Magnetic Signatures for Satellite Anomalies

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Similarities have been found between the yearly trends of magnetic activity and the occurrences of electrostatic discharge events on a geosynchronous communication satellite from April 1983 to December 1987 in the declining portion of the 11-year solar cycle. The seasonal variations of magnetic activity and electrostatic discharge events show maxima around the equinoxes and minima during solstitial months. Detailed comparisons of the events with magnetograms from Yellowknife, Canada, near the footprint of the satellite, indicate that magnetic storms, substorms, and bays offer magnetic signatures for the discharge events with substorms playing a dominant role. A study of the occurrences of electrostatic discharge with respect to the magnetic perturbations indicates a variable time delay in the occurrence after the initiation of the magnetic disturbance. The local time variation pattern in the occurrence of electrostatic discharge shows preferred occurrences in the afternoon and evening sector. It is possible that a delay mechanism is operating, whereby the surface of the satellite is charged differentially in the midnight to dawn sector during substorm and discharged at some later time. It is also conceivable that the daytime anomalies are caused by buried charge processes. The occurrences of electrostatic discharge events in the traditional midnight to dawn sector and in the local time interval encompassing the Harang discontinuity appear to be immediate responses to the magnetic perturbations.

Introduction

NEGATIVE charging of spacecraft in synchronous orbit can occur due to incidence of a large incoming flux of electrons in the absence of sufficient charge drainage by mechanisms such as photoemission. Large negative potentials in the multikilovolt range were observed in geostationary satellites as early as 1972.[1] The subject has since received much attention because electrostatic discharges induced by differential surface charging on a spacecraft have been considered to be responsible for some of the anomalous behavior of geostationary satellites.[2,3] The spacecraft surface charging phenomenon has been reviewed extensively by Garrett[4] and Whipple.[5] There also have been four conferences held specifically on the topic of spacecraft charging in 1976, 1978, 1980, and 1989. More information and references on the subject matter can be found in the latest published proceedings of the Spacecraft Charging Technology Conference.[6]

Anomaly occurrences on geostationary satellites show a dependence on geophysical conditions.[7-11] McPherson et al.[7] observed that the vast majority of anomalies occurred in the local time sector from midnight to dawn. Pike and Bunn[8] reported that 90% of the anomalies occurred during auroral and magnetospheric substorms. Serious anomalous events have been related to geomagnetic disturbances for the European MARECS-A maritime communication satellite,[9] the Canadian ANIK-D2 domestic communication satellite,[10] and the American SCATHA satellite.[11] The SCATHA satellite, which was launched in 1979 to specifically measure the characteristics of the spacecraft charging process, had, on one occasion, a kapton sample negatively charged to 3 kV in concurrence with a several-orders-of-magnitude change in electron flux during a substorm expansive phase.[12] Electrical discharges that are caused by differential charging were reported to occur at higher rates during periods of increasing geomagnetic activity.[13] These studies and others suggest that anomaly occurrences, spacecraft charging, and electrical discharges correlate with geomagnetic activity. Most past studies involving geomagnetic activity utilized only geomagnetic indices, which are crude indicators of geomagnetic conditions. It is the objective of this paper to relate the reported electrostatic discharges from a single geostationary satellite to geomagnetic conditions using not only crude geomagnetic indices but also detailed magnetic records from a ground station near the footprint of the satellite.

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Approach

The satellite data used in this study were derived from a proprietary listing of geostationary satellite anomalies provided by a commercial operator of such satellites. (These data have been merged into the Spacecraft Anomaly Data Base maintained by the National Geophysical Data Center, NGDC, in Boulder, Colorado.) From the list, only events identified as static discharge coupling (SDC) by the operator from a single communication satellite were considered, discarding anomalies that were likely to be due to a telemetry error, mission control problem, single event upset, etc. SDC is also commonly referred to as electrostatic discharge (ESD). The term SDC will be used in this paper to respect the source of our data. Our data set consists of 122 well-documented SDC experienced by a single communication satellite in geostationary orbit from April 1983 to December 1987.

The ground magnetic data used in this study are the values of a planetary magnetic index and a localized magnetic index. Also, magnetic records were used. The planetary magnetic index used here is the Ap index, which is a daily index and an average of eight Ap indices. The Ap index gives a global measure of the magnetic deviations in a 3-h interval. More information on geomagnetic indices can be found in Rostoker.[14] Since the Ap index is global in nature and is based on midlatitude magnetic observatories, we also used a localized magnetic index pertinent to a particular magnetic observatory. This localized index is the DRX index, which is defined as the daily mean of the hourly ranges (difference between maximum and minimum in an hour) in the X component of the geomagnetic field and is a daily index introduced by Hruska and Coles[15] and Lam.[16] Therefore, DRX gives a better measure of the local magnetic conditions than Ap. However, geomagnetic indices are inherently statistical in nature and are crude indicators of the geomagnetic conditions. Therefore, magnetograms from an auroral zone magnetic observatory located in Yellowknife, Canada, were also examined in detail with regard to the SDC events. Yellowknife (62.5°N, 245.5°E) was chosen because it is the only observatory that lies close to the footprint of this particular satellite (longitude 242°E) used in this study. The Yellowknife L value of 8.25 is fairly close to the L value of 6.6 for geostationary satellites.

