Introduction

Geomagnetic storms are multifaceted and macroscale phenomena. They carry with them the ability to affect humanity in profound ways. These storms can produce mass blackouts in industrial electric grids and cause extensive damage to manmade satellites such as telescopes, telecommunication devices, and monitoring devices, which ironically include those satellites used by meteorologists to monitor weather patterns on Earth. Dr. Anthony Lui at John Hopkins University has observed that due to the seemingly exponential increase in the amount of fiscally and scientifically valuable technologies in space since the 1960's, there is "an ever-increasing dependence on space and ever-growing need to monitor and forecast the space environment to avoid potential hazards (Lui 2000)". Analysts have estimated the economic impact of an intense geomagnetic storm to be in the billions of dollars range (Barnes & Van Dyke 1990). In light of this, it is apparent that the physical processes that allow geomagnetic storms to occur should be investigated and understood.

Knowing the characteristics of these storms allows scientists to predict storm activity, a valuable tool for large electric companies like Consolidated Edison Co. in Chicago, with millions of dollars tied to potentially compromised assets. The electric systems implemented by such companies must be specifically engineered to be able to cope with various effects of geomagnetic storms, including voltage spikes and frequency shifts (Albertson & Thorson 1974). To begin to grasp the causes of these storms, and to gain true appreciation for their threat to human systems, one must understand the physics of nanoscale particles, their conglomerate contributions to spatial systems, and the source and effects of powerful interplanetary forces.

Solar Activity

Solar Flares and Solar wind

Solar activity is for the most part capricious and extremely energetic. Numerous solar happenings can induce atmospheric disturbances on Earth. These include “localized changes in the sun’s temperature and in the strength or direction of its magnetic fields, and the eruption of gases and plasmas from its surface (Dooling 1995).” Solar flares and coronal mass ejections are two of the most intense energy bursts the Sun can produce.

Solar flares are explosive phenomena that have been observed to take place in the midst of groups of sunspots on the surface of the sun. These huge bursts of energy can release as much as 10^{32} erg in the most severe cases (Kosugi & Shibata 1997), equivalent to 10^{25} joules, 10^{11} times more energy than that released by the atomic bomb that exploded over Hiroshima. The energy released is visible via chromospheric brightenings, which allow physicists to observe and record the flares. Flares can be viewed in the hydrogen-alpha spectral line ($H\alpha$). Excited electrons in the hydrogen atom produce this emission line as they give off light at a 653.6 nm wavelength when jumping from the 3rd to the 2nd orbit (Sungazer). “It is on this line, near the red end of the visible spectrum, that most of the activities on the visible surface of the sun can be seen (Dooling 1995).” Solar flares can energize electrons and ions “up to MeV and GeV/n, respectively, and [heat] plasmas up to temperatures exceeding 3×10^7 K (Kosugi & Shibata 1997).” These high plasma temperatures increase the kinetic energy of suspended particles, resulting in increased particle velocity. The flux of these particles is referred to as solar wind (Britannica Online).

The mechanics of the processes that allow for solar flares are enigmatic and often debated in academic circles, but it is consensus that the energy of a solar flare is provided by the magnetic fields that exist in the high temperature, gaseous region on the sun’s atmosphere, called the corona. The heterogenic nature of the corona gives rise to what are called coronal holes: open field regions on the Sun which give rise to fast solar winds (Gopalswamy et al. 2006). These magnetically inactive regions allow the solar wind to escape freely (Dooling 1995). “Corotating, fast solar wind streams emanating from enlarged polar coronal holes sweep past the Earth’s magnetosphere every solar rotation, ~27 day (Tsurutani et al. 2006).”

This cyclical pattern of energy output gives rise to *recurrent* geomagnetic storms, characterized by their comparatively low intensity and slow onset (Kahler 1992).

Coronal Mass Ejections

Coronal mass ejections (CME) also contribute to solar wind. They are the most energetic events in the solar system (Klimchuk 2001). Unlike fast solar winds, CMEs originate from closed field regions. Ejecta often reach super-Alfvenic speeds in the Sun's magnetized coronal plasma and can drive shockwaves across the interplanetary plasma (Gopalswamy et al. 2006). The exact correlation between flares and CMEs is still open to research and discussion, but some sort of causal relationship is undeniable.

An article in IEEE Spectrum June 1995 describes coronal mass ejections as simply "plasma bubbles carrying their own magnetic fields that apparently escape into space through coronal holes (Dooling 1995)." These 'bubble' explosions can occur at anytime during the solar cycle but are most common around the solar maximum, the peak of solar activity. It is not uncommon for the mass of the ejecta to be in the billions of tons range (Pluto.space.swri.edu).

