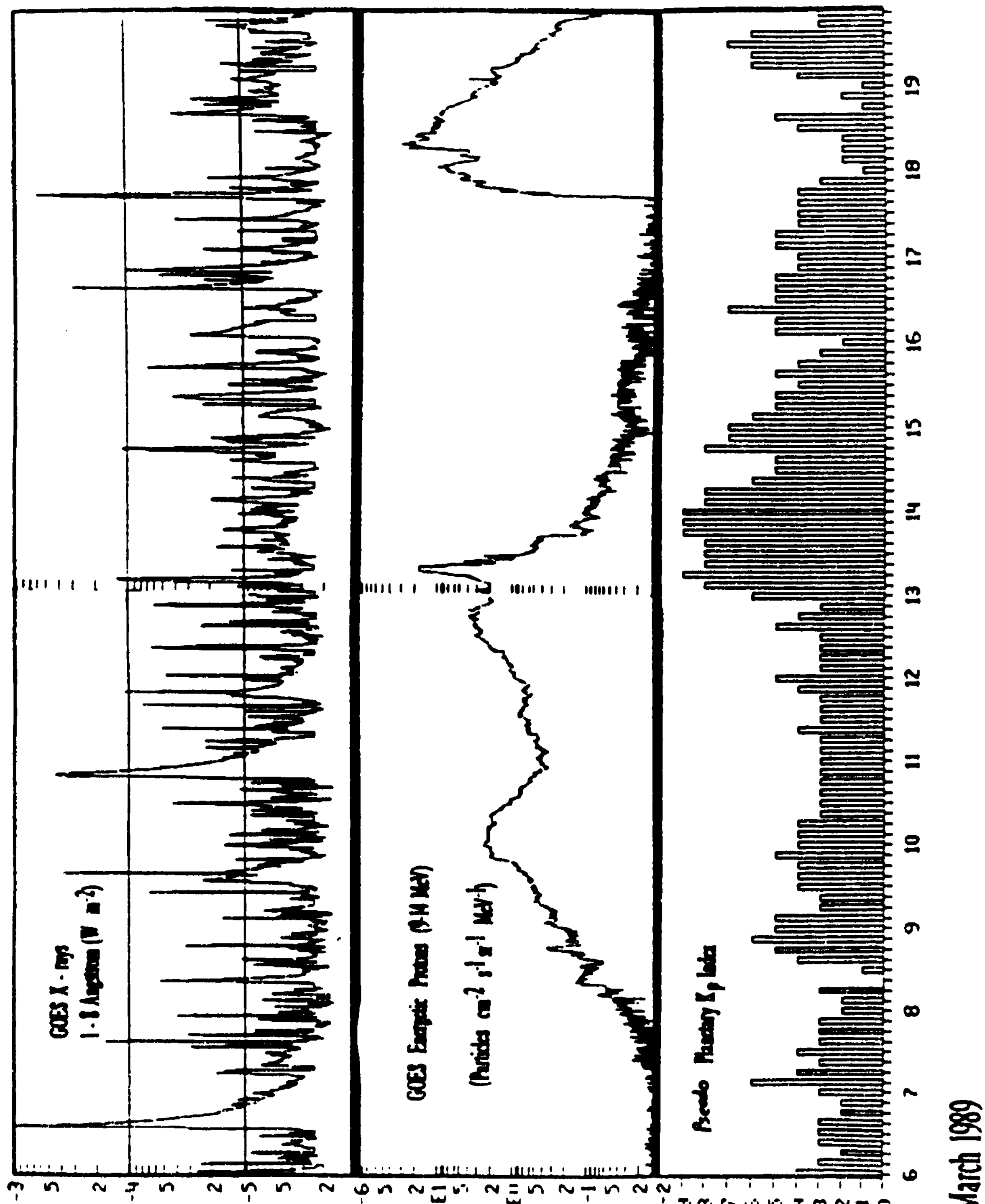

Figure 4.