Although it is easy to identify a magnetic storm from a magnetogram with its wildly fluctuating trace, it is necessary to describe the magnetic perturbations observable in the magnetogram with certain terms. The terms substorm and bay will be used in this study. A working definition for the terminology is warranted here since these two terms were used interchangeably up until the late 1960s[17] and the substorm terminology involves a historic definition[18] and a modern definition.[19] For our purpose here, the term substorm refers to a magnetic substorm, which is the ground magnetic signature of a sudden and dynamic energy release process on the night side of the Earth known as magnetospheric substorm. (Other manifestations of magnetospheric substorms include such explosive night-time phenomena as auroral substorms.) The term bay refers to a large excursion of the trace on a magnetogram that resembles a bay on the coastline of a landmass. Since bays are caused by enhanced current flow in the auroral electrojet and since magnetic substorms are due to the intensification of the substorm westward electroject, a substorm has the form of a sharp negative bay in the X-component magnetogram from an auroral zone magnetic observatory. Thus, all substorms have the form of a bay, though bays are not necessarily substorms. To differentiate between the two, any sharp negative bay that occurs in the midnight sector (i.e., a few hours before and after local midnight) is referred to as substorm and any bay-type disturbance in the other local time sectors is simply referred to as bay. The substorm events and bay events were classified subjectively here in this manner. Finally, it should be noted in passing that on a few occasions SDC occurred during intense magnetic pulsations (which are the rather sinusoidal waveforms on a magnetogram). In the data set available, these correlations were rare, but a more thorough analysis of links between pulsations and satellite anomalies might be a topic worth pursuing in the future.

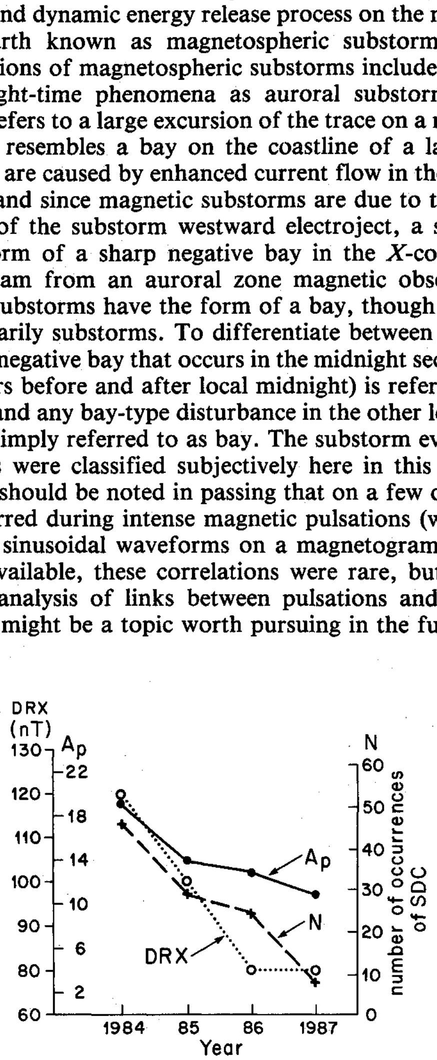

Fig. 1 Variations of the yearly means of Ap (solid line) and DRX (dotted line), together with the number of occurrences of SDC during each year (dashed line) from 1984 to 1987.

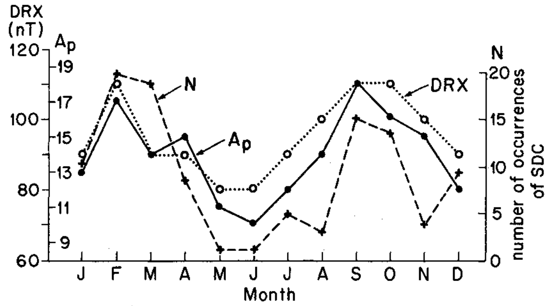

Fig. 2 Variations of the monthly means of Ap (solid line) and DRX (dotted line), together with the number of occurrences of SDC during each month (dashed line) from 1984 to 1987.

Comparison with the Ap and DRX Geomagnetic Indices

The geomagnetic indices are used here to delineate the general geomagnetic conditions under which SDC occurred. The Ap index, which is basically a midlatitude index, describes only the general trends of the global magnetic activity, as mentioned in the previous section. Since the footprint of the satellite is in the auroral zone, where the magnetic variations are larger and more frequent because of the occurrence of substorms and bays, we have, therefore, also compared the occurrence of SDC with the local DRX index in addition to the Ap index.

The period 1984–1987 falls in the declining portion of the 11-year solar cycle. The magnetic activity, as represented by the yearly means of Ap and DRX, was declining, and this trend was followed by that of the yearly total of occurrences of SDC (Fig. 1). For a close scrutiny, we compared the monthly values of Ap and DRX with the monthly occurrences of SDC for the 1984–1987 period (Fig.2). The figure indicates that magnetic activity and the occurrence of SDC have similar seasonal variations with maxima during the equinoxes and minima in the solstitial months. The correlation coefficient for the occurrence of SDC and Ap from these data was found to be 0.68, whereas the correlation coefficient between SDC and DRX is 0.62. (The correlation coefficient between these Ap and DRX is 0.92.) Since linear correlation coefficients > 0.53 are significant at the 95% confidence level for the number of data points considered here, the correlation coefficients obtained here from our data are, therefore, significant. It is a bit surprising that the correlation between SDC and Ap is higher than that between SDC and DRX. Perhaps the occurrence of anomaly is more dependent on global magnetic activity than local magnetic activity. The lower correlation between SDC and DRX also may be due to the position of the footprint of the satellite not being located exactly at the magnetic observatory. Figure 3 shows the monthly occurrences of SDC vs the monthly values of Ap for 1984–1987 with a regression line fitted through the data. There appears to be a linear relationship between SDC and Ap. Thus, although the spacecraft eclipses (which are periods of high absolute negative potential) also show maxima near the equinoxes and plasma dropouts (which occur when the charging environment suddenly disappears during the satellite transit out of the high latitude plasma sheet) occur at the solstices as well, our analysis, here, strongly suggests a dependence of the occurrence of SDC on geomagnetic activity. From our data suite of 122 SDC, only five events actually occurred during eclipses.

