Exercise 3. Find the magnetic latitudes for field lines that cross the equatorial plane at L = 3.0, L=10.0, L=20.0 and L = 30.0. If magnetic storms are produced by magnetic reconnection events between L=15 and L = 35, at what magnetic latitudes will ground stations observe significant changes?

Answer: In the above equation, a dipole field line that extends to L = 4Re, reaches the surface of the Earth (r = 1.0) at a magnetic latitude of 60^{o}.

II. Space Weather Effects

2.1 Magnetic Storms and Auroral Activity

Near the poles of Earth, observers have often seen glowing clouds shaped like curtains, tapestries, snakes, or even spectacular radiating beams. Northern Hemisphere observers call them the Northern Lights or Aurora Borealis. Southern Hemisphere observers call them the Southern Lights or Aurora Australis. Because most people, and land masses, are found north of the equator, we have a longer record of observing them in northern regions such as Alaska, Canada, Scandinavia, but sometimes as far south as the Mediterranean Sea or Mexico!

Figure 23 - A photograph of an aurora borealis taken in Alaska. (Courtesy Dick Hutchenson).

The most spectacular manifestation of the connection between the Sun and Earth are the aurora. For millennia, people have watched them and worried about what ill portents they were heralding. It wasn't until the mid-1800s that scientific studies began to uncover many of their mysteries.

Scientists learned that auroras often accompanied magnetic changes. They came and went with the sunspot cycle, and their colors were the product of excited oxygen and nitrogen atoms hundreds of miles above the surface of the Earth.

By the turn of the 20th century, scientists actually created artificial aurora in their laboratories. Once television and the fluorescent lamp were invented, it was pretty clear just how aurora worked. What scientists still didn't understand was what was triggering them. Some thought it was from direct currents of particles from the Sun itself. Others felt it was more complicated than that.

Thanks to intensive study by research satellites during the Space Age, auroras have been substantially de-mystified, even as their ethereal beauty has remained to dazzle us and inspire awe. When the magnetism of the solar wind is the same as the south-type polarity in the daytime side of the Earth, an invisible valve opens in the magnetotail region, allowing particles and energy to penetrate deep into the magnetosphere (see Figure 17). In the delicately balanced magnetic tail of the Earth, magnetic fields can become crossed just as in solar flares. The energy stored in the magnetic field can be liberated as currents of charged particles.

Auroras are formed in the atmosphere at elevations from 100 to 300 kilometers where the density of the air is very low - in fact almost a perfect vacuum. Enormous amounts of electrical energy are produced during an aurora when millions of amperes of electric currents pass through the atmosphere and generate nearly 900 billion watts of energy - mostly in heat but about a few percent in light. One of the biggest mysteries to science during the 18th and 19th centuries was the reason behind why Earth has aurora at all. It wasn't until scientists began to measure auroral properties and to describe them in detail by cataloging their forms, that progress was eventually made to understand them.

The other planets that have magnetospheres also have auroras in part because of the interaction with the solar wind and the planet's magnetosphere. Jupiter is a spectacular example of such another planet, with auroras covering its polar cap region.

In the 1740's, George Graham (1674-1751) in London, and Anders Celsius (1701-1744) in Uppsala, Sweden began taking detailed hourly measurements of changes in the Earth's magnetic declination. The fact that this quantity varied at all was known as early as 1634 by Gellibrand's observation of the 'variation of the (magnetic) variation' (Fleming, 1939). It didn't take very long before Celsius and his assistant Olof Hiorter uncovered in the 6638 hourly readings, a correlation between these disturbances and local auroral activity. Moreover, comparing the records between Uppsala and London, it became quite apparent that the magnetic disturbances occurred at the same times at both locations. By 1805, the independently wealthy, scientific traveler, Baron von Humbolt (1769-1859), had also noted these magnetic disturbances and called them magnetic storms' since they caused the same gyrations of his compass needles as local lightning storms would do. Just as Celsius and Hiorter nearly 100 years earlier, during a 13 month period, Humbolt and his assistant also made thousands of half-hourly readings of a compass needle.

Using his considerable influence and popularity, following a two-decade hiatus caused by European wars, von Humbolt acquired the resources needed to set up a number of magnetic 'observatories' in Paris, Freiburg, and later across Russia in the 1830's. The first magnetometers were quite crude affairs. A human 'reader' would peer into a microscope at a needle on a graduated scale, little more than an ordinary compass. At half-hourly intervals, day and night, the position of the needle would be noted. By the 1850's, networks of observatories amassed millions of these observations.