X-ray, Particle, and pseudo Kp from 06-19 March 1989.

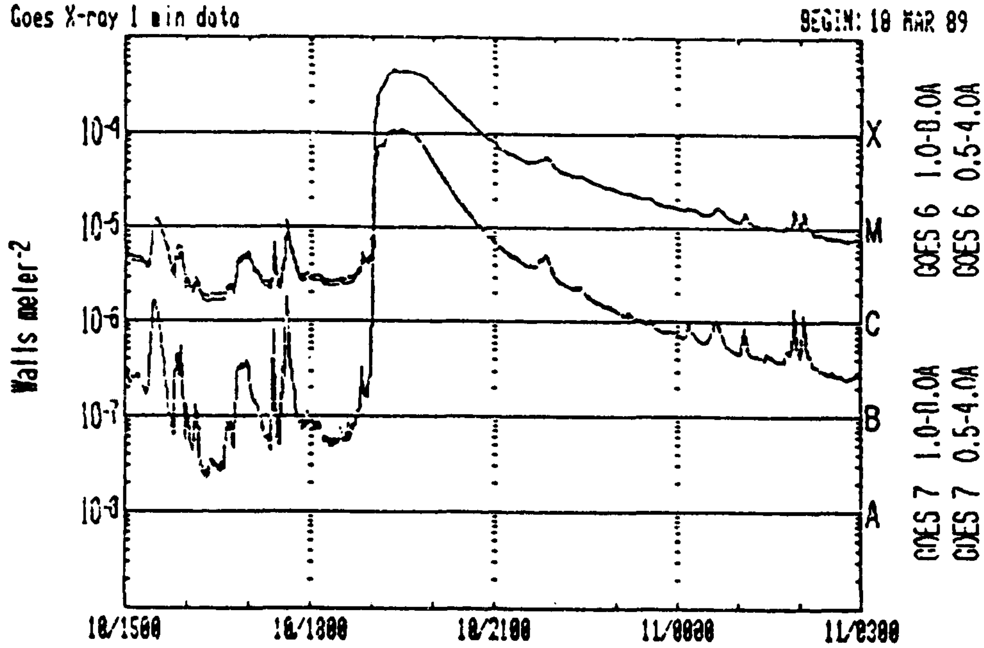

Figure 5. X-ray flux profile for X3/4B flare of 10 Mar 89

The main geomagnetic response to the solar activity was on 13-14 March. Figure 5 shows the X-ray emission from the X4/3B of 10 March. The event was very long in duration, indicative of a coronal mass ejection, an acceleration of plasma away from the sun and into interplanetary space. If the trajectory of this plasma cloud is earthward, and the magnetic fields in the cloud interact favorably with the earth's magnetosphere, a geomagnetic storm results. And such was the case of March 13. A sudden storm commencement was observed at 0128UT on 13 March, signaling the initial impact of the plasma cloud on the earth's environment. Extreme magnetic field variations were observed worldwide, but it was between 13/2100UT-14/0300UT that the disturbance was most severe in the U.S.

Numerous system effects which were observed at the time of the storm have been documented elsewhere (Allen, 1989), so these are now discussed here only in general terms. Geomagnetic storm conditions are associated with frequent injections of energetic electrons (10's to 100's of KeV), which have been known in the past to cause surface charging difficulties for some satellite systems. In addition earth surface potentials can develop in areas of non-conducting geology, and this can lead to induced currents in long line systems. Such induced currents can lead to operational difficulties; in particular electrical power systems and longline communications links can be affected. Solar x-ray activity and the geomagnetic activity affect the earth's ionosphere in differing ways yet with the same consequence: numerous radio communications which use or transit the ionosphere are affected and unusual operational behavior is observed.