To see if the 27-day recurrent tendency of magnetic disturbances (which dominates the declining portion of the 11-year solar cycle) is also discernible in the occurrences of SDC, the data were grouped in 27-day periods according to the Bartels rotations. In Fig. 4, eight Bartels rotations from rotation 2065 to 2072 (from September 6, 1984 to April 9, 1985) are shown. In this figure, the daily Ap indices (represented by dots) and

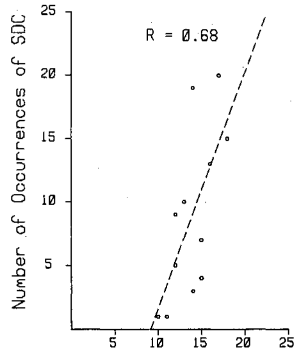

Fig. 3 Monthly occurrences of SDC vs the monthly values of Ap for the 1984–1987 period. The correlation coefficient $R = 0.68$.

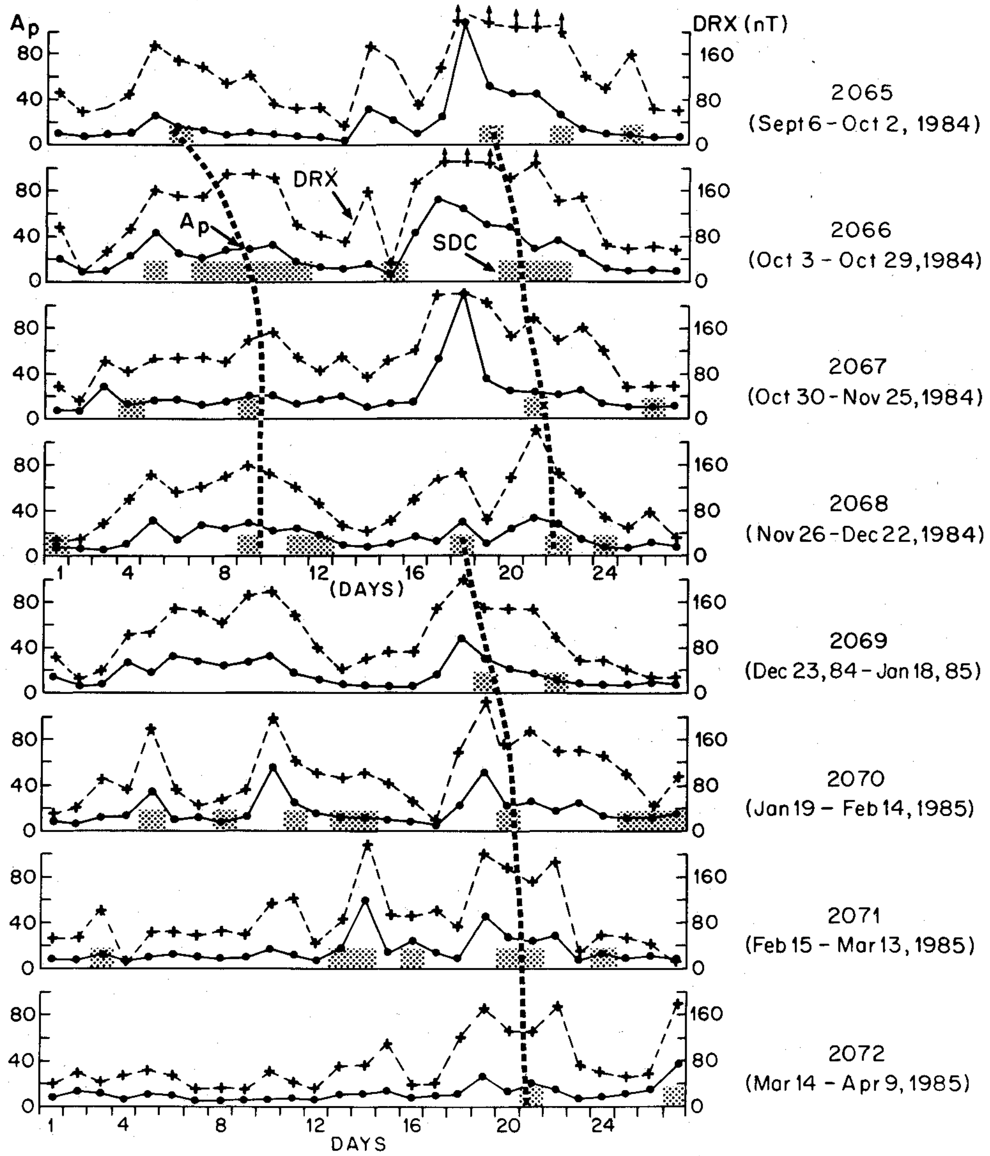

Fig. 4 Variations of Ap (solid line), DRX (dotted line), and SDC (squares on horizontal axis) for Bartels rotations 2065–2072. Note the recurrence of SDC, as indicated by the dotted lines. The arrows on the top two panels indicate that the values of DRX exceed the scale given on the right.

the daily DRX indices (represented by crosses) were plotted together with the occurrences of SDC (represented by shaded squares on the horizontal axes). This figure illustrates the occurrences of SDC in conjunction with the enhancement of magnetic activity indicated by the peaks in Ap and DRX. Furthermore, there is evidence of recurrence in SDC (for example, during days 5–13 in rotations 2065–2068 and days 18–27 for all the rotations as indicated by the dotted lines in the diagram). We shall discuss more of this SDC recurrent tendency with respect to the very high energy electrons later. This figure also shows that SDC often occurred after the peak of magnetic activity. To pursue this point further, we have calculated the average values of Ap and DRX for the same day that SDC was reported and also for the previous day. The average values for Ap and DRX are 21 and 140, respectively, for the same day and 25 and 150 for the previous day. The higher values in the previous day category than in the same day category are suggestive of a time delay in the occurrence of SDC following an active magnetic period. We shall examine this in more detail in the next section.

