SOLAR AND GEOMAGNETIC ACTIVITY DURING MARCH 1989 AND LATER MONTHS AND THEIR CONSEQUENCES AT EARTH AND IN NEAR-EARTH SPACE

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Spacecraft Charging Technology Conference
Naval Postgraduate School, Monterey, California
October 31-November 3, 1989

ABSTRACT

From 6-20 March 1989 the large, complex sunspot group Region 5395 rotated across the visible disc of the Sun producing many large flares that bombarded Earth with a variety of intense radiation although the energetic particle spectra were unusually "soft". Aurorae were observed worldwide at low latitudes. On 13/14 March a "Great" magnetic storm occurred for which Ap* = 279 and AA* = 450. By both measures, this event rates among the largest historical magnetic storms. Geostationary satellites became interplanetary monitors when the magnetopause moved earthward of 6.5 Re. Ionospheric conditions were extremely disturbed, affecting hf through X-band communications and the operation of satellites used for surveys and navigation. At lower altitudes there were problems with satellite drag and due to the large magnetic field changes associated with field-aligned current sheets. We are seeking reports of satellite anomalies at all altitudes. Reports also have been received about effects of these Solar-Terrestrial disturbances on other technology at Earth and in near-Earth space. This presentation draws heavily on material in a shorter, summary paper "in press" for "EOS" (Allen, et. al., 1989). Recent major solar activity since the abstract was submitted happened in mid-August, late September, and mid-October 1989. These events and their consequences at Earth and in Space are covered briefly.

SOLAR AND GEOMAGNETIC ACTIVITY DURING MARCH 1989 AND LATER MONTHS AND THEIR CONSEQUENCES AT EARTH AND IN NEAR-EARTH SPACE

On Monday, 6 March 1989, a very large and complex sunspot group, Region 5395, rotated into view around the east limb of the Sun and quickly gained attention when it produced an X15/3B flare (N35, E69). This event began a period of high solar activity that lasted two weeks and had many important consequences at Earth and in near-Earth space. From 6-19 March, Region 5395 produced 11 X-class and 48 M-class X-ray flares. Prolonged proton events occurred lasting several days and with an unusually high proportion of lower-energy particles. This solar activity produced an historically "great" magnetic storm, long-lasting Polar Cap Absorption events and a major Forbush decrease. The ionosphere was greatly disturbed. Many problems were reported with operational satellites; increased drag caused extensive orbit perturbations, telecommunications and navigation systems failed because of the disturbed conditions; aurorae were seen at unusually low latitudes (above the Tropic of Capricorn in Australia and from Mexico and Grand Cayman Island in North America); and there was a major electrical power outage in Quebec Province, Canada that affected some six million customers for nine or more hours.

Full analysis of this series of exciting events is just beginning, with the data bases now being assembled. Interested scientists have been in contact via e-mail and written correspondence even while the events were in progress. In addition, the spectacular imagery (some of which is shown here) has received a good deal of attention in the popular press as well. Scientists who are interested in participating in this study should contact Joe Allen (SPAN address 9555::jallen). Figure 1 summarizes the activity and its effects. Figure 1(a) shows GOES-7 solar X-rays, proton fluxes (one energy range), and magnetic field (Hp component) variations. Panels of ground-based data show the H-component of the geomagnetic field measured at Boulder Magnetic Observatory (USGS) and the flux from the Deep River Neutron Monitor (Canada), for March 5-6, 1989. Corresponding data for March 13-14 are shown in Figure 1b. A full set of the stack plots for March is given in the April and May 1989 issues of "SOLAR-GEOPHYSICAL DATA: Part 1, prompt reports".

SOLAR FLARES:

Following the long-lived X15/3B flare of 5 March, Region 5395 produced one or more flares daily near or surpassing the X1.0 level until the 18th of March. The X4.0 flare of Thursday, 9 March, peaked at 1532 UT and optically was rated a 4-Bright (4B), the highest categories of both area and intensity. Figure 2 is an H-alpha image of this flaring region taken by the USAF Solar Optical Observing Network (SOON) telescope at Holoman, NM, about five minutes before maximum.

On Friday, 10 March, another long-lasting flare reached the X4.5/3B level. At this time, Region # 5395 was still 22° east of Central Meridian and at relatively high latitude, considering that the sunspot cycle is almost at maximum. The flare on the 10th and its electromagnetic characteristics were the basis for an SESC forecast of high magnetic activity at Earth on the 12/13th. The last of the large flares from Region 5395 was an X6.5 at 1736 UT (N33,W62) on the 17th.

INJECTION OF ENERGETIC PARTICLES TO GEOSTATIONARY ORBIT:

On Tuesday, 7 March, the flux of 4.2-8.7 MeV protons began to rise gradually above the background level so that early on the 8th it was an order of magnitude higher. Just before 1800 UT the flux increased sharply by about two orders of magnitude (see April SGD, Part 1, p. 168) and continued at high levels through the 14th. Maximum was reached at about 0700 UT on the 13th (see Figure 1b). The SESC announced that at 1735 UT on the 8th the flux of >10 MeV protons exceeded 10 particles/cm2/sec/steradian so that a "Proton Event" was officially in progress. The proton flux continued at event levels until the 14th. The onset of high flux was probably caused by the flare of March 6 and was sustained by new injections from subsequent flares.

EXTREME MAGNETOSPHERIC COMPRESSION:

The March 1989 solar and geophysical activity was accompanied by a series of magnetopause crossings with extreme characteristics. Figure 1(b), third panel, shows the GOES-7 one-minute-averaged observations of the Hp component (approximately parallel to Earth's rotation axis) of the magnetic field at geostationary altitude during March 13 and 14, 1989. The reversals of the Hp component of the geostationary field to negative values indicates that the magnetopause, typically located at 10 Re distance, moved inside the geostationary orbit (6.6Re). Such rare events are called "Geostationary Magnetospauce Crossings" (GMC), and are caused by extreme conditions of solar wind pressure, often coupled with strong southward IMF components. Given a reasonable model for the magnetopause shape, the minimum distance to the subsolar point was 4.7 Re, or over a fact of two compression in linear size. The first of several crossings was observed by GOES-7 on the 13th at 14:16 UT (07:02 local time), and by GOES-6 some 36 minutes later at 05:52 local time. For this episode, the magnetopause was within 6.6 Re at the dawn magnetosphere for approximately 3.2 hours. Together with the crossings later that day, these episodes comprise the longest-duration compressions observed by the GOES satellites during a study period extending from 1979 to the present.

One may estimate the energy (work) required to compress the magnetosphere from a quiescent subsolar boundary distance of 10 Re to our estimated minimum distance of 4.7 Re. The product of the projected cross-sectional dawn-dusk area of the magnetosphere and the pressure ($B^2/8D$) of the dayside magnetic field, B, given by the simple model of Roederer (1970), yields the force exerted at the magnetopause. Integrating from the initial to the final subsolar distance using the magnetopause boundary shape of Holzer and Slavin (1978), we find that the work done is 4 x 1015 joules, about 1/6th the average daily US electrical energy consumption in 1987.

COSMIC RAY PENETRATION:

The geomagnetic field provides partial shielding against penetration to Earth of energetic particles of solar or galactic origin (cosmic rays). The minimum energy required to reach Earth's atmosphere or surface is a decreasing function of geomagnetic latitude; particles of the order of 100 keV or higher have essentially free access to latitudes poleward of the auroral zones. For an axially symmetric field such as that of a dipole, the fraction of the primary flux at a given energy reaching Earth as a function of decreasing latitude would suffer an abrupt transition from full transmission to none at a specific latitude, the "cutoff latitude" for that energy. For the real, asymmetric magnetosphere, however, the transition from full transmission to no transmission occurs over a latitude range of several degrees; i.e. the cutoff is not "sharp".

Figure 3 shows 2.5-16 MeV cutoff-latitude observations by SEL instruments aboard the low-altitude, polar orbiting, NOAA-10 satellite for all 13 passes of March 13, 1989. The cutoff range is denoted by radial line segments, with the higher latitude end-bar indicating the 2.5 MeV cutoff and the lower latitude end-bar indicating the 16 MeV cutoff. These cutoffs have been defined as the latitude of a measurable decrease below full transmission for the respective energy. A region of partial transmission extends several degrees southward of the indicated boundaries. Observations of all traversed cutoff latitudes are plotted as a function of geographic longitude in the upper panel (a), and as a function of magnetic local time in the lower panel (b). Northern- and southern-hemisphere observations have been combined, since no systematic differences have been found between them for this day.

Cutoffs were observed from a minimum of about 44^{o} to a maximum of about 72^{o} geomagnetic latitude. It will be noted the latitude range of the observed cutoffs for that day was quite broad: about 25^{o} wide at $60\text{-}120^{o}$ east geographic longitude, while significantly less (about 10^{o}) some 180^{o} away. Panel 5(b) indicates that the cutoffs were generally lower in the evening hours, with the most equatorward being 44^{o} latitude occurring about 1830 UT at about 82^{o} east longitude, placing it over the central USSR.

A solar proton event was in progress on March 13, the launch date of Discovery. However the spectrum of the particle event was quite "soft;" that is, there were relatively few higher-energy (>30 MeV) protons and alpha particles present. Even with the southward excursion of cutoff latitudes on March 13, Discovery's maximum excursion to about 28^{o} latitude, and the softness of the particle spectrum, prevented the solar proton event from posing a radiation hazard to that activity. In contrast, the Soviet vehicle MIR, with a maximum orbital latitude of about 51^{o}, would be expected to have suffered a significantly increased exposure to energetic proton and alpha particle radiation, but fortunately was not exposed to a major hard event such as those of August 16 or September 29, 1989.

RADIATION BELT PRECIPITATION:

The energetic particle sensors aboard the NOAA-10 low-altitude, polar-orbiting satellite measure electrons and protons in the energy ranges of > 30 keV to > 300 keV, and > 300 keV to > 80 MeV, respectively. Figure 4 shows a gray-shade plot of the 10-day averages of the proton fluxes observed by NOAA-10 in the evergy range 30-80 keV. The fluxes are averaged in 5^{o} bins of geographic latitude and longitude.

The pre-activity averages (bottom panel) illustrate typical values with obvious high fluxes in the auroral regions and in the region of the South Atlantic anomaly, approximately centered at 20^{o} S, 340^{o} E. At mid- to lower-latitudes the average fluxes are several orders of magnitude smaller. For the average of the active (March 10 to 20) period (top panel), overall flux intensities have strongly increased. The auroral and anomaly regions are stronger and broader, as expected, and so are the equatorial fluxes. Thirteen high intensity 'striations' across the otherwise depleted mid-latitude regions imply that the most intense increases, significantly above background averages at mid-latitudes, lasted for a total period of about a day (13 orbits). Similar behavior is observed at proton energies up to about 2 MeV and in the electron data at energies of > 30 and > 100 keV.