Solar Activity update: major events since March 1989

Since March, 1989, the sun has continued to produce remarkable activity. In particular, high solar activity and intense particle events were observed during 12-17 August, 29 September to 05 October, and from 19-31 October. These events are briefly discussed in the following sections. It should be noted that the data for particle fluxes in figures 6 - 9, and the values referenced in the text were those available at SESC at the time of the events of interest. Recently, corrections have been made in the particle algorithm to subtract excess counts introduced by high energy particle contamination. The corrected data plots can be found in Zwickl and Kunches (1989).

12-17 August

Active region 5629 produced two weeks of remarkable solar-geophysical activity. In particular, the region produced the largest solar x-ray event on record. The event saturated the GOES sensors at X12 for about 25 minutes and the peak flux was estimated by SESC to be X20 (2×10^{-3} watts/m^2). Flares from the region resulted in the largest proton event that had been seen since August 1972, although it would soon be surpassed by events which followed in later months. Figure 6 is a plot of the x-ray flux and proton flux profiles during the period.

Late on 11 August flare activity picked up noticeably: the region produced 3 M-class events within 9 hours, and one of these was the region's first major flare, an M5/1B at 2302UT. The subsequent days were marked by a series of five X-class x-ray events, a complicated proton event, and a period of increased geomagnetic activity.

The first X-class flare occurred at 12/1427UT: an X2/2B. A proton event started shortly thereafter at 1600UT. The proton event attained maximum of 9200* protons/cm^2/s/steradian at 13/0710UT. This peak flux was the largest since August 1972: A comparison of peak fluxes shows that the August 1972 event was about 6 times the size of this event. A major geomagnetic storm, presumed to be produced as a result of this flare, began at 14/0614UT and lasted through the 15th.

The largest X-class event from the region was the record-breaking X20/2N (S18W84) which attained maximum at 16/0118UT. The event was of long duration and had all the signatures typical of a big flare. High energy particle enhancements began at 0140UT and the high-energy fluxes rose quickly to 58* protons/cm^2/s/steradian at greater than 100 MeV by 16/0500UT. Increases on the already enhanced greater than 10 MeV channels were less dramatic but resulted in a secondary maximum of 2300* protons/cm^2/s/steradian at 16/1430UT. Neutron monitor data indicated that a ground level event also occurred as a result of this flare.