Comparison with Ground Magnetic Records

Using the *X*- (north) component magnetograms from Yellowknife Magnetic Observatory, we studied in detail the local magnetic perturbations that may be responsible for SDC. Adopting the definitions for bay and substorm given in the previous section and designating stormy conditions as very active and conditions devoid of noticeable magnetic perturbations as very quiet, we can group the magnetic conditions under which SDC occurred into five categories, as shown in Fig. 5. The figure shows that although only 4% occurred during very quiet conditions (with $Ap \leq 5$) and 14% during very active conditions (with $Ap > 35$), the majority (56%) occurred following a combination of substorm and bay with 13% following a bay or substorm alone. It is evident that substorms play an important role with about 70% of SDC associated with them.

Some typical magnetic signatures for SDC are shown in Fig. 6. In this figure, the local time occurrence of SDC is indicated and is marked as zero hour in the bottom. Also, the Ap and DRX values for the same day that SDC occurred are shown. Figure 6a shows the occurrence of SDC during the magnetic storm of February 1986 with an Ap value of 82 and DRX of 320. The SDC occurred during the storm almost 12 h after its beginning. Figure 6b shows examples for moderately disturbed days with Ap values ranging from 11 to 43 and DRX values from 100 to 160. The first three panels indicate occurrence of substorm followed by bay and then SDC. The bottom panel shows two bays before SDC. Figure 6c gives examples of SDC during low magnetic activity when Ap values were < 10 and DRX values < 100. The top panel shows occurrence of a combination of substorm and bay and the bottom two panels show occurrence of substorm before SDC. It is clear from the figures that SDC do not always occur immediately after a disturbance. There is a time delay involved.

To study further the time delay, we measured the time interval in hours between the start of substorm or bay and the occurrence of SDC. The occurrences of SDC under the categories of substorm, bay, and substorm and bay shown in Fig. 5 were all used in this study. Figure 7 shows the number of occurrences of SDC after the start of substorm for four local time sectors. In this approach, we noted the occurrence of SDC within the given local time sector and then searched for the last occurrence of substorm backward in time to compile the time delay. In the midnight to dawn sector, there appeared to be an immediate response and a slight delayed response of SDC to the onset of substorm, as indicated by the first peak between 0–1 h and the second peak between 4–5 h. Throughout the daytime sector from dawn to dusk, SDC occurred long after the cessation of substorm (panels 2 and 3) as delayed response. In the dusk to midnight sector, the immediate response of SDC to substorm is again evident by the peak between 0–1 h in addition to the rather long delayed response shown by the second group of peaks. Examples for bays as precursors are shown in Fig. 8. Similar patterns are discernible here. To see the aggregate effects of substorms, we superimposed the time delays of all the SDC events, taking into consideration not only the last occurrence of substorm prior to the SDC event but all the substorm occurrences during the past 24 h, and the results are shown in the upper panel of Fig. 9. It is justifiable to do so because Inouye[20] showed that buildup of potential differences may occur over a number of successive substorms. The lower panel of Fig. 9 is a similar histogram for bays. The striking feature of these two diagrams are the prominent peaks after the 12 h delay in addition to the peak in the 0–1 h delay. Thus, we can see that the effect of the magnetic perturbation may not be immediate, and SDC could occur long after the cessation of the perturbation.

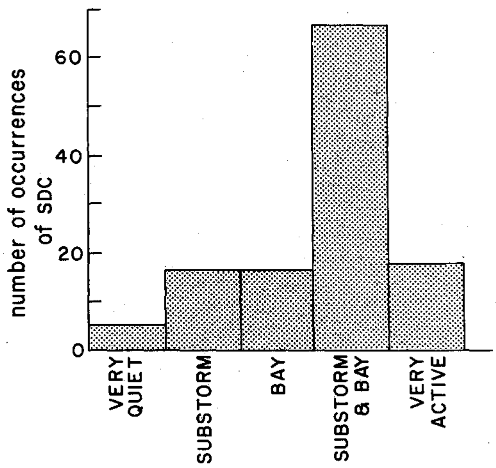

Fig. 5 Number of occurrences of SDC under different magnetic conditions.

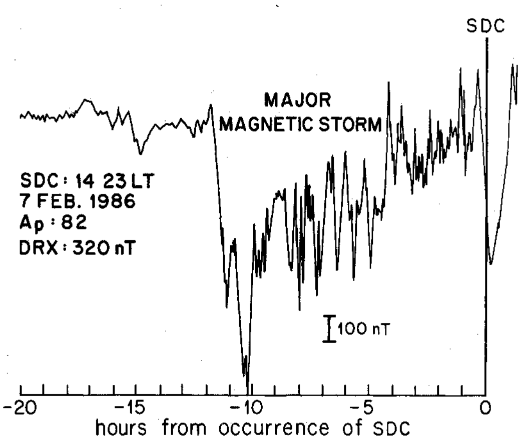

Fig. 6a *X*-component magnetogram from Yellowknife, Canada during very disturbed time. Occurrence of SDC is indicated by the zero hour.

