Introduction to Space Weather

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Abstract. Adverse space weather is one of the principal threats to modern human technology. Solar coronal mass ejections, large solar flares, and high-speed solar wind streams often lead to sequences of damaging disturbances within the Earth's magnetosphere, in the atmosphere, and even on the Earth's surface. Powerful and long-lasting geomagnetic storms can develop following solar disturbances and enhancements of the highly relativistic electron populations throughout the outer terrestrial radiation zone can also result. High-energy protons and heavier ions arriving in near-earth space – or trapped in the magnetosphere and having clearest effect in the South Atlantic Anomaly (SAA) – can damage satellite solar power panels, confuse optical trackers, and deposit harmful charges into sensitive electronic components. Recent international space science programs have made a concerted effort to study activity on the Sun, the propagation of energy bursts from the Sun to near-Earth space, energy coupling into the magnetosphere, and its redistribution and deposition in the upper and middle atmosphere. Extreme solar, geomagnetic and solar wind conditions can be observed by a large array of international satellites and ground-based sensors. Many types of space weather-related problems have been identified in recent years. This chapter presents examples of space weather-induced anomalies and failures and discusses community efforts to propose technical and operational solutions to space weather problems now and in the future.

1 Introduction

Above the thin layer of Earth's atmosphere where normal weather occurs (the troposphere), there is a vast region extending into interplanetary space that is permeated by highly fluctuating magnetic fields and very energetic particles. The collective, often violent, changes in the space environment surrounding the Earth are commonly referred to as "space weather". For several decades now, humans have increasingly used space-based assets for navigation, communication, military reconnaissance, and exploration. New observations, numerical simulations, and predictive models are helping to make important strides to deal with (if not alter) space weather (National Space Weather Program Strategic Plan, 1995 [13]; Baker, 1998 [2]).

As shown by Fig. 1 (taken from NASA "Roadmap" documents), the Sun and its interaction with the Earth is a prototype for much of our understanding of cosmic plasma physics. The upper chain of insets suggest that our understanding of the fundamental elements of magnetospheric physics,

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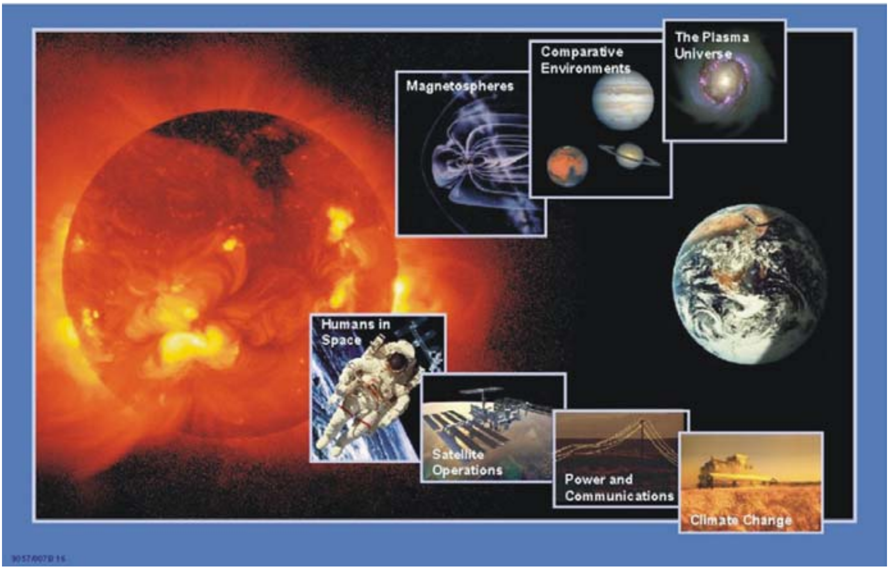


Fig. 1. Scientific and applications-related aspects of the Sun-Earth Connections research (courtesy of NASA).

our approach to comparative planetary environments, and ultimately our understanding of the plasma universe springs from our studies of Sun-Earth connections.

The lower chain of insets in Fig. 1, however, makes another important point: The space environment that we study for its intrinsic science value (as just described) is also an environment that has crucial practical importance. The effects of the space environment on humans in space, spacecraft operations, communications systems, power systems, and even (possibly) on climate make the understanding of Sun-Earth connections a manifestly important subject from a very pragmatic standpoint. Thus, the space weather "branch" of Fig. 1 is highly important much as is the basic science "branch".

Figure 2 shows in a schematic way the linked Sun-Earth system. It is known from several decades of research that the Sun is the overwhelming driver of space weather effects in near-Earth space. The solar wind emanating from the Sun – and the embedded interplanetary magnetic field (IMF) – provides the momentum, the energy, and much of the mass that fills and powers the Earth's magnetosphere. The Earth's ionosphere and atmosphere responds to this solar wind driving in complex ways. The ionosphere can also supply particles (mass) to populate the terrestrial magnetosphere and, of course, the neutral atmosphere responds strongly to solar irradiance (photons) as well as to plasma interactions with the solar wind.