*Uncorrected

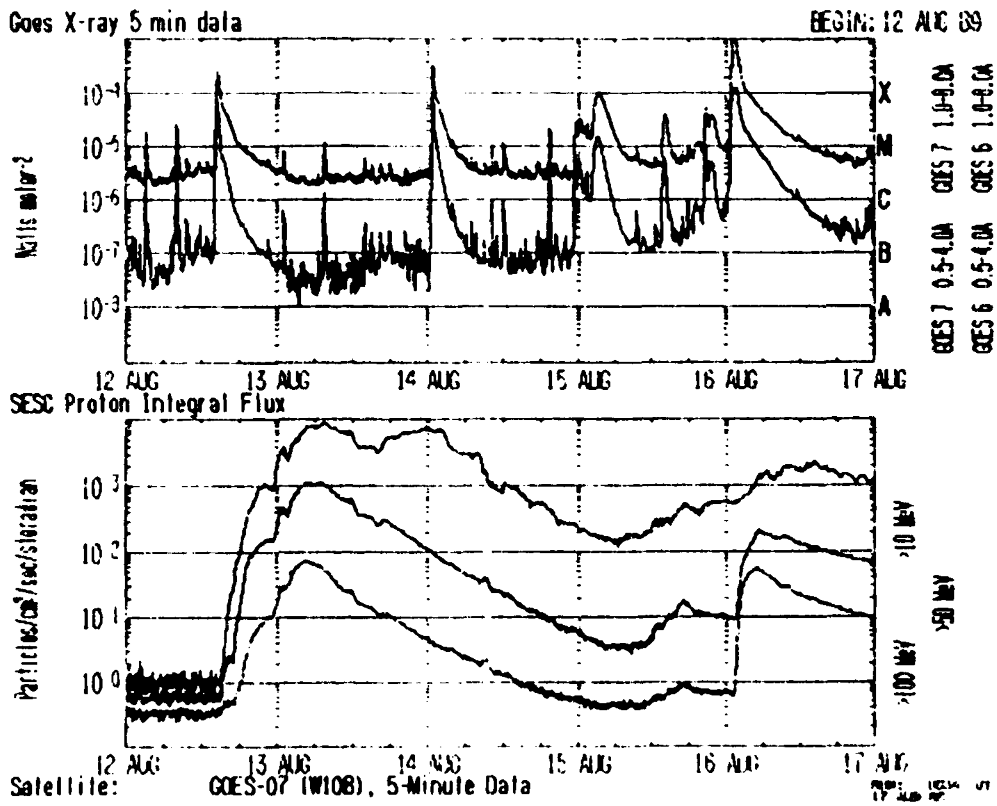

Figure 6. X-ray (top) and proton (bottom) flux profiles during the period. In the top panel, the upper trace is the x-ray emission at 1.0-8.0 Angstrom, and the lower trace is 0.5-4.0 Angstrom. X-ray classifications are based on the 1.0-8.0 Å band. In the bottom panel the different traces show the uncorrected proton fluxes which exceed different energy levels as follows: the upper trace is for energies ≥ 10 MeV, the middle trace is for energies ≥ 50 MeV, and the bottom trace is for energies ≥ 100 MeV.

