Solar Magnetism and Phenomena

By Ben Wagner

4/26/2011

Ben Wagner

Dr. John Stewart

Physics 2074 H002

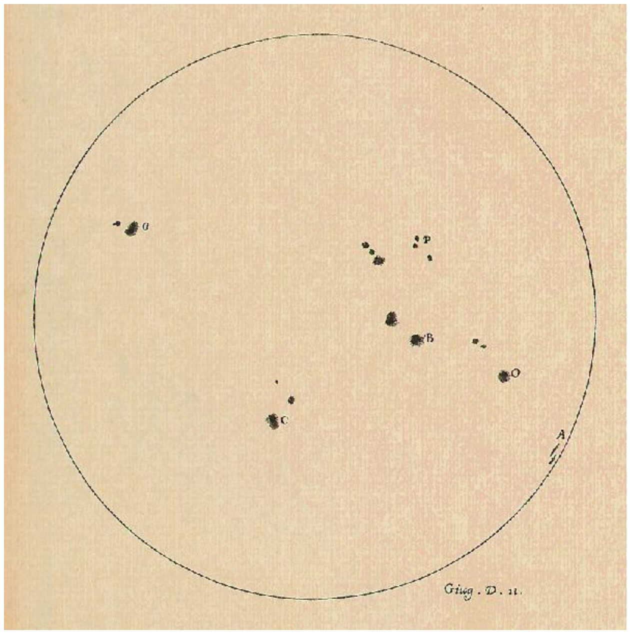
April 26, 2011

Solar Magnetism and Phenomena

It was the early sixteen hundreds when sunspots were first observed in Europe. Men like Johannes and David Fabricius, Christoph Scheiner, Galileo Galilei and Thomas Harriot began to examine the sun through telescopes. They appeared as dark features on the sun. There was some argument as to whether these mysterious things were satellites of the sun, clouds, or actual blemishes on the surface of the sun. Fast forward to the year 1908 when strong magnetic fields are discovered in sunspots by George E. Hale. This discovery was a major breakthrough. It explained one of the most observed variable features of the sun as a result of the magnetic field. Further experiments by the National Aeronautics and Space Administration and other groups further confirmed and gathered new data on the influence of the solar magnetic field. Since then, many of the phenomena surrounding the sun can be explained by or linked to magnetic field of the sun. In addition to the aforementioned sun spots other curious properties of the sun are attributed to the influence of the magnetic field including solar flares, coronal mass ejections, and solar wind. This paper will focus on these four occurrences of solar activity and how they are related to the variability of the magnetic field.

Galileo's drawings of sunspots.

http://www.orbit.zkm.de/?q=node/194



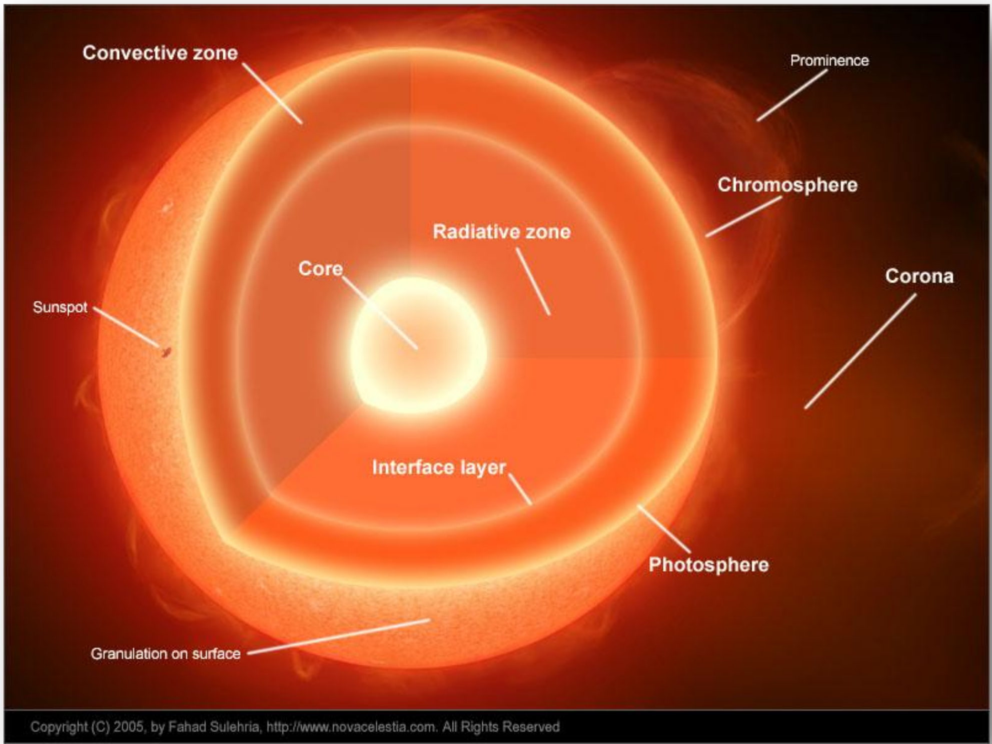
Understanding the magnetism of the sun is key to understanding the activity of the sun. But before one can delve into the effects of the magnetic field, there has to be study of the physical structure of the sun. The study of the internal makeup of the sun was mostly a theoretical exercise until the early 1960's when Robert B. Leighton was studying supergranulation. As a Caltech professor he pioneered the study of solar physics through the development of new instrumentation. (Greenstein, 1998) "Supergranules" are patterns of heated gas rising and cooled gas sinking in the photosphere. Leighton noticed that these supergranules reappeared in the same spot in with identical velocity and spatial qualities. These oscillations were later explained in the 1970's by Roger Ulrich (in 1970) and John Leibacher and Robert Stein (in 1971) as propagating sound waves. These discoveries gave rise to the branch of study called helioseismology. This is the method by which modern scientists use to gain insight into the conditions of the interior of the sun, namely the temperature, composition, and motions of the medium. These variables influence the oscillations, allowing the astrophysicists to peer into the inner workings of the sun by observing the wave motions.