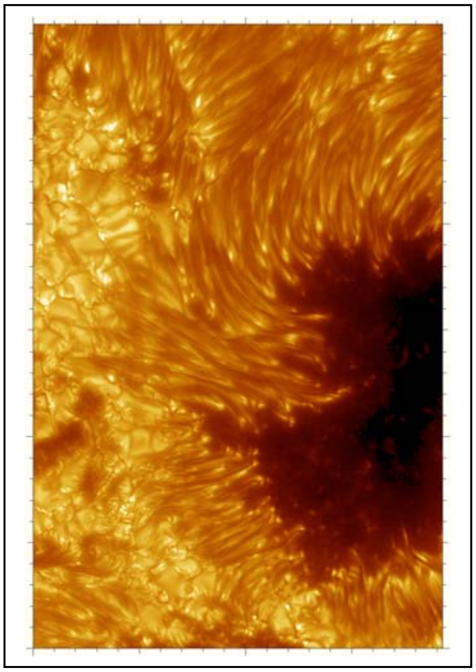
2.2 Solar Storms

Believe it or not, although you cannot hold in your hand a piece of the Sun, you can explore a model of the forces that control most of its active surface. The Sun has a magnetic personality. For over 100 years, astronomers have known from direct observations that the Sun's surface has an average magnetic field that is about twice as strong as the Earth's, but spread out over 10,000 times the area. We don't exactly know where it comes from. It may have been left over from the interstellar cloud that created the Sun over 4.5 billion years ago. Astronomers think it is actually generated by the Sun itself. Over all, the Sun's field looks a lot like a bar magnet. It has a north and south polarity as all magnets do. Much of its shape can be seen during a total solar eclipse as it leaves an imprint on the Sun's outer gases, just like iron filings outline the field of a bar magnet. But there is more to the Sun's magnetism than what you might find by just looking at a bar magnet.

In the mid-1800s astronomers discovered from thousands of sunspot sightings that, when they tabulated and graphed them, their numbers increased and decreased over time in a repeatable cycle. These extremes represent the amplitude of the cycle. We now call this the solar activity cycle or the sunspot cycle, which you can see in Figure 21. During the last 200 years, the period of the cycle has been about 11 years, but sunspot cycles can be as short as 9 (Cycles 1, 3 and 8) or as long as 13 years (Cycle 4). During sunspot minimum conditions, such as the year 1996, astronomers counted fewer than 5 sunspots on the surface of the Sun at any one time. During sunspot maximum conditions, as many as 250 could be seen. On September 20, 2000 one very large sunspot group could be seen with the naked eye with the proper safety precautions.

(You should never look directly at the Sun without proper shielding to avoid eye damage!).

Sunspots contain a dark, central region called the umbra, surrounded by a lighter region called the penumbra. Magnetic fields from below the solar surface become buoyant, like helium balloons released in the air, and float up to the surface. They erupt as a loop of magnetism with two 'foot points' forming a pair of sunspots. The magnetic field near the center can be over 5,000 Gauss in strength—or nearly 1000 times stronger than the average solar field. This causes the normal convection of energy below the surface to be reduced, causing a cooling of the surface by up to 2,000 K in the umbral region of a sunspot. Sunspots appear dark only because the gases emit about 1/10 the light of the rest of the solar surface!



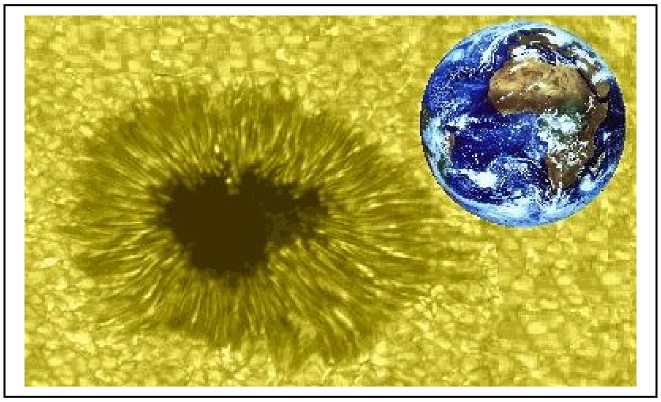


Figure 24 - Two views of sunspots showing solar surface and magnetic details. Note the Earth disk size in relation to a small sunspot!

Scientists can learn a great deal about how the currents and magnetism on the Sun work as a system by studying models of the Sun's surface in their laboratories or in detailed computer calculations. Even though the difference in radius between the Sun (6.9 x 10^8 meters) and a lap top computer (0.3 meters) is enormous (about 2x 10^{11} times), many physical laws can be scaled up or down in size so that even enormous solar flares can be investigated in human-sized models. Sometimes one group of sunspots collides with another, like ships floating on the Sun's plasma ocean. Sometimes a brand new sunspot can appear inside one that was