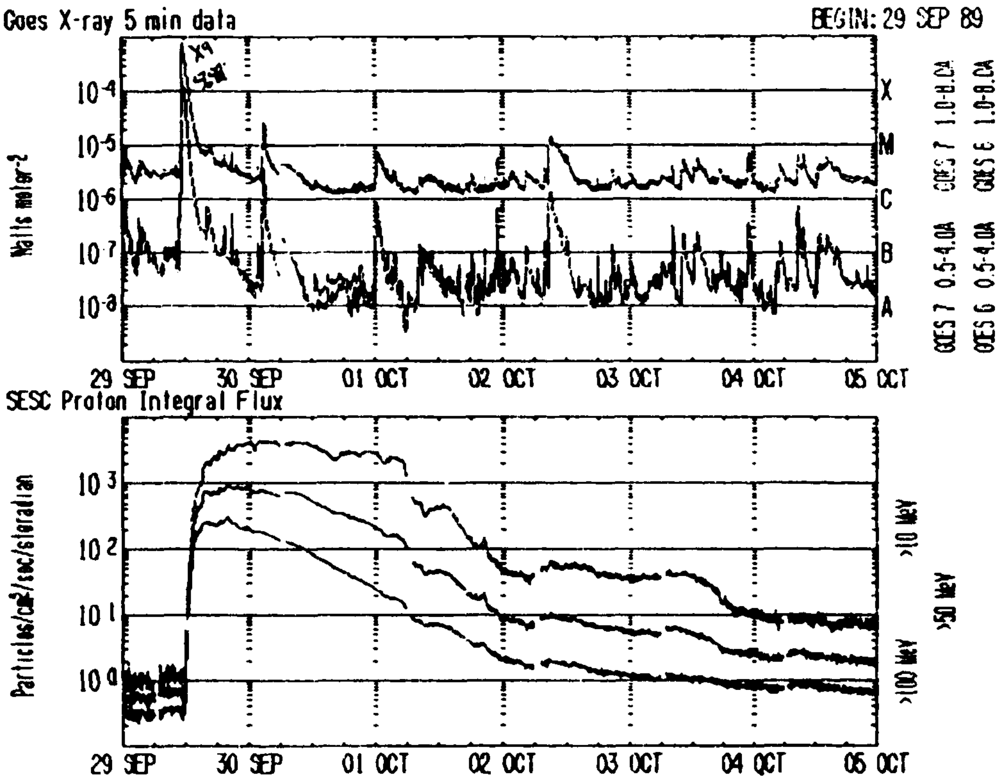

Figure 7. X-ray and particle fluxes, 29 Sep - 05 Oct 1989

29 September - 05 October

The x-ray flux and particle flux profiles for this time period are illustrated in Figure 7. High levels of solar activity occurred on 29 September as SESC region number 5698 produced an X9 x-ray flare at 1133UT as it was going around the sun's west limb. As an immediate consequence of the flare a very energetic particle event started at 29/1205UT, and a ground level event also began. The greater than 10 MeV proton fluxes attained a peak of 4800* protons/cm^2/s/steradian, and the greater than 100 MeV proton fluxes attained a peak of 310* protons/cm^2/s/steradian. The ground level event attained a peak of 500 percent above background and was noted as the largest GLE observed since 1959 at the time.

19-31 October

This phenomenal period of solar-geophysical activity began with the return of old region 5698 which was assigned as SESC region 5747. A plot of the x-ray and particle emission is displayed in Figure 8. During the region's transit it produced 5 X-class flares and 22 M-class flares. Three of these X-class events led to three separate ground level events and high energy particle flux enhancements in the earth's space environment. These are described as follows: on 19 October at 1958UT an X13/4B flare occurred which produced a proton event which attained a peak flux of greater than 10 MeV particles of 73000* protons/cm^2/s/steradian at 20/1600UT, a peak flux of greater than 100 MeV particles of 680* p/cm^2/s/steradian at 20/1530UT, and a ground level event of 45% above background. The next injection of particles occurred in response to an X2/2B flare at 22/1805UT and resulted in 8300* protons/cm^2/s/steradian at greater than 10 MeV at 23/0710UT, 230* protons/cm^2/s/steradian

