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National Oceanic and Atmospheric Administration's Spacecraft Anomaly Data Base and Examples of Solar Activity Affecting Spacecraft

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The National Oceanic and Atmospheric Administration's National Geophysical Data Center maintains a data base of anomalous spacecraft behavior attributed to environmental interactions. This paper introduces the data base and its capabilities. Examples from the data base are presented, and their environmentally related trends are illustrated. The active sun during 1989 provided valuable lessons in the interaction between the space environment and space borne technology. The effects of that activity are summarized.

Introduction

THE National Oceanic and Atmospheric Administration (NOAA) is the primary U.S. civilian agency responsible for the operation of environment monitoring spacecraft. These responsibilities include the Geosynchronous Operational Environmental Satellite (GOES) series of weather and space environment monitoring satellites and the polar orbiting NOAA satellites. Long and productive spacecraft lifetimes are of major importance to NOAA.

NOAA also operates a system of data centers that includes the National Geophysical Data Center (NGDC) in Boulder, Colorado, which has responsibility for collecting, archiving, analyzing, and disseminating solar-terrestrial data and information. NGDC, under the auspices of World Data Center A for Solar Terrestrial Physics, services worldwide interests in data and information about the origin of solar activity, the transfer of energy from the sun to Earth, and its effects in interplanetary and near-Earth space. NGDC has made a deliberate effort to apply these data resources to the problem of spacecraft interaction with the space environment.

Spacecraft Anomaly Data Base

Data on spacecraft anomalies are maintained at the Solar-Terrestrial Physics Division of NGDC. Date, time, location, and other pertinent information about the anomaly are included. These events range from minor operational problems to permanent spacecraft failures. The data base currently contains over 3000 anomalies spanning 1971 to the present with contributions from seven countries: Australia, Canada, Germany, India, Japan, United Kingdom, and the United States. Data suppliers are asked to provide the anomaly type and diagnosis.

The data base is maintained on an IBM compatible personal computer. To facilitate access to this information, software has been written to perform a range of functions for managing and displaying the contents. Satellite operators can use the spacecraft anomaly manager (SAM) software to create a data base containing their anomalies and forward the result to NGDC on floppy disk for inclusion in the archive. To preserve confidentiality, spacecraft may be identified by aliases. SAM also includes two important functions to test anomaly collections for environmental relationships. Histograms of local time and seasonal frequency show distinct patterns for space susceptible to static charge buildup and subsequent discharge. The current version of the software does not provide statistical validation, but the user may convert the data to a standard ASCII file that can be uploaded to any computer and processed by user supplied software.

Figure 1 shows that the failure of the visual and infrared spin-scan radiometer (VISSR) on GOES-4 coincided with the arrival of 110-500 MeV protons resulting from an X3 solar flare. The GOES-4 failure prompted some interesting questions. What was it about this particular proton event that could cause such a failure? Are proton events of this magnitude common? Have GOES satellites survived similar proton events? Could the 12 h of enhanced > 2-MeV electron flux cause a charge buildup on internal dielectric materials that discharged when the energetic protons arrived? Or, was it only a coincidence that GOES failed during the proton event? Some of these questions can only be answered if historical information is available about the space environment and the interaction of GOES and similar spacecraft with that environment. Others can never be answered. The failure of GOES-4 prompted the creation of the spacecraft anomaly data base in the hope that such a historical record would help answer questions about future failures.

Trends in Environmentally Induced Anomalies

Two statistical methods are used to analyze anomaly trends. The chi-square test for randomness can determine the probability that a given distribution, or one with similar deviations from the mean, could occur randomly. The Pearson product-moment correlation coefficient can determine both the

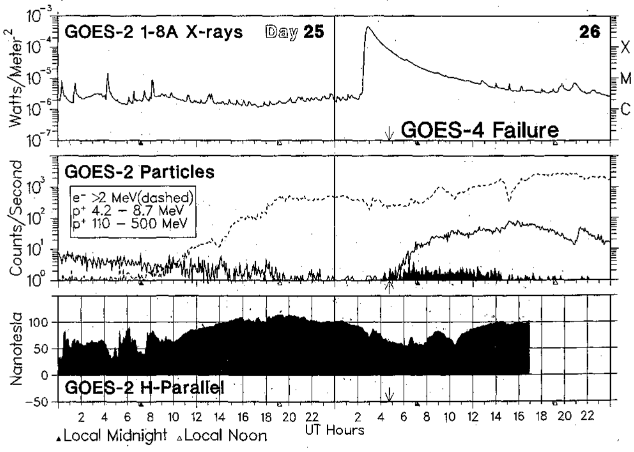

Fig. 1 GOES-4 failure, November 1982.