The magnetosphere-ionosphere-atmosphere system is immensely complicated and constitutes a high-coupled system (see Fig. 3). There are several

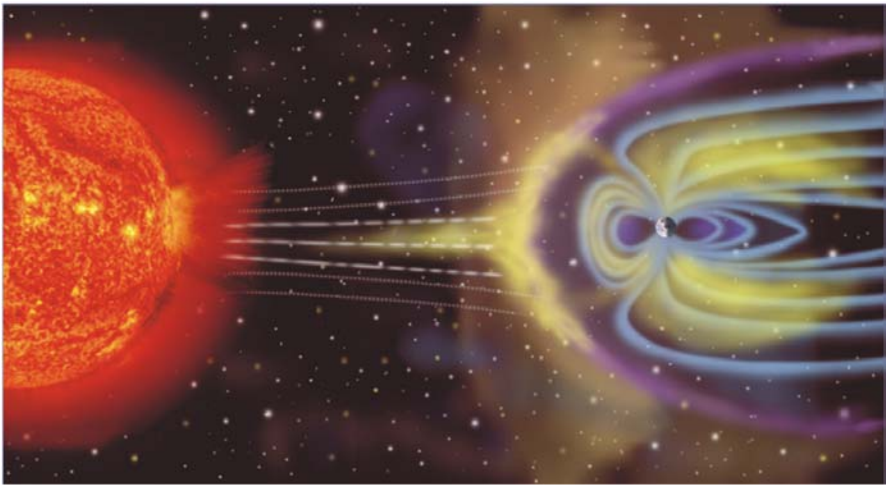


Fig. 2. The Sun, the interplanetary medium, and the near-Earth environment represent the region in which space weather plays out (courtesy of NASA).

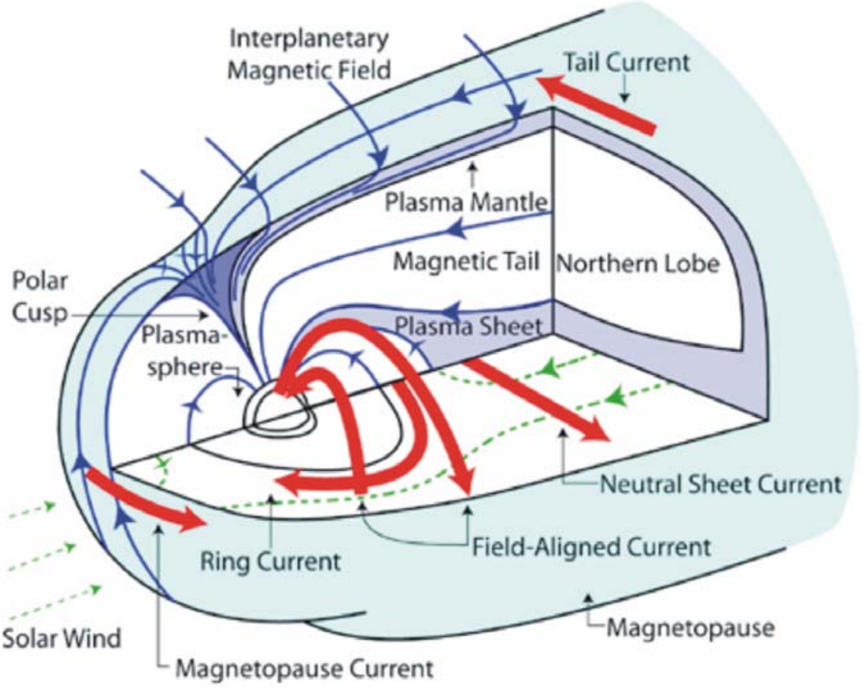


Fig. 3. The near-earth space environment showing the magnetosphere and many of the key plasma regions and current systems.

large-scale current systems and there are key regions of distinct plasmas (often separated – at least conceptually – by boundary layers). Trapped energetic particles constitute the van Allen radiation belts and a cold plasma region in the inner magnetosphere is called the plasmasphere. These plasma regions extend along magnetic field lines and couple into the ionosphere and the neutral atmosphere. Other chapters in this book will treat many aspects of the Sun-Earth system in great detail.

A point to bear in mind from Figs. 2 and 3 is that virtually all human technological systems operate on (or near) the Earth's surface or else in near-Earth space. Thus, power grids, communications systems, navigation satellites, and military space assets are all within – and are very much affected by – solar and magnetospheric disturbances. In this sense, space weather is an ever-present set of factors for advanced human technological resources. This chapter provides an overall introduction to space weather consequences and mitigation strategies.

2 Space Weather Effects

As shown in Fig. 4, the Sun can emit giant clouds of ionized gas (coronal mass ejections, CMEs) which contain upwards of 10^{16} grams of hot plasma. These CMEs can move outward from the Sun's surface at speeds of 1000 km/s (or more) and can have embedded within them strong magnetic fields and highly energetic particle fluxes. The active Sun is also the source of powerful solar flares and streams of high-speed solar wind flows. As these solar disturbances reach the Earth and its vicinity, they can give rise to long-lasting and disruptive disturbances called geomagnetic storms. High-energy ions and electrons produced during geomagnetic storms, as well as fluctuating magnetic fields themselves, can have detrimental effects on Earth-orbiting spacecraft and on humans in space (Lanzerotti, 2001 [12]).

As shown in Fig. 5a, high-energy protons and heavier ions arriving in near-Earth space can interact with spacecraft in several damaging ways. The ionization track that energetic ions can leave in microminiaturized electronics can upset spacecraft computer memories and can otherwise disrupt sensitive space electronics. The result can be damage to satellite solar power panels, confusion to optical tracker systems, and scrambling of spacecraft command and control software. Even more worrisome is the fact that high-energy solar particles can be damaging, or even potentially deadly, to astronauts who are in space at the time of major solar particle events (Turner, 2000 [19]).