*Uncorrected

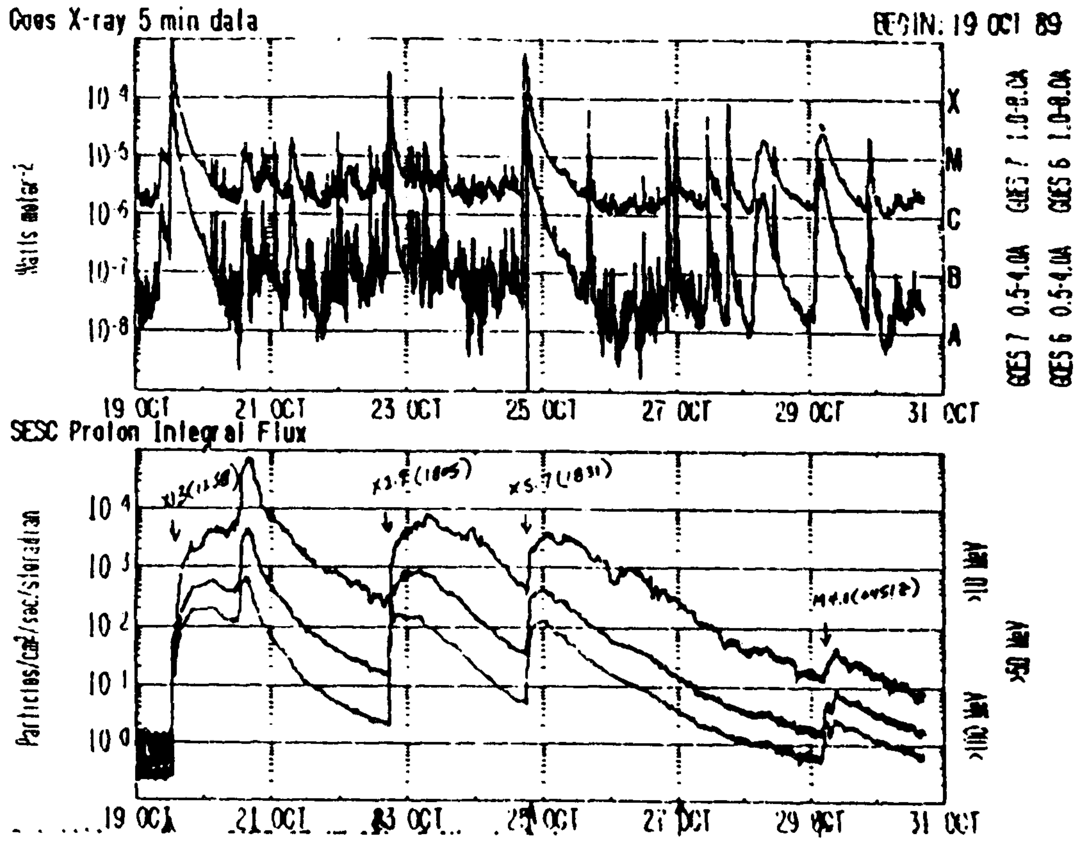

Figure 8. X-ray and particle fluxes, 19-31 October 1989

at greater than 100 MeV at 22/1855UT, and 25% ground level event. The third injection resulted from an X5/3B flare at 24/1831UT, with a peak of greater than 10 MeV protons of 4100* protons/cm^2/s/steradian at 25/0210UT, 130* protons/cm^2/s/steradian at greater than 100 MeV at 25/0015UT, and a 90 percent ground level event. A comparison plot of proton flux profiles for August 1972, August 1989, and October 1989 is shown in Figure 9. The geomagnetic response to these events peaked from 20-22 October which witnessed major to severe storm conditions. The Fredericksburg A-indices from 20-22 October were 64, 86, and 29.