The interior of the sun can be separated into four main sections: the Core, the Radiative Zone, the Convection Zone, and the Interface Layer (or Tachocline). (Zirin, 2008) Each of these areas is distinguished from one another by the processes that take place within them. The Sun's core is the center of the sun where nuclear fusion takes place. Energy is produced through a process called the proton-proton chain which converts hydrogen to helium. Special conditions are required for the proton-proton chain to occur: the temperature is roughly 15,000,000 K and the density is 150 $\frac{g}{cm^3}$ at the center. The core is thought to be around 25% of the radius of the sun. At the outer reach of the core and beginning of the radiative zone the temperature drops to about 7,000,000 K and the density decreases significantly to 20 $\frac{g}{cm^3}$. The radiative zone extends from the end of the core to about 70% of the radius. The density and temperature over this distance both decrease; the temperature to 2,000,000 K and the density to 0.2 $\frac{g}{cm^3}$. This zone is characterized by the transfer of energy through radiation. The hydrogen and helium ions discharge photons which collide with particles as they travel through the radiative zone. The convection zone is the last 30% of the sun's radius ending at the visible surface. It is here that the material of the sun becomes "opaque". The ions that make up the convective zone are at a temperature that ranges from 2,000,000 K to 5,700 K at the surface. This allows the ions to retain their electrons making it hard for energy to be transferred through radiation. The convection of fluids comes as a result of the heat trap that the ions create. So when a volume of plasma becomes hotter than the surrounding plasma it rises. Now in this part of the sun, the temperature gradient exceeds the adiabatic lapse rate (the rate at which temperature changes without exchanging heat with the surrounding). In other words, the temperature of this thermal column loses its temperature slower than the contiguous plasma. When the heated plasma reaches the surface it cools and expands thus creating the patterns of granulation and supergranulation.