Another aspect of the space environment that can be quite harmful to spacecraft is very energetic ("relativistic") electrons. As shown in Fig. 5b, these energetic electrons can penetrate through even thick spacecraft shielding and can bury themselves within dielectric (insulating) materials deep within spacecraft systems and subsystems. When sufficient charge has built up within dielectric materials such as coaxial cables or electronics boards, a

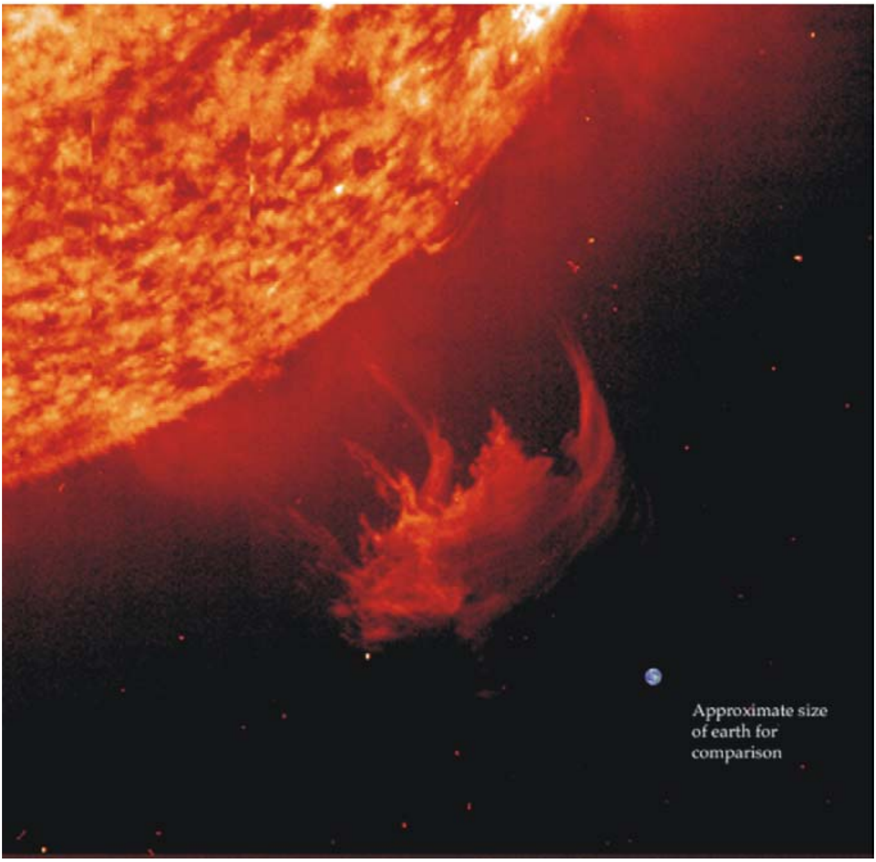


Fig. 4. A diagram illustrating a coronal mass ejection and also showing the Earth on a relative scale (courtesy of NASA).

powerful internal electrical discharge can occur (Baker, 1998 [2]; Robinson, 1989 [15]). This is very much like a miniature lightning strike within sensitive spacecraft electronics. Numerous recent spacecraft failures have been laid at the feet of this "deep dielectric charging" mechanism (Vampola, 1987 [20]; Baker, 1998 [2]; Baker et al., 1998 [8]).

Yet another space weather phenomenon of concern, known as "surface charging", is illustrated by part (c) of Fig. 5. Electrical charges coming from 10-100 kilovolt electrons within Earth's magnetosphere can accumulate on insulating surfaces of satellites. As with interior spacecraft insulators, if enough charge builds up on a region of surface dielectric material there can be a powerful, disruptive discharge. This can generate electrical signals in the spacecraft vicinity that can scramble and disorient the satellite and its subsystems (Robinson, 1989 [15]).

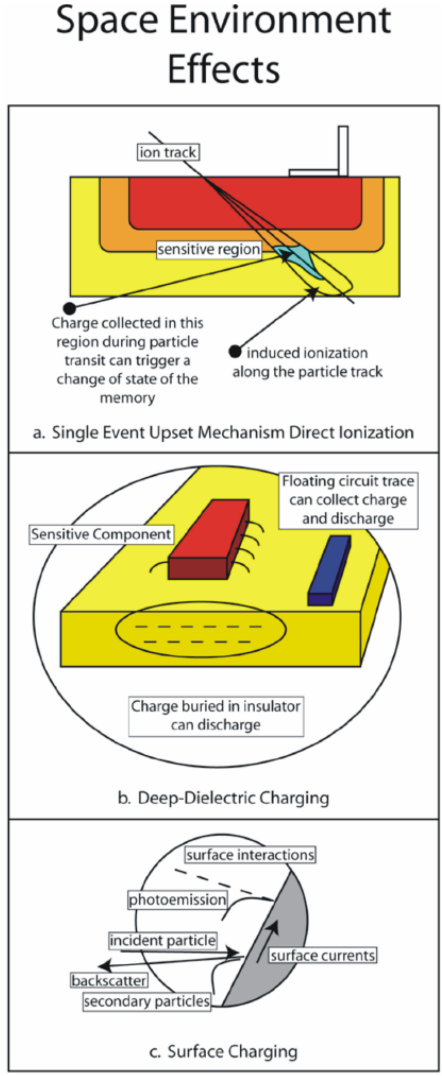


Fig. 5. A diagram illustrating space environment effects due to (a) Ions causing single-event upsets, (b) deep-dielectric charging, and (c) surface charging (adapted from Baker, 1998 [2]).

It is becoming increasingly understood and appreciated that continental-scale power generation and distribution systems are also vulnerable to the effects of space weather (Kappenman, 2001 [11]). Space storms can impact the operational reliability of electric power systems. For example, a major storm in 1989 shut down the Hydro Quebec power system in Canada for many hours. Space storms can disrupt power grids by introducing geomagneticallyinduced currents (GICs) into the transmission network. The GICs which flow through transformers, power lines, and grounding points can sometimes disrupt large portions of the power distribution system and such disruptions can occur within remarkably short periods of time (Kappenman, 2001 [11]). There are many other effects of space weather that manifest themselves in both subtle and very obvious fashions. A major space storm can modify the ionosphere of the Earth and therefore change the wavelength at which high-frequency (HF) radio communication is possible. This is a problem to the military and to airlines that are attempting to communicate with aircraft flying transpolar routes. Space weather can also cause sudden, unexpected heating of the Earth's upper neutral atmosphere. This heating causes an expansion of the upper atmospheric layer (the thermosphere) which can suddenly increase the drag force on low-altitude spacecraft (Lanzerotti, 2001 [12]; Singer et al., 2001 [18]).

