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Introduction

Space weather describes how conditions in space can affect human activity and technology both in space and on the ground (National Research Council, 2008), and has been actively monitored for a number of years now, most notably by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC)¹. In the past few years space weather monitoring activities in both Europe and the UK have developed rapidly, most recently with the formation of the space weather service at the Met Office, described elsewhere in this special issue. Space weather can affect power grids, pipelines, transoceanic communication cables, satellites, aviation, global navigation satellite systems, telecommunications and radio communications, to list just the major impacts identified by a recent Royal Academy of Engineering study (Cannon *et al.*, 2013). As a specific example, in 2003 a series of strong space weather events had a very wide ranging impact, documented by a subsequent NOAA Service Assessment (Balch, 2004). Space weather is now included in the Cabinet Office National Risk Register of Civil Emergencies (Cabinet Office, 2013).

¹<http://www.swpc.noaa.gov>

Space weather is ultimately driven by solar activity (Schwenn, 2006; Eastwood, 2008). There are two basic types of space weather drivers generated by the Sun: solar flares, powerful transient emissions of electromagnetic energy at a wide range of wavelengths, and coronal mass ejections (CMEs), eruptions of material from the solar corona that have initial speeds typically 500–2000kms⁻¹, and extremes of ~3000kms⁻¹. If a CME is Earth-directed, its interaction with the Earth's magnetosphere can cause a geomagnetic storm. However, the ability of a CME to generate a storm strongly depends on its internal magnetic field structure and this can only be established by satellites making *in situ* measurements. As such, whilst we can image CMEs leaving the Sun and track their progress into the interplanetary medium (see Harrison and Davies, 2014), it is simply not yet possible to know immediately after the launch of a CME whether it will harmlessly pass the Earth or whether it will cause a geomagnetic storm. In fact, remote determination of the magnetic field is now recognised as a key scientific challenge, stimulating research into alternative techniques that include measurements of the source magnetic field at the Sun and forecasts of its evolution as the CME travels to Earth, and adaptation of radio astronomy techniques for remote sensing magnetic fields in space. However, *in situ* measurements are still the only reliable way to establish the magnetic field.

In the context of space weather these are currently provided by NASA's Advanced Composition Explorer (ACE) satellite, just upstream of the Earth at the L1 Lagrange point, which is located on the Sun–Earth line ~1.5 × 10⁶km sunward of the Earth (approximately 1% of the distance from the Earth to the Sun). At L1, the gravitational pull of the Sun and the Earth conspire to ensure a satellite placed there will maintain an orbital period equal to that of the Earth². From this location the solar wind can be monitored *in situ* before its arrival at Earth. For solar

²For more information about the Lagrange points (also referred to as Lagrangian points) see http://en.wikipedia.org/wiki/Lagrangian_point or <http://www.nasa.gov/missions/solarsystem/f-lagrange.html>

wind structure moving at typical speeds of 400kms⁻¹, this provides just over 1h of lead time before the event arrives at Earth. In the case of an extremely fast moving CME, e.g. observed by ACE to be moving at 1000kms⁻¹, the transit time to Earth is reduced to ~24min. To increase the warning time, measurements made further upstream from the Earth are required but the basic laws of orbital mechanics make this extremely difficult.

The solution may come from what seems to be the realm of science fiction: solar sailing, where the pressure of sunlight itself enables a spacecraft to station-keep far upstream of the Earth indefinitely. Families of so-called artificial Lagrange points for solar sail spacecraft were devised in the UK some time ago (McInnes *et al.*, 1994). Sunjammer is a mission concept that would use a solar sail and the pressure of sunlight to station-keep at such an artificial Lagrange point, sunward of the L1 Lagrange point. It would carry a space weather payload, designed and built in the UK, validating new miniaturised sensor technology, and measuring both the solar wind and its magnetic field. The payload builds on the UK's strong heritage in observing space weather phenomena, particularly in developing instrumentation for satellites studying solar-terrestrial physics such as STEREO, Cluster, SOHO and the upcoming Solar Orbiter mission.