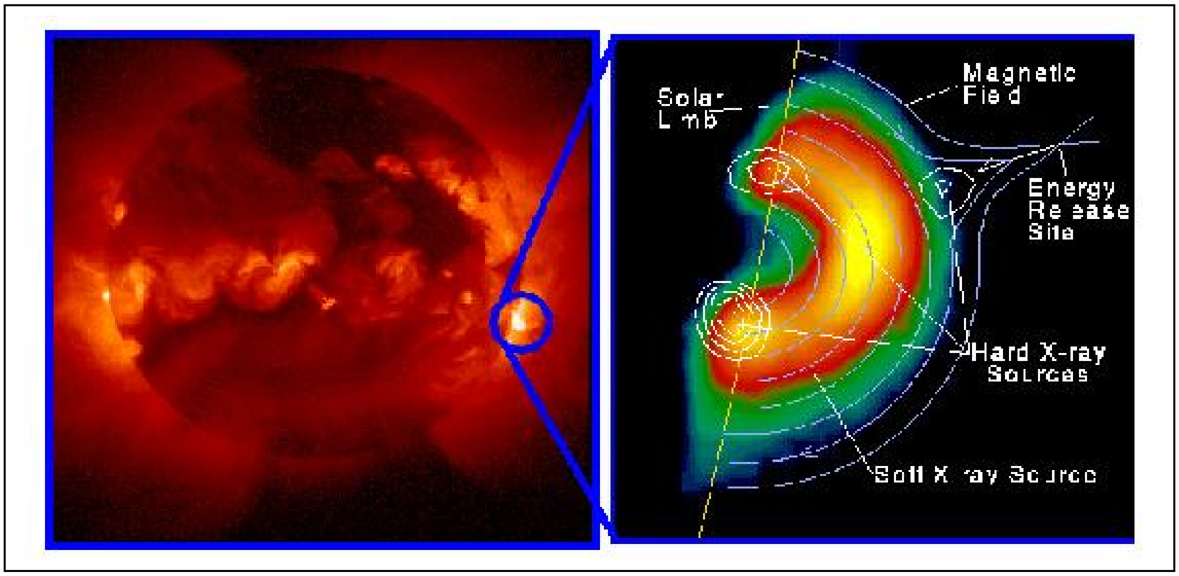


Figure 25 - An X-ray image of the Sun reveals the patterns of magnetic energy being released (left), and a zoom-in of one of these regions shows the many distinct physical regions that make-up a solar flare.

already there. These conditions lead to the build up of magnetic energy and inevitably the release of this energy in powerful solar flares.

Because sunspots and the gases around them can flow at thousands of miles a minute, it only takes a few seconds before magnetic conditions can escalate from a minor solar squall to a major explosion of energy. The billions of amperes of current moving through the solar atmosphere release over 10^{15} (1000 trillion) Joules of energy; more energy than in a thousand hydrogen bombs. Within five minutes, the magnetic field reconnects into a smoother shape to release the energy. Meanwhile, gas has been heated to millions of degrees and a blast of x-rays and other energetic particles leaves the scene of the event. In a little over 8 minutes, the x-rays traveling at the speed of light (300,000 kilometers/second) arrive at the Earth, located 149 million kilometers from the Sun, and cause short-wave radio blackouts across the entire daytime face of the planet. An hour or so later, a burst of slower-moving but enormously energetic particles flows by the Earth. Any astronauts in space, or sensitive satellites, will be bombarded by these particles and may suffer lethal doses of radiation. These solar flare events, though spectacular, have no effect upon Earth’s magnetic field. To find the culprits behind magnetic storms we have to look at another type of solar storm, which often accompanies solar flares.

For days, a heated cloud of plasma can be suspended by magnetic pressure just above the photosphere in a region called the *chromosphere*. Then, for reasons not fully understood, this billion-ton cloud can become unhinged and be propelled away from the Sun. The cloud may only have started off as a gentle puff of plasma. As it enters the lower reaches of the solar corona, the Sun's outer atmosphere, the cloud expands and accelerates enormously to speeds of millions of kilometers per hour. Within a few days, the cloud has reached the orbit of Earth, while parts of the cloud itself still envelop the orbits of Venus and Mercury.

In time, these coronal mass ejections cause interplanetary space to be filled with a changing palette of cloud fragments and magnetic field blobs, millions of kilometers across, and flowing in a great pinwheeling pattern, out beyond the orbit of Pluto.

No two CMEs are exactly the same, so astronomers describe these explosions by average properties, just as we often say that the average adult human being is about six feet tall. CMEs are actually not very dense by the time they reach the Earth's orbit. As they expand through space, their density falls from millions of particles per cubic centimeter near the

Sun, to barely a dozen particles per cubic centimeter near Earth. Most of them travel at nearly one million kilometers per hour and take two to three days to reach Earth's orbit. The fastest ones can travel at nearly three times this speed and get to Earth within 18 to 24 hours. Many CMEs are actually quite hollow and resemble enormous soap bubbles blown into space by the Sun.