GEOMAGNETIC STORMS/SUBSTORMS:

Magnetic substorms were occurring in the auroral zone before the particles from the March 6th flare arrived at Earth. For example, College and Anchorage recorded about 2,000 nT amplitude negative bays in H around 1100-1200 UT on the 5th. However, at mid-latitudes across the US, magnetic conditions were rather quiet until a storm sudden commencement (ssc) at 1735 UT on the 8th. The main-phase H minimum followed at around 0100 UT on the 9th with slightly disturbed conditions lasting through the 10th.

The "great magnetic storm" of 13/14 March 1989, began with a sudden storm commencement at 0128 UT on the 13th (afternoon/evening of the 12th over N. America). Another ssc occurred around 0747 UT and a large negative-H bay was recorded at Boulder Magnetic Observatory around 1100 UT. Near 2100 UT the Boulder H-component began a rapid positive excursion that carried the flux-gate sensor off-scale at +2,000 nT. Large positive-H values continued for about 5 hours after which the trace returned to conditions of negative-H recovery from a main-phase depression. Comparison of H variations from USGS observatories and the NORDA site show large positive H deviations across the mid-latitude US for about six hours at the end of the 13th and early on the 14th (UT) [Figure 5, Herzog and Wilson personal communication]. All observatory magnetometers were off scale at +2,000 nT for part of this time.

It appears likely that for extended periods on 13/14 March the eastward Auroral Electrojet was located over the central United States for several hours. This is consistent with the DE-1 auroral imagery recorded in the southern hemisphere when it is projected onto the northern hemisphere and the wide, intense belt of discrete aurora remaining when DMSP F9 passed over N. America around 0400 UT on the 14th (cover illustration, EOS, Nov 14, 1989).

In the auroral zone, substorm conditions persisted before, during, and after the most active interval of 6-20 March. A sketch of preliminary, graphical Auroral Electrojet indices shows the character of auroral zone substorm activity on March 13/14th (Figure 6, Kamei). Plots of AU and AL variations were produced graphically in Kyoto from records of some 11 observatories that were promptly available in digital format. Preliminary AE is the range between AU and AL at each instant. It ranges from low values near zero to as large as 3000 nT. However, any AE-type index should be used with caution during this time of peak activity because, as noted above, the highly-expanded auroral zone was far south of "auroral" magnetic observatories. Toyo Kamei (Kyoto) has suggested that he may try deriving special mid-latitude AE indices using records from North American sites such as Boulder, Fredericksburg, and Newport which were closer to the electrojet.

Global magnetic activity indices were made available promptly from Goettingen (Kp) and Paris (aa). At NGDC we calculated 8-point running means of the 3-hourly ap and aa indices and selected the most-disturbed 24-hour values of each as Ap* and AA*, respectively, for comparison with the historical record. For the 13th, beginning at 0300 UT, Ap* = 279 (2 nT units). Likewise, AA* = 450 (1 nT units) starting at 0600 UT. According to these measures, this magnetic storm had one of the most disturbed 24 hour periods of any recorded since the mid-19th century. As shown in Table 1, the March Ap* value ranks as the third largest magnetic storm since 1932 based on indices of disturbance derived from records of a global network of 12 or 13 observatories. According to the March AA* this was the largest magnetic storm since 1868 as recorded by the 2-station network of almost antipodal sites in the UK and Australia.

EXTREMELY LARGE AURORAL ZONE:

Both spacecraft and ground-based sightings indicated the extreme coverage of the aurora. The satellite DE-1 was passing over the Antarctic during this key time and obtained striking auroral images at ultraviolet wavelengths (1360 A to 1650 A), mainly due to emissions from the Lyman-Birge-Hopfield bands of molecular nitrogen. Figure 7 is DE-1 imagery from two separate passes over the Antarctic six years apart (color images have here been reproduced as Xerographic copies in black and white). The quiet auroral oval on the left was recorded at 1623 UT on 22 March 1983 and the enormously expanded auroral oval on the right was recorded at 1826 UT on 13 March 1989 from a similar viewpoint and season, and at about the same Universal Time as the earlier image. This was during a time of widely reported auroral sightings across Australia and Tasmania. The 13 March 1989 oval was one of the largest recorded by DE-1 until that recorded on the 14th.

The second DE-1 image over Antarctica (to appear on an EOS cover) was recorded at 0151 UT on 14 March 1989, and coastlines are superposed here. The image was mapped onto the Northern Hemisphere at 200 km altitude using a MAGSAT geomagnetic field model. In this projection two broad bands of auroral emissions are seen. The northerly band is centered along the US-Canadian border and the equatorward band is at unusually low latitudes. Patches of the projected aurora appear over Alabama, Georgia, and northern Florida and over Texas, Oklahoma and New Mexico. These images agree well with visual aurora sightings reported from across the southern United States during local nighttime hours of the 13th and early 14th. This DE-1 image was obtained about one-half hour after the end of the period of extended positive-H recorded at Boulder Magnetic Observatory when the eastward Auroral Electrojet appeared to lie across the US from Washington state to Virginia.

The USAF meteorological satellite DMSP recorded the image of visible aurora around 0355 UT on 14 March 1989 (Figure 9). It shows a wide band of discrete aurora extending from just below Hudson's Bay to above Chicago at its narrowest extent. Lights of cities and other heat sources (e.g. oil field gas flares) from the east coast of the US to the central states and along the Gulf, and in Mexico and Cuba help a viewer to position the aurora. In the high contrast original imagery it is possible to see wisps of diffuse aurora in a band across New Mexico, Texas, Oklahoma, Arkansas, and spreading over most of the S.E. US.

RADIO AURORAE:

Radio aurora conditions were reported by at least 50 operators at 144 MHz across the southern US and extending down to Cancun, Mexico and the Carribean islands. Other reported logs documented radio aurora activity on 50, 220 and 432 MHz.

Ionospheric conditions for the period 6-20 March are shown in Figure 10 which plots the recorded hourly critical frequency of the F2-layer, foF2, scaled from vertical incidence soundings at the Boulder observatory. Local noon is at 1900 UT and the rapid rise in foF2 at 1300 UT is caused by sunlight beginning to illuminate the ionosphere above Boulder. These days have their local evening foF2 values near the monthly median except for the 15th. On 13 March at 0600 UT the Boulder foF2 value drops well below the median and stays low (or missing) until 0600 UT on the 14th. Daylight values on the 14th recover to near the median until around local noon and are then depressed through the 15th and into the 16th. Daytime values on the 16th are again depressed and then near-median conditions persisted until the 19th.

CONSEQUENCES OF THE MARCH ACTIVITY AT AND NEAR EARTH:

Reported consequences of the March solar activity as sensed at or near Earth include documented effects on satellites in space (geostationary and lower altitude), ionospheric perturbations that affected telecommunications and navigation systems (satellite and ground-based), the great magnetic storm described above, aurorae reported at unusually low latitudes (mistaken for fire reflecting off clouds or other unusual phenomena), and documented effects on technological systems -- some amusing and some serious. We do not include any material from classified sources. Failures in commercial and defense systems are sensitive topics and are not referenced here. There probably are other failures of which we are unaware. In the listing below, if an item is given without specifics, it is because our sources asked us not to reveal details.

EFFECT ON SPACE SYSTEMS:

- o There was concern about the launch of the shuttle Discovery during Ground Level and PCA Events; however, as discussed above the low inclination and low-altitude orbit combined with the soft spectra of the particle event to minimize radiation exposure to the astronauts. There was concern about the injection of TDRS-D into its operating geostationary orbit during the progress of a major magnetic storm, and in fact some anomalous behavior of the TDRS-D satellite in orbit has been reported. It is being investigated whether the launch conditions or the continuing geomagnetic activity was responsible.

- o A previously stable low-altitude satellite in near circular orbit at roughly 60^0 inclination began episodes of uncontrolled tumbling on March 6, 8/9, and 14th, which interferred with operations.

- o GOES-7 had a communications circuit anomaly on the 12th, lost imagery and had a communications outage on the 13th.

- o Three low-altitude NOAA polar orbiting weather satellites and the USAF DMSP counterpart to the NOAA series had trouble unloading torque due to the uncommonly large ambient magnetic field changes.

- Japanese geostationary communications satellite CS-3B had a severe problem at 1050 UT on 17 March that involved failure and permanent loss of half of the dual redundant command circuitry on-board.

- Barnes limb sensors used to lock low-altitude polar orbiters onto CO_2 brightening at the Earth's limb have sensor degradation well-correlated with rising solar activity. This was encountered in 1978-79 "but the problem went away" without engineering fixes.

- Operational satellites of the European Space Agency were reported not to have experienced outages but MARECS-1 (177°) had many switching events on 3, 17 and 29 March.

- A series of seven commercial geostationary communications satellites had considerable problems maintaining operational attitude orientation within specified ranges. They required some 177 manual operator interventions to make thruster adjustments in order to maintain the required attitude during the disturbed conditions on the 13/14th. These were more than are normally required during a year of regular operations.

- The Japanese geostationary meteorological satellite GMS-3 "suffered severe scintillations during 1200-1430 UT on March 23." Data transmissions were lost for about 1 hour around 1300 UT.

- Geostationary communications satellites reported operational anomalies on 18 and 20 March but not on earlier disturbed days.

- The aging NASA satellite SMM was said to have made good recordings of conditions during the disturbances but "it dropped in altitude as if it hit a brick wall" during the time of highest magnetic activity. It is reported to have dropped 1/2-km at the start of the "big storm" and to have dropped "3 miles" during the entire disturbed period.

- More than 80,000 items in orbit are tracked daily from Earth and most are identified and orbits calculated. When a new object is detected it is commonly called an "Uncorrelated Target" (UCT) and efforts are made to identify it as either a new object in space or a previously known object whose orbit has changed. Most UCTs are debris from satellite launches or breakups but some are "lost" satellites whose orbits are changed by increased drag due to heating of the upper atmosphere by solar and geomagnetic activity. Around 1000 UCTs are normally encountered daily but on 13 March there were about 2000 reported. The number rose daily by about 500 to 800 events (the largest increase was on the 17th March) to reach a maximum on 18 March of almost 6000 UCTs. After that, the number declined to around 2300 UCTs by 23 March.

COMMUNICATIONS AND NAVIGATION DIFFICULTIES:

- On March 6 a commercial radio network warned affiliates of potential for signal relay problems during the two weeks ahead.

- The US Coast Guard reported numerous LORAN navigation problems, particularly on 6 and 13 March. These were accompanied by problems with using hf-radio communications to alert users to the problems.

- The US Navy MARS (marine hf-radio network) circuits on 10-20 MHz were out worldwide while 144-148 MHz transceivers used for shorter-range communications were receiving powerful signals from remote locations.

- A new hf-Direction Finding system to be demonstrated in Texas on 13 March failed to work due to "removal of the ionosphere."

- A ham operator in Minnesota reported "auroral radio propagation features observed down to Ecuador and Columbia." Below 50 MHz "the ionosphere disappeared" while at higher frequencies range and intensity were enhanced, e.g. California Highway Patrol messages were overpowering local transmissions in Minnesota.

- VLBI observer in the Florida keys reported exceptional communications at frequencies > 140 MHz.

- In Australia there were many reports of poor hf-radio conditions on 13/14 March. Polar to mid-latitude circuits were "useless" and equatorial circuits were "very weak and noisy." During daytime foF2 on the 14th was "mostly < 5 MHz". Large, rapid swings of foF2 occurred at night on the 14/15th.

- In the US, the Boulder Ionosonde recorded foF2 at night as low as 2 MHz and there were periods when it could not be measured because of D-layer absorption. During the daytime foF2 was 4 to 5 MHz.

- Geodetic surveys in the US and, possibly, ship navigation near Australia using signals from navigation satellites were impaired.

- Automatic garage doors in a California coastal suburb began to raise and close without apparent reason. The phenomenon was eventually traced to a Navy ship that was employing a special shore-based system in an attempt to maintain remote radio communications while hf-radio was out of operation.

POWER FAILURES AND OTHER EFFECTS OF INTENSE AURORAL CURRENTS:

- The Hydro-Quebec Power Company experienced a massive failure that darkened most of Quebec Province for up to nine hours. It was caused by large ambient magnetic field changes at 0244 local time on Monday morning, 13 March. The magnetic storm induced a very low frequency current in power lines of the James Bay generating station. When transformers became saturated by line harmonics, the overcurrent protection on three static "volt-ampere reactive" (var) compensators that control line voltages tripped circuit breakers shutting down about 44% of the power then being distributed. When four other vars shut down due to unbalance protection on the third harmonic filter, the system crashed. Power to Montreal and Quebec City failed and this was quickly followed by collapse of other generating capacity as the networked power grid "protected itself" from the excessive load demands caused by the first massive failure. Hydro-Quebec customers lost use of some 19,400 MW of power in Canada; there was a further loss of 1,326 MW of power exported to the US; and other available power could not be accessed because of the distribution system failure. Some 6 million customers were without power early in the morning of a new work week. The major restoration effort took more than 9 hours and many customers were without power for longer times.

- In central and southern Sweden there was a simultaneous power loss (within one second) on six different 130 KV power distribution lines at about the same time as the Hydro-Quebec system failure.

- Local power systems in Pennsylvania, New Jersey, Maryland, New York, New Mexico, Arizona, and California noted effects of the magnetic storm: capacitor banks tripped, voltages were depressed and transformers were noisy but there were only short outages and no general blackout.

- Aeromagnetic and other field survey conditions were reported as "impossible" from South Africa, Australia, Canada, and the US.

- Declination changes of greater than 3^{0} measured at US magnetic observatories exceeded design specifications for a new aircraft magnetic navigation system being tested in the central US.

- Record -2000 nT H-deviations occurred at Moscow and -620 nT at Kakioka. Magnetometers in Australia were "offscale for 6 hours on the 14th centered on 0000 UT". Magnetometers at mid-latitude US observatories repeatedly off scale on the 13/14th at + 2000 nT.

- The value Ap* = 279 (derived from ap indices) was the third largest 24-hour disturbance recorded since these global indices began in 1932. The value AA* = 450 (from a 2-station global index) was the largest 24-hour disturbance recorded since 1868.

AURORAE VIEWING REPORTS FROM GROUND OBSERVERS:

- Brilliant aurora was seen across the US on the night of Sunday/Monday (12/13 March) and Monday/Tuesday (13/14). Reports were received from upstate New York, New Jersey, Colorado (Boulder), Texas (Brownsville and San Antonio), New Mexico (Los Alamos), Arizona (Ft. Huachuca), and California (Los Angeles and San Francisco). Bright green, blue and white forms were reported over the eastern US with mainly red aurora reported from farther south. Backpackers in the mountains of western North Carolina reported interesting observations from a very isolated location. They saw mostly static bright red aurora for about four-to-six hours but with white beams converging toward the southern horizon. Red aurora were reported from Florida Keys, Grand Cayman Island and Cancun, Mexico.

- Aurora was reported on the night of 13/14th seen from near London and extending to the southern horizon. It was "brighter than anything I have ever seen ... in terms of 630 nm F-region emissions" according to David Rees (U. College London).

- Southern Australia was largely under cloud cover that prevented viewing aurorae; however reports were received from large regions of north Australia, including Exmouth (above the Tropic of Capricorn) on the night of 13/14 March.

SURFACE TECHNOLOGY AFFECTED:

- o Geophysical exploration surveyor reports --
  S. Africa: "Conditions unlike any seen before! Nothing worked."
  W. Australia: "Never seen conditions quite like it."
  Bass Strait, Australia: concern over increased pipeline corrosion.

- o Microchip production facilities in N.E. US out of operation two or more times due to magnetic activity.

- o Undersea cables in Atlantic and Pacific had large voltage swings.

- o High levels of UV-B measured around time of naked eye spotting of sunspot region 5395 near Seguin, Texas.

- o Power distribution facility black outs in Canada and Scandinavia.

- o Out of worldwide hf-radio contact from southern US transmitter.

CONCLUDING THOUGHTS:

As the geophysical record is accumulated and evaluated, it is certain that other types of data and other examples of the consequences of the major solar activity of 6-20 March 1989, will become known. We know that there are instances of effects worldwide that have not been publicly reported because of commercial or national security concerns. National, regional and World Data Centers are actively seeking to gather comprehensive data sets from this time for future analysis and are also interested in receiving documented reports of effects.

From comparisons of the annual number of days of high magnetic activity with the annual sunspot number and the annual number of solar flares, it is known that the peak(s) of magnetic storminess do not occur during the years of the maximum solar activity measures. Comparison of the reported number of in-orbit operational satellite anomalies for spacecraft not mainly affected by cosmic rays shows that the frequency of anomalies follows mainly the occurrence of major magnetic storms. Although the current solar cycle is rising rapidly toward maximum (probably to occur in early 1990), the overall level of magnetic activity has not shown a similar increase (E. Hildner, personal communication). The short list of major magnetic storms in Table 1 shows that in 1940-41 and 1959-60 two or more events occurred within 18 month periods. There have been few storms, if any, as great as that of 13/14 March; however, the possibility that another may occur in 1990 or soon after must be considered.

As society continues to move to wider uses of high-technology devices, often controlled by faster and more compact micro-chip electronics, in space, in aircraft, and on the ground and as communications and power distribution grids become more important and more tightly networked, our susceptibility to major impacts on the population and systems increases.

RECENT SOLAR ACTIVITY:

After submission of the abstract for this talk and preparation of the summary review paper on the March activity, more episodes of large solar flares occurred often accompanied by major proton events; also, there were periods of increased fluctuations in the > 2 MeV electron level at geostationary altitude -- sometimes with major magnetic storms sometimes without. Flare locations ranged from central meridian to the west limb and beyond. It is not clear that spacecraft charging was a common occurrence during these episodes but some significant and many less important effects are known.

AUGUST 1989 EVENTS:

On 1 and 2 August there were large, long-lasting diurnal changes in the level of > 2 MeV electrons recorded by GOES-7 (Figure 11). These events, almost surely arising from passage of the satellite through a trapped population of energetic electrons, are not seen every day. On days when there are also energetic proton events, the electron sensor mainly records the changes of proton counts. From 2 August onwards there are one or several upper level C-type or M-type flares daily until on the 12th there was an X2/2B level (X-ray/optical) flare beginning shortly before 1400 UT and peaking around 1430 UT. The differential proton energy traces began rising out of the background about 1520 UT and the integral flux of > 10 MeV protons reached a maximum of 9,200 pfu on the 13th at 0710 UT. J. Feynman has plotted the comparable proton fluxes from the August 1972 and 1989 events (Figure 12, personal communication). Further X-level flares occurred daily on the 14th-17th with one early on the 16th from region # 5629 near the west limb that reached an off-scale estimated maximum of X20.0/2B at 0118 UT. This flare on the 16th produced a step-like increase in the highest energy proton counts around 0140 UT (Figure 13) and cosmic ray neutron monitors worldwide recorded a 7% to 10% increase, a "Ground Level Event" (GLE). Apart from a possible small GLE in July 1989, this was the first such widely recorded event in 11 years, i.e. the first of cycle # 22.

Geomagnetic storm sudden commencements (ssc's) occurred on 14, 21, 23, and 27 August and there was an intense magnetic storm on 28/29 Aug. Auroral zone magnetic conditions from Greenland across N. America to Alaska were extremely disturbed during this storm. The flux of lower energy electrons at geostationary altitude in the 290 KeV - 2 MeV range was about 10^6 and in the 30 - 300 KeV range was about 5×10^7 at 0330 UT on the 29th. These disturbed magnetic conditions and high electron fluxes corresponded exactly in time with the permanent failure of half of the GOES-6 telecommunications circuitry. This failure was progressive. It began with the start of the magnetic storm and ended at the peak with total system outage until a separate, redundant circuit was activated. This is only the second such GOES central telecommunications unit failure. The "New Scientist" magazine of 9 September 1989 carried an article "Solar storms halt stock market as computers crash" describing the failure of the Toronto Stock Exchange computer system during this magnetic activity when its three "fault-tolerant" disc drives failed in succession.

Without specifying particular satellites or orbit locations, we have heard that the hard spectrum particle events characterizing solar activity during mid-August affected star sensors and caused a greatly increased number of SEUs compared to the softer spectrum events of March and that during this period multiple flares occurred in quick succession from a sunspot group near to central meridian until it moved onto the west limb. These events combined increased fluxes of both high-energy protons and lower energy electrons and produced major magnetic storms.

LATE-SEPTEMBER/EARLY-OCTOBER 1989 EVENTS:

On Friday, 29 September, region # 5698 (S26^{o},W105^{o}) produced an X9.8 flare beginning around 1047 UT from around the far side of the sun's west limb. No optical flare was seen from Earth; however, the MAGELLAN satellite enroute to Venus was at 0.7 Re and about 45^{o} west of Earth and well positioned to receive a direct exposure to the flare particles. From Earth, a large loop prominence truncated at the bottom was observed rising above the sun's west limb. This region was the source of X-ray emissions seen by GOES-6 and -7. Energetic protons recorded by GOES began to rise above background levels around 1150 UT and reached a maximum at 0210 UT on the 30th. The event had a very hard spectrum and lasted through 4 October.

The Thule Neutron Monitor reached a 378% increase above background level (Figure 14, SESC), making this the largest amplitude GLE since February 1956, some 33 years earlier. Margaret Smith (Canada) reported that the GLEs recorded at Deep River and Ottawa were both > 300% and at Inuvik > 475%. The event showed an unusual double-humped trace. Louise Gentile (AFGL) is compiling cosmic ray event amplitudes and related information with Peggy Shea (AFGL). She reports that two monitors near Rome, Italy recorded GLEs of 98.2% and 124.4%. John Humble (U. Tasmania) reported that the GLE at Hobart exceeded 400%.

One family of 13 geostationary communications satellites recorded 46 "hits" from 0912 UT on 29 September through 0048 UT on 5 October. On the 30th these satellites experienced about one hit per hour. Most were relatively minor "pitch glitches"; however, some were SEUs and some were phantom commands that could have fired thrusters except for software safeguards. From 09/29-10/01, TDRS-A (now a reserve satellite) recorded 53 RAM hits in the memory chips now known to be susceptible to cosmic ray energy. The normal number is about 1 hit every other day. However, the two newer satellites TDRS-C and -D did not have RAM hits due to the changeover to hardened chips. NOAA's GOES-5 and -6 experienced SEUs on 30 September. GOES-5, -6, and -7 experienced "severe drops in current" output by solar power panel arrays on the 29-30th (about 0.1 amp). The polar orbiter NOAA/TIROS-10, in 100% sunlight, experienced an uncommanded telemetry change on 1 October at N73.8^{o},E166.6^{o} at 0619 UT.

Many star sensor hits are known to have caused orientation problems in some satellites and a greater incidence of SEUs was logged during these six days than during the record days in August 1989. Suddenly, it was an interesting topic to compare total fluence during the maximum 24-hours at the end of September with the maximum period in August 1972 which has long served as the anomalously large proton event.

MID-OCTOBER 1989 EVENTS:

On Thursday, 19 October 1989, at about 1230 UT a large solar flare began near the Sun's central meridian. It peaked at 1258 UT at an estimated X13 level (above X12 is off scale on GOES). Optically the flare was rated 4B (as was the large flare on 9 March 1989).

Relativistic protons began to arrive at GOES-7 just after 1300 UT and another GLE was recorded worldwide. Prompt contacts from satellite teams and operations groups revealed concerns about: communications satellites having unusually frequent pitch glitches, GALILEO enroute to circle the Sun being exposed to high energy particles that could impede important communications during these early stages of deployment, MAGELLAN had a serious star sensor hit that finally made it necessary to try and find a software contingency means to orient the satellite when it arrives at Venus.

Reports from 19 Oct and following days included:

- GOES-6 had 2 SEUs and GOES-5 had 1.

- GALILEO project team turned on the > 10 MeV/nucleon sensor to monitor heavy ions during the flare emissions. Since Friday at 8:00 pm PDT, Tom Garrard (Cal Tech) confirms that they recorded clear flare signatures in the particle composition and that oxygen ions are an important part of the plasma.

- A polar orbiter lost a microwave transmitter unit. It was reset from ground control and went out again after about 2 minutes. They were advised to leave it off until the activity ends.

- TDRS operations reported: TDRS-A had 50 RAM hits on 19/20th. TDRS-C had 2 and TDRS-D had 4 SEUs.

- MAGELLAN star sensor not recovered as of 26 Oct and major loss of power output from solar panels.

- Joan Feynman (JPL) estimated solar wind velocity > 2000 Km/sec.

- ESTEC preparing SEU list for low-altitude ESA satellite UOSAT-2 in polar orbit.

- GOES-5, -6 and -7 power panel output losses about factor of six greater than during September 29, 1989 period.

- Strong geomagnetic storm on 21 Oct recorded in Japan. Bright red aurora seen in N. Japan at $N35^{0}$ geomagnetic latitude during two separate intervals on 21st. Report of large voltage fluctuations of electrical power for optical communications cable between Japan and USA.
- Low-latitude aurora sightings reported from Australia ($-S35^{0}$) at 1330 UT on 20 Oct and 1430 UT on 21 Oct. From Deltona, Florida ($-N28.5^{0}$) at 0030 on 21 October. Many other sighting reports.

- Magnetic storms recorded by US observatories on 20 and 21 October.

- Magnetopause Crossing (MPC) by GOES-6 and -7 on Friday, 20 Oct, from 1700-1900 UT as both GOES moved outside magnetopause.

- GLEs recorded on 19 October at Jungfraujoch (5%), Kerguelen (25%), Ottawa (41%), and Oulu (38%). Another GLE occurred on 22 October and measured 17% at Oulu.

- Solar power panel array systems on commercial geostationary communications satellites degraded about 0.3 amp each on two oldest spacecraft and about 0.7 amp each on 11 others. These 13 satellites had the following pitch glitches and SEU counts: 19th - 7; 20th - 68; 21st - 13; 22nd - 5; 23rd - 28; 24th - 9; and 25th - 7.

- On 24 Oct another large, long-lasting X5.7/3B flare occurred from near the west limb. It added another positive upward kick to the high levels of energetic protons persisting since the 19 Oct.

Another "Dear Colleague" memo was assembled dealing with the solar activity affecting Earth and satellites in orbit (similar to that circulated for the March events). It included selected prompt plots from SELDADS-II and was sent to a contact list maintained by Joe Allen of persons and institutions interested mainly in satellite anomalies from environmental causes.

Prompt reports of solar-geophysical activity for the days from 19 October are available in the weekly "*Preliminary Report & Forecast of Solar Geophysical Data*" from the Space Environment Services Center (SESC) of NOAA's Space Environment Laboratory. At the end of November the National Geophysical Data Center (NGDC) will publish worldwide early data in *Part 1: Prompt Report* of "*Solar-Geophysical Data*" (SGD) reports.

Six months later *Part 2: Comprehensive Report* of SGD will contain more extensive data listings and figures. If community support warrents the effort, NGDC's STP Division -- including WDC-A for STP -- will attempt to assemble a comprehensive multi-volume "UAG Report" on the October activity or possibly on the entire "Solar-Terrestrial Highlights of 1989", that is, unless the Sun provides even more impressive events to distract us during the months and years just after sunspot maximum (see the history of cycle 19).

ACKNOWLEDGEMENTS:

Reports of data and information collected by many different people worldwide are integrated into this paper. Sometimes they are from research projects but more often they are from monitoring systems. Often there is no known person to acknowledge or at best only an institutional or national reference is possible. So much of this paper is taken more or less directly from the joint work referenced at the beginning but not yet published (at time of submission) that I wish particularly to acknowledge the major contributions of Herb Sauer, Pat Reiff, and Lou Frank. Without access to the on-line computer system SELDADS-II (NOAA/ERL Space Environment Laboratory Data Acquisition and Display System-II) and the staff that maintain it and the many data bases there, such timely compilations and opportunity for analysis would be impossible. Access to SELDADS is a tremendous asset in trying to follow solar activity and related phenomena. Dan Wilkinson (also a Conference participant) is responsible for developing the multifacet stacked plots of satellite and ground-based data used in this report, in SGD, and in several other presentations.

MAJOR MAGNETIC STORMS

- **AA* Most Disturbed 24-hours index (2-stations from 1868)**

Rank	AA*	Start Date	Start Time
1	450	1989/03/13	0600 UT
2	429	1941/09/18	0600 UT
3	377	1940/03/24	1500 UT
4	372	1882/11/17	0900 UT
5	372	1960/11/12	1800 UT
6	357	1959/07/15	0600 UT
7	356	1921/05/14	1200 UT

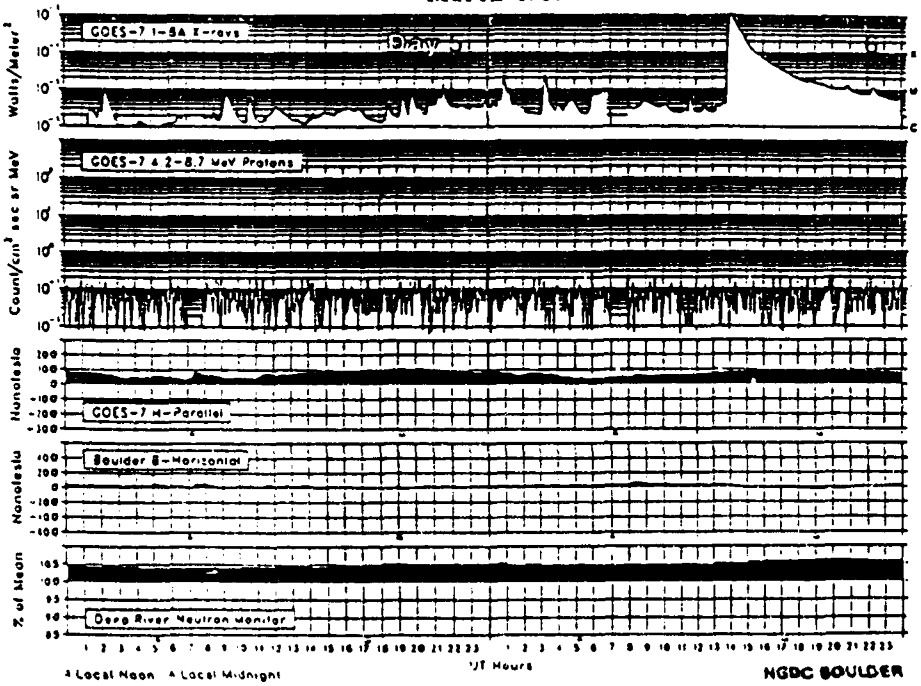
- **Ap* Most Disturbed 24-hours Index (13 stations since 1932)**

Rank	Ap*	Start Date	Start Time
1	312	1941/09/18	0900 UT
2	293	1960/11/12	2100 UT
3	279	1989/03/13	0300 UT
4	277	1940/03/24	1200 UT
5	258	1960/10/06	0900 UT
6	252	1959/07/15	0600 UT
7	251	1960/03/31	2100 UT

NOAA/NESDIS/NGDC May 1989

Table 1

SOLAR-TERRESTRIAL ENVIRONMENT
March 1989



SOLAR-TERRESTRIAL ENVIRONMENT
March 1989

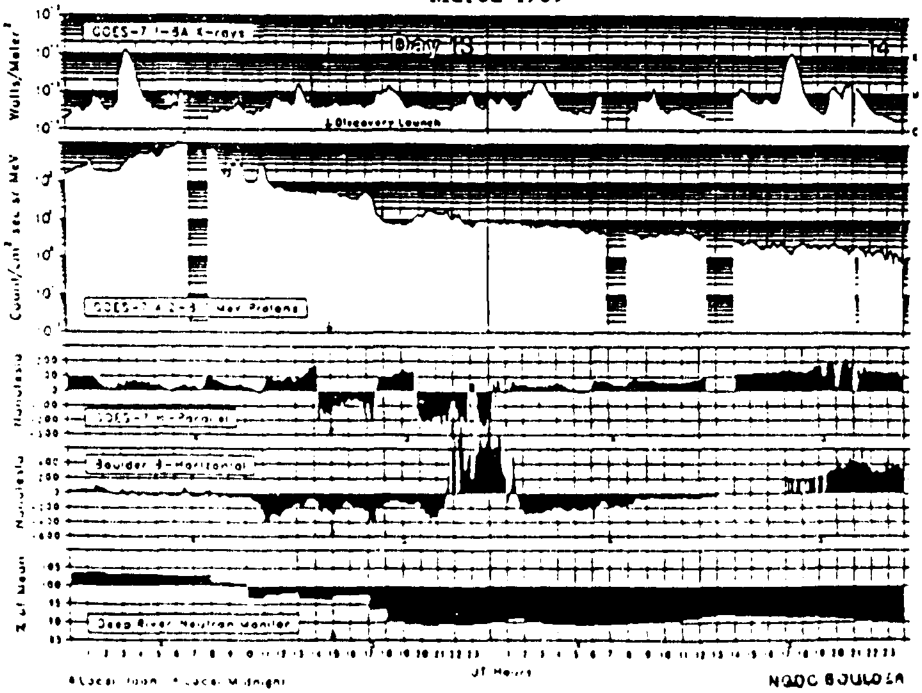


FIGURE 1

FIGURE 2

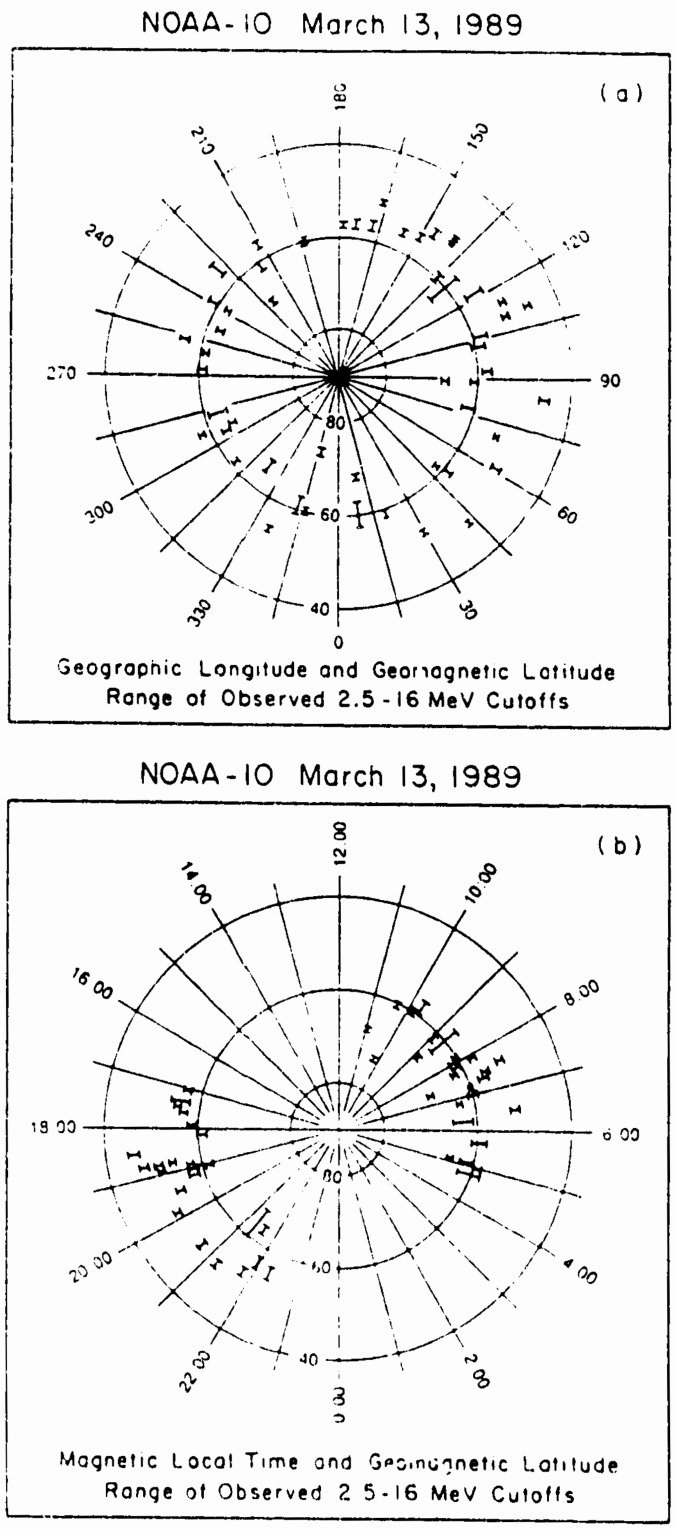

NOAA-10 March 13, 1989
(a)
180
150
120
90
60
30
0
330
300
270
240
210
80
60
40
Geographic Longitude and Georagnetic Latitude
Range of Observed 2.5 - 16 MeV Cutoffs
NOAA-10 March 13, 1989
(b)
12.00
10.00
8.00
6.00
4.00
2.00
22.00
20.00
18.00
16.00
14.00
80
40
Magnetic Local Time and Geomagnetic Latitude
Range of Observed 2.5 - 16 MeV Cutoffs

FIGURE 3

NOAA-10 30 - 80 keV PROTON FLUXES

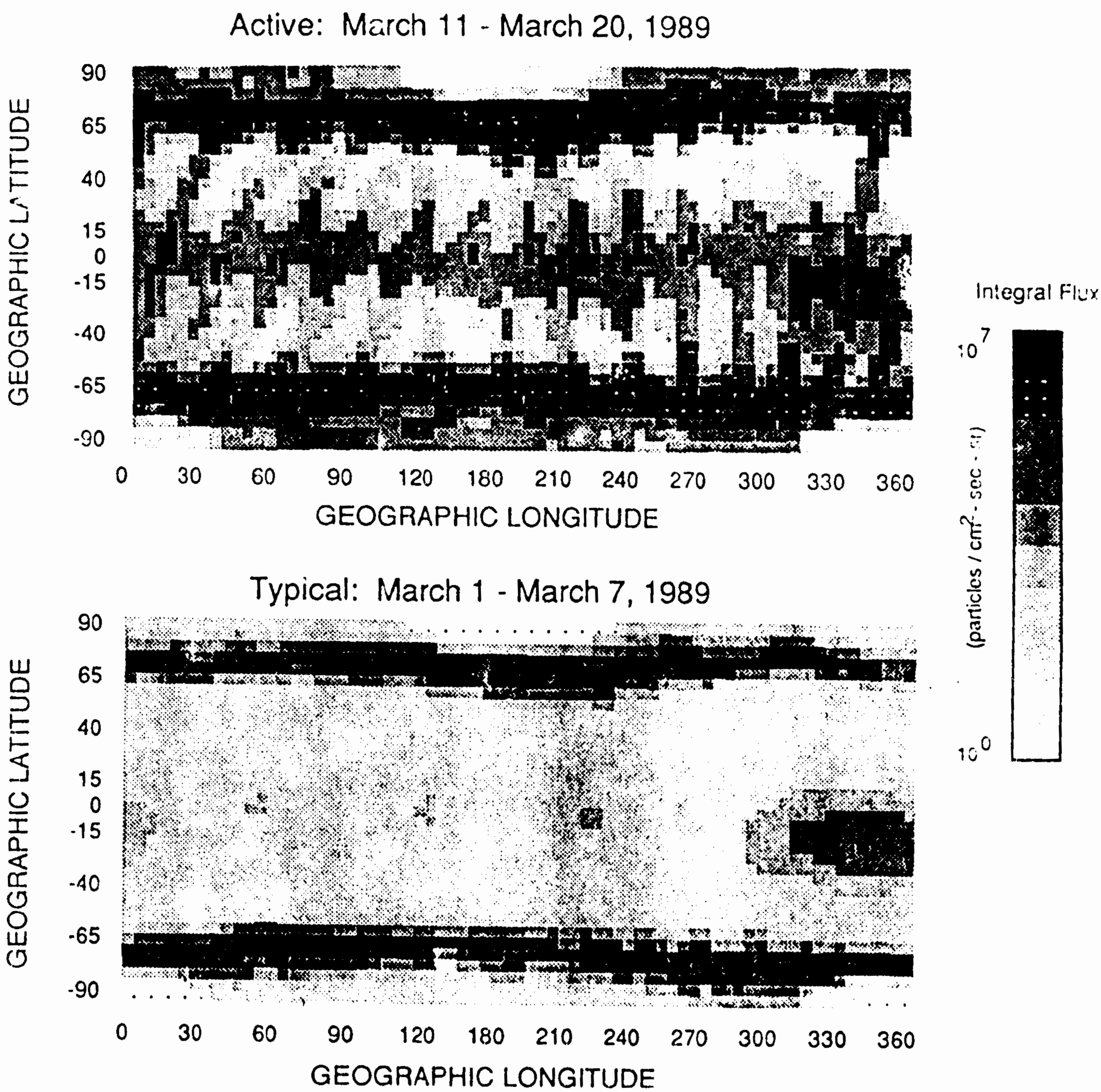


Figure 4

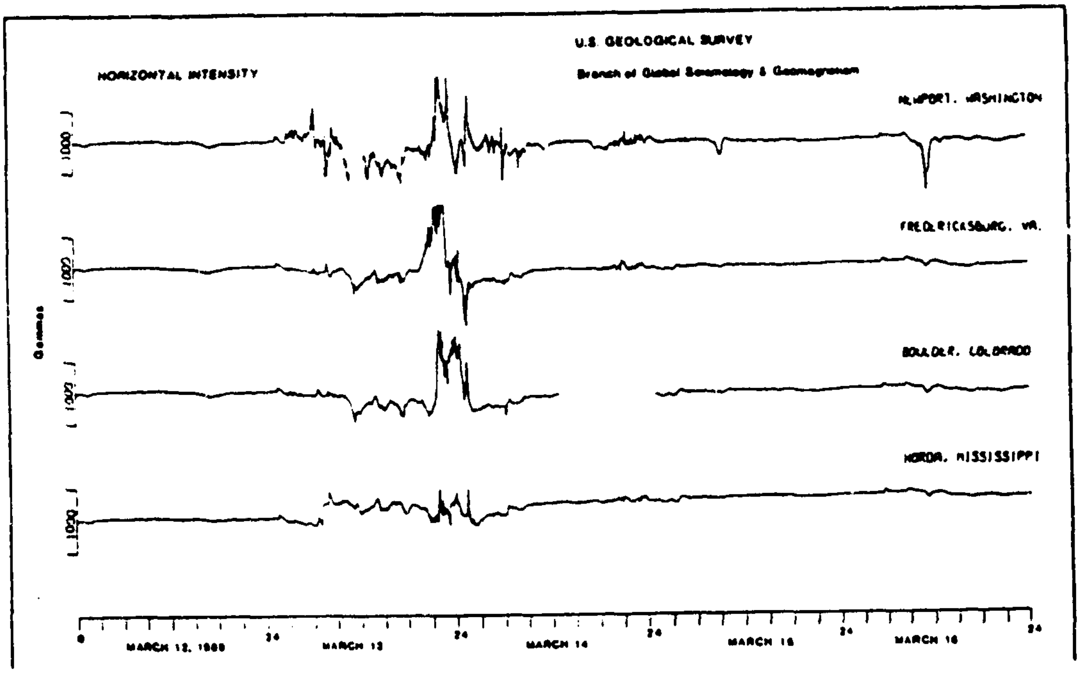


Figure 5

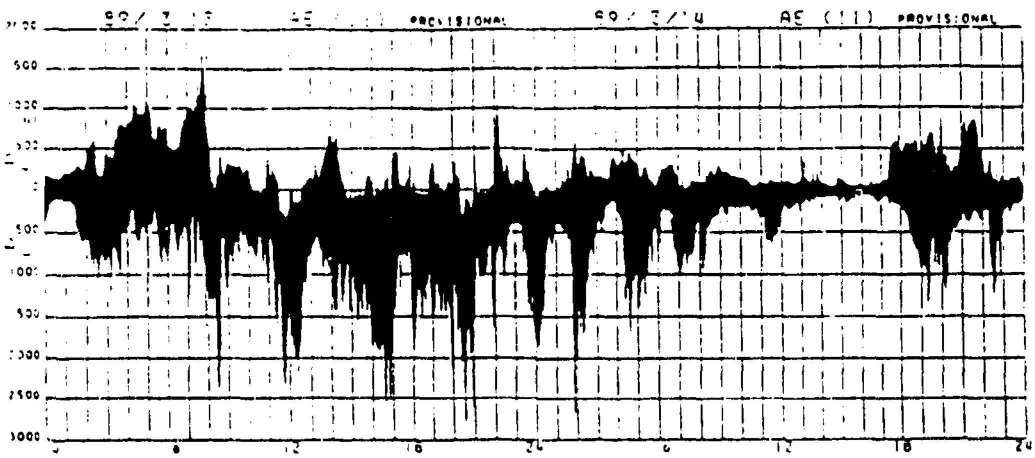
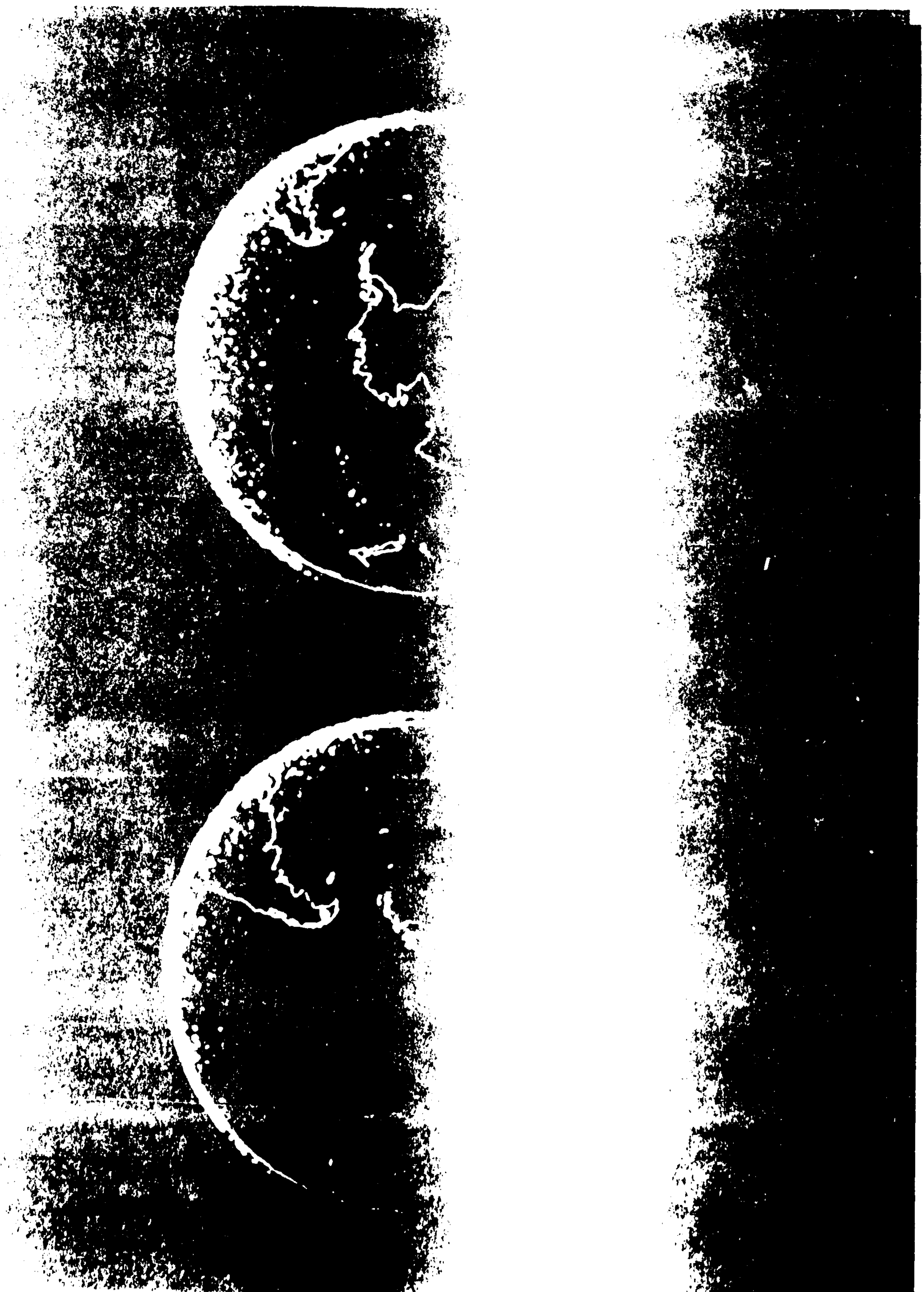
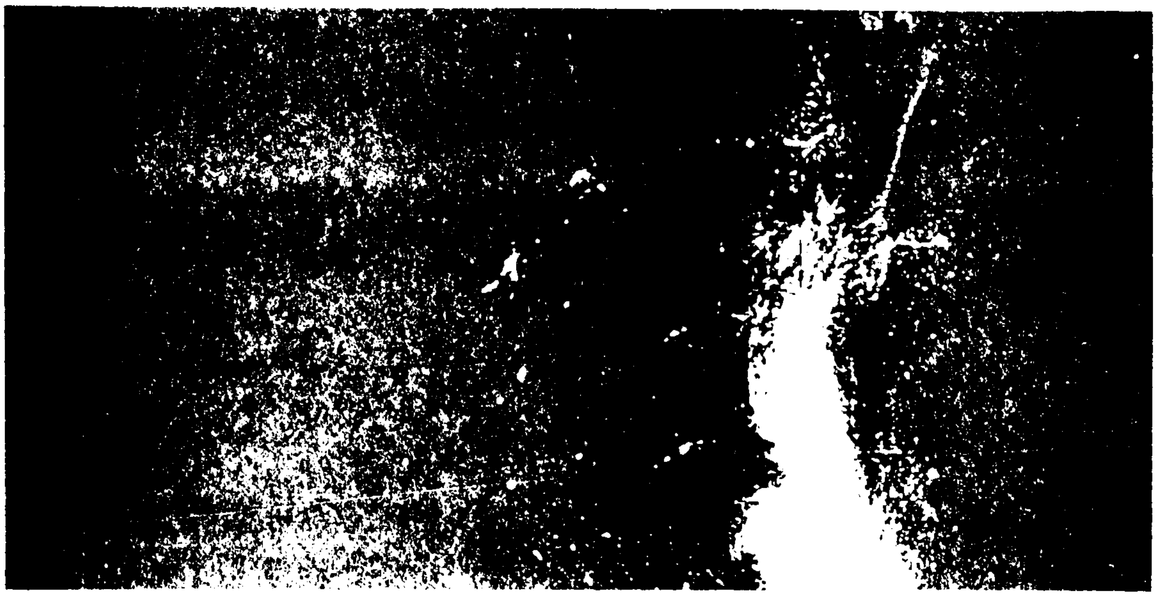
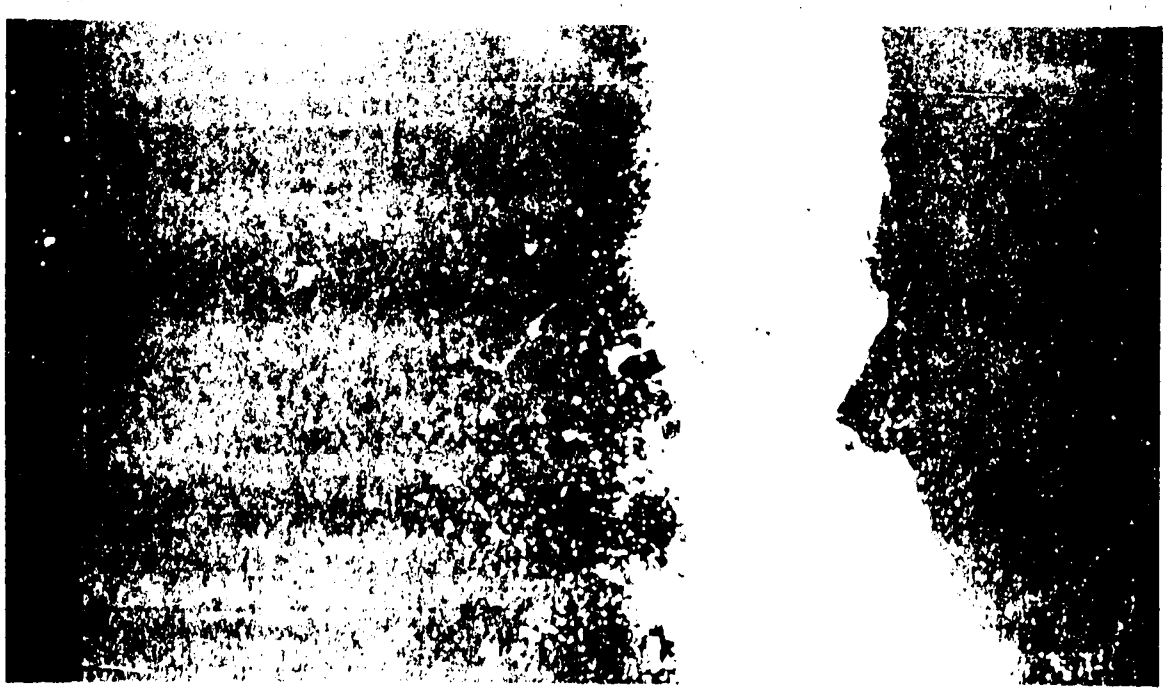