3 Energetic Electrons and Space Weather

As illustrated in Fig. 5b, very high-energy electrons can penetrate through spacecraft walls and through electronics boxes to bury themselves in various dielectric materials (e.g. Robinson, 1989 [15]). This can, in turn, lead to electric potential differences in the region of the buried charge. In some instances, intense voltage breakdowns can occur leading to surges of electrical energy deep inside circuits. This can cause severe damage to various subsystems of the spacecraft.

Many examples of such "deep-dielectric charging" have been presented by various authors (e.g., Vampola, 1987 [20]; Baker et al., 1987 [7]). An interesting case study presented by Baker et al. (1987) [7] is shown in Fig. 6. In this figure, smoothed daily averages of $E = 1.4 - 2.0$ MeV electron fluxes at geostationary orbit are plotted versus time (late 1980 through early 1982). Also shown by bold vertical arrows are some of the main occurrences of star tracker anomalies onboard this geostationary operational spacecraft. The star tracker upsets were normally associated with high intensities of relativistic electrons. However, some high intensity electron events did not produce star tracker anomalies (see Baker et al., 1987 [7]) so there are more subtle controlling factors as well. Figure 7 shows how electrons must build up in dielectric materials for quite some time before a harmful discharge can occur. Thus, it is both the intensity of relativistic electron irradiation and its duration that is important. During some intense events in late 1981, the star trackers were actually turned off and so no operational "anomalies" could be recorded. The anomalies tended quite clearly to occur only during relatively long-duration events. Thus, it was not only the peak intensity of electrons, but also the duration of exposure that proved to be important.

Numerous previous studies (e.g., Reagan et al., 1983 [14]; Robinson, 1989 [15]; Wrenn, 1995 [22] have shown the clear role-played by high-energy elec-

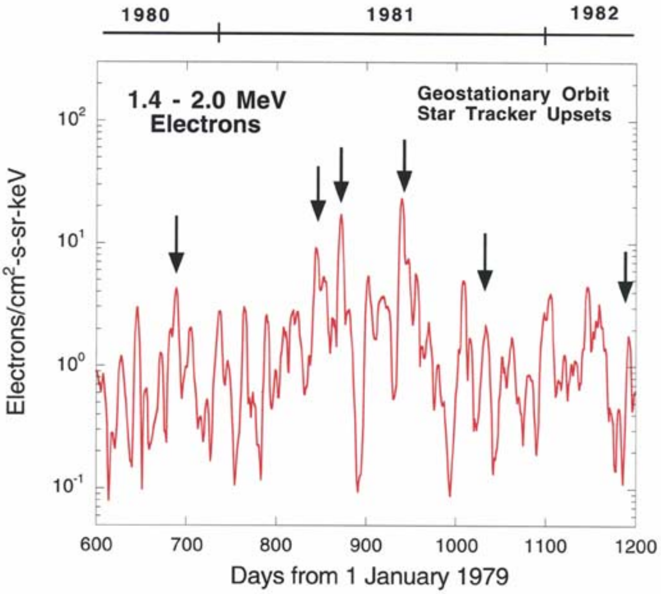


Fig. 6. Fluxes of 1.4-2.0 MeV electrons at geostationary orbit from late 1980 through early 1982. High electron flux events tended to be associated with star tracker anomalies (vertical arrows) on the spacecraft (from Baker, 2001 [4])

trons in many classes of spacecraft operational problems. Moreover, the quantitative level of radiation needed to produce deep-dielectric discharges has been rather clearly established in laboratory and spacecraft studies (e.g., Vampola, 1987 [20]). Figure 8, for example, adapted from Vampola's work shows results from the SCATHA mission that operated near geostationary orbit during the late 1970s and early 1980s. Deep dielectric discharges were monitored onboard the spacecraft and the daily fluences of E >300 keV electrons were concurrently measured. The probabilities of discharges went up dramatically when daily fluences exceeded 10^{11} electrons/cm^2. Above 10^{12} electrons/cm^2, the probability of discharges approached unity.

4 Magnetospheric Substorms

A significant effect of moderate geomagnetic activity ("magnetospheric substorms") from the standpoint of space operations is the occurrence of spacecraft surface charging (see Rosen, 1976 [17]. During a surface-charging event, insulated regions on a spacecraft may charge to several kilovolts potential (usually negative relative to the ambient potential). This charging occurs because of a lack of current balance between the ambient plasma medium and