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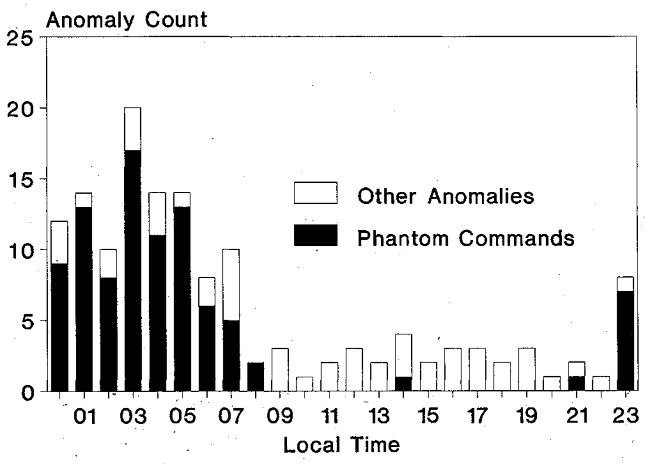

Fig. 2 Local-time distribution of GOES anomalies.

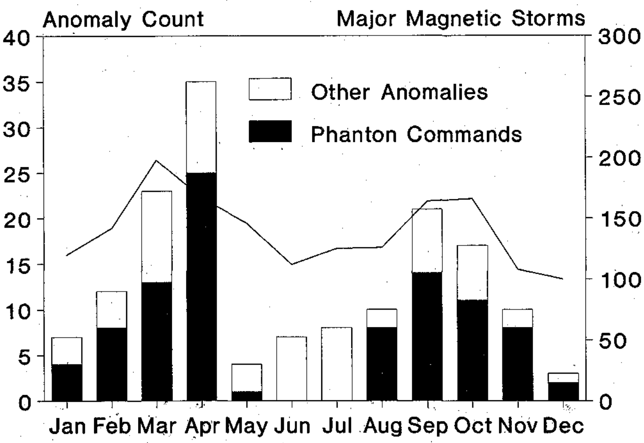

Fig. 3 Seasonal distribution of GOES anomalies.

strength of a correlation and the probability of error in establishing a correlation where none exists. A coefficient of 1 indicates perfect correlation, 0 indicates no correlation, and −1 indicates perfect anticorrelation.[1]

The first contributions to the data base were from the GOES satellites. GOES anomalies have been of two distinct types: 1) phantom commands attributed to differential surface charging and 2) telemetry errors due to single event upsets (SEUs). Phantom commands are commands executed without intention. An SEU is a logic upset caused by the deposition of charge into a sensitive electronic component by an energetic particle. The phantom command anomalies have been correlated with geomagnetic substorms[2] which cause an injection of energetic electrons into the path of geostationary spacecraft when traveling near local midnight.[3]

The local-time clustering of phantom commands shown in Fig. 2 demonstrates the extent of the injection and the subsequent discharging due to high surface potentials. The probability that this distribution of phantom commands is random is very small, 0.0000022. The "other anomalies" show no such grouping and have a high probability of being random, 0.94.

Figure 3 shows that the same phantom command anomalies show a strong seasonal dependence. The other anomalies do not. Since the phantom commands have been correlated to substorms, it would follow from this result that geomagnetic activity must also exhibit a seasonal trend. Indeed, a plot of the major magnetic storms since 1932 shows such a trend.

The history of SEUs from the University of Surrey satellite (UOSAT-2) shown in Fig. 4 is a recent addition to the anomaly data base. UOSAT-2 travels in a 700-km altitude orbit inclined at 98 deg. A number of memory systems totaling 2.4 megabits were monitored. During the monitoring interval approximately 200 upsets per month were recorded.[4] The geographical pattern in the data illustrates a dramatic effect on the SEU rate caused by the South Atlantic Anomaly—a depression in the geomagnetic field that allows the radiation belt to extend into lower altitudes.