"[I]n a geomagnetic storm the most important factor is the strength of the southward field component associated with the ICME [interplanetary CME] (Kamide et al. 1997)." However, physicists are limited in their ability to view such magnetic fields. Information concerning the intensity and topology of strong storms can be inferred from microwave measurements and soft X-ray images respectively. Observations of filament disappearances can also give the scientist further information regarding the position of CMEs with respect to time. The best images are usually provided by white-light coronagraphs, although these still provide an unfortunately insufficient amount of data, and have limitations of their own (Kamide et al. 1997). There are many useful ways of modeling CME activity over time. However, since most models are based on imperfect or ambiguous solar images, only further observational research will show which model, if any, accurately reflects reality (Klimchuk 2001).

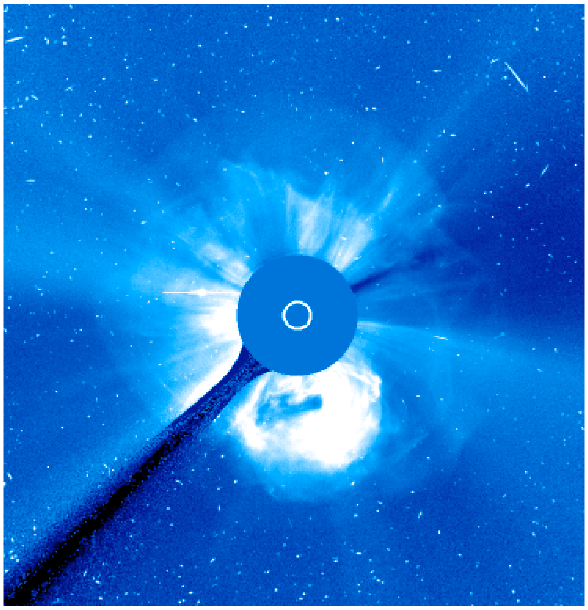

Figure 1 RHESSI

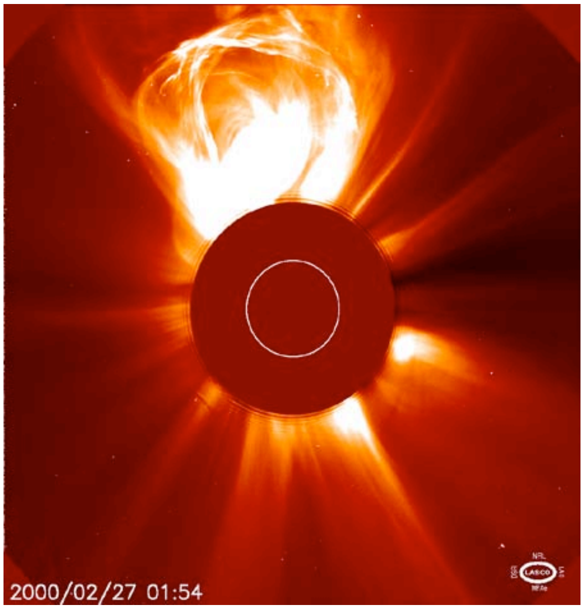

Figure 2 Armagh Observatory

The individual magnetic fields contained in ejected plasma, when proceeding at high velocity through the heliosphere or magnetosphere, wreak havoc on the magnetic fields of the Sun and Earth. The majority of CMEs occur in streamers, "which consist of closed magnetic loops at their bases with overlying current sheets which extend into interplanetary space. The current sheets are imbedded in high-beta plasmas with slow solar wind speeds (Kamide et al. 1997)." CMEs can greatly alter the structure of coronal holes as the streamer envelope passes through it. Potential causes of this instability include excitation of Alfvenic waves and the modification of the high-speed flux of particles from the holes (Kamide et al. 1997).

CME-driven shocks accelerate electrons and ions. The accelerated electrons emit radiation known as type II radio bursts, which can be used to track the shocks from the Sun to the Earth (Gopalswamy et al. 2006). "CME-driven shocks reaching Earth are also responsible for the ESP [energetic storm particle] events, which can be a direct radiation hazard for space-based assets (Gopalswamy et al. 2006)." Takeo Kusogi and Kazunari Shibata comment that these shocks "might be interpreted as resulting from a pressure pulse caused by flare energy deposition into the dense chromosphere. Alternatively their existence may be interpreted as inherently magnetic in nature (Kosugi & Shibata 1997).” Despite this vagueness, the effects of the shocks on the Earth’s magnetic field are consistent – consistently disruptive.