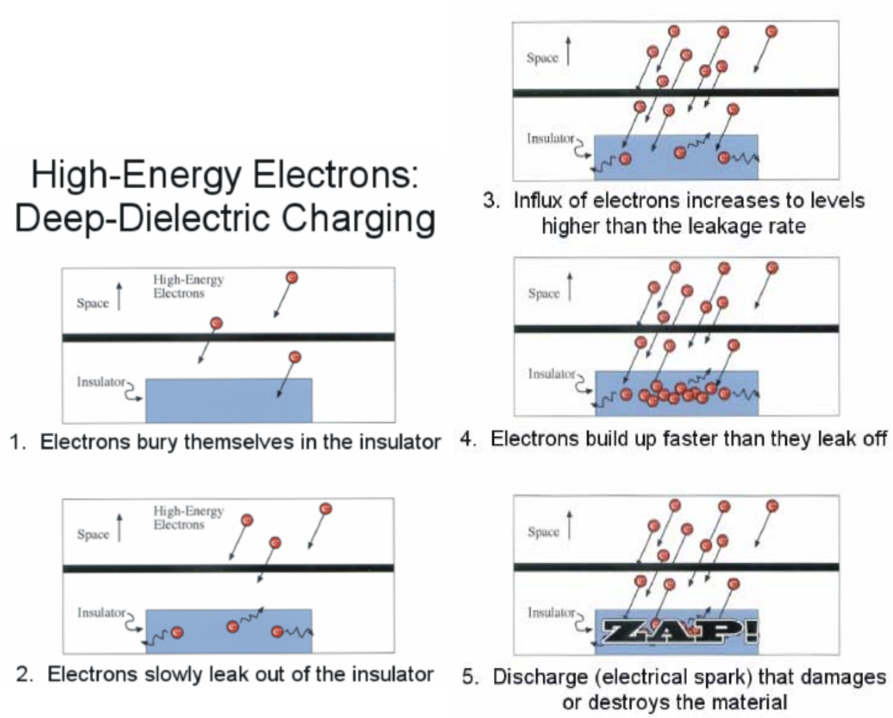


Fig. 7. A sequence of illustrations that show how high energy electrons can penetrate into buried material and cause deep-dielectric charging. The ultimate discharge (panel 5) can be very damaging to spacecraft subsystems (courtesy of G.D. Reeves).

the spacecraft surface (as illustrated in Fig. 5c). When a spacecraft is immersed in a cool, dense plasma, the incident particles (electrons and ions), as well as secondary emitted particles, photoelectrons, and backscattered electrons, all balance. This gives a low net spacecraft potential. However, in a very hot, tenuous plasma, current balance can be difficult to achieve and large potentials can build up.

Figure 5c shows the interaction at the surface of a spacecraft. This points out that there are currents near the surface of the spacecraft due to incident, backscattered, and photo-emitted particles. These various populations can, in principle, be examined to calculate the charge configurations for a given spacecraft. A sheath region that forms around the spacecraft is a volume strongly affected by the spacecraft. The plasma there is distorted by electric fields due to the charge of the spacecraft. The sheath region can also be affected by activity on the spacecraft such as thruster firings which extend the influence of the spacecraft farther into the plasma (e.g., Robinson, 1989 [15]). The sheath is complex in shape and depends on the motion of the spacecraft

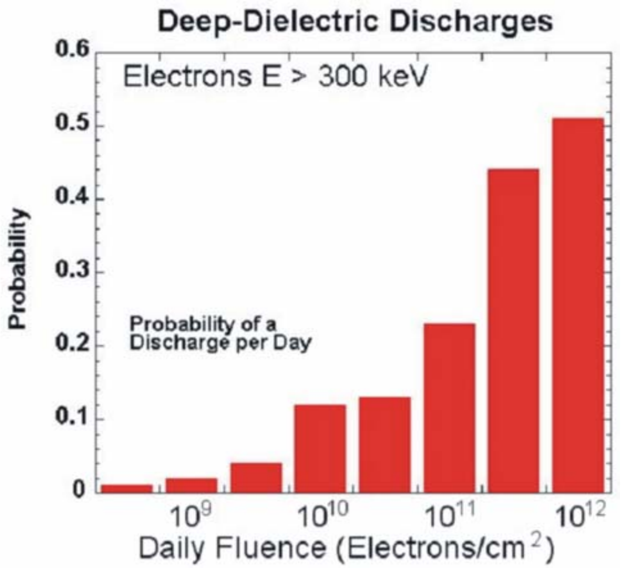


Fig. 8. Experimental results from Vampola (1987) [20] showing the probability of observing a dielectric discharge event as a function of the daily-integrated flux(fluence) of electrons with energy $E > 300$ keV (from Baker, 2000 [3]).

through the plasma as well as the plasma properties and the surface materials of the spacecraft. From an operational standpoint, differential charging of spacecraft surfaces that can lead to discharges. Discharges introduce noise into the system and may interrupt normal spacecraft operation, or represent a false command. In the process of discharge breakdown, physical damage may occur. This, in turn, may change the physical characteristics (thermal properties, conductivity, optical parameters, chemical properties, etc.) of the satellite. Furthermore, the release of material from the discharge site has been suggested as a contamination source for the remainder of the spacecraft (see Baker, 1998 [2] and references therein).

Figure 9, adapted from data presented in Rosen (1976) [17], shows the number of spacecraft anomalies detected at geostationary orbit as a function of spacecraft local time (LT). The anomalies include logic upsets as well as other significant operational problems for both military (Defense Support Program, DSP, and Defense Satellite Communications System, DSCS) and commercial (Intelsat) spacecraft. As may be seen, there is a very strong local time asymmetry in the number of anomalies with the vast majority occurring roughly between local midnight and local dawn. This is where substorm-injected electrons are seen most prominently (e.g., Baker (1998) [2], and references therein) and the LT distribution shown in Fig. 9 supports the view that surface charging has constituted a major cause of operational anomalies near geostationary orbit.