*Uncorrected

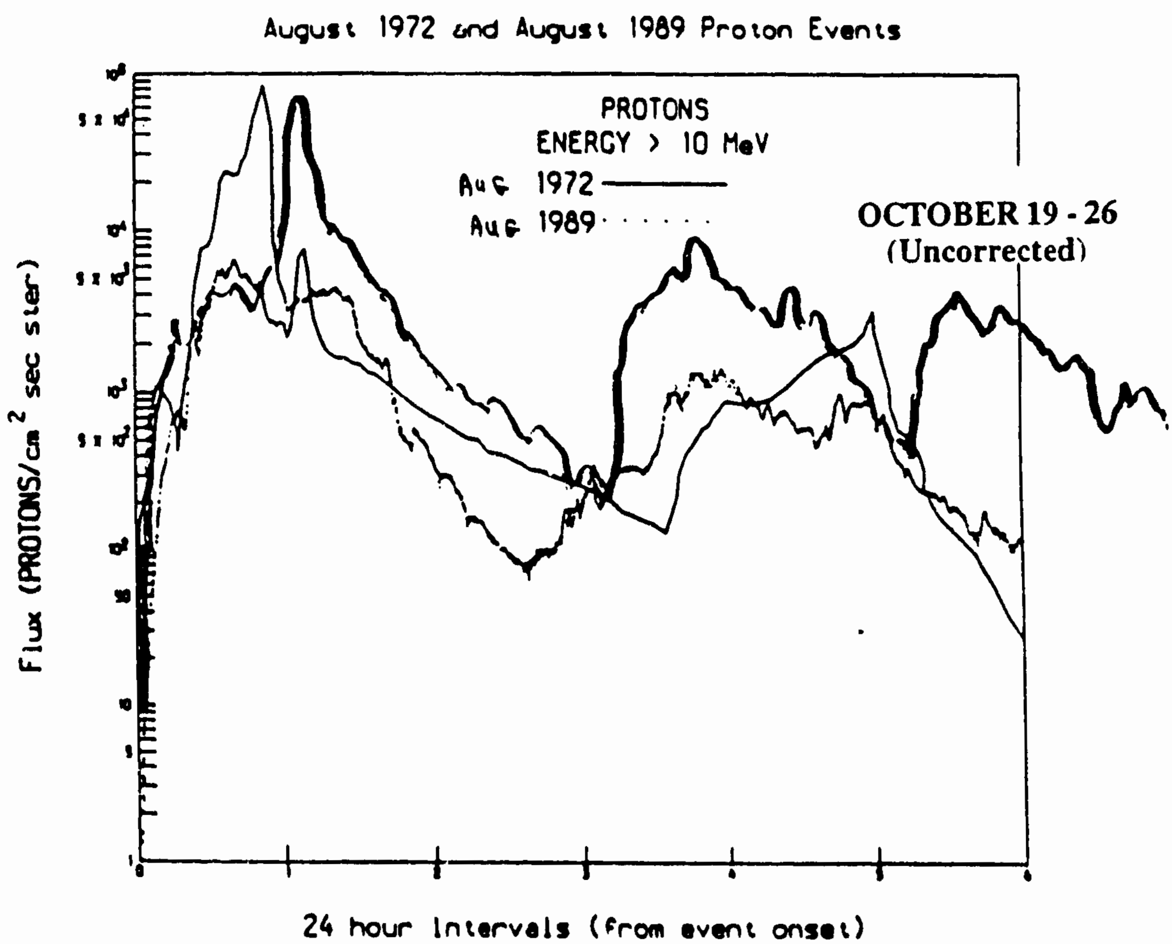

Figure 9.

Flux profiles of August 1972, August 1989, and October 1989 proton events.