The first satellite in the Telemetry Data Relay Satellite System (TDRS-1) experienced an unexpected high number of SEUs.[5] Figure 5a displays the weekly SEU rate beside the cosmic ray flux rates as measured by a ground-based neutron monitor. The sunspot data are displayed to demonstrate the solar cycle dependence. Shaded areas indicate the extent of each solar activity cycle.

The anticorrelation between sunspot number and cosmic ray flux is due to the solar cycle influenced interplanetary magnetic field. During solar maximum, as indicated by the

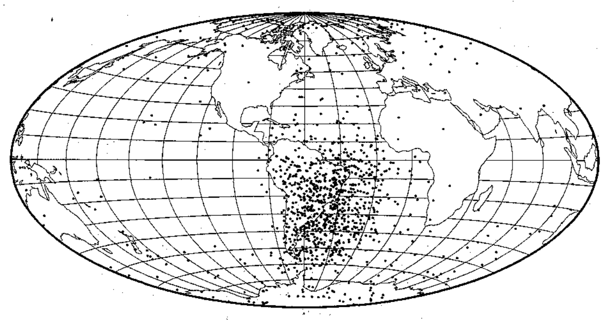

Fig. 4 Geographic distribution of UOSAT-2 SEUs.

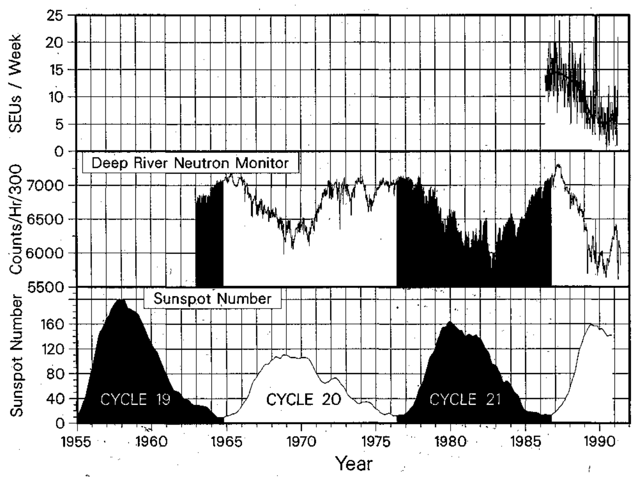

Fig. 5a Solar cycle dependence of TDRS-1 SEUs.

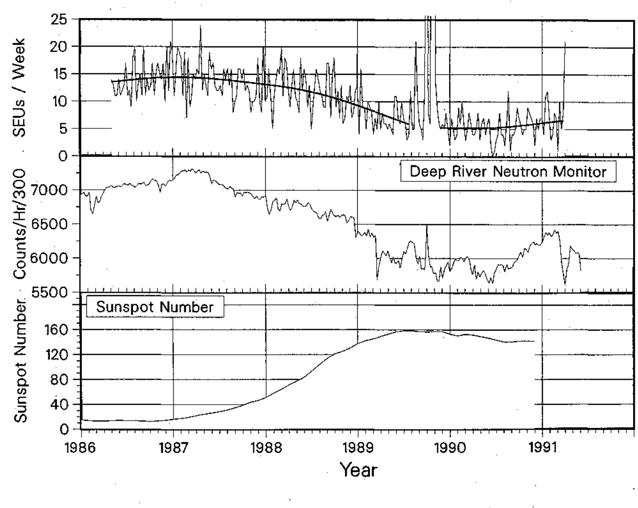

Fig. 5b TDRS-1 SEUs and galactic cosmic rays.