Terrestrial Activity

Earth’s Magnetic Field

The Earth’s magnetic field can be roughly modeled as a bar magnet. Magnetic field lines originate near the South Pole, and end near the North Pole. This is consistent with the bar magnet model if we consider ‘south’ on Earth to be the ‘north’ of the magnet, as field lines produced by magnetic dipoles must begin at the north end of the magnet. The magnetic field tilts approximately 11 degrees from Earth’s axis of rotation. Electric currents in the Earth’s metallic core are thought to be the origin of the magnetic field, and probably arise from the rotation of the Earth, which causes liquid metal to move through magnetic fields, which creates induced currents, which in turn produce magnetic fields of their own. This is referred to as the dynamo effect (Hyperphysics).

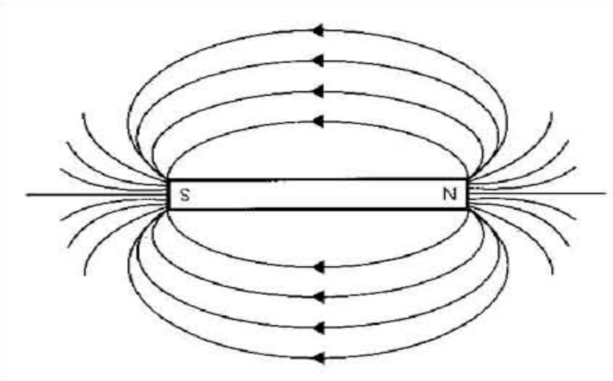

Figure 3 Magnetic Shield Corporation

The area of space dominated by a planet’s magnetic field is referred to as its magnetosphere. The Earth’s magnetosphere takes a unique shape due to its interaction with solar wind (Cosmicopia). The flow of particles coming from the sun compresses the magnetosphere on the sunward side of the Earth’s atmosphere. The interaction of solar wind with the magnetosphere creates a supersonic shock known as the bow shock on the sunward side. This slows and deflects solar wind around the obstacle. The boundary between magnetosphere plasma and solar wind plasma is called the magnetopause (Physics.usyd.edu). The night side of the magnetosphere stretches out approximately 1000 times the radius of Earth and is called the magnetotail (Cosmicopia). A simple diagram of this system is shown in Figure 4.

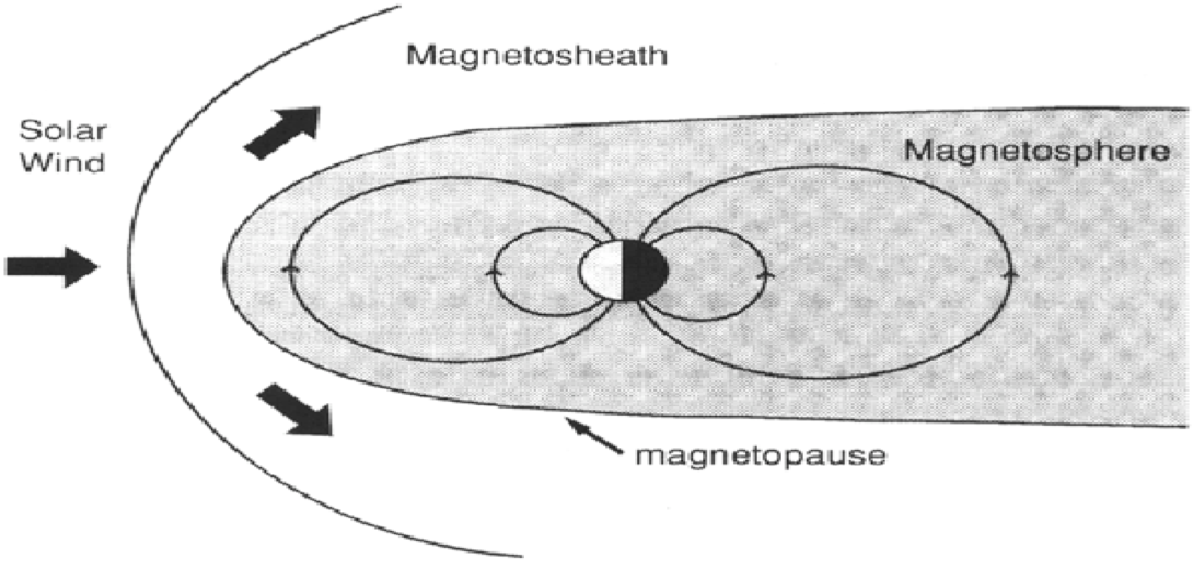

Figure 4 Physics.usyd.edu

Lui comments, “the Earth’s intrinsic magnetic field is a very effective barrier to charged particles such that direct entry of solar particles is very limited (Lui 2000).” However, openings in the magnetosphere occur at the geomagnetic poles, where field lines are vertical. Through these holes, charged particles enter the Earth’s outer atmosphere, resulting in the beautiful phenomenon called the aurora. In northern latitudes it is known as aurora borealis, Latin for ‘the northern dawn’, referred to more commonly as the northern lights (Dooling 1995).

