The Impact of Solar Weather
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1. Introduction
Without the Sun there would be no weather on Earth, no atmosphere in which differential heating cause winds to blow, no oceans to store heat and evaporate into water vapour, to condense as clouds and fall as rain. Yet the Sun itself has its own weather, convective processes like our own atmosphere and magnetic storms of a nature unknown on any planet.

2. The Sun
The Sun, like the Earth, requires a source of energy to drive its weather processes. Unlike the Earth, the Sun's source of energy lies within. Robert Atkinson and Fritz Houtermans (1929), based on suggestions by Arthur Eddington (1926) and recent discoveries in quantum physics, were the first to determine the nature of this energy source. The incredible densities and temperatures at the core of the Sun, up to 160,000 kg/m$^3$ and over fifteen million Kelvin (Freedman & Kaufmann 2002), mean that the nuclei of hydrogen atoms can collide with enough energy to fuse and form helium. In the process energy in the form of gamma radiation is released.

Fusion only occurs within the central quarter of the Sun's interior. The gamma ray photons produced in the reactions then make their way slowly out towards the surface in a random walk that takes, on average, 30,000 years (Shu 1982) as they are absorbed and re-emitted.

2.1 Solar Convection
At a bit over two-thirds the distance from the centre of the Sun to its surface we see the first “weather” effects. The temperature there is low enough that hydrogen exists in its atomic form, which is more efficient at absorbing photons of energy (it is said to be opaque). Heated from below, the hot gas becomes less dense and rises towards the surface, to be replaced by cooler gas from above. As the gas reaches the surface it cools, eventually sinking back to the interior and the cycle then repeats. This process is called convection, and some of the same energy that it carries up from the interior of the Sun will find its way to Earth, where it will heat the planet's surface. The surface, in turn, heats the atmosphere, generating the convective processes such as winds and vast underwater rivers of warm water such as the Gulf Stream.
The Sun's convection processes are visible to us as granulation in the photosphere, the thin surface layer of the Sun where the density is low enough that visible light photons can escape. The granulation is even more apparent in ultraviolet light, as can be seen in the photograph of the Sun's surface made by NASA TRACE spacecraft (TraceWeb) (Figure 2). These granules average about one thousand kilometres in size, the bright areas corresponding to the rising hot gas, while the darker edges are where the cooler gas falls away.

This motion can also be observed by measuring the Doppler shift of spectral lines from the different points on the Sun's surface. Using this technique, much larger granules, supergranules, approximately 25 to 30 thousand kilometres in diameter (Hart 1954), can also be seen, although there is some dispute as to whether they are the direct effect of convection (Hathaway et al. 2000).

Above the photosphere lies the chromosphere, a layer of gas producing emission spectra, a sign that it is being stimulated to release energy. Indeed the bottom of the chromosphere is five times cooler than the top. Beyond the chromosphere is the corona, the extensive, but very low density upper reaches of the Sun's atmosphere. The temperature here is around two million degrees. The source of this energy is suggested to be shock waves generated by convection processes travelling up the photosphere and into the chromosphere and corona (Shu 1982).

The high temperature of the corona means that many of its atoms have a high enough velocity to escape from the Sun's gravity. This outward stream of atoms and ions is called the solar wind and it stretches up to approximately 160 AU (Gurnett 2003) outside of the solar system, meeting interstellar space at a region known as the heliopause.

1.2 Sunspots and the Sun's Magnetic Fields

The ionised material within the Sun forms an electrically charged plasma and the rotation of the Sun and the plasma acts as a dynamo to generate a powerful magnetic field. Other components of the field are caused by the differential rotation (Parker 1955a) of the solar interior (27 days) and the convective zone (from 25 to 35 days) at an area called the tachocline.

The rotation of the convective zone decreases with latitude between the aforementioned numbers. Babcock (1961) proposed that this differential rotation causes the magnetic field to become distorted as it is dragged along, causing it to become kinked and tangled. Components of the magnetic field are also distorted by the rise and turbulent motions of the convection cells (Parker 1955a).

The tangled magnetic fields become highly concentrated in certain regions of the Sun, deflecting the heated rising plasma away from the area, thus interrupting convection in the local region. This leaves a patch of cooler and therefore darker gas known as a sunspot (Parker 1955b). Sunspots generally form in groups. The preceding members of the group migrate towards the solar equator while the following members move towards the poles. Sunspots are associated with the Sun's magnetic field (Hale 1908) and are magnetically polarised (Hale et al 1919), with preceding sunspots sharing the polarity as the pole of their local hemisphere, while the reverse is true of the following members.

It has long been noted that sunspot numbers appear to vary over periods of 11 years, which corresponds with a reversal of the Sun's polarity. Babcock (1961) proposed that the convergence of the following sunspots at the Sun's magnetic poles causes the overall field to first cancel out, then reverse. The magnetic field then begins its next cycle of differential rotation induced distortion, until, 11 years later, the polarity reverses again, a 22 year cycle of sunspots and other solar phenomena.
2.3 Prominences, Flares and Coronal Mass Ejections

Hot plasma rising to the surface of the Sun can drag magnetic field lines with it. These field lines can loop out of and back into the surface forming arcs of plasma into the corona. The prominences and the interaction of magnetic field lines may be the source of energy that powers the corona (Freedman & Kaufmann 2002). The more active of these prominences are associated with the complex magnetic fields around sunspot groups, but quiescent prominences may be caused by the interaction between magnetic fields and normal convective processes (StanWeb).