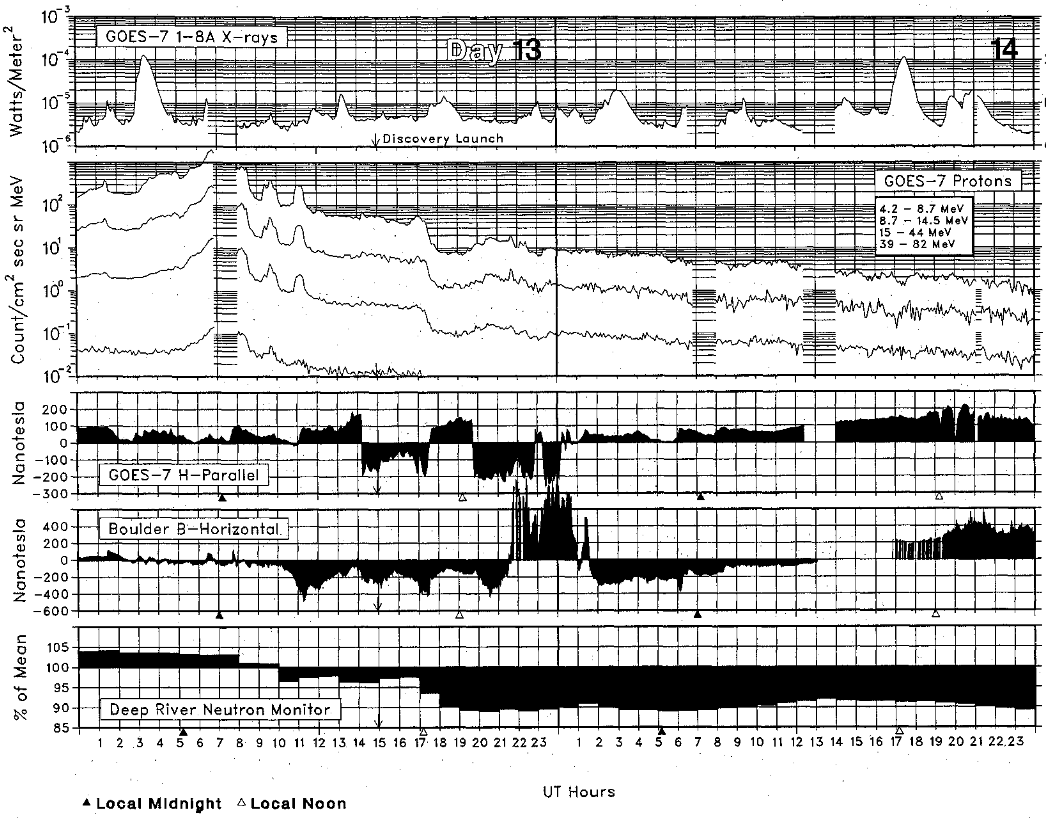

Fig. 6 Solar-terrestrial environment during the March 13 and 14, 1989, great geomagnetic storm.