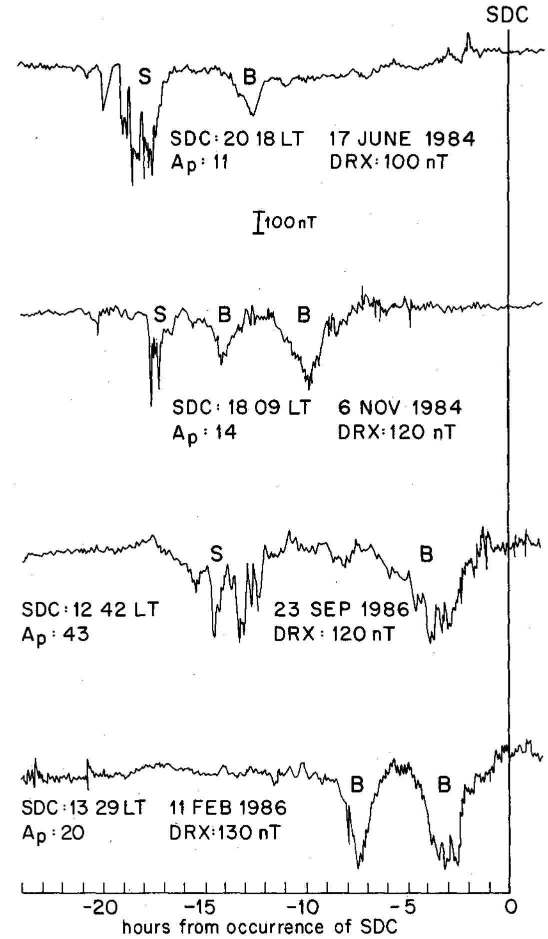

Fig. 6b Same as Fig. 6a except for moderately disturbed days. Note S and B indicate substorm and bay, respectively.

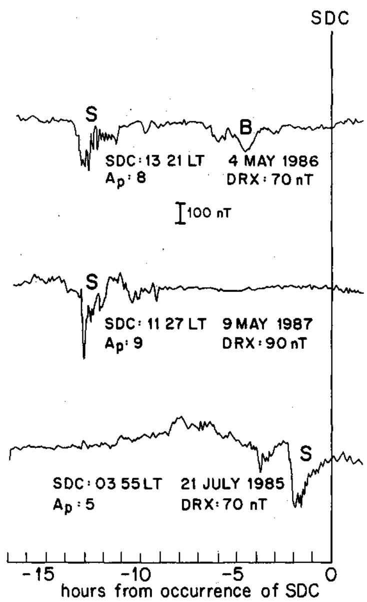

Fig. 6c Same as Fig. 6b except for days with low activity.

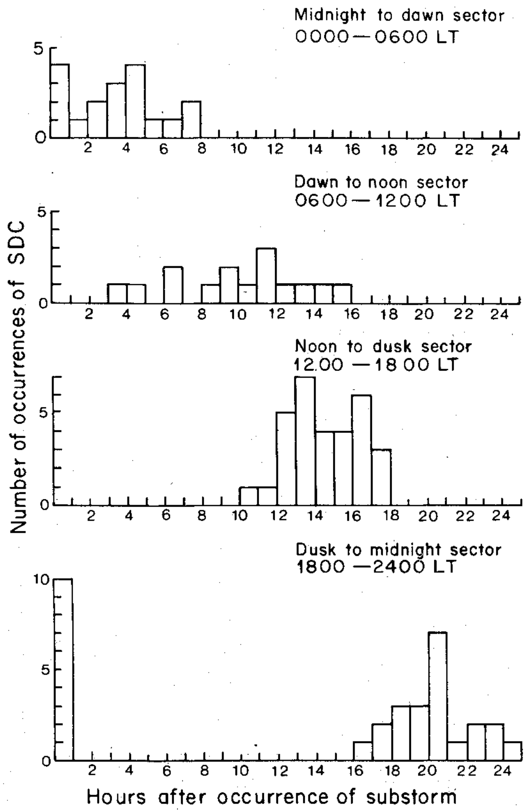

Fig. 7 Distribution of SDC in four local time sectors after the occurrence of substorm. Note that SDC occurred within the given local time sector, whereas substorms may occur outside that local time sector.

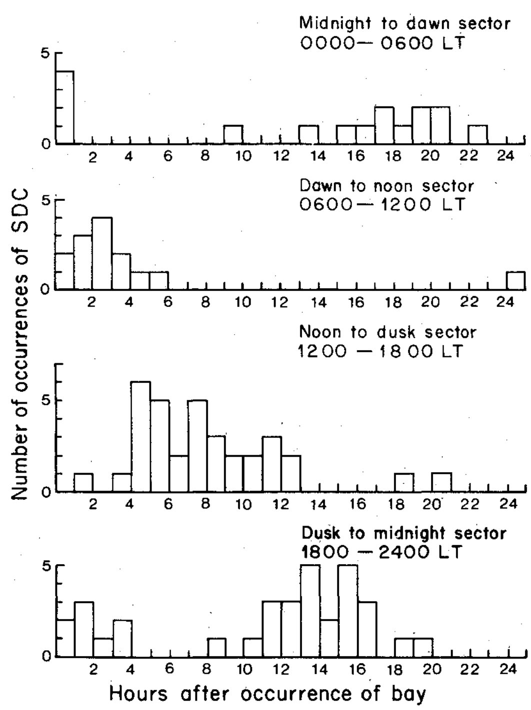

Fig. 8 Same as Fig. 7 except for the occurrence of bays.