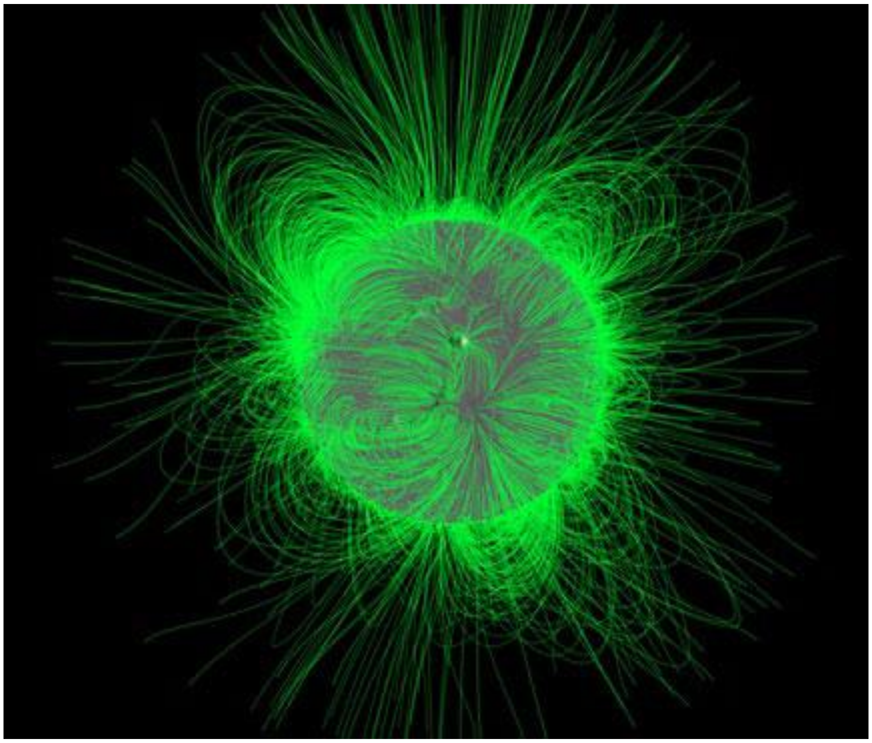
The fourth layer, the tachocline, is currently under study to fully understand its full effect. At this time, it is thought that the magnetic field is created here. This region forms the boundary between the radiative zone and the convection zone. The material in the convection zone rotates slower at the poles and faster near the equator. It is here that the nearly uniform rotation of the radiative zone meets the differential rotation of the convection zone. These conditions create shear which produces a circular electric current. Ampere's law describes the magnetic dipole field that is created by the flow of electrically conducting plasma. This whole process is called a solar dynamo. (Hathaway, 2011)

Illustration of the interior of the sun.

http://www.windows2universe.org/sun/Solar_interior/solar_furnace.html



The variable rotation of the convection zone creates a magnetic field with all sorts of structures and changing characteristics. The majority of the currents produced by shear flow in the direction of the rotation of the sun and these create an overall dipole field. This is called the omega effect. The magnetic field created by the sun is strong and constantly changing. Because of the nature of the differential rotation that creates the magnetic field, the magnetic field lines become twisted, stretched, and strengthened. The magnetic helicity of the field lines has been called the alpha effect, because of the way the lines are twisted in a loop. (Kuzanyan *et* al, 1999) Sometimes, the magnetic flux becomes coiled to the point where it extends in a loop into the atmosphere of the sun. When bipolar flux exit the surface of the sun, they observe Hale's law which observes that a group of two regions of opposite magnetic polarities are oriented east-west. All the magnetic regions in one hemisphere point in one direction while the other hemisphere is arrayed in the opposite direction. In 1919, Alfred H. Joy discovered that these magnetic polarities actually have a tilt so that the leading (in the direction of the rotation) pole is closer to the equator while the "following" pole is closer to the sun's North or South pole. This holds true for all the erupting flux causing each of the sun's poles to have either a positive or negative magnetic field. Due to the extensive work of George E. Hale, it is now known that this property is reversed every 11 years. During that 11 year phase there is roughly a 5-year lag from the maximum "eruption rate" and the maximum strengths of those magnetic fields. These phases result in a 22 year cycle called the solar magnetic cycle. Occasionally, due to the constantly changing magnetic fields, there exist large magnetic quasi-monopoles. This happens when regions of opposite polarity are separated by large distances simulating the existence of monopoles as the field lines stream away from the sun. This event is the source of many solar disturbances in the corona.



A mathematical representation of the sun's magnetic field.