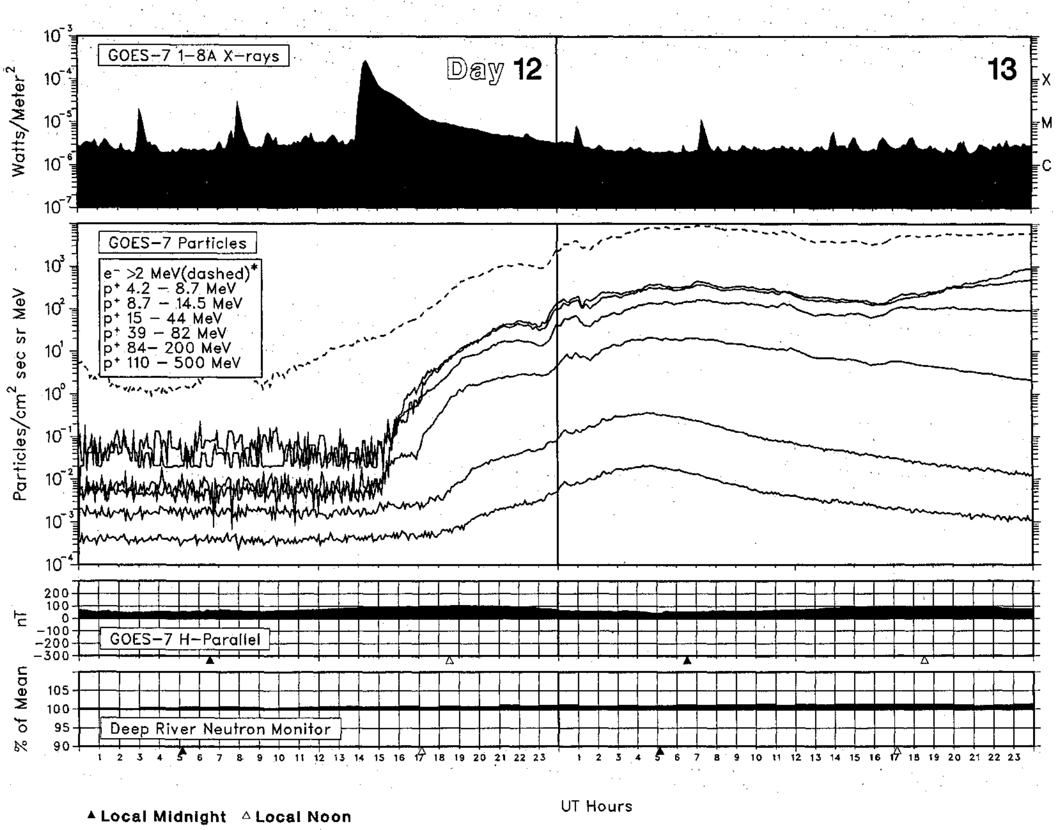

Fig. 7a Solar-terrestrial environment during the August 12 and 13, 1989, solar flares.

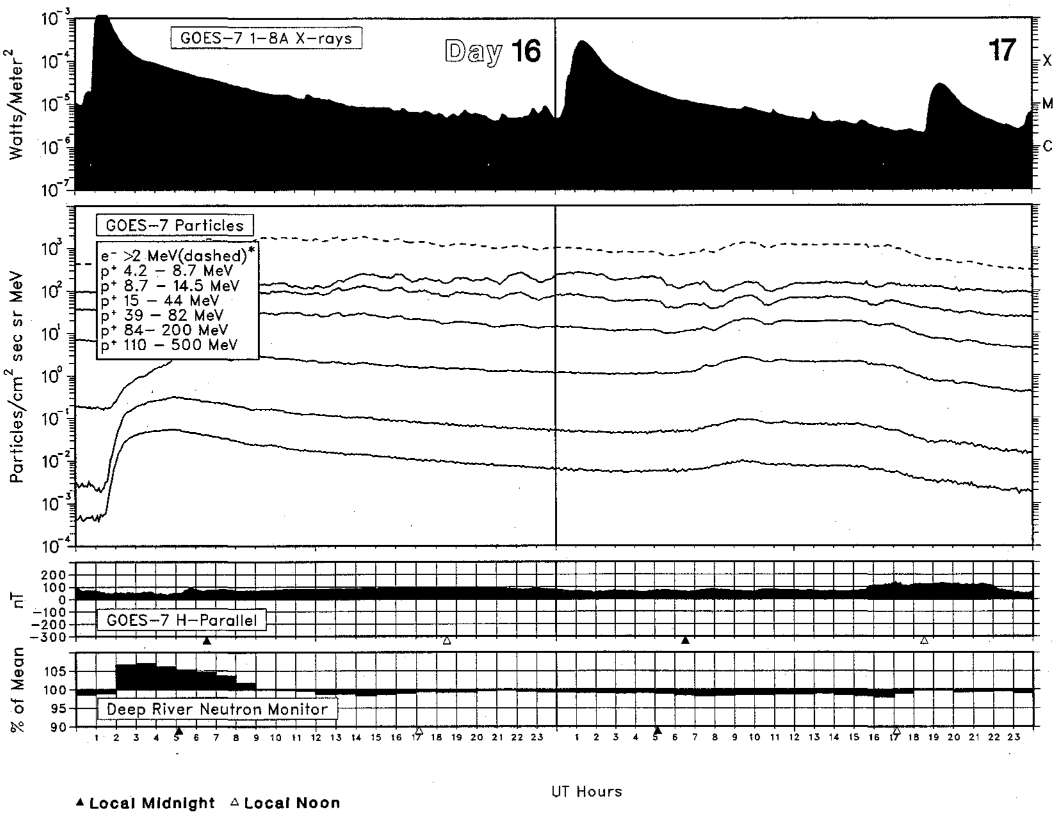

Fig. 7b Solar-terrestrial environment during the August 16 and 17, 1989, solar flares.