The outer surface still contains some of the Sun's original magnetic field, though weakened by over a million times as it is stretched across the orbits of Mercury and Venus. The field arriving at Earth is still magnetically connected to the surface of the Sun, making this one of the largest natural structures in the solar system!

As spectacular as these solar storms can be, there is little cause for concern that the Earth's atmosphere will be 'blown away' by them. A CME blast wave is actually a better vacuum than what you would find in a television picture tube, but this doesn't mean that they are completely without any consequence.

Many systems in our solar system, and even in the Milky Way galaxy, are like pencils balanced on their points. The subtle pressure changes that CMEs bring with them into the depths of the solar system can affect the delicate balances in other physical systems elsewhere in space.

2.3 Magnetic storms and substorms

Since Kristian Birkeland (1867-1917) first coined the term ”magnetic” storm in the early 1800's, magnetic disturbances have been further categorized as either magnetic storms, or substorms. The former are typically very large events during which time the local magnetic field conditions change abruptly during the so-called Storm Sudden Commencement (SSC) phase. Within a matter of minutes, measurements of the field may change from quiescent conditions to very disturbed conditions, and the new level of activity can persist for hours or days. Auroral displays may be seen in many localities across the globe, especially the Great Aurora which can be seen as far south as the Mediterranean or Japan.

Magnetic storms are apparently spawned by major Coronal Mass Ejections (CMEs). If the Earth happens to be in the wrong place in its orbit, within a few days, these million kilometer/hour plasma clouds reach the Earth and impact its magnetic field. The momentary compression of the field causes an increase in the field strength at the Earth's surface causing the SSC. Many physical processes are then precipitated as the CME particles and magnetic fields invade geospace (the space around Earth enclosed by Earth’s magnetosphere), especially the amplification of the equatorial Ring Current. This current induces its own magnetic field which interacts with the Earth's field to cause fluctuations in the geomagnetic field near ground level and a net decrease in the field strength. Magnetometers then notice complex field changes which last until the CME plasma passes the Earth and geospace conditions return to normal. Major magnetic storm events also lead to spectacular auroral displays even at low geographic latitudes.

Substorms were first documented in 1964 by Syun-Ichi Akasofu of the University of Alaska using a network of all-sky cameras. They are generally less dramatic than magnetic storms, and may come and go within a few hours or so, always with accompanying auroral displays seen in the upper latitudes in Canada, Scandinavia and Alaska. Although there is considerable variation on a central theme, the evolution of substorm aurora (also called auroral substorms) follows a non-random basic script. Beginning with quiet auroral curtains near the horizon in the late evening, they brighten and pick up streaks or rays. Then a series of sweeping folds or spirals appear near the eastern horizon and surge westward as the 'expansion phase' begins. Near local midnight, the sky brightens again and dissolves into a myriad of rapidly moving forms, followed by a 'recovery phase' where conditions return to a vague diffuse cloudiness, with patches of diffuse glow pulsating on and off with a period of a few seconds.

Substorms are thought to be produced by minor changes in the orientation of the solar wind magnetic field as it collides with the geomagnetic field. If magnetic 'kinks' in the solar wind field meet up with the geomagnetic field, rapid polarity changes can lead to reconnection and current disruption events in the magnetopause and geotail regions. These events can cause particles to be accelerated to high energy and flow into the atmosphere to produce aurora. Substorms cannot be anticipated in advance because the interplanetary magnetic field is a complex phenomenon that is largely invisible. Major magnetic storms, however, are known to follow the Sun spot cycle; a fact uncovered by Edward Sabine in 1839, but not formally recognized by the scientific community until the turn of the 20th century. The best time to observe magnetic storms is when the solar surface is active, or has large sunspot groups transiting its surface.

III. The THEMIS mission

3.1 Scientific Objectives

The Time History of Events and Macroscale Interactions during Substorms (**THEMIS**) program consists of a five-satellite constellation with the job of determining the causes of the global reconfigurations of the Earth's magnetosphere observed during the abrupt beginning of 'onset' of an auroral substorm. Each satellite carries identical electric, magnetic, and particle detectors that will be put in carefully coordinated orbits. Every four days, the satellites will line up like pearls on a string along the Earth's magnetic tail, allowing them to track disturbances from this distant region, all the way to Earth’s outer atmosphere. The satellite data will be combined with observations of the aurora from a network of observatories across Canada and Alaska, as well as additional magnetic observatories located in schools in the northern U.S. states.

"Basically, we hope to solve the mystery surrounding the transport and explosive release of solar wind energy within Earth's space environment," said Michael J. Cully, Director of Civil and Commercial Programs for Swales Aeospace. "In addition, we believe THEMIS will also be able to answers some critical questions about radiation belt physics as that science relates to solar winds." The launch of the THEMIS mission aboard a