The time delay in the occurrence of SDC is also implicit in the local time occurrences of SDC, as shown in Fig. 10. The data were plotted in the same format as in Fig. 11, which was adapted from McPherson et al.[7] for comparison purposes. Note that the radial distances for the data points for both diagrams have no meaning here other than for graphical convenience. Whereas Fig. 11 indicates that the majority of SDC occurred in the local time sector from midnight to dawn, the

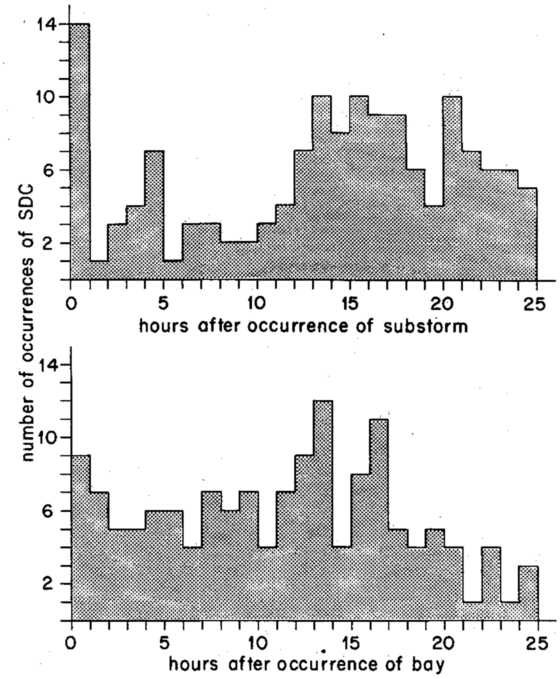

Fig. 9 Distribution of SDC after the occurrence of substorm (upper panel) and after the occurrence of bay (lower panel).

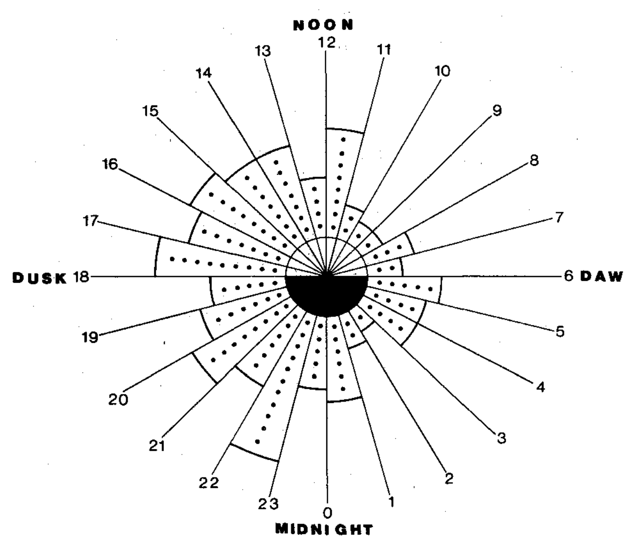

Fig. 10 Local time distribution of the occurrences of SDC. Note that the radial distances of the data points have no meaning other than for graphical conveniences.

specific data set displayed in Fig. 10 shows otherwise. Instead, most anomalies appeared in the afternoon and evening sector, a result contrary to the classic picture of McPherson et al.[7] This may be due to the fact that the study by McPherson et al.[7] used several types of anomalies from several satellites, whereas our study concentrated on only SDC from one satellite. Perhaps more importantly, Fig. 10 is a clear indication of the time delay in the occurrence of SDC after the initiation of a magnetic perturbation. As shown in Fig. 5, a vast majority of the events (~70%) were related to substorms, which occurred in the midnight sector. If there was no time delay, the majority of SDC would have occurred in the midnight to dawn sector, as in the plot of McPherson et al.[7] shown in Fig. 11. This is not the case. The majority of SDC occurred in the afternoon and evening sector long after the occurrence of substorms in the midnight sector. It is worth mentioning the following with regard to Fig. 10. As pointed out earlier, only five events out of the total of 122 anomalies occurred during

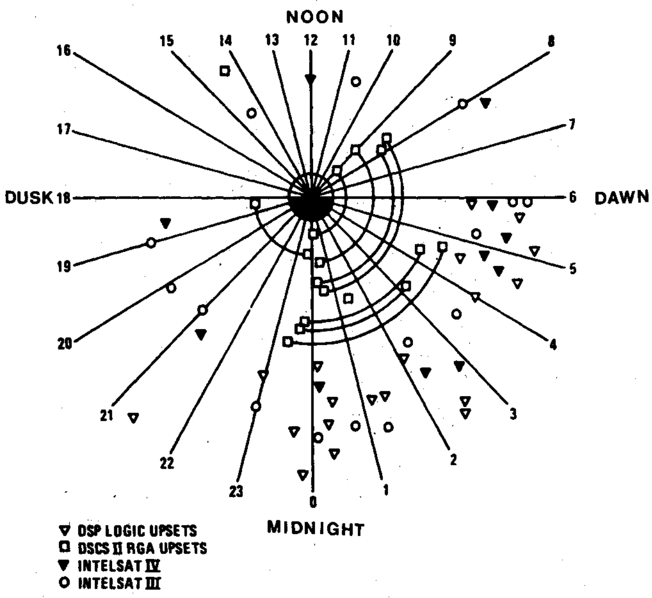

Fig. 11 Local time distribution of satellite anomalies adapted from McPherson et al.[7] Note that the radial distances of the data points have no meaning.

eclipses. Of these five events, four occurred between 0 and 1 LT and one occurred between 1 and 2 LT. Also, in the dusk to midnight sector, the largest number of SDC occurred in the 22–23 LT interval where the Harang discontinuity[21] is located. (The Harang discontinuity is a transition region in the polarity of the ionospheric electric field in the auroral oval.) Furthermore, 9 out of the 11 SDC in the 22–23 LT interval occurred within 1 h after the initiation of a substorm (see also lower panel of Fig. 7). We shall comment more on this later.

Discussion

Our study here involving only electrostatic discharge events from a single geostationary communication satellite indicates that the trend in the occurrence of the anomaly follows that of geomagnetic activity in gross terms (Figs. 1–4). However, not all anomalies occurred during magnetic storms. Instead, a majority of the events were related to substorms (Fig. 5). Furthermore, some events appeared to be related to bays. Although previous work[2,6] also established substorms in the midnight sector as responsible for satellite anomalies, the evidence presented here that shows a link with bays has not been reported before. Also, our study indicates that whereas some discharge events occurred as immediate responses to magnetic perturbations, most discharges occurred as delayed responses.