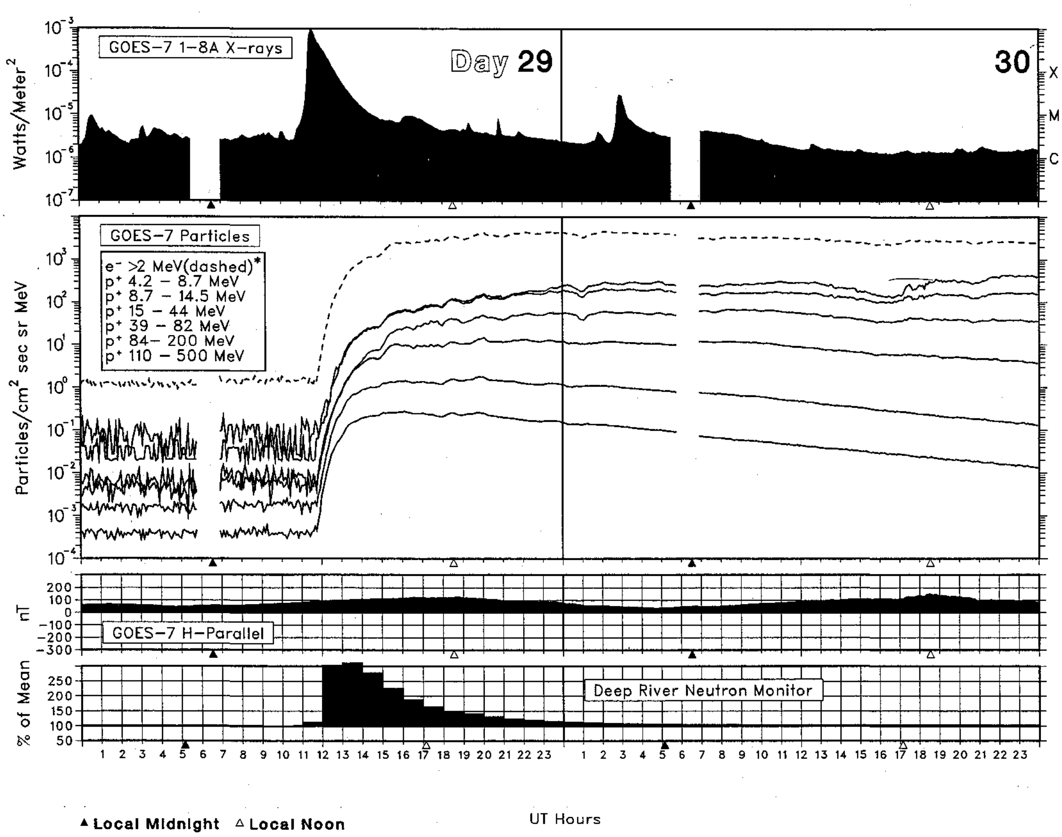

Fig. 8 Solar-terrestrial environment during the September 29 and 30, 1989, solar flares.