Space Storms

Ring Currents

Lui states that the “magnetic field depression during the storm main phase was first attributed to electrical currents flowing near the Earth from charged particles originating directly at the Sun (Lui 2000).” However, it is now known that the magnetosphere greatly limits the effects of solar particles on the Earth. “Nevertheless, the idea that magnetic storms are caused by a ring of electrical current encircling the Earth called the ring current is essentially a correct one… …the charged particles responsible for the ring current are trapped by the Earth’s magnetic field similar to the energetic charged particles in the Van Allen radiation belts (Lui 2000).”

The equation for the motion of a particle of mass m, charge q, and velocity v, in a uniform magnetic field B is:

$$m(dv/dt) = qv \times \mathbf{B}.$$

Resolving the velocity into parallel and perpendicular components shows that the derivative of the parallel velocity as a function of time is equal to zero, implying the acceleration of the particle along the magnetic field line is zero, and the parallel particle velocity is constant. The two expressions below result:

$$dv_{II}/dt = 0 \qquad dv_{\perp}/dt = (q/m)v_{\perp} \times \mathbf{B}$$

When a magnetic field is nonuniform and converging, there is a mirroring force that acts on charged particles, equal to $-\mu\nabla B$. This force repels a particle away from strong field regions. Because the Earth has two regions of strong field, the mirroring force traps particles. At the mirror point, v_{II} equals zero (Lui 2000).

Charged particles gyrate about magnetic field lines. “[T]he gyration motion of a charged particle generates a circular current loop, equivalent to a small magnet with a magnetic moment:

$$\mu = -mv^2_{\perp}\mathbf{B}/(2B^2)$$

(Lui 2000).” By neglecting the fast gyration around the magnetic field, the drift motion of the center of the fast gyration under a given force F is:

$$v = (F \times \mathbf{B})/qB^2$$

Dr. Lui explains the significance of this equation. “Based on this simplified expression, we can readily obtain the drift motions of a charged particle moving in a nonuniform magnetic field (Lui 2000).” These are shown below with P as the particle pressure.

Curvature Drift Gives Rise to Current Density	$j_c = [(\mathbf{B} \times (\mathbf{B}\cdot\nabla)\mathbf{B})/B^4]P_{II}$
Current Density Associated With Gradient B Drift	$j_g = [(\mathbf{B} \times \nabla B)/B^3]P_{\perp}$
Magnetization Current	$j_m = -\nabla \times [(\mathbf{B}/B^2)\, P_{\perp}]$

“The combination of all these real and apparent drift motions give rise to electrical currents which are quite ubiquitous in space… …all these drifts may be added and simplified after some vector algebra to give the equation for the total electric current j perpendicular to the magnetic field carried by charged particles in the nonuniform magnetic field of the magnetosphere as

$$j = (\mathbf{B}/B^2) \text{ x } [\nabla P_\perp + (P_{II} - P_\perp)((\mathbf{B}\cdot\nabla\mathbf{B})/B^2)]$$

(Lui 2000)."

Storm-Time Ring Currents

During magnetic storms, some of the numerous solar wind particles in the magnetotail are transported into the ring current region. "The conventional idea is that a magnetic storm results from the accumulation of many elementary disturbances, termed magnetospheric substorms… …Each substorm produces an enhanced westward electric field in the outer ring current boundary and brings the particles in from the plasma sheet, a phenomenon known as substorm injection (Lui 2000)." However, Lui argues against this traditional view of a storm as a sum of substorms. He states that the conditions that allow for magnetic storms – long-duration (>3 hours) and strong southward interplanetary magnetic field ($B_Z < -10$nT) – imply that the reason for ring current development is not frequent and cumulative substorms, but rather results from "sustained enhancement of magnetospheric electric field… …In other words, a magnetic storm is a result of sustained strong magnetospheric convection (Lui 2000)." A consensus on the origin of ring currents has yet to be made, however Lui comments that a combination of varying models may yield a more accurate theory for their behavior. Regardless, in times of high storm activity, it is apparent that these ring currents have an effect on human systems.