Geomagnetic Storms and Coronal Mass Ejections

The Earth's magnetic field extends into space where it forms the magnetosphere, a magnetic 'bubble' in near Earth space that is confined by the solar wind (see Figure 1). The solar wind is a continuous supersonic stream of material emitted by the Sun in all directions. Both the solar wind and the magnetosphere are plasmas (i.e., quasi-neutral gases of electrons and ions, mainly protons), and the solar wind–magnetosphere interaction is ultimately governed by plasma physics. The solar wind is magnetised, and this magnetic field behaves as if it is embedded in the solar wind flow. At Earth the strength and orientation of the solar wind magnetic field continuously varies on time scales of minutes to hours.

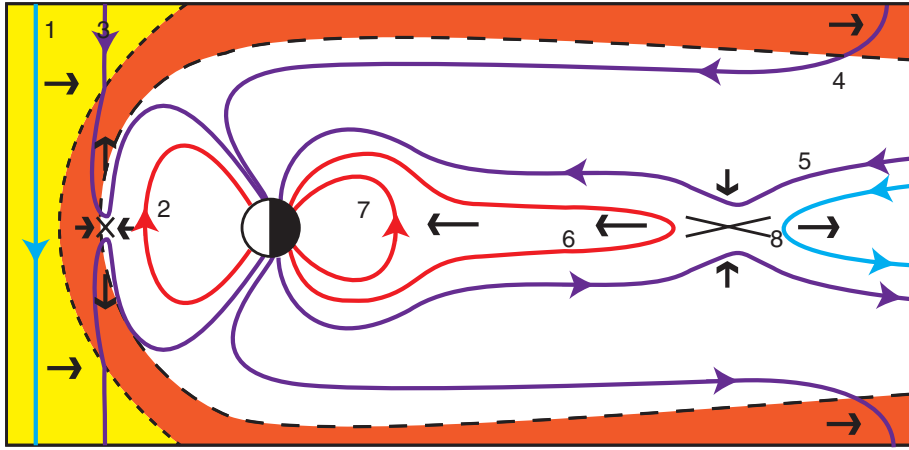


Figure 1. The Earth's magnetosphere. The Sun is to the left, and solar wind (yellow) flows from left to right. Since the solar wind is supersonic, a bow shock forms (short-dashed line), and the shocked solar wind (orange) flows around the magnetosphere (white). The magnetopause (long-dashed line) separates the solar wind and the magnetosphere. If the solar wind magnetic field points 'southward', opposite to the Earth's magnetic field at the nose of the magnetosphere, then magnetic reconnection will occur, allowing the solar wind to enter the magnetosphere. This interaction is described in more detail in the text. An animated version (produced by NASA) can be found at <http://www.youtube.com/watch?v=mgUZwoR0gcE>.

The solar wind plasma cannot easily penetrate the magnetosphere and the boundary between the solar wind and the magnetosphere is known as the magnetopause. However, under certain conditions the magnetopause can 'break down', allowing solar wind plasma and energy to enter and be stored in the magnetosphere. The most important plasma physics process controlling the entry of plasma across the magnetopause is 'magnetic reconnection'. This is most likely to occur on the magnetopause at locations where the solar wind magnetic field points in the opposite direction to that of the Earth. In particular, if the solar wind magnetic field has a southward orientation (blue field line '1' in Figure 1), opposite to the Earth's magnetic field (red field line '2'), then reconnection will occur at the nose of the magnetosphere at an X-line. As illustrated in Figure 1, the consequence of this is a reconfiguration of the magnetic field topology so that the solar wind and magnetospheric magnetic fields link (or 'reconnect'), creating a so-called open magnetic field line (purple field line '3'). This open magnetic flux is convected by the solar wind flow over the poles of the Earth (purple field line '4'), adding magnetic flux and associated stored energy to the magnetotail. This energy cannot be stored indefinitely, and is explosively released during another reconnection event in the magnetotail, where open field lines (purple field line '5') reconnect to form closed field lines in the tail (red field line '6') energising and driving plasma into the inner magnetosphere (red field line '7') where it enhances the ring current. Plasma particles and energy are also delivered along field lines to the polar regions, where bright auroral displays can be observed. Magnetic flux is also returned to the solar wind (blue field line '8'). Whilst in reality the process is

slightly more complicated than outlined here (for a more technical review see Eastwood *et al.*, 2014a), the basic qualitative features of plasma entry, storage and subsequent explosive release lie at the heart of geomagnetic activity. This mechanism is known as the Dungey cycle, named after the UK scientist Jim Dungey who first proposed the concept of the open magnetosphere (Dungey, 1961).

In the context of space weather it is therefore of primary concern to determine when and for how long southward magnetic field conditions will persist at the magnetopause, together with the solar wind speed. There is natural variability in the solar wind magnetic field orientation, and so small loading/unloading events called substorms occur on an almost daily basis. Strong driving (i.e. long durations of southward interplanetary magnetic field (IMF) together with fast solar wind flow) tends to be caused by discrete events – in particular by CMEs because they often contain a helical magnetic field structure. As the CME passes over the Earth, this manifests itself as a steady rotation in the solar wind magnetic field orientation at the magnetopause, which can take a day or more in the largest events. A second important driver of geomagnetic storms are stream interaction regions where regions of fast solar wind catch up with slower solar wind, forming compressed regions following a spiral pattern in interplanetary space (Balogh *et al.*, 1999). These regions contain large-amplitude waves, which can have long duration intervals of southward IMF and cause moderate geomagnetic storms. These are common in the declining phase of solar cycles, and will become important in the next few years.

As described in the introduction, measurements have to be made *in situ* by a satellite upstream of the Earth. This can lead to some confusion about warning times.

For example, we can image a CME leaving the Sun and estimate its arrival time. But, we cannot say whether it will cause a significant storm until we can measure its magnetic field. In particular, it is quite possible that the CME magnetic field will rotate northward, in which case weaker geomagnetic activity will be experienced. This is not uncommon; for example, on 8–9 January 2014 there was notable UK media coverage about an impending CME arrival, but in the event its magnetic field did not rotate southward and the geomagnetic field was only weakly disturbed.

Measuring the solar wind *in situ*

To date, real-time monitoring of the solar wind is provided by the ACE satellite³, orbiting the L1 Lagrange point. ACE, which launched in 1997, will soon be joined by the DSCOVR spacecraft which is set to launch into orbit around L1 in early 2015.

Placing spacecraft monitors on the Earth–Sun line closer to the Sun than L1 is extremely difficult because of the fundamental equations governing orbital mechanics. A satellite closer to the Sun will naturally orbit faster, and so will move away from the Earth–Sun line. One elegant solution is to use a solar sail, which employs the pressure of sunlight itself to generate a continuous thrust that enables artificial Lagrange points closer to the Sun as we now discuss.

It is well known that electromagnetic radiation exerts a pressure and as such, a reflective surface experiences a force. This force is small: at Earth's orbit, the pressure of sunlight is $\sim 9\mu\text{Pa}$, one millionth of the wind pressure from a gentle breeze. Nevertheless, although the pressure is small, it acts continuously and over time it can significantly change a satellite's orbit. The effects of solar radiation on satellite orbits has been known for some time, from the early balloon satellites in the 1960s (e.g. ECHO and PAGEOS) to more recent interplanetary missions such as NASA's MESSENGER mission to Mercury. When making its initial fly-bys of the planet Mercury, mission planners tilted MESSENGER's solar panels and used solar radiation pressure to fine tune the trajectory, saving fuel in the process.

Evidently, to maximise this effect one requires an extremely light spacecraft and an extremely large reflective area. In fact, a solar sail can modify orbits in several different ways (McInnes, 2004). For example, Sun-centred orbits can be displaced above the ecliptic plane. Alternatively, equipped with a solar sail, one can place a spacecraft into a solar polar orbit that is synchronous to the Earth. However, most relevant to the problem of space weather monitoring is the

³http://www.srl.caltech.edu/ACE/ace_mission.html

existence of another family of orbit solutions that enable artificial Lagrange points closer to the Sun. In fact, a continuum of solutions can be generated, which depends on the attitude of the sail and the inherent properties of the spacecraft (effectively its mass and surface area). With a sail it is thus possible to fly and station-keep closer to the Sun, and thus provide longer lead time warning of space weather events.

The first serious proposals for space missions that would use a solar sail to achieve their objectives were developed in the 1970s. Particular effort was expended by NASA's Jet Propulsion Laboratory (JPL) in developing a rendezvous mission with comet Halley, but unfortunately this mission was not selected for flight. The first successful solar sail mission was the Japanese Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) mission, launched in 2010 as a secondary payload accompanying the Akatsuki spacecraft to Venus. IKAROS successfully deployed a 200m² sail in interplanetary space, and demonstrated 'photon propulsion' for the first time.

The Sunjammer mission concept

The first concrete ideas for a sub-L1 space weather monitor using solar sail technology date to the 1990s when the Geostorm Warning Mission was investigated by NASA's JPL at the request of NOAA. This study showed that existing and emerging technology could be used to build a solar sail spacecraft capable of station-keeping near the Sun–Earth line, at $\sim 3 \times 10^6$ km upstream from the Earth, doubling the L1 warning time and also validating solar sail technology. This then led to the Geostorm Warning Mission proposal, submitted in 1999 to NASA's New Millennium Program Space Technology-5 flight validation opportunity (West, 2004). Led by JPL, the design of the solar sail itself was developed by L.Garde, Inc. Whilst the proposal ultimately was not selected, development work continued, and successful ground deployment tests of an 83m² and then a 318m² sail were completed in 2004 and 2005 respectively (see Figure 2).

The Sunjammer mission concept has since been developed by L.Garde, Inc. (Barnes *et al.*, 2014). It is named (with permission) after the Arthur C. Clarke short story describing a *solar-sail yacht race* and an artist's impression of Sunjammer is shown in Figure 3. Four beams extend from the central spacecraft body with the four sail quadrants suspended between them. The triangular section at the end of each beam is a vane – a control surface whose orientation can be adjusted to alter the attitude of the spacecraft, and can be set to ensure passive stability (i.e. ensure that once the orientation of the sail is set, there are no

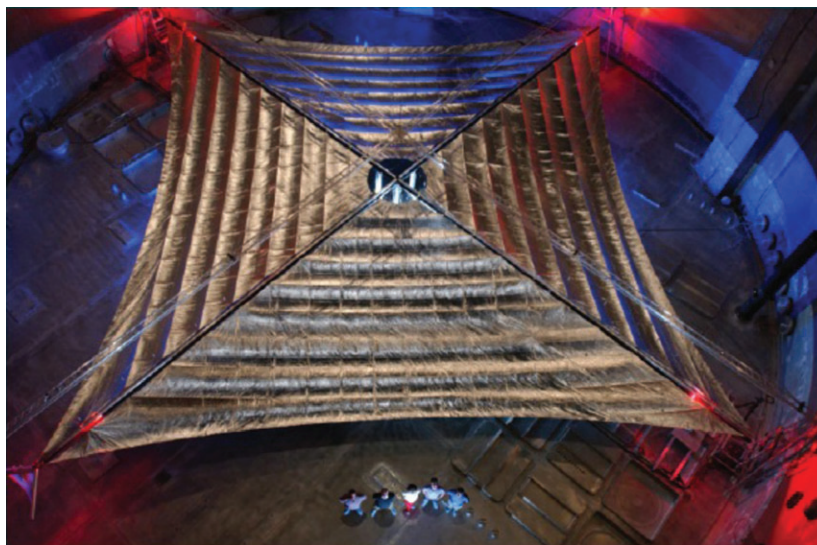


Figure 2. The successful ground deployment test of the 318m² sail in 2005. (Image Credit: NASA.)

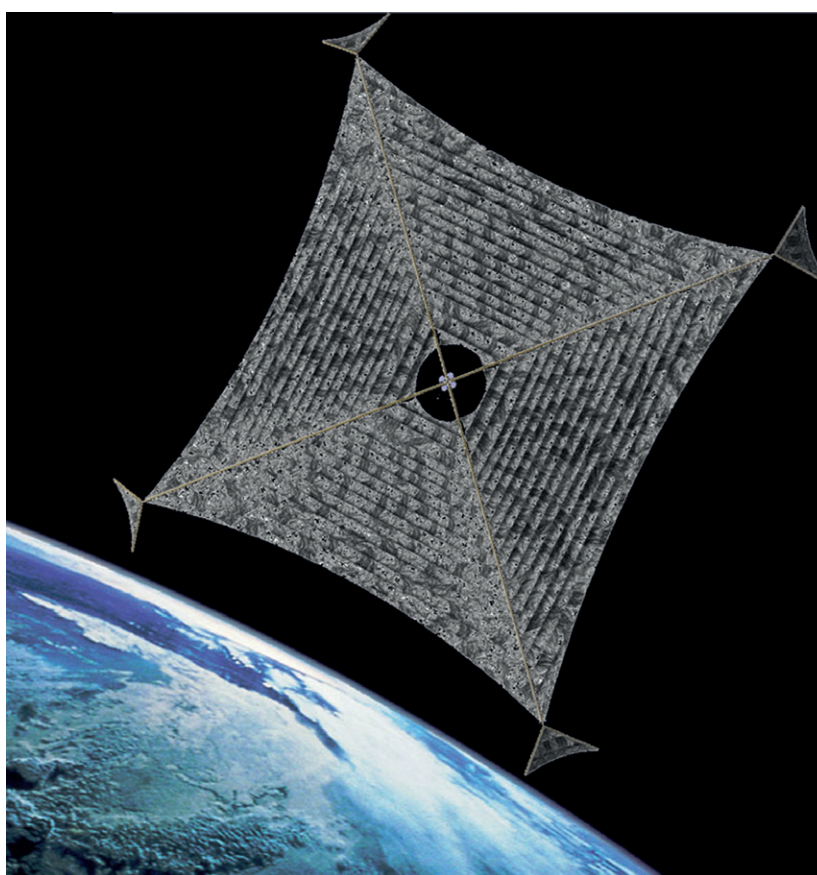


Figure 3. Artist's impression of Sunjammer. The sail is approximately 40m²; the spacecraft itself is relatively small and located within the centre of the sail. (Image credit: L.Garde, Inc.)

torques that will cause it to rotate). The sail membrane itself is a 5µm thick Kapton film, coated with Aluminium on the sun-side and chromium on the reverse. The sail area is ~ 1200 m², four times larger than that shown in Figure 2, but weighs only 8.5kg.

Perhaps the biggest challenge of any solar sail mission is the deployment of the large sail structure once in space. In the Sunjammer concept the sail and the booms would be stowed into the spacecraft itself, in a package about 0.5m³. The deployment then occurs in a controlled fashion. The

booms are slowly inflated with gas, and as they extend they draw the sail out with them. The material of the boom is such that when it drops below a certain temperature, it becomes very rigid. While stowed, the thermal design ensures that they remain above this temperature, but once exposed to space they will cool and thus harden. Once fully deployed, the inflatant is expelled and the support module containing the gas canisters and associated deployment mechanisms can then be discarded.

A key requirement of any solar sail mission is that the instruments are as light as possible. The UK Space Agency has funded the engineering development of two highly-miniaturised instruments that would be suitable for a sub-L1 solar sail mission. MAGIC (MAGnetometer from Imperial College) is designed to measure the solar wind magnetic field, and SWAN (Solar Wind ANalyser) is designed to measure the solar wind itself. The instruments have been developed by Imperial College London and University College London's Mullard Space Science Laboratory (MSSL), respectively, and are world-leading in terms of their minimal mass and power requirements.

The MAGIC magnetometer uses magnetoresistive (MR) sensor technology which enables a 100× reduction in both the sensor mass and volume compared to the typical fluxgate magnetometers that are used for science missions (Brown *et al.*, 2012). MR sensors are solid state devices, and work on the principle that in the presence of an external magnetic field, their resistance changes. A possible implementation of MAGIC on Sