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Effects of the March 1989 Solar Activity

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On Monday, March 6, 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). The 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 March 6–19, Region 5395 produced 11 X-class and 48 M-class X ray flares. Prolonged proton events occurred that lasted several days and had an unusually high proportion of lower-energy particles. The solar activity produced an historically "great" magnetic storm, long-lasting Polar Cap Absorption events, and a major Forbush decrease, which is a decrease of the galactic cosmic ray flux observed at Earth. 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.

Analysis of this series of exciting events is underway and the data bases are now being assembled. Interested scientists have been in contact through electronic mail and written correspondence, even while the events were in progress. In addition, the spectacular imagery has received a good deal of attention in the popular press. Scientists who are interested in participating in this study should contact Joe Allen (on SPAN, 9555::jallen; on INTERNET, jallen%9555.span@ames.arc.nasa.gov).

Figure 1 summarizes the March 9-16 activity and its effects. Figure 1a 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 the U.S. Geological Survey's Boulder Magnetic Observatory and the flux from the Deep River Neutron Monitor in 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 1989 issue of *Solar-Geophysical Data: Part 1, prompt reports* (SGD-1).

Solar Flares

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

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

Injection of Energetic Particles to Geostationary Orbit

On Tuesday, March 7, the flux of 4.2-8.7 MeV protons began to rise gradually. By early on March 8 it was an order of magnitude higher than background level. Just before 1800 UT the flux increased sharply by about two orders of magnitude (see April *SGD-1*, p. 168) and continued at high levels through March 14.

Maximum was reached at about 0700 UT on March 13 (see Figure 1b). When the flux of >10 MeV protons exceeded 10 particles per (cm^2-s-ster) at 1735 UT on March 8, the SESC announced that a "Proton Event" was officially in progress. The onset of high flux was probably caused by the flare of March 6 and was sustained at event levels until March 14 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 1b, 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 to negative values indicate that the magnetopause, typically located at 10 R_E (Earth radii) distance, moved inside the geostationary orbit (6.6 R_E). Such rare events are called Geostationary Magnetopause Crossings (GMC) and are caused by extreme conditions of solar wind pressure, often coupled with a strongly southward interplanetary magnetic fieldy components.

Given a reasonable model for the magnetopause shape, the minimum distance to the subsolar point was 4.7 RE, or more than a factor of two compression in linear size. The first of several crossings was observed by GOES 7 on March 13 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 dawnside magnetopause was within 6.6 R_E for approximately 3.2 hours. Together with the crossings later that day, these episodes comprise the longest-duration compressions observed by the GOES satellites from 1979 to the present.

We can estimate the energy (work) required to compress the magnetosphere from a quiescent subsolar boundary distance of 10 R_E to our estimated minimum distance of 4.7 R_E. The product of the projected cross-sectional dawn-dusk area of the magnetosphere and the pressure ($B^2/8\pi$) 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 $\times$ 10^{15} joules, about one-sixth the average daily U.S. 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 surface increases with decreasing 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 would show an abrupt transition from full transmission at high latitudes to none at a specific latitude, the "cutoff latitude" for that energy. For the real, asymmetric magnetosphere, however, the transition occurs over a latitude range of several degrees; i.e., the cutoff is not "sharp."

Figure 2 shows 2.5–16 MeV cutoff latitude observations by NOAA Space Environment Laboratory 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

Cover. Auroral image taken in ultraviolet light from the Dynamics Explorer 1 satellite at 0151 UT March 14, 1989, shown as observed over the southern hemisphere (left) and magnetically mapped to the northern hemisphere (right). Inset shows the sunspot region 5395 causing the flares, taken in Hα. See "Effects of the March 1989 Solar Activity" by Joe Allen, Herb Sauer, Lou Frank and Patricia Reiff, this issue.

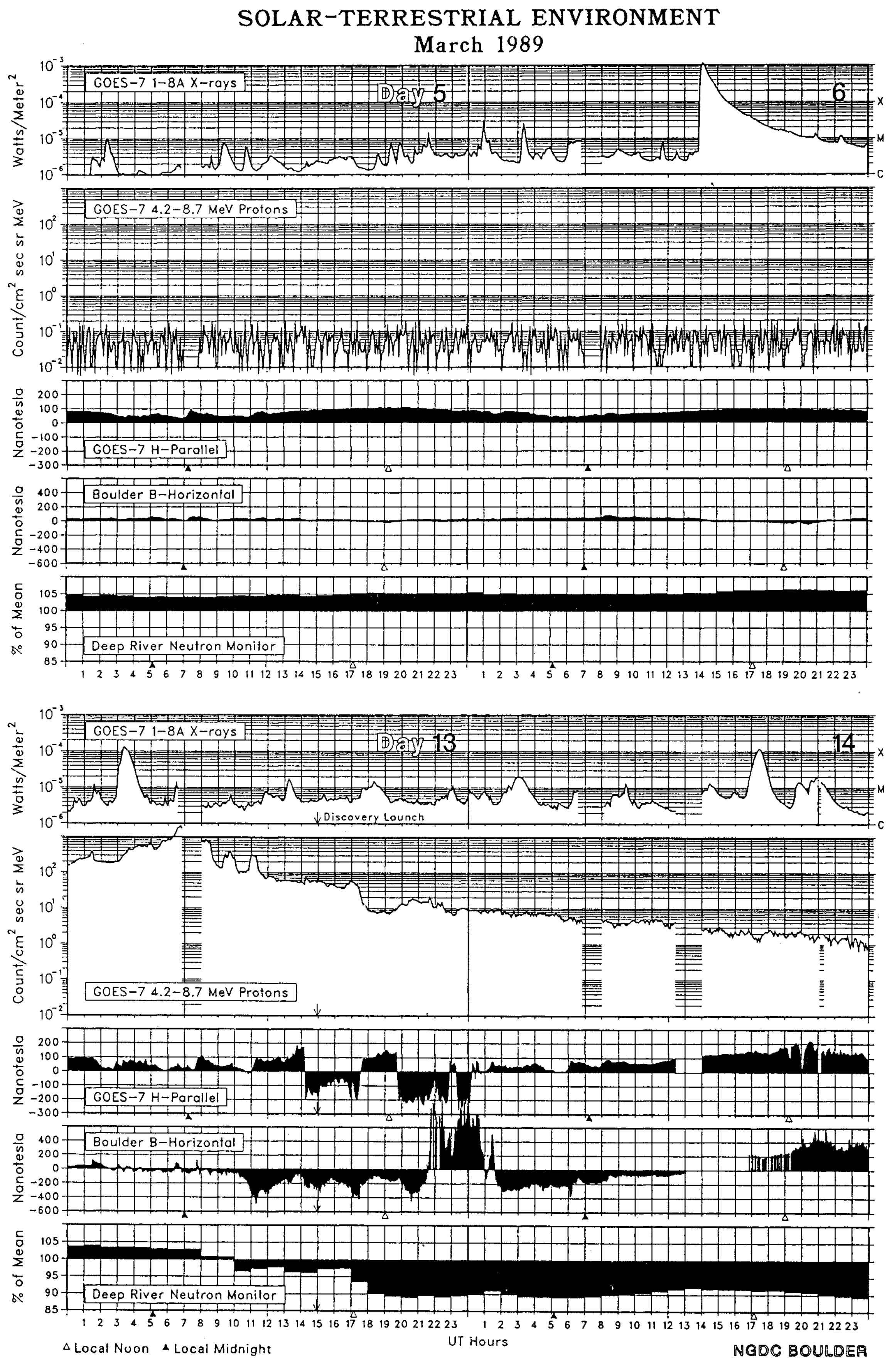
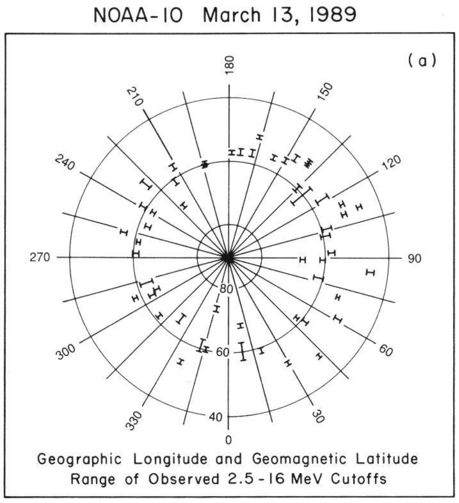


Fig. 1. Summary data from (a) March 5-6 and (b) March 13-14, 1989.



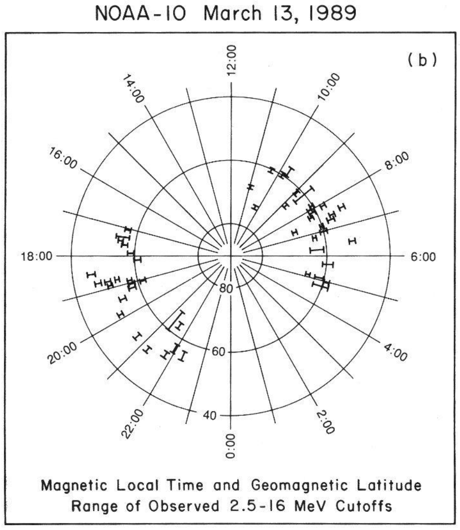


Fig. 2. Cosmic ray cutoffs from NOAA 10.

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 equatorward 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° to a maximum of about 72° geomagnetic latitude. Note that the latitude range of the observed cutoffs for that day was quite broad—about 25° wide at 60–120° east geographic longitude—while significantly less (about 10°) some 180° away. Figure 2(b) indicates that the cutoffs were generally lower in the evening hours, with the most equatorward being 44° latitude occurring about 1830 UT at about 82° east longitude, placing it over the central U.S.S.R.

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° latitude and the softness of the particle spectrum prevented the solar proton event from posing a radiation hazard to the mission. In contrast, the Soviet vehicle MIR, with a maximum orbital latitude of about 51°, would be expected to have suffered a significantly increased exposure to energetic proton and alpha particle radiation, but apparently was not exposed to a major hard event.

Radiation Belt Precipitation

The energetic particle sensors aboard the NOAA 10 low-altitude, polar-orbiting satellite measure electrons and protons in the energy ranges >30 keV->300 keV, and >300 keV->80 MeV, respectively. Figure 3 shows a gray-shade plot of the 10-day averages of the proton fluxes observed by NOAA 10 in the energy range 30-80 keV. The fluxes are averaged in 5° bins of geographic latitude and longitude.

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

Geomagnetic Storms and Substorms

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

The "great magnetic storm" of March 13-14, 1989, began with an ssc at 0128 UT on

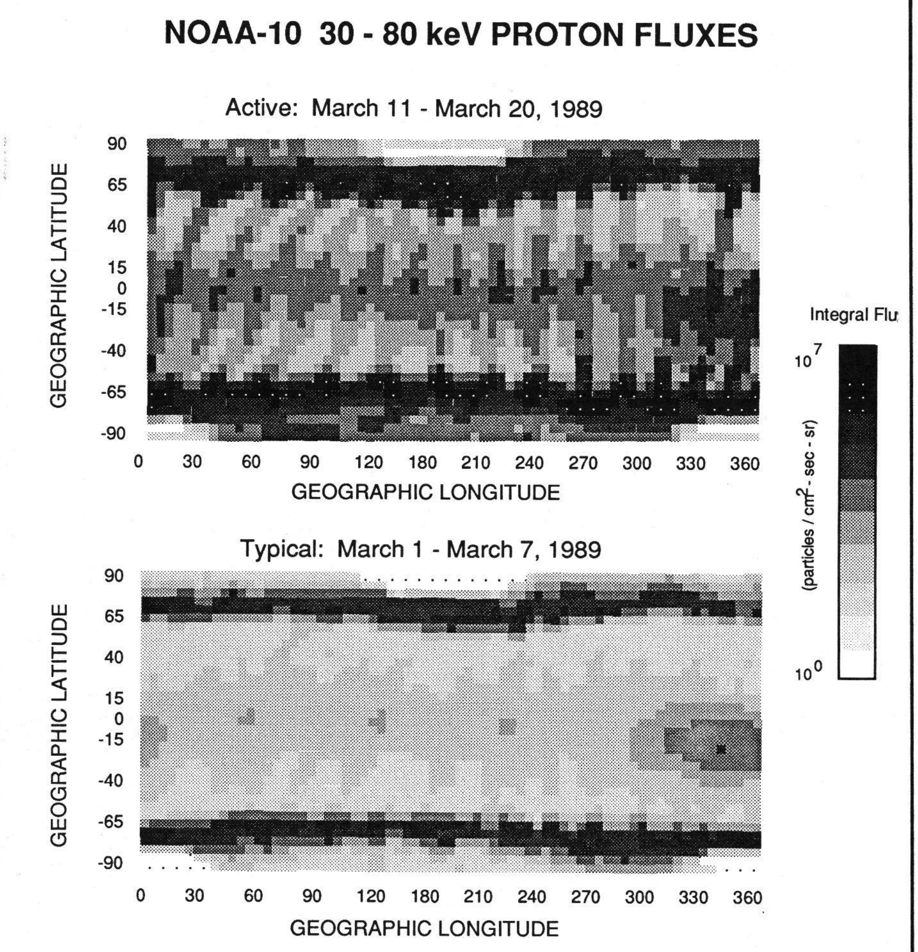


Fig. 3. Integral proton flux from 30-80 keV measured by NOAA-10 (normal and disturbed conditions).

March 13 (the afternoon and evening of March 12 over North America). Another ssc occurred around 0747 UT and a large negative H bay was recorded at Boulder Magnetic Observatory in Colorado around 1100 UT. Near 2100 UT the Boulder H-component began a rapid positive excursion that carried the fluxgate 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 (Naval Ocean Research and Development Activity) site at the Stennis Space Center, Bay St. Louis, Miss., shows large positive H deviations across the midlatitude U.S. for about 6 hours at the end of March 13 and early on March 14 (UT) (Figure 4; Herzog and Wilson, personal communication, 1989). All observatory magnetometers were off scale at +2,000 nT for part of this time.

It appears likely that for extended periods on March 13-14 the eastward Auroral Electrojet was located over the central U.S. for several hours. This is consistent with the Dynamics Explorer (DE) 1 auroral imagery (cover illustration) and the similar image taken by satellite F9 of the Defense Meteorology Satellite Program (DMSP) around 0355 UT on March 14 (*Eos, 70*, May 16, p. 595).

In the auroral zone, substorm conditions persisted before, during, and after the most active interval of March 6–20 . The Auroral Electrojet index shows the intensity of auroral zone substorm activity on March 13-14 (Figure 5, from *Kamei et al.* [1989]). 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 and many stations were saturated. Toyo Kamei at Kyoto University, Japan, has suggested that he may try deriving special midlatitude AE indices using records from North American sites such as Boulder, Fredericksburg, Va., and Newport, R.I., which were closer to the electrojet.

Global magnetic activity indices were made available promptly from Goettingen, Federal Republic of Germany, (Kp) and Paris, France, (aa). At the National Geophysical Data Center in Boulder 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 March 13, 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

Table 1. Major Magnetic Storms

Rank	AA*	Start Date	Start Time, UT
AA Most Disturbed 24-Hour Index (2 Stations From 1868)*			
1	450	March 13, 1989	0600
2	429	Sept 18, 1941	0600
3	377	March 24, 1940	1500
4	372	Nov. 17, 1882	0900
5	372	Nov. 12, 1960	1800
6	357	July 15, 1959	0600
7	356	May 14, 1921	1200
Rank	**Ap***	**Start Date**	**Start Time, UT**
Ap Most Disturbed 24-Hour Index (13 Stations Since 1932)*			
1	312	Sept. 18, 1941	0900
2	293	Nov. 12, 1960	2100
3	279	March 13, 1989	0300
4	277	March 14, 1940	1200
5	258	Oct. 6, 1960	0900
6	252	July 15, 1959	0600
7	251	March 31, 1960	2100

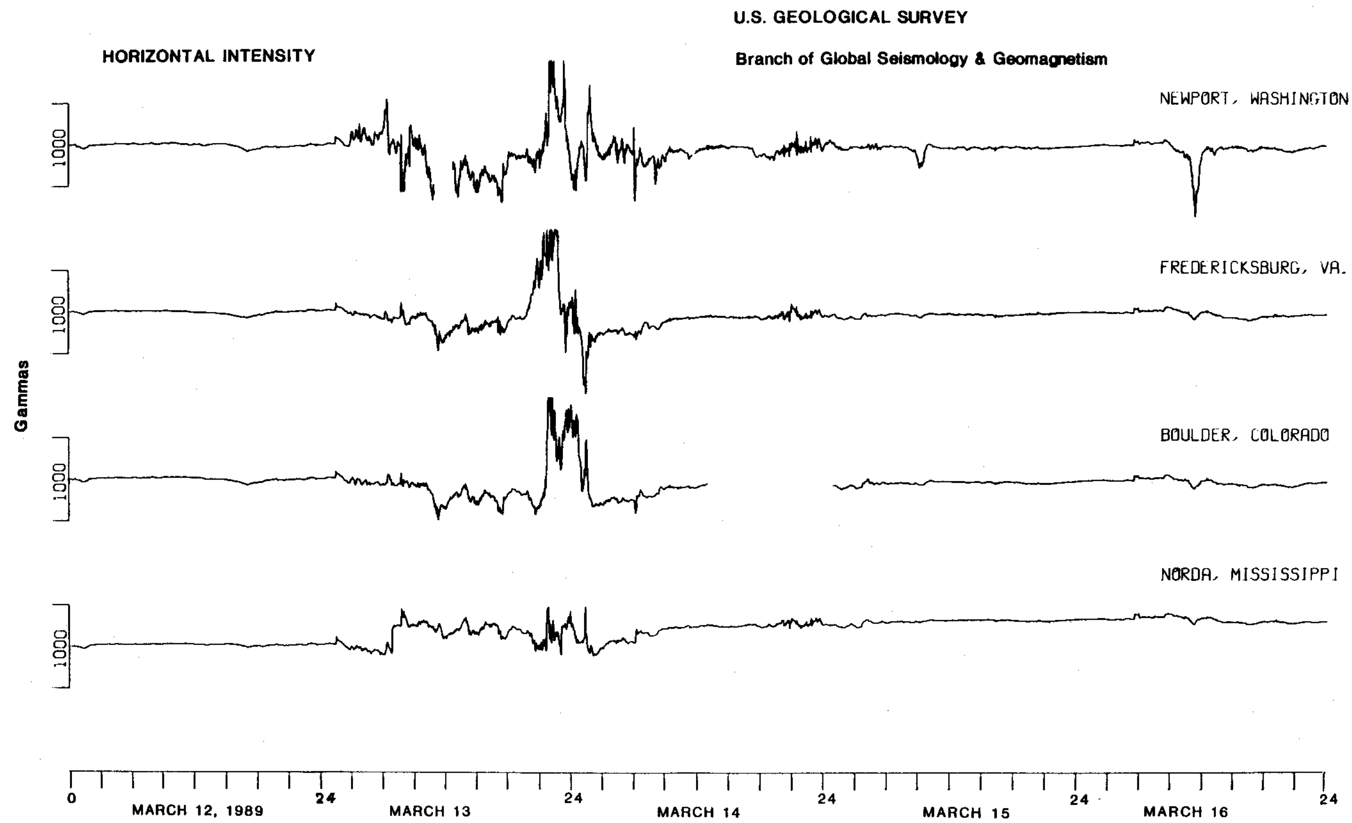


Fig. 4. Midlatitude magnetometers measuring auroral currents (many going off-scale).

third largest magnetic storm since 1932 based on indices of disturbance derived from records of a global network of 13 observatories. According to the March AA* this was the largest magnetic storm since 1868 as recorded by the 2-station network of antipodal sites in the U.K. and Australia.

Extremely Large Auroral Zone

Both spacecraft and ground-based sightings indicated the extreme coverage of the aurora. DE 1 was passing over the Antarctic during this key time and obtained striking auroral images at ultraviolet wavelengths (1360 Å to 1650 Å), mainly due to emissions from the Lyman-Birge-Hopfield bands of molecular nitrogen. Figure 6 is DE 1 imagery from two separate passes over the Antarctic, 6 years apart. The quiet auroral oval on the left was recorded at 1623 UT on March 22, 1983, and the enormously expanded auroral oval on the right was recorded at 1826 UT on March 13, 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 second DE 1 image over Antarctica (cover, left side) was taken at 0151 UT on March 14, 1989; coastlines are superposed here. The image was mapped onto the Northern Hemisphere at 200 km altitude using a Magsat geomagnetic field model (cover, right side). In this projection two broad bands of auroral emissions are seen. The northerly band is centered along the U.S.-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 auroral sightings reported from across the southern U.S. during local nighttime hours of March 13 and early March 14. 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 current appeared to lie

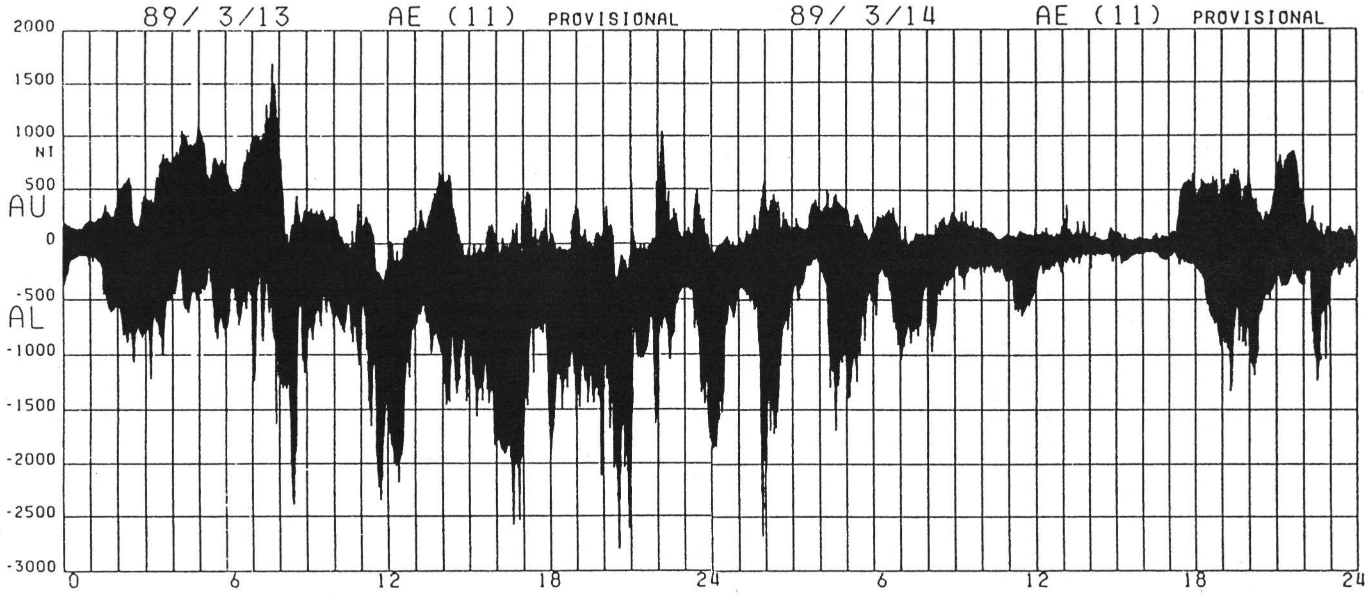
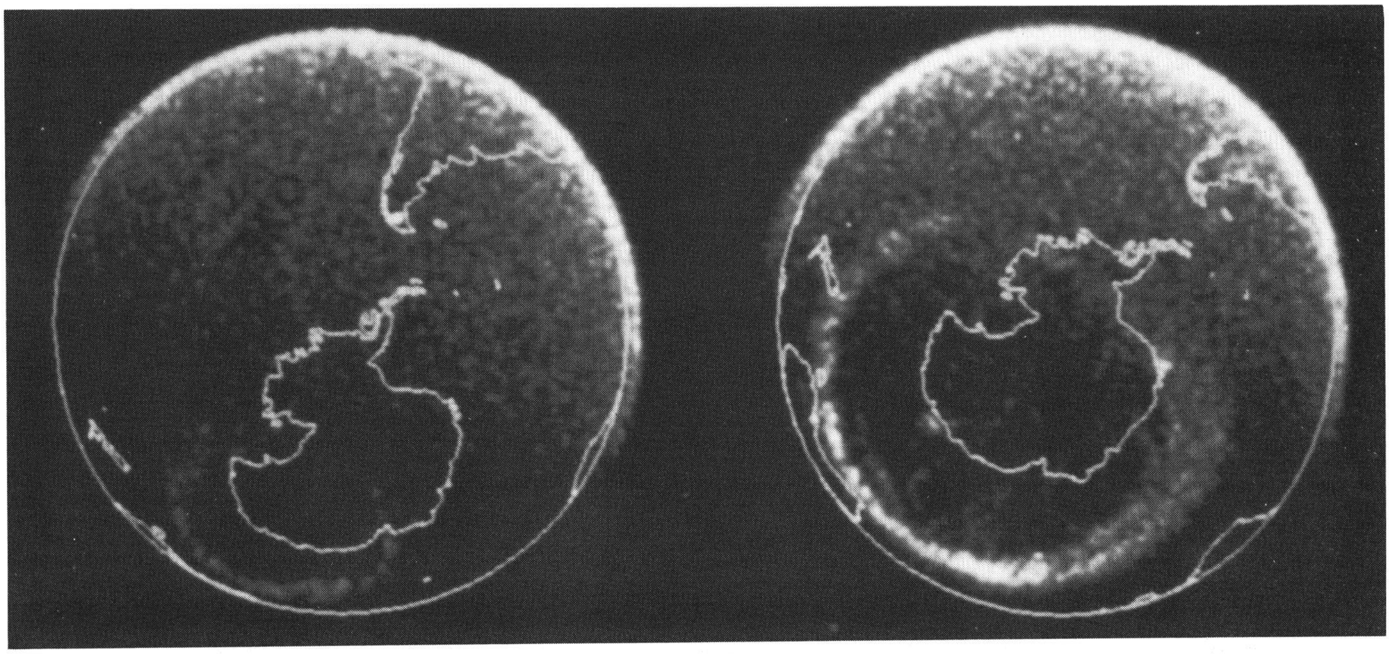


Fig. 5. Provisional Auroral Electrojet indices for March 13–14, 1989 [after *Kamei et al.*, 1989]. The AE index = Au − Al; however, this must be considered a lower limit since the auroral currents were well equatorward of the typical auroral zone stations and many even so were saturated.



across the U.S. from Washington state to Virginia.

DMSP F9 recorded several spectacular auroral images in visible light during this time. The one published in *Eos* shows a wide band of discrete aurora extending from just below Hudson's Bay to above Chicago at its narrowest extent.

Radio Aurorae

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

Ionospheric conditions for March 6–20 included very disturbed conditions mixed with hours when typical monthly median values were observed. On normal quiet days hourly observations of the critical frequency of the F2 layer, foF2, above Boulder are lowest around 1200 UT (~5 MHz at 0500 local time) and rise to a daytime maximum around 1900 UT (~12 MHz at local noon). There is a rapid rise in foF2 around 1300 UT on undisturbed days when the sun begins to illuminate the ionosphere above Boulder. Most days during March 6–20 have their local evening (0000 UT) foF2 values near the monthly median except for March 13-14, when foF2 "disappears." On March 13 at 0600 UT the Boulder foF2 value drops well below the median and stays low (or missing) until 0600 UT on March 14. Daylight values on March 14 recover to near the median until around local noon and afterwards are depressed through March 15 and into March 16. Daytime values on March 16 begin to recover to the median and continue at normal levels until March 19 when foF2 was again very depressed.

Consequences of the March Activity at and near Earth

Reported consequences of the March solar activity as sensed at or near Earth were widespread—some amusing and some serious. Failures in commercial and defense systems are sensitive topics, and there may be other failures of which we are unaware. In the listing below, if an item is given without specifics, it is because our sources have asked us not to reveal the details.

Effects on Space Systems

- There was concern about the launch of the shuttle *Discovery* during a Forbush decrease 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 geomagnetic activity was responsible.
- A previously stable low-altitude satellite in nearly circular orbit at roughly 60° inclination began episodes of uncontrolled tumbling on March 6, 8-9, and 14, which interfered with operational functions. GOES 7 had a communications circuit anomaly on March 12 and lost imagery and had a communications outage (ground control problem) on March 13.
- Three low-altitude NOAA polar-orbiting weather satellites and the USAF DMSP counterpart to the NOAA series had trouble unloading torque due to the large ambient magnetic field changes in orbit.
- Japanese geostationary communications satellite CS-3B had a severe problem at 1050 UT on March 17 that involved failure and permanent loss of half of the dual redundant command circuitry onboard.
- Barnes limb sensors used to lock low-altitude polar orbiters onto CO_2 brightening at Earth's limb have sensor degradation well-correlated with rising solar activity. This was encountered in 1978–79, "but the problem went away" so no engineering fixes were attempted.
- Operational satellites of the European Space Agency were reported not to have experienced outages but MARECS-1 (177°) had many switching events on March 3, 17 and 29.
- 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 orbit to maintain the required attitude during the disturbed conditions March 13-14. This is more than is normally required of controllers during a year of routine operations.
- The Japanese geostationary meteorological satellite GMS-3 "suffered severe scintillations during 1200–1430 UT on March 23." Data transmissions were lost for about an hour around 1300 UT.
- Geostationary communications satellites reported operational anomalies on March 18 and 20 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 half a kilometer 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 March 13 about 2000 were reported. The number rose daily by about 500 to 1000 events (a larger increase on March 17) to reach a maximum on March 18 of almost 6000 UCTs; then the number declined to around 2300 UCTs by March 23.

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 U.S. Coast Guard reported numerous LORAN navigation problems, particularly on March 6 and 13. There was even difficutly using hf-radio (high frequency) communications to alert users to the problems.
- The U.S. 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 March 13 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 transmission range and intensity was enhanced, e.g. California Highway Patrol messages were overpowering local transmissions in Minnesota.
- A VLBI (very long baseline interferometer) observer in the Florida keys reported exceptional communications at frequencies >140 MHz.
- In Australia there were many reports of poor hf-radio conditions on March 13-14. Polar to midlatitude circuits were "useless" and equatorial circuits were "very weak and noisy." During daytime foF2 on March 14 was "mostly <5 MHz." Large, rapid swings of foF2 occurred at night on March 14/15.
- The Boulder CO 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 only 4 to 5 MHz.
- Geodetic surveys in the U.S. and, possibly, ship navigation near Australia using signals from navigation satellites were impaired.
- Automatic garage doors in a California coastal suburb began to open 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, March 13. 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; 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 U.S.; 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, and Canada; a U.S. declination change of 6° was reported.
- Declination changes of greater than 3° measured at U.S. 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 March 14 centered on 0000 UT." Magnetometers at mid-latitude U.S. observatories went offscale repeatedly on March 13-14 at +2000 nT.
- Record Ap* = 279 and AA* = 450 values (see above).

Aurorae Viewing Reports from Ground Observers

- Brilliant aurora was seen across the U.S. on the nights of Sunday-Monday, March 12-13, and Monday-Tuesday, March 13-14. Reports were received from upstate New York, New Jersey, Colorado (Boulder), Texas (Brownsville, Houston and San Antonio), New Mexico (Los Alamos), Arizona (Fort Huachuca), and California (Los Angeles and San Francisco). Bright green, blue and white forms were reported over the eastern U.S. with mainly red aurora reported from farther south. Backpackers in remote mountains of western North Carolina reported static red aurora for about four to six hours but with white beams converging toward the southern horizon. Red aurora were reported from the Florida Keys, Grand Cayman Island and Cancun, Mexico.
- Aurora was reported on the night of March 13-14 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 of University 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 March 13-14.

Surface Technology Affected

- Geophysical exploration surveyor reports: From South Africa, "Conditions unlike any I've seen before! Nothing worked." From Western Australia, "Never seen conditions quite like it." From Bass Strait, Australia, concern over increased pipeline corrosion.
- Microchip production facilities in the northeastern U.S. out of operation two or more times due to magnetic activity.
- Undersea cables in Atlantic and Pacific oceans experienced large voltage swings.
- High levels of UV-B measured near Seguin, Tex., around time of naked eye spotting of sunspot region 5395.
- Power distribution facilities blacked out in Canada and Scandinavia (see above).
- Out of hf-radio contact from southern U.S. to sites around the world.

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 March 6-20, 1989, will become known. We know 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 peaks 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, 1989). 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 March 13-14; however, the possibility that another may occur in 1990 or soon after must be considered.

Major episodes of solar activity affecting Earth and near-Earth space occurred since the writing of this report about the March activity. They began in August, September and October 1989. A flare on August 12 produced a major particle event and a subsequent large flare on August 16 produced a major high-energy proton event with increased neutron flux measured worldwide at cosmic ray monitors. Spacecraft and ground-based systems were affected. Similarly, on September 29 a probable large flare occurred on the back side of the Sun and was seen above the west limb as a loop prominence and as an X-9.8 level X ray flare recorded by GOES 6 and 7 satellites. This flare event produced a major increase (ground-level event) in neutron monitors around the world, for example, at Thule, Greenland, the neutron flux increased approximately 380% above the normal monthly quiet-time level. This was the largest such event in 33 years, hence the largest since satellites. Beginning on October 19 major flares from sunspot region 5747 produced three large energetic ground-level particle events. The total proton fluence during this event sequence in October was comparable to that during the record August 1972 event. Many satellites were affected, in particular, star sensors were upset, power-panel arrays deteriorated significantly, and single-event upsets occurred.

As society continues to move to wider uses of high-technology devices, often controlled by faster and more compact microchip 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.

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