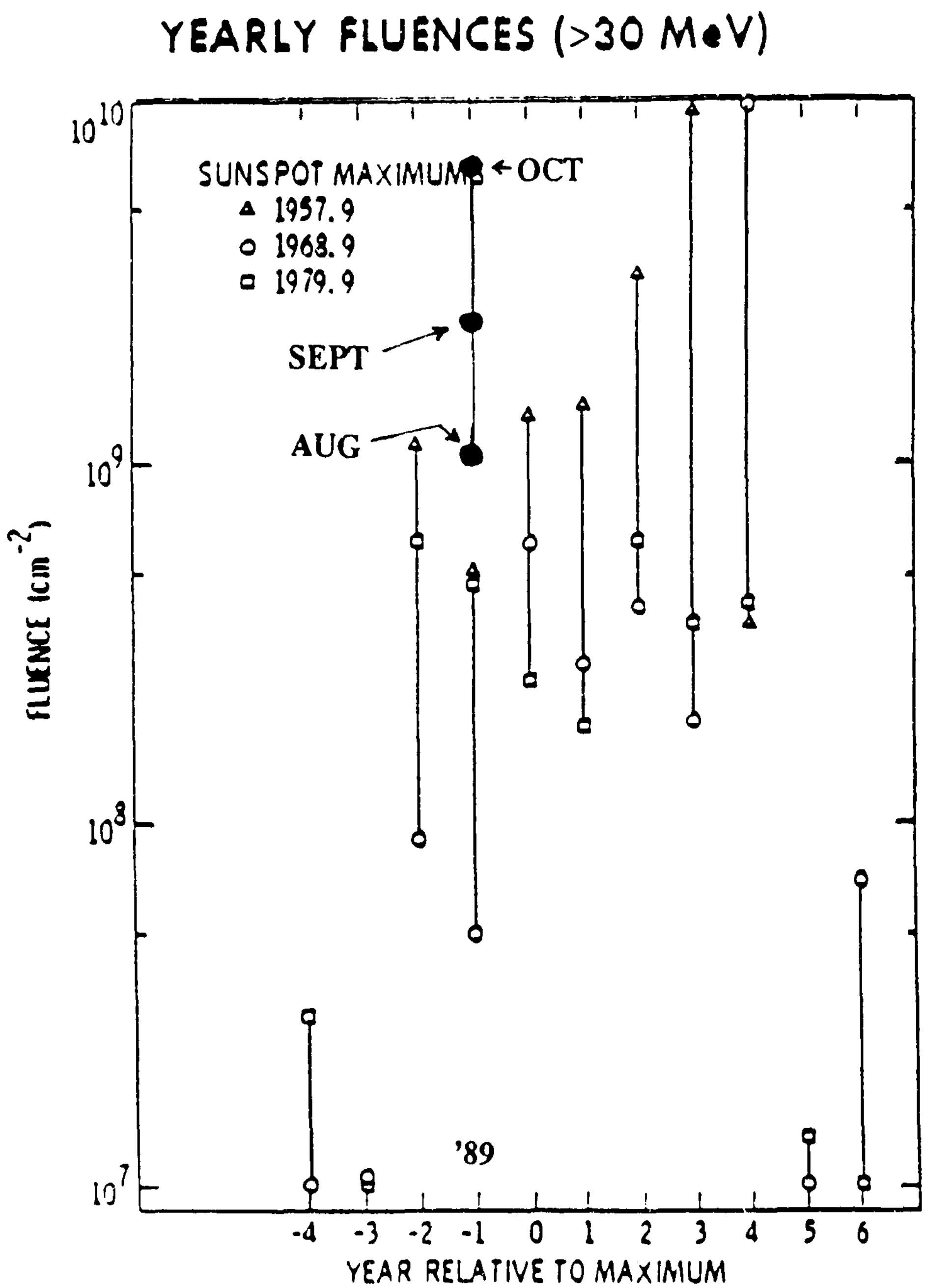

Figure 10. Yearly proton fluence comparisons

A comparison of proton fluences (a summation of proton fluxes over time) can be made to put these events in proper perspective. Figure 10 shows a plot of particle yearly fluence calculations as determined by Feynman et al (1988), but with the fluences (corrected data) from the August, September, and October 1989 events added as calculated b· Zwickl (private communication, 1989). The point labeled September is cumulative (i.e. August plus September fluence), as is the October point. This graph demonstrates that recent activity has been remarkable and has exceeded total yearly output for several solar cycles.

The following table (Zickl and Kunches, 1989) is a solar cycle fluence comparison with recent events, again emphasizing the dramatic size of recent activity. It should be of concern to total dose planners that recent activity has outstripped what was known about solar cycle 21 (1975-1986) which has often been used as a reference for environmental specification.

TOTAL SOLAR CYCLE FLUENCE		
CYCLE NUMBER	FLUENCE	
	E > 10 MeV	E > 30 MeV
19	6.6×10^{10}	1.8×10^{10}
20	2.2×10^{10}	0.7×10^{10}
21	1.8×10^{10}	0.3×10^{10}
22 (August - October 89)*	3.1×10^{10}	0.5×10^{10}
October Events*	1.9×10^{10}	0.3×10^{10}
*Corrected		

The services provided by SESC

SESC provides services to meet the needs of users affected by the space environment. Daily predictions are made for a three day and seven day forecast period. Warnings are issued when geomagnetic disturbances are expected, A > = 20 (active), A > = 30 (minor storm), A > = 50 (major storm), and alerts are issued when significant activity is observed: A-indices > = 20, 30, or 50 and K-indices of 4, 5, or > = 6. Alerts are also issued for sudden impulses, solar flares, and particle events.

SESC's satellite broadcast system is an easy, quick way to get SESC's solar-geophysical data, indices, forecasts and warnings in real-time. The update is within one second of receipt and free software is available that can run on PC based systems to store data and generate real time magnetometer plots. The cost for the necessary receiving equipment is about $3000.

A public bulletin board system containing numerous SESC data sets is available at (303) 497-5000. SESC also provides user accounts on the Space Environment Laboratory Data Acquisition and Display System (SELDADS) to users who want explore the data base in greater depth.

SESC publishes a weekly summary of solar and geophysical activity in the 'Preliminary Report and Forecast of Solar Geophysical Data'. The publication includes a 27 day outlook for activity. Users are charged a nominal yearly subscription rate.

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