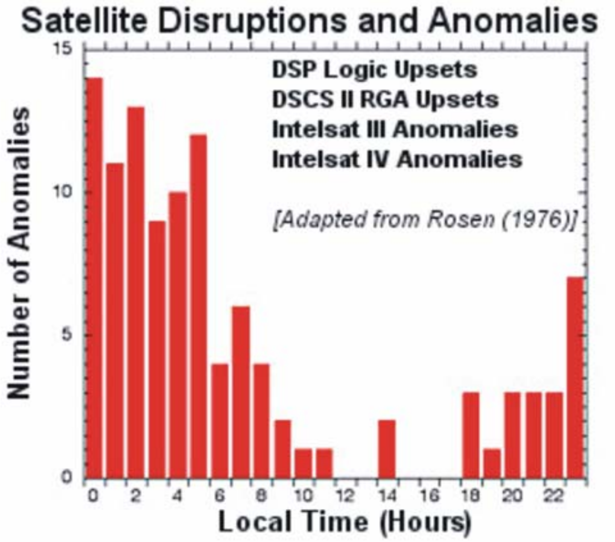


Fig. 9. Local time (LT) distribution of satellite disruptions and anomalies showing a strong occurrence frequency peak in the midnight and local morning hours (data from Rosen, 1976 [17]).

5 Space Weather Effects on the Electric Power System

Abelson (1996) [1] discussed the extensive changes that have recently characterized the electric power industry. He pointed out that modern, sophisticated end-users of electric power are growing increasingly susceptible to even momentary fluctuations of power. The standards for quality of the power supply continue to increase with the increased sophistication of society's utilization of electricity. He noted that interruptions and voltage sags cost users some $3 to $5 billion dollars per year and he went on to discuss new methods and technologies that may help to detect and correct for impending power quality problems.

The ever-evolving power grid is a complex and unique network of systems in which the production and delivery of the electrical energy all occurs at the speed of light. The design of the grid always took into consideration an array of contingency events and environmental challenges such as severe lightning, wind, and winter storms. Moreover, power grids have developed into continent-wide networks in which large blocks of power can be economically brokered over long distances and operation can be controlled by high speed devices. Notably, however, the size and complexity of the modern grid has introduced new vulnerabilities from the Sun (Kappenman, 2001 [11]).

Solar activity and eruptions commonly associated with the sunspot cycle can produce magnetic storms on Earth which have proven to have increasing impacts on technology systems such as electric grids as these systems be-

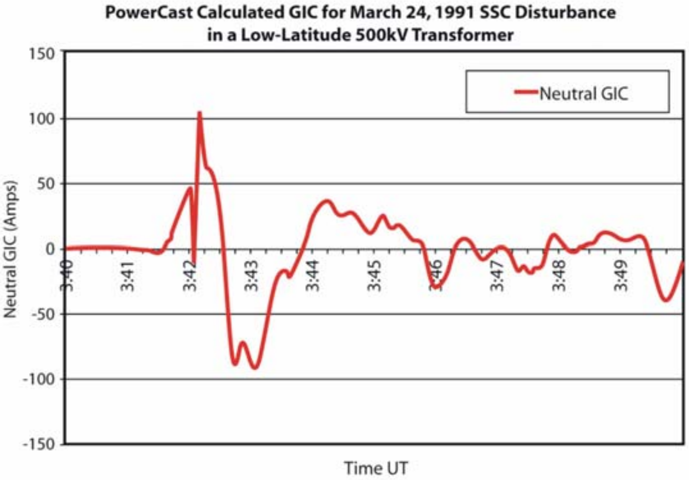


Fig. 10. PowerCast^{TM} Models of a power grid can calculate GIC flows in every transformer for actual and hyopothetical storm scenarios. This is an example from a large SSC in March 1991 (courtesy of J. Kappenman, Metatech Corp.).

come more sophisticated. The example noted previously was a March 1989 geomagnetic storm that resulted in a day-long outage to the entire province of Quebec. This occurred due to a complex chain of events stemming from the unanticipated interaction of thyristor switched voltage regulators (SVC's) which culminated only one and a half minutes later in a complete blackout across the province. Further, this storm had the potential to drive a blackout that could have covered an area extending from Washington DC up through the New England states, according to an assessment made by the North American Electric Reliability Council. Figure 10 shows a large current surge (GIC) associated with a similarly powerful storm in March of 1991.

An Oak Ridge National Laboratory study indicated that a disturbance of this scale could have resulted in a potential economic cost of $3-6 billion. In similar effects on other technology systems (defense, communication and satellite systems) equally substantial costs and compelling impacts can be felt. Since these extreme storms can simultaneously affect entire continents, their impacts are in a category equivalent to large hurricanes and/or the San Francisco earthquake as it effects the reliability of the power grid (J. Kappenman, private communication).

Given the importance of reliable and uninterrupted power throughout the world, it is concluded that more effort needs to be made to provide warnings of geomagnetic disturbances (Baker and Kappenman, 1996 [6]). Reliable advance warnings would allow those impacted by storms the ability to prepare for these disturbances. In fact, this is the consensus of a joint commerce, research, and military task force under the sponsorship of the National Science

Foundation that was convened in 1994 to formulate a U.S. "National Space Weather Program Strategic Plan". This plan was issued in August 1995 and as noted in the executive summary, "The Nation's reliance on technological systems is growing exponentially, and many of these systems are susceptible to failure or unreliable performance because of extreme space weather conditions. We now have the scientific knowledge and the technical skills to move forward to dramatically improve space weather understanding, forecasts, and services to meet customer needs." The U.S. is now undertaking a multi-agency Space Weather Initiative (National Space Weather Program Strategic Plan, 1995 [13]) to provide early warning of impending space disturbances. This has the goal of devising methods to avoid power system failures and other impacts of the space environment on human technological systems. The space research and applications community has urged NASA, NOAA, NSF, and other government agencies to cooperate in the development of warning and amelioration methods to avoid catastrophic failures in power systems. Such warning methods could save millions or even billions of dollars each year. Figure 11 shows an example of the present state-of-the-art in specifying auroral current and GICs (courtesy of J. Kappenman).