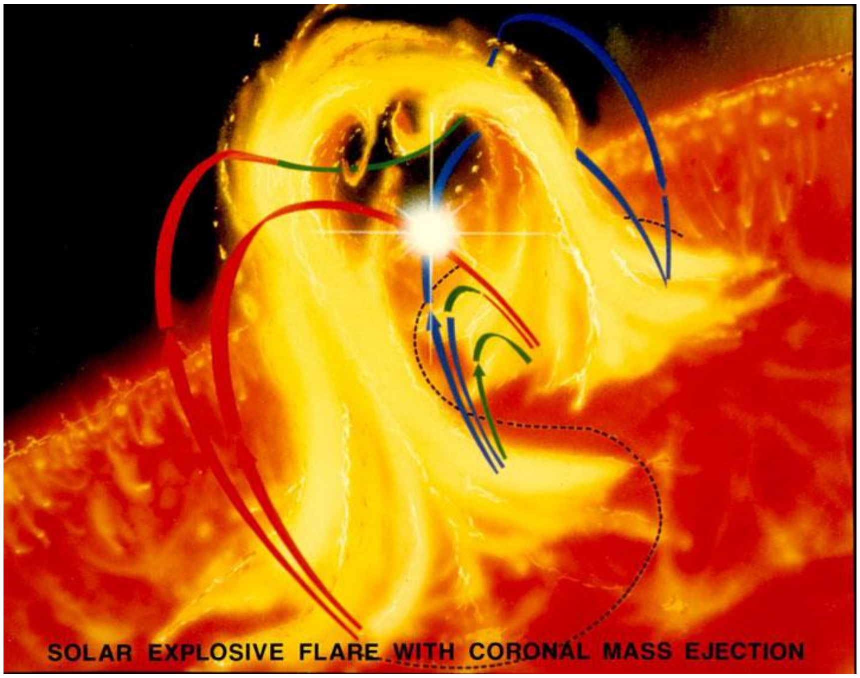
http://www.windows2universe.org/sun/Solar_interior/solar_furnace.html

The longest studied and most important indicators of solar activity are sunspots. Most other solar phenomena are directly affected by the behavior of sunspots. Sunspots appear as definite dark spots on the photosphere of the sun. The darkest part of the sunspot is labeled the umbra and lighter fringe is called the penumbra. In 1769, astronomer Alexander Wilson observed characteristics of the umbra and penumbra that indicated that sunspots are in fact depressions. Sunspots appear darker than the surrounding material because the temperatures of the spots are around 3700 K as opposed to 5700 K surrounding it. This drop in temperature is linked to the strong magnetic flux located at the center (creating a very large field nearly normal to the Sun's surface in the umbra and a more horizontal field in the penumbra). This increased flux induces eddy currents that resist the convection (and thus the changing flux), as illustrated by Lenz's law. The restrained convection inhibits the heated plasma from reaching the surface making it cooler that the rest of the photosphere. The area adjoining the sunspot is home to an intense region of magnetic energy being released and a corona close to three times as hot and dense as "quiet" parts of the surface. Normally, sunspots transpire in pairs inhabiting a region of emanating bipolar flux. The first sunspot represents one magnetic pole which loops into the corona entering the photosphere through the second sunspot. Naturally enough a group of sunspots move in unison across the sun's surface, representing the ever changing nature of the magnetic field. The number of sunspots that appear at a time varies over an 11 year period. The rate peaks at the start and dwindles to a minimum at the end. During the maximum rate, the sunspots occur around the 35 degree latitude (above and below the equator) varying with wider range at first. As the rate decreases and the end of the cycle nears, the latitudes of occurrence narrows closer to the equator in a pattern described by Spörer's law. There are several qualitative theories that seek to explain this law including meridional circulation and the Babcock Model. (Thomas and Weiss, 1991)

Solar flares are large explosions are massive explosions that release enormous amounts of energy. Currently, it is thought that they are caused by a physical process called magnetic reconnection. Although there is a consensus that magnetic reconnection occurs during solar flares, there is an ongoing argument on *how* it operates. (Priest *et al*, 2000) The material of the sun is made up of electrically conductive plasma. In this plasma magnetic field lines are bundled up into a group, a string of finite length. A particular domain has a magnetic moment that differs from other field lines close to it. When field lines from different magnetic domains in a region become twisted together it changes the "connectivity of its field lines." (Priest *et al*,

2000) This concentrates magnetic energy in a small space and releases a large store of energy into the solar atmosphere in a relatively small amount of time. This energy is released in the form of electromagnetic radiation; including gamma rays and x-rays. It also energizes electrons and protons, accelerating them to speeds near that of light. Finally, solar flares heat plasma in excess of tens of millions of Kelvin's and create mass flows. During a solar flare, there is a sudden upsurge in Hα emission from the sunspot it originates from. Hα is the red spectral line light produced by hydrogen; it has a wavelength of 656.3 nm. Most telescopes that monitor solar flare activity have filters to capture Hα as the brightness is sometimes eight times that of the chromospheres. Solar flares are typically classified by the peak soft x-ray flux it emits, measured W/m^2 at the earth. So X-class rays have a peak flux of 10^{-4} W/m^2, M-class are a tenth of that, and C-class are a tenth of M-class. The duration of the solar flares is not taken into consideration.