Effects of Geomagnetic Storms

Rating Storms

Storm intensity is commonly measured using the Dst index, which assumes a correlation between the horizontal component of the magnetic field and the strength of the storm. The progress of a storm can generally be broken down into three stages. The initial phase is characterized by rapid increase in the horizontal component of the magnetic field, known as sudden storm commencement or SSC. In the main phase, which lasts several hours, the field is greatly reduced. The recovery phase brings field strength back to normal values and can take anywhere from days to weeks (Lui 2000). All three stages can be clearly seen in the graph below, although there are exceptions to this general pattern.

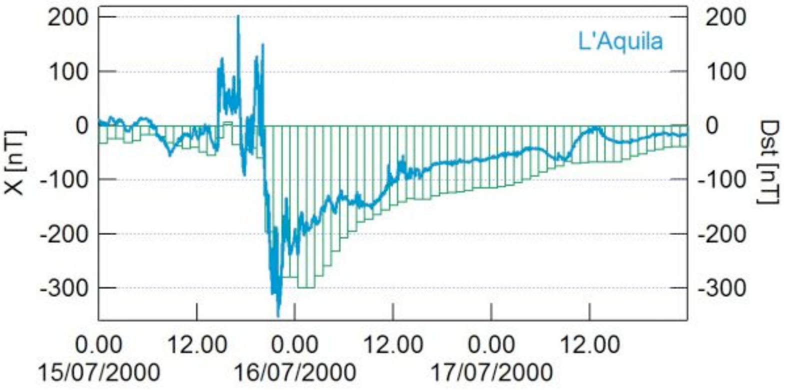

Figure 5 INGV

Another rating scale, called the K-index, is also commonly used to rank geomagnetic activity and is a “quasi-logarithmic scale extending from zero to nine (Albertson & Thorson 1974),” with K-0 indicating no geomagnetic field fluctuations.

Power System Disturbances

On August 4, 1972, a large geomagnetic storm with a K-level of K-8 occurred. “The categories of disturbances reported include shifts in MVAR flow, shifts in MW flow, voltage fluctuations, frequency shift, relay operations, third-harmonic currents in transformer tertiary windings, and communication, telemetering, and supervisory alarm failures (Albertson & Thorson 1974).” Most of these disturbances were ultimately related to the presence of solar induced currents (SICs) in transformer wirings. SICs are quasi-dc currents which when coupled with normal ac currents in transformers produce what is called half-cycle saturation of the transformer core, which is responsible for “increased transformer inductive VAR requirement, and an increase in harmonic generation by the transformer (Albertson & Thorson 1974).” Despite high levels of current irregularity, some power systems on August 4 experienced little or no system operating error. Areas in more northern latitudes were observed to be more susceptible to system operation failure (Albertson & Thorson 1974).

Effects on Technology and Economy

Protons and other charged particles have been long known to “disrupt computer memories or even damage the structure of semiconductor microelectronics… …satellites are always launched with far more solar cells than they need at first, so enough cells will be left undamaged to power the craft as it nears the end of its mission (Dooling 1995).” Protecting such spacecraft is not always straightforward, as it adds weight and costs money. A geomagnetic storm destroyed part of Canada’s Anik E-1 communications satellite, and caused the lifespan of the satellite to be reduced by six years (Dooling 1995).

On March 13, 1989 a geomagnetic storm caused a mass blackout in North America. “The blackout cascaded through the Hydro-Quebec Power system in just 90 seconds, faster than human operators could comprehend the problem, and leaving 1.5 million people in the dark for up to 12 hours (Dooling 1995).” This storm occurred 20 years ago, in a time with significantly less integrated and long distance power systems. Observations have supported the notion that transporting large amounts of power over long distances increases the vulnerability of electric power systems. The economic consequences of a modern day outage of a similar size in north-eastern United Staes would be somewhere between 3 and 6 billion dollars (Barnes & Van Dyke 1990).

Discussion and Conclusion

Because strong geomagnetic storms are often characterized by fast onset, early detection is necessary to avoid catastrophic damage in the case of a high K-level storm. Further advances need to be made in solar imaging to allow for more accurate models of the origins of solar flares and their relation to CMEs. Also critical is a unified theory on the operation of geomagnetic storms and substorms. Understanding what exactly causes the damage may provide us with crucial information for protecting assets. Finally, much research and development could be put forth in the investigation of how to protect space satellites and other devices that are orbiting in the tumultuous and unforgiving climate of space. A better understanding of the causes of these storms will undoubtedly lead to more sophisticated ways of reducing or eliminating their effects on human systems, and may prevent an economic loss of hundreds of millions of dollars.

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