The complex magnetic processes around sunspot regions can cause magnetic field lines to break and reconnect (Weber 1998). This can release a enormous amount of energy, flinging great quantities of charged particles out into space in a process called a solar flare. As can be seen in Figure 3 a solar flare also affects the surrounding surface generating seismic waves dubbed sunquakes.

Even more energetic than solar flares are coronal mass ejections (CME's). These are huge bubbles of high temperature coronal gas that can be millions of kilometres in size. CME's were reveal by space based observation platform and it is now accepted that CME's and not solar flares are the major source of high energy particle storms that strike the Earth (Freedman & Kaufmann).

3. The Earth

3.1 The Earth's Magnetic Field

The Earth, like the Sun, is surrounded by a magnetic field. The field is generated by electric currents within the Earth's liquid outer core, again like the Sun, related to the rotation of the planet. The alignment of the magnetic field is at an angle of approximately eleven degrees to the rotational axis of the Earth and it is subject to continual movement and reversals (BGSWeb). The variation and movement of the field are believed to be due to the fluid movement of the liquid outer core and the coupling of the magnetic field with the solid inner core. (Gubbins, 1999).

The Earth's magnetic field shields the planet's surface from the solar wind. The charged electrons and protons of the solar wind drag the Sun's magnetic field along with them, distorting the Earth's magnetic field, compressing the daylight side and producing a long tail on the reverse (OuluWeb). The region of space around the Earth where the terrestrial magnetic field dominates is called the magnetosphere, its boundary, the magnetopause.

Within the magnetosphere are two regions, the Van Allen belts, where high energy particles are trapped by the magnetic field (Van Allen et al., 1958; Van Allen and Frank, 1959). The inner belt primarily contains protons that result from interactions between energetic cosmic rays and the Earth's atmosphere (MgxWeb), whereas the outer belt traps solar ions and electrons. The ions can leak out of the belts, spiraling down the magnetic field lines towards the Earth's magnetic poles. There they may collide with atmospheric atoms, which then release the light that we see as aurorae.
3.2 The effects of Coronal Mass Ejections on the Earth

Ground and space based solar observatories, such as IPS Radio and Space Services (IPSWeb) and SOHO (SOHOWNet) keep close watch for CME's and solar flares. The electromagnetic radiation from these events travels to the observer at light speed, taking roughly eight minutes to reach Earth, while the charged particles have lower velocities and may take days to arrive at Earth (ISTPWeb).

The effect of a sudden influx of charged particles on the magnetosphere can be very severe. The magnetosphere becomes distorted, with magnetic reconnection allowing the charged particle plasma to enter the magnetosphere at much higher rates than normal (USGSWeb). The charged particles are accelerated down the magnetic field lines creating powerful currents. Electrical power grids, oil pipelines and other long conductive networks can act as antennas with great current surges running through them via induction (Clark). This was demonstrated in 1989 when a CME induced blackout hit Quebec (HQWeb).

A CME can also affect radio communications. The upper level of the Earth's atmosphere, between approximately 50 to 100 kilometres in altitude is called the ionosphere and it contains charged particles, the density being height dependent. This variance in densities causes the reflection of high frequency radio waves, allowing radio operators to communicate for very long distances (ECJWeb). An influx of high energy plasma from a CME disrupts this process.

Collisions between the incoming plasma and atoms in the upper atmosphere cause the atmosphere to heat up and expand. The atmospheric expansion can increase the drag on low earth orbit spacecraft causing their orbit to decay. The was spectacularly demonstrated by the NASA space station Skylab, which broke up over Australia in 1979 after greater than predicted solar activity caused its previously stable orbit to decay (SKLWeb).

Space craft and astronauts can also suffer directly due to the particle fluxes caused by solar activity. High energy electrons can disrupt integrated circuit based processors and memory, triggering false commands and degrade solar panels (Poppe et al. 2004) . The particles can also penetrate into the bodies of astronauts, damaging DNA and disrupting cellular processes (NSBRIWeb). This is a particularly important issue for future manned interplanetary missions.

3.3 The Maunder Minimum

Sunspots and other energetic solar phenomena are associated with the Sun's 22 year magnetic reversal cycle. However, for a period of 70 years between 1645 and 1715 very few sunspots were observed. This period, known as the Maunder Minimum, corresponded to a very cold period in Europe called the Little Ice Age and may have involved a decrease in the energy output of the Sun (Ribes & Nesby-Ribes 1993). The causes of the Maunder Minimum are unclear and the effect of small variations of solar irradiience on the Earth's climate is a controversial topic, especially with the current debates over global climate change and the greenhouse effect (Beckman & Mahoney 1998).

4. Conclusion

The Sun's weather is inextricably linked to a complex magnetic field that undergoes a 22 year cycle of polarity reversals. The effects of this cycle include cooler regions of the solar surface called sunspots, solar prominences that transfer energy from the Sun's surface into its upper atmosphere and coronal mass ejections which throw huge quantities of charged particles into space. The particles may strike the Earth's own magnetic field, causing a range of phenomena including power surges in the electrical grid, disruption to communications and increased atmospheric drag on spacecraft. There may even be connections between solar events and the Earth's climate. Without the Sun's energy life would not be possible on Earth, but that life would not exist without the protection of the Earth's magnetic field.

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References
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