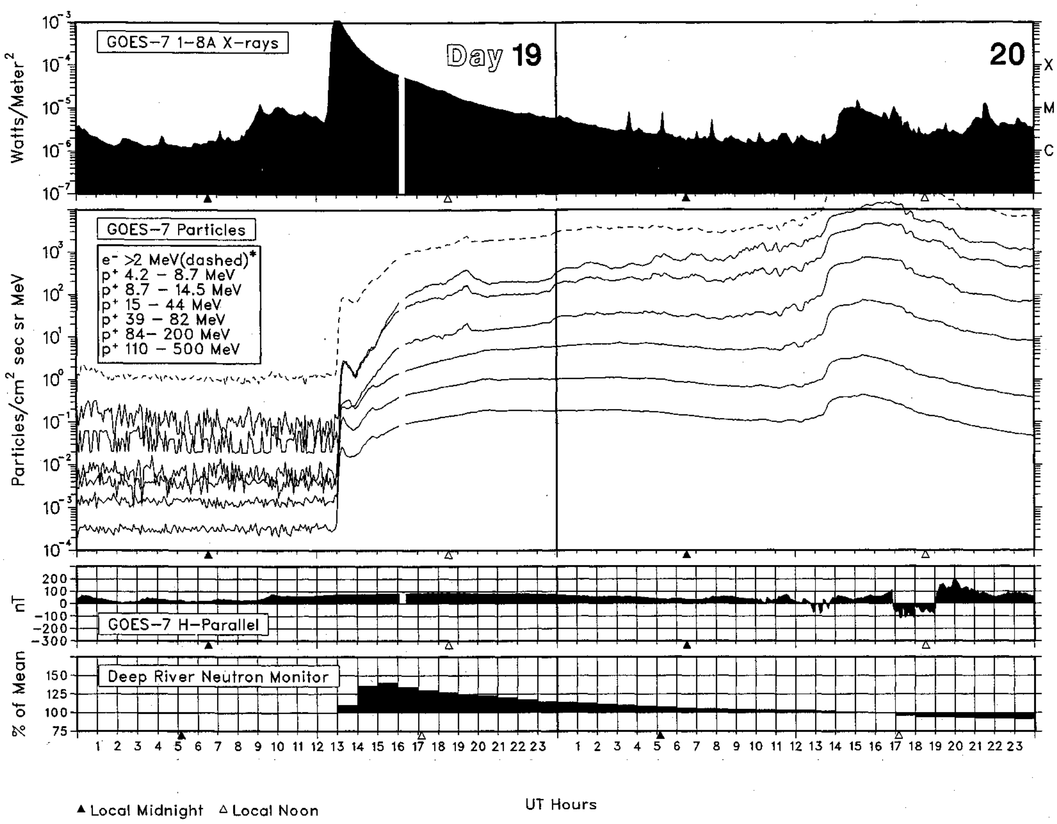

Fig. 9a Solar-terrestrial environment during the October 19 and 20, 1989, solar flares.

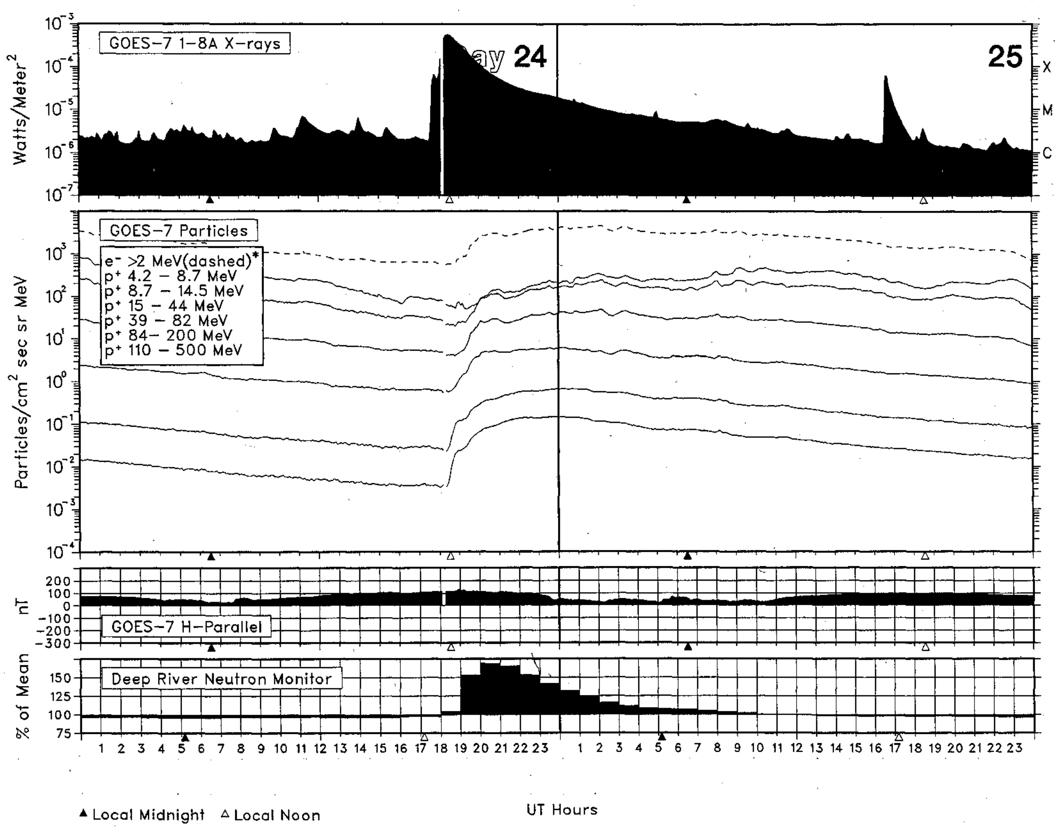

Fig. 9b Solar-terrestrial environment during the October 24 and 25, 1989, solar flares.

sunspot number, the state of this field partially shields the solar system from galactic cosmic rays.

A closer look at years 1986–1989 in Fig. 5b reveals that the TDRS-1 SEUs follow the same trend as the Deep River neutron monitor fluxes. Figure 5b also reveals an increase of SEUs in September and October of 1989 that deviates from the neutron monitor trend. During these months solar flares caused energetic proton fluxes of such magnitude that they have challenged the benchmark for such events, recorded in August of 1972.

1989 Solar Activity

On March 13, 1989, the solar-terrestrial environment was dramatically affected by a great magnetic storm shown in Fig. 6. A solar flare on March 10 initiated a solar proton event that peaked on March 13 at about 0700 UT. The magnetosphere was compressed from its usual extent of 10 Earth radius (RE) to within geostationary orbit (6.6 RE) as indicated by the negative swings in the GOES-7 H-parallel component of the magnetic field. The Boulder, Colorado magnetic observatory recorded the largest fluctuations in its history and the Deep River neutron monitor recorded the classic Forbush decrease often associated with large magnetic storms.

Although the Space Shuttle Discovery was launched in the midst of this activity, the low altitude and inclination of its orbit reportedly prevented any mission disruptions. During March 13 and 14 a series of seven commercial geostationary communications satellites experienced difficulties maintaining attitude and required 177 manual adjustments. This is more than is typically required in the course of 1 yr. Because of atmospheric expansion the solar maximum mission (SMM) satellite dropped 3 miles during the disturbed period.

On August 12 (Fig. 7a) and August 16 (Fig. 7b) proton events occurred in response to solar flare activity. Reports were made of star sensor anomalies and increased SEUs. An intense magnetic storm on August 28 and 29 and an increase in electron flux at geostationary altitude coincided with the failure of half of the GOES-7 telemetry unit.

On September 29 an X9.8 flare induced a proton storm that resulted in a ground level event (GLE) being recorded at Deep River and other neutron monitoring stations. This GLE shown in Fig. 8 was the largest in the previous 30 years and demonstrates the energy of the proton event.

A family of 13 geostationary communications satellites recorded 46 SEUs between September 29 and October 5. On September 30 they experienced approximately 1 SEU per hour. From September 29–October 1, TDRS-A recorded 53 SEUs. GOES-5 and GOES-6 experienced SEUs on September 30. From September 29–October 1, GOES-5, -6, and -7 experienced drops in solar panel output current of 0.09, 0.08, and 0.13 A, respectively.[6] The polar orbiting NOAA-10 experienced an uncommanded telemetry change on October 1. Numerous star sensor anomalies were reported.

On October 19, 1989, an X13 solar flare again produced an energetic proton event accompanied by a GLE shown in Fig. 9a. On October 24 an X5.7 flare shown in Fig. 9b added to the already elevated energetic proton fluxes.

From October 19–26 GOES-5 experienced 4 SEUs, and GOES-6 experienced 7 SEUs. From October 19–31, GOES-5, -6, and -7 solar panel output dropped by 0.63, and had a serious star sensor outage and major loss of solar-panel output. A polar orbiter experienced the temporary outage of its microwave transmitter. TDRS-1 had 50 SEUs on October 19 and 20. TDRS-3 had 2 SEUs, and TDRS-4 had 4 SEUs. A system of 13 commercial geostationary communication satellites experienced solar panel degradations between 0.3 and 0.7 A. These same satellites experienced 7 SEUs on October 19, 68 on October 20, 13 on October 21, 5 on October 22, 28 on October 23, 9 on October 24, and 7 on October 25.

Conclusions

The evaluation of long term trends in spacecraft anomalies and the observation of solar event related spacecraft disruptions both demonstrate the profound effect that the space environment can have on space missions of all types. The understanding of these interactions can be greatly facilitated by maintaining a history of anomalous spacecraft behavior. Statistically verified anomaly trends provide an excellent reference point to begin analysis of a spacecraft's susceptibility to environmental conditions.

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