The solar corona forms part of the outer atmosphere of the sun. The low density gas that makes up the corona exhibits very high temperatures of up to 4,000,000 K. The corona contains three elements. The E corona (emission corona): the emission lines of highly ionized iron and other elements. The K corona (for Kontinuierlich corona) extends twice the distance of the sun's radius and is caused by light from the photosphere scattering off free electrons in the corona. The F corona (or Fraunhofer corona) is the furthermost part and is product of sunlight reflecting off dust. A coronal mass ejection is an explosion of solar wind, plasma, and magnetic fields propelled beyond the solar corona. CME's routinely obtain velocities of 489 km/s upwards to 3,200 km/s. Recently, research has shown a strong indication that CMEs are the result of magnetic reconnection (the same as solar flares). Both CMEs and solar flares usually originate in active regions, groups of sunspots, which contain stronger than average magnetic fields. The magnetic fields here are strong enough to contain large bubbles of plasma. So when these field lines are broken, the mass escapes into space. However, even though CME's often happen in concurrence with solar flares and prominence eruptions they are also capable of occurring individually.



A coronal mass ejection shown with the magnetic field lines interwoven.

http://www.msfc.nasa.gov/NEWSROOM/news/photos/2002/2002images/rons_flare_m.jpg

Solar wind is yet another example of phenomena arising from corona. It is a continuous stream of charged particles that radiate outward in all directions from the sun. There are two types of solar wind: slow and fast. Slow solar wind has a velocity of 300 km/s, these are located over coronal streamers, while fast solar winds attain velocities of 800 km/s over coronal holes (over the poles for instance). (Hundhausen, 2008) One fascinating result of solar wind is the heliosphere. The solar wind emanates in all directions at supersonic velocities, even beyond the orbit of Pluto. However, as the solar wind travels farther away from the sun it loses density until it is not dense enough to push back the interstellar gasses. At this point, the solar wind experiences a shock which balances solar wind pressure with the interstellar medium. This point of the heliosphere is called the heliopause and it represents the edge of the solar wind. Another interesting characteristic that inhabits the heliosphere is the heliospheric current sheet (HCS). This phenomenon is a product of the rotation of the sun. The sun's rotation causes the magnetic field to twist into a shape called the Parker spiral, named after the discoverer of the shape Eugene Parker. Solar winds carry the magnetic field out into the interplanetary field. As can be deduced from the name, the HCS contains a small current of around $10^{-10} A/m^2$.

For most of history, the activity of the sun has been constantly observed and studied. Mankind has always endeavored to learn more about the life giving force of this solar system. From telescopes to satellites the science of astronomy is constantly evolving and advancing. Even so, science has only just begun to understand the significance of the internal workings of the sun. The study of the solar magnetic field has exciting implications. A complete understanding of magnetic field could be the key to understanding solar phenomena like sunspots, solar flares, coronal mass ejections, and solar wind just to name a few.

Bibliography

Harold Zirin, "Sun," in AccessScience, ©McGraw-Hill Companies, 2008, http://www.accessscience.com

M. J. Thompson, A. Balogh, and J. L. Culhane. *The Origin and Dynamics of Solar Magnetism* (Springer, 2009)

Hathaway, David H. "The Solar Interior." NASA/Marshall Solar Physics. Solar Physics Group, 4 Apr. 2011. <http://solarscience.msfc.nasa.gov/interior.shtml>.

Neil R. Sheeley, Jr., "Solar magnetic field," in AccessScience, ©McGraw-Hill Companies, 2008, http://www.accessscience.com

Hathaway, David H. "The Solar Dynamo." NASA/Marshall Solar Physics. Solar Physics Group, 4 Apr. 2011. <http://solarscience.msfc.nasa.gov/dynamo.shtml>.

John H. Thomas and Nigel O. Weiss, *Sunspots:Theory and Observations*, (Kluwer Academic Publishers 1991)

A. J. Hundhausen, "Solar wind," in AccessScience, ©McGraw-Hill Companies, 2008, http://www.accessscience.com

Kirill Kuzanyan and Shudong Bao and Hongqi Zhang, "Probing Signatures of the Alpha-Effect in the Solar Convection Zone," 1999, ftp://helios.izmiran.rssi.ru/050905/KuBaZh00.pdf

Eric Priest and Terry Forbes, *Magnetic Reconnection: MHD Theory and Applications*, (Cambridge University Press, 2000)

Jesse L. Greenstein, *Robert B. Leighton: 1919-1996 A Biographical Memoir*, (National Academies Press Washington D.C., 1998)