Magnetic perturbations do not charge up a spacecraft. It is the hot electrons (1–80 keV) that charge up the surface of a spacecraft. Magnetic perturbations merely reflect a change in the plasma and particle population in space. During substorms, streams of electrons are injected Earthward from the magnetotail around local midnight and then drift eastward from midnight to dawn and encounter the satellite at geostationary altitude. Bays are indications of enhanced current flow in the auroral electrojets, which are related to enhanced plasma flow in the magnetosphere. Thus, the magnetic signatures presented here are indications of particle population changes in space that could cause the satellite to charge up. If one then assumes that magnetic perturbations indicate spacecraft differential surface charging, our results suggest that discharges would occur without much delay during substorm environment in the midnight to dawn sector (upper panel of Fig. 7 and Fig. 10) consistent with the classic picture of McPherson et al.[7] (Fig. 11) and also, hitherto unreported, in the 22–23 LT interval associated with the Harang discontinuity in the dusk to midnight sector (lower panel of Fig. 7 and Fig. 10). Since the discontinuity becomes quite dynamic during substorms, an association of the discharge events in the 22–23 LT interval with the Harang discontinuity is a reasonable conjecture. In the region of the discontinuity, auroral breakup arcs brighten and net field aligned current diverges upward. Thus; the precipitating electrons associated with these phenomena could, during an expansion of the auroral oval to lower L values, charge up the spacecraft differentially leading to immediate discharges.

In addition to immediate discharges, our study also suggests that discharges would occur many hours after charging, as indicated by the large number of discharge events some 12 h after the magnetic perturbations (Fig. 9), with a consequence that anomalies were more concentrated in the noon to dusk sector (Fig. 10). These results are consistent with the work of Inouye[20] who, in his spacecraft charging model study, showed that delays in discharge times may be of the order of many hours and that the results are dependent on spacecraft configuration, solar direction, and material parameters. Wadham[22] noted the occurrences of cyclic charging and discharging on a metal lens barrel of an Earth sensor during revolutions of the satellite from shadow to sunlight. Discharging was caused by photoemission when the barrel was exposed to sunlight. The ultraviolet light, which reduces the negative surface potential by photoemission, may therefore act as a discharge trigger. Furthermore, in the case of shadowing on parts of the surface, sunlight would enhance the potential difference between adjacent parts, and the buildup of a large differential potential gradient could result in discharging. Thus, the satellite, having been charged up on the night side during substorm, may not discharge immediately but, instead, may discharge at some later time after building up an even larger differential potential due to shadowing and photoemission (which may also act as a trigger for discharging).

In the previous discussion, the discharge events were assumed to be caused by differential surface charging. However, some of these events, particularly those that occurred on the dayside, may be induced by buried charges that could be caused by another charging mechanism commonly known as deep dieletric charging or bulk charging or simply buried charge process. This concept of buried charge was proposed by Meulenberg.[23] In this mode of charging, energetic electrons (with energies from hundreds of keV to multi-MeV) penetrate the surface of the spacecraft and deposit charges within the bulk of dielectric material or on the surface of isolated conducting material interior to the spacecraft. Discharging occurs as a result of the cumulative storage of these charges that generate strong voltage gradients that exceed the breakdown threshold. The diurnal distribution of these energetic electron fluxes peaks around noon, and many dayside satellite anomalies have been attributed to buried charge process.[24–27] Although the energetic electrons may be associated with large magnetic storms, their origin is by no means certain. However, Baker[28] pointed out that the increases in very energetic electron flux recur with a regular 27-day periodicity. We have noted earlier in describing Fig. 4 that the discharge events also seem to recur with a 27-day periodicity. Thus, some of the anomalies reported in this paper, especially those dayside events, may be caused by buried charge. Substorms may also play a role in the buried charge process in that the energetic portion of substorm electrons in the 100-keV range may be available[12] and could be buried within the satellite during substorms. Discharge would then occur later on the dayside after being triggered, perhaps, by varying surface potentials due to photoemissions and shadowing.

Conclusions

From a comparison of geomagnetic indices and ground magnetograms with electrostatic discharge events experienced by a single geostationary satellite, a link has been established in this study between these satellite anomalies and geomagnetic activity. Although some anomalies occurred as immediate responses to magnetic perturbations in the midnight to dawn sector and in the local time interval encompassing the Harang discontinuity, most occurred as delayed responses to the perturbations. It is clear that the majority of the anomalies did not occur in the traditional midnight to dawn sector. If the magnetic perturbations are indicative of spacecraft differential surface charging by hot electrons, some sort of delay mechanism must be at play as there is a long delay, up to many hours, between charging and triggered discharging. Alternatively, a buried charge process due to energetic electrons may also be a potential origin of discharges for the daytime anomalies. A clarification of the charging processes would require in-situ particle data.

Acknowledgments

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References

[1]DeForest, S. E., "Spacecraft Charging at Synchronous Orbit," *Journal of Geophysical Research*, Vol. 77, No. 4, Feb. 1972, pp. 651-659.

[2]Rosen, A. (ed.), "Spacecraft Charging by Magnetospheric Plasmas," *Progress in Astronautics and Aeronautics*, Vol. 47, MIT Press, Cambridge, MA, 1976.

[3]Garrett, H. B., and Pike, C. P. (eds.), "Space Systems and Their Interactions with Earth's Space Environment," *Progress in Astronautics and Aeronautics*, Vol. 71, MIT Press, Cambridge, MA, 1980.

[4]Garrett, H. B., "The Charging of Spacecraft Surfaces," *Reviews of Geophysics and Space Physics*, Vol. 19, No. 4, Nov. 1981, pp. 577-616.

[5]Whipple, E., "Potentials of Surfaces in Space," *Reports on Progress in Physics*, Vol. 44, No. 11, Nov. 1981, pp. 1197-1250.

[6]Stevens, N. J., and Pike, C. P. (eds.), "Spacecraft Charging Technology 1980," NASA-CP-2182, Air Force Geophysics Lab., TR-81-0270, 1981.

[7]McPherson, D. A., Cauffman, D. P., and Schober, W. R., "Spacecraft Charging at High Altitudes: SCATHA Satellite Program," *Journal of Spacecraft and Rockets*, Vol. 12, No. 5, 1975, pp. 621-626.

[8]Pike, C. P., and Bunn, M. H., "A Correlation Study Relating Spacecraft Anomalies to Environmental Data," *Spacecraft Charging by Magnetospheric Plasma, Progress in Astronautics and Aeronautics*, Vol. 47, MIT Press, Cambridge, MA, 1976, pp. 45-60.

[9]Capart, J. J., and Dumesnil, J. J., "The Electrostatic-Discharge Phenomena on MARECS-A," *ESA Bulletin 34*, 1983, pp. 22-27.

[10]Wadham, P. N., "The Effects of Electrostatic Discharge Phenomena on Telesat's Domestic Communication Satellites," AGARD-CP 406, 1987, p. 25-1.

[11]Koons, H. C., Mizena, P. F., Roeder, J. L., and Fennell, J. F., "Severe Spacecraft-Charging Event on SCATHA in September 1982," *Journal of Spacecraft and Rockets*, Vol. 25, No. 3, 1988, pp. 239-243.

[12]Reagan, J. B., Nightingale, R. W., Gaines, E. E., Meyerott, R. E., and Imhof, W. L., "Role of Energetic Particles in Charging/Discharging of Spacecraft Dielectrics," *Spacecraft Charging Technology 1980*, NASA-CP-2182, Air Force Geophysics Lab., TR-81-0270, 1981, pp. 74-85.

[13]Shaw, R. R., Nanevicz, J. E., and Adamo, R. C., "Observations of Electrical Discharges Caused by Differential Satellite-Charging," *Spacecraft Charging by Magnetospheric Plasma, Progress in Astronautics and Aeronautics*, Vol. 47, MIT Press, Cambridge, MA, 1976, pp. 61-76.

[14]Rostoker, G., "Geomagnetic Indices," *Reviews of Geophysics and Space Physics*, Vol. 10, No. 4, Nov. 1972, pp. 935-950.

[15]Hruska, J., and Coles, R. L., "A New Type of Magnetic Activity Forecast for High Geomagnetic Latitudes," *Journal of Geomagnetism and Geoelectricity*, Vol. 39, No. 9, Sept. 1987, pp. 521-534.

[16]Lam, H.-L., "Forecasts of Gemagnetic Activity in Canada by Linear Prediction Filtering," *Journal of Geomagnetism and Geoelectricity*, Vol. 39, No. 9, Sept. 1987, pp. 535-542.

[17]Rostoker, G., "Classification of Polar Magnetic Disturbances," *Journal of Geophysical Research*, Vol. 74, No. 21, Feb. 1969, pp. 5161-5168.

[18]Akasofu, S.-I., *Polar and Magnetospheric Substorms*, Astrophysics and Space Science Library, Vol. 11, D. Reidel, Dordrecht, Holland, 1968.

[19]Rostoker, G., Akasofu, S.-I., Foster, J., Greenwald, R. A., Kamide, Y., Kawasaki, K., Lui, A. T. Y., McPherson, R. L., and Russell, C. T., "Magnetospheric Substorms—Definition and Signatures," *Journal of Geophysical Research*, Vol. 85, No. A4, April 1980, pp. 1663-1668.

[20]Inouye, G. T., "Spacecraft Potentials in Substorm Environment," *Spacecraft Charging by Magnetospheric Plasma, Progress in Astronautics and Aeronautics*, Vol. 47, MIT Press, Cambridge, MA, 1976, pp. 103-120.

[21]Heppner, J. P., "The Harang Discontinuity in Auroral Belt Ionospheric Currents," *Geophysic Norvegica*, Vol. 29, No. 6, June 1972, pp. 105-120.

[22]Wadham, P. N., "Operational Experience with Anik A," AIAA Paper 80-0549, April 1980.

[23]Meulenberg, H., Jr., "Evidence for a New Discharge Mechanism for Dielectrics in a Plasma," *Spacecraft Charging by Magnetospheric Plasma, Progress in Astronautics and Aeronautics*, Vol. 47, MIT Press, Cambridge, MA, 1976, pp. 237-246.

[24]Johnstone, A. D., Wrenn, G. L., Huckle, H. E., and Scott, R. F., "Meteosat - F2 Spacecraft Charging Monitors," Final Report ESA Contracts, 47/5/81/F/CG, 5911/84/f/CG, 1985.

[25]Wrenn, G., and Johnstone, A., "Spacecraft Charging: Meteosat Experiences," AGARD-CP-406, 1987.

[26]Baker, D. N., Belian, R. D., Higbee, P. R., Klebesadel, R. W., and Blake, J. B., "Hostile Energetic Particle Radiation Environments in Earth's Outer Magnetosphere," AGARD-CP-406, 1987.

[27]Garrett, H. B., Whittlesey, A., and Daughtridge, S., "Environment-Induced Anomalies in the TDRS and the Role of Spacecraft Charging," AIAA Paper 90-0178, Jan. 1990.

[28]Baker, D. N., "Effects of the Solar-Terrestrial Environment on Satellite Operations," *Artificial Satellites*, Vol. 22, No. 1, Polish Scientific Publisher, Warsaw, Poland, 1987, pp. 103-119.

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