6 Future Directions in Space Weather Studies

Space weather is, of course, not a new phenomenon. In a fascinating account written in the New Yorker magazine in 1959 (Brooks, 1959 [9]), John Brooks wrote about "The Subtle Storm". This was a major solar flare that commenced on February 9, 1958 and caused numerous problems with communications and other systems. Compared to 1958, the present-day world is immensely more complex and interconnected. The Earth's surface is criss-crossed by communication links, power grids, and a host of technological systems that did not even exist in 1958. When one considers the range of satellites orbiting the Earth from low to high altitudes, it is obvious that there is a complex "cyberelectric" cocoon that envelopes our entire planet and most elements of this web are susceptible in one way or another to space weather effects (Baker, 2002 [5]). Certainly, modern communication systems rely heavily on elements that include both ground links and satellite links. It is clear that world-wide communication systems can be detrimentally affected by adverse space weather (Lanzerotti, 2001 [12]; Baker et al., 1998 [8]; Singer et al., 2001 [18]. The failure and loss of even one key communication satellite – as occurred on May 19-1998 with the Galaxy IV satellite failure (see Fig. 12) – can affect millions or tens of millions of customers relying on telephones, pagers, and other communications technologies (Baker et al., 1998 [8]).

The first line of defense for human technology against the effects of space weather is, of course, to build robust systems that confidently withstand any space weather effects. To a large extent, this has already been done: Were it

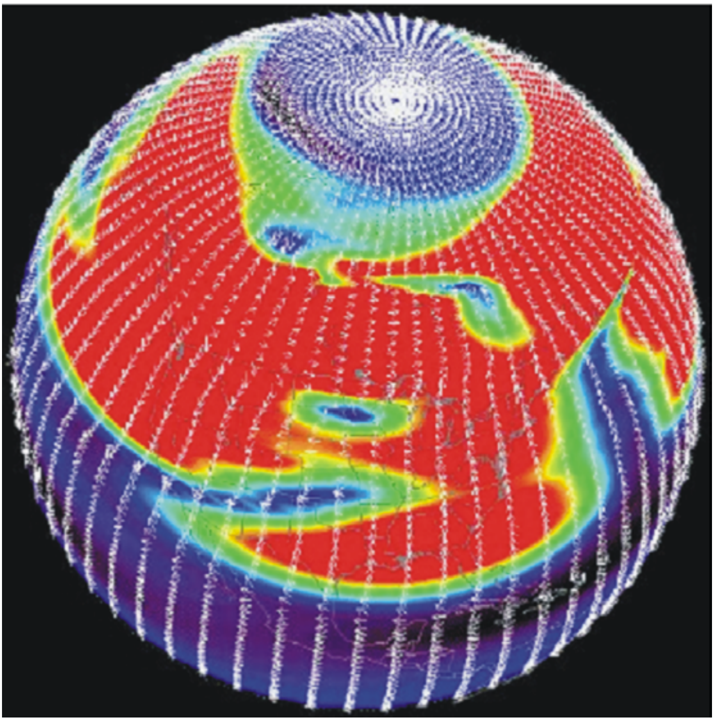
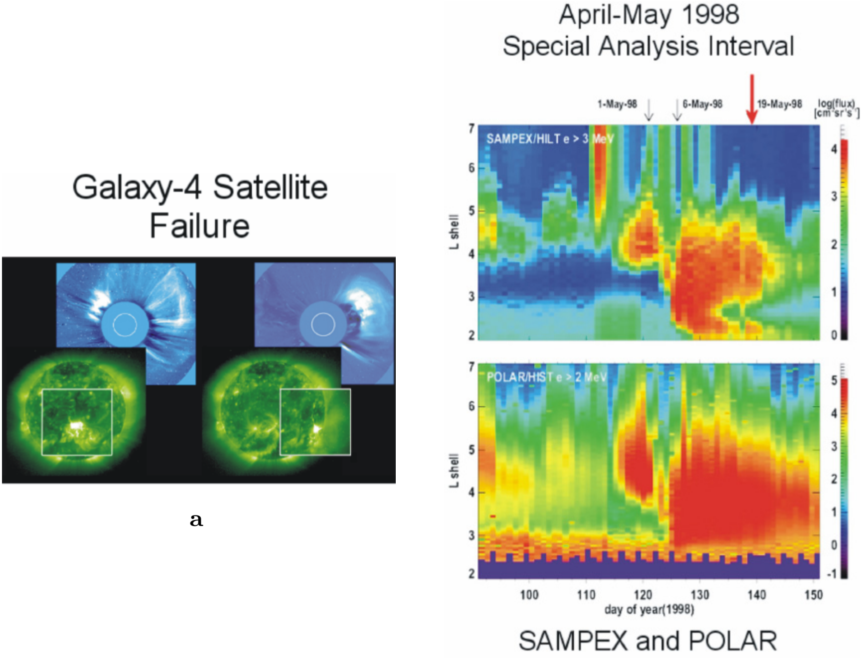


Fig. 11. A map showing magnetic field disturbances near the Earth's surface during a large geomagnetic storm on 15 July 2000 (courtesy of J. Kappenman, Metatech Corp.).

not so, there would be many more space weather-induced failures than we presently see. It is obvious that ground communication links, national power grids, and military installations – which must all withstand hurricanes, earthquakes, and floods – are very resilient and robust systems. Also, it is obvious that there are today many hundreds of satellites in Earth orbit fulfilling a wide variety of military and civilian purposes. Few of these fail catastrophically due to space weather. On the other hand, some spacecraft do fail suddenly due to space weather effects and nearly all spacecraft eventually fail due to the rigors of the hostile space environment. Thus, we need to know more about the nature of space weather elements, we need to specify better what the space environment is at any point in space, and we ultimately want to be able to predict (i.e., forecast) what the space weather environment will be anywhere in Earth's neighborhood many hours or days in the future. This is the goal of the U.S. National Space Weather Program (NSWP) (National Space Weather Program Strategic Plan, 1995 [13]; Robinsn and Behnke, 2001 [16]).