Figure 6







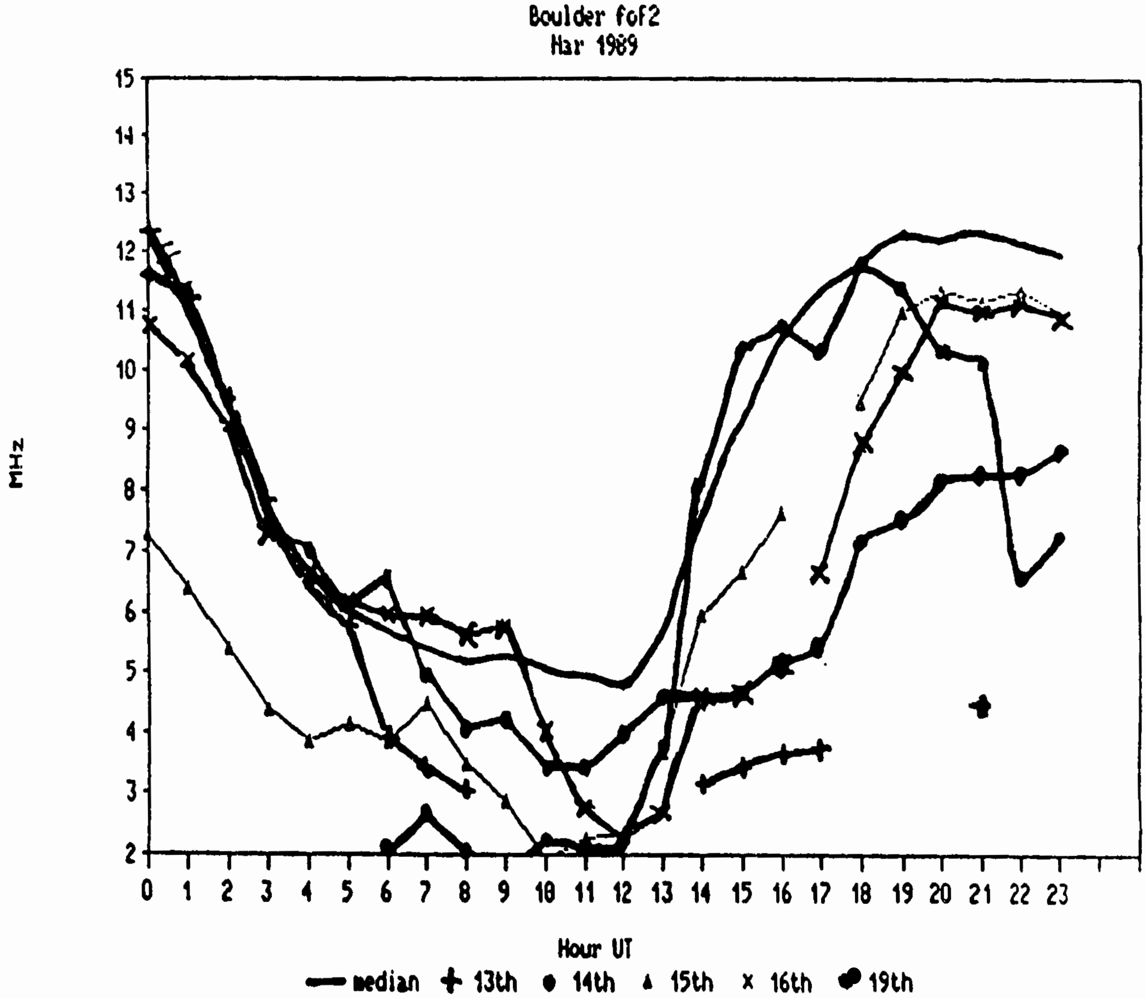
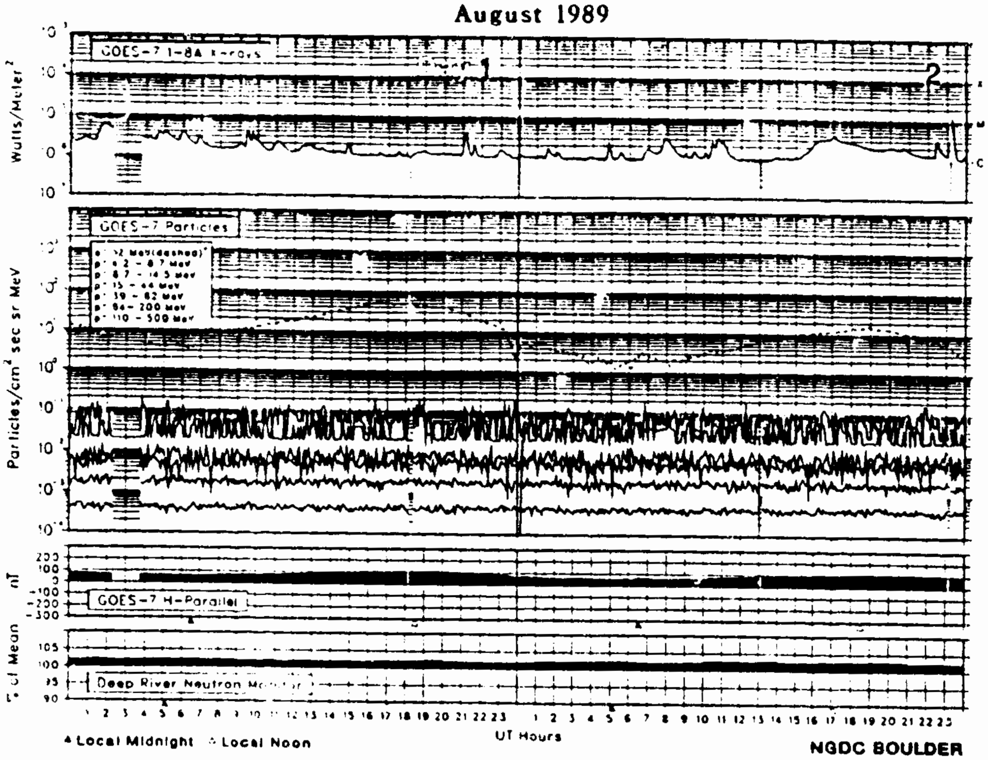

Boulder foF2
Mar 1989
15
14
13
12
11
10
9
8
7
6
5
4
3
2
MHz
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Hour UT
median
13th
14th
15th
16th
19th

Figure 10

SOLAR-TERRESTRIAL ENVIRONMENT
August 1989



SOLAR-TERRESTRIAL ENVIRONMENT
August 1989

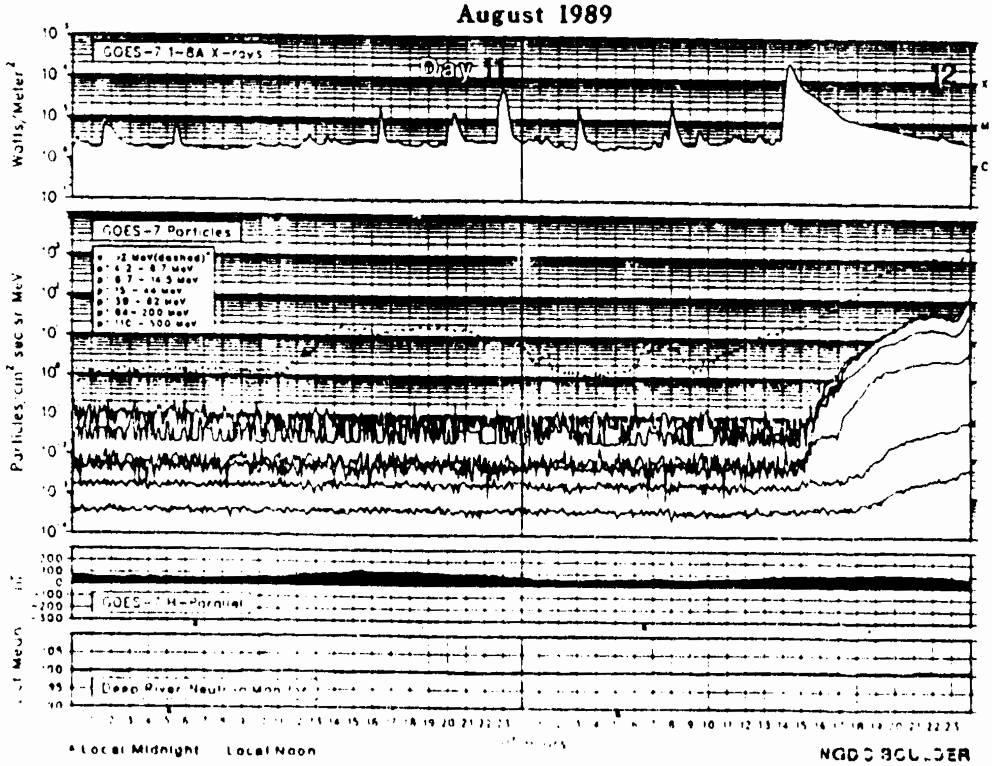
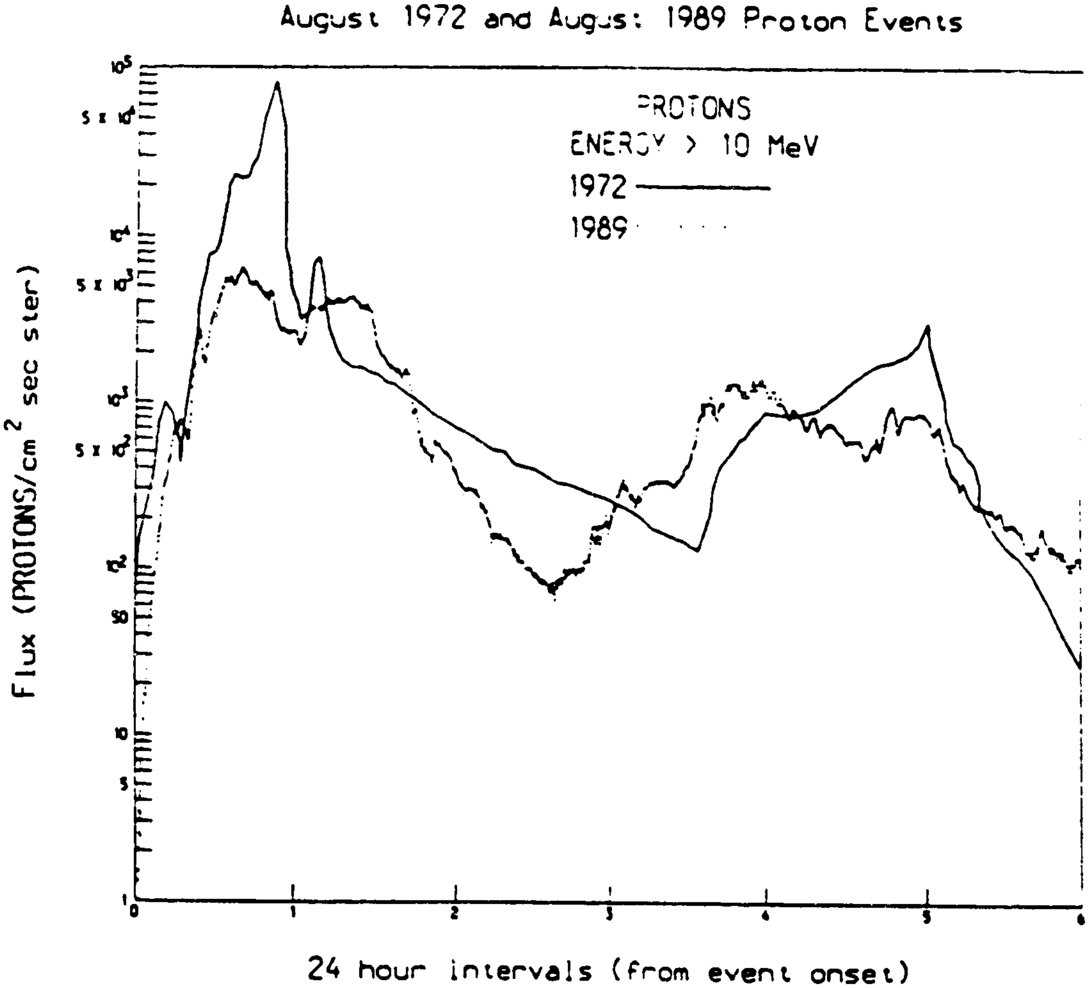


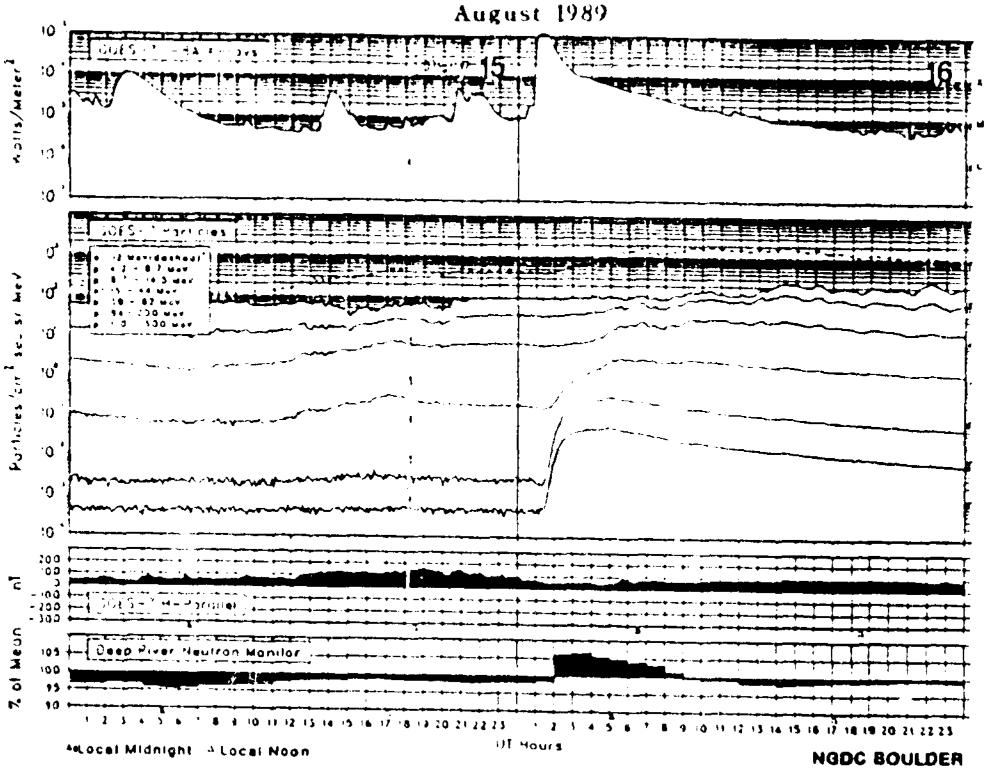
Figure 11



From Joan Feynman (JPL)

Figure 12

SOLAR-TERRESTRIAL ENVIRONMENT
August 1989



SOLAR-TERRESTRIAL ENVIRONMENT
September 1989

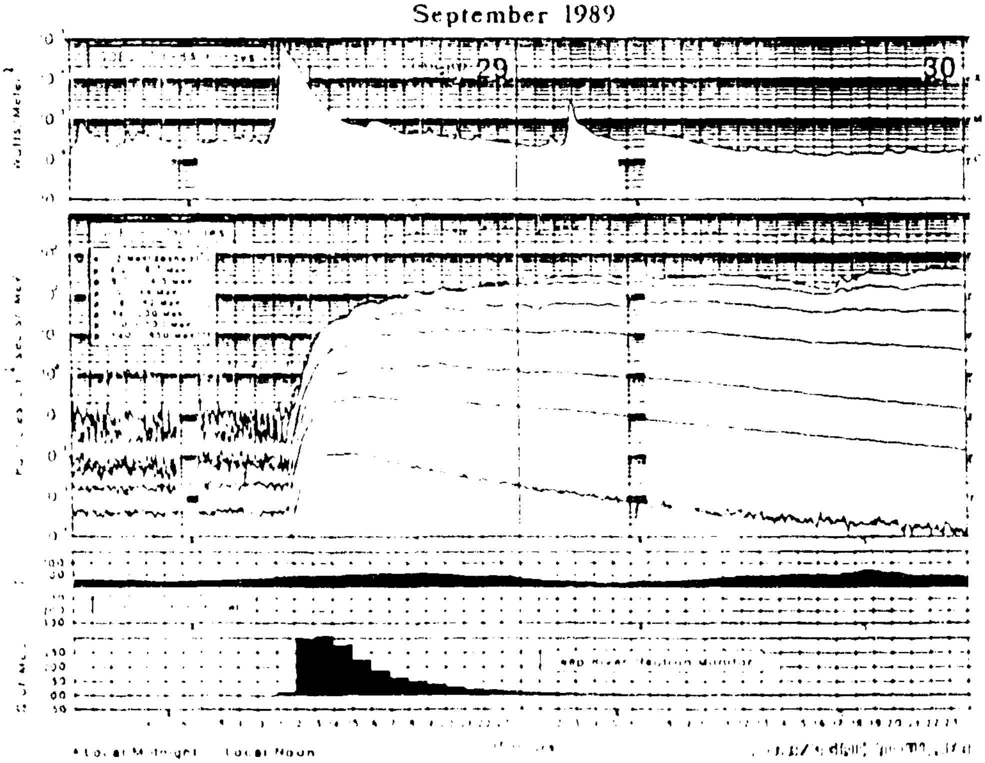
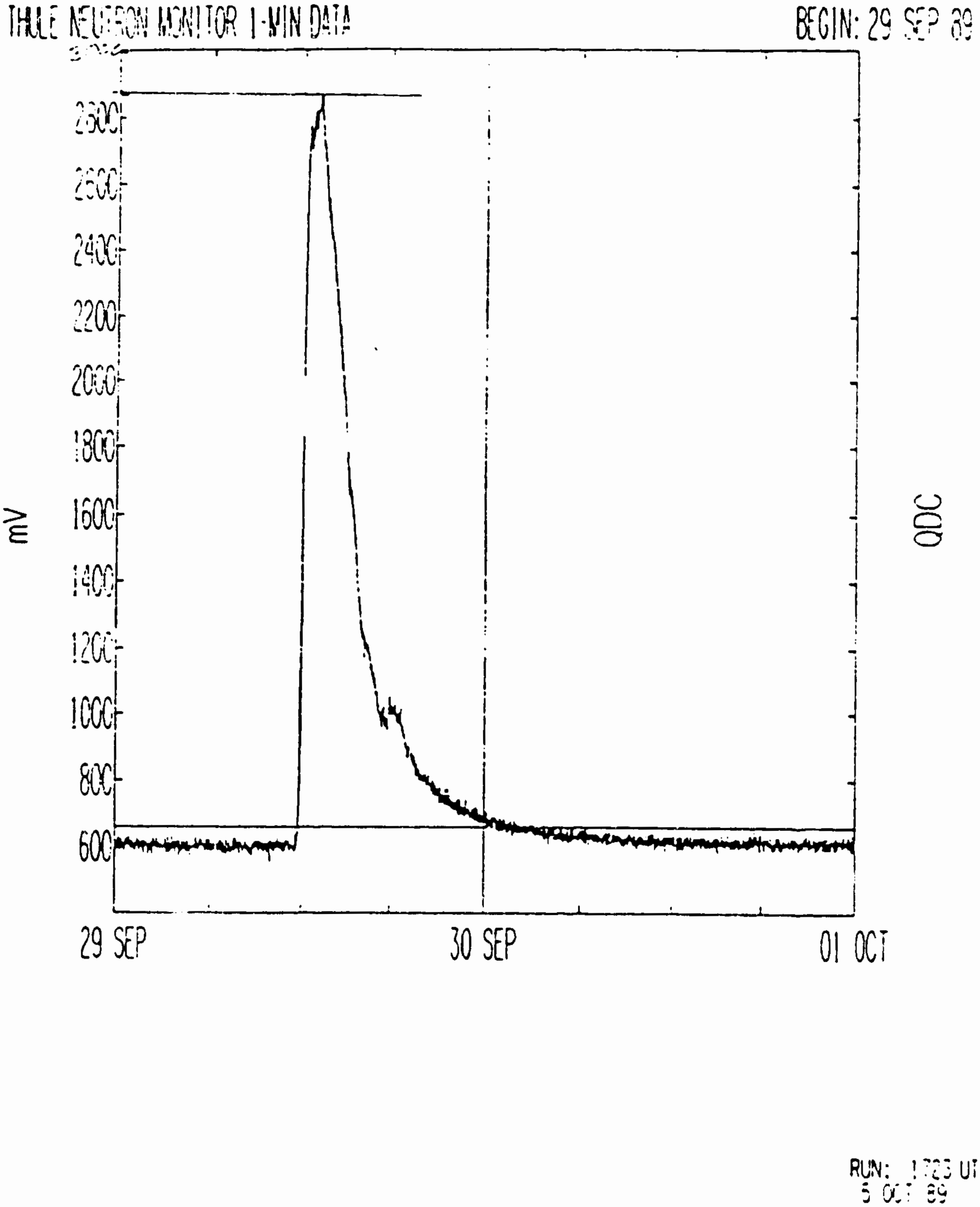


Figure 13



From Herb Sauer (NOAA/SEL)

Figure 14