Space weather has become a major unifying theme and a uniting force for the entire solar-terrestrial research community. Understanding and predict-



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b

Fig. 12. (a) Active regions on the Sun during April-May 1998, (b) and (c) The response of the Earth's radiation belt electrons to solar wind drivers. The time of the Galaxy-4 satellite failure is shown by the large vertical arrow (adapted from Baker et al., 1998 [8]).

ing such events is a challenge of great scope and complexity (Singer et al., 2001 [18]). The National Aeronautics and Space Administration (NASA) has now undertaken a major new initiative called "Living With a Star" (LWS) to observe systematically the disturbances arising on the Sun and to follow these space weather drivers all the way to their ultimate dissipation in Earth's atmosphere (Withbroe, 2001 [21]). The National Science Foundation (NSF) has also been a leading agency in the development of the National Space Weather Program (National Space Weather Program Strategic Plan, 1995 [13]; Robinsn and Behnke, 2001 [16]).The NSF has now selected a consortium of universities, industry partners, and national laboratories to form a Science and Technology Center dedicated to space weather. This "Center for Integrated Space-Weather Modeling" (CISM) is funded at several million dollars per year for the next 5-10 years and will have as its goal the building of physics-based models all the way from the Sun to the Earth's atmosphere. It involves numerous institutions (see Fig. 13) all around the U.S., and it works closely with the National Oceanic and Atmospheric Administration (NOAA).

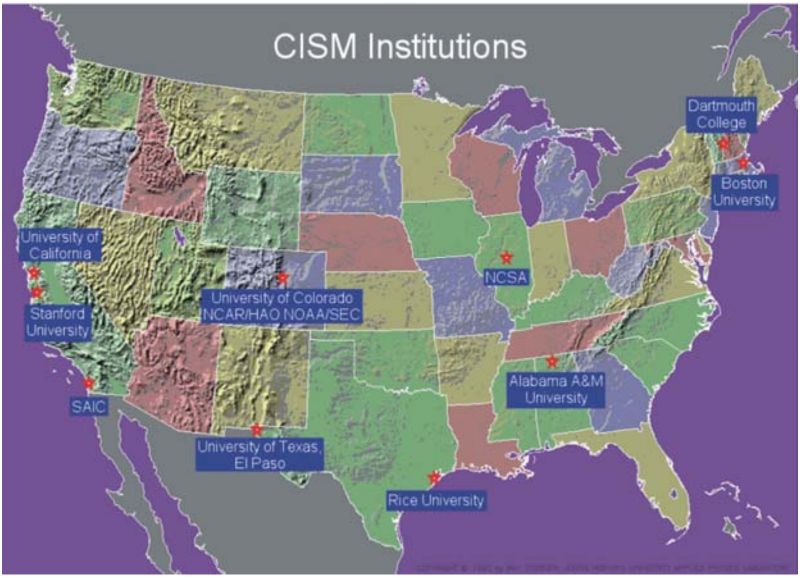

Fig. 13. Map of the U.S. showing the principal institutions involved in the NSF Center for Integrated Space Weather Modeling (CISM) (courtesy of W.J. Hughes).

7 Summary

Storms from the Sun are fascinating examples of energy transport and dissipation processes that are of undoubted importance in many cosmic contexts. Such storms are also beautiful when one observes the roiling surface of the Sun in soft X-rays or one stands outside on a dark night to observe the aurora borealis at northern latitudes. There is a splendor that accompanies space weather and there is also a danger from these powerful events that attracts and inspires popular readers (e.g., Carlowicz and Lopez, 2002 [10]). It is exciting to have the observational and modeling tools before us to be able to understand both the beauty and the threats presented by space weather. It is hoped that researchers from throughout the world can become engaged in space weather research. As shown by Fig. 14, agencies world-wide have now undertaken major space weather initiatives.

It is reasonable to expect that space weather research will continue and will, in fact, intensify over the next decades. Certainly, space-based and Earth-based human technology will remain susceptible to space weather effects. The increasing complexity and capability of human technology systems suggests that space weather will become more important as time goes on.

This chapter has given a very broad overview of several facets of space weather events and mechanisms. Subsequent chapters in this book go into much greater detail concerning the space environment, space weather mecha-

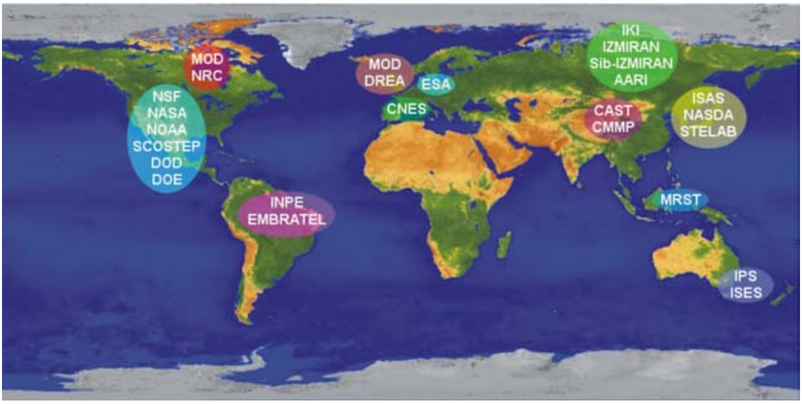

Fig. 14. A world-wide map showing agencies that are active in various aspects of space weather monitoring or forecasting (courtesy of J.H. Allen).

nisms, and technological consequences. The reader is urged to consult specific chapters if interested in a particular facet of space weather.

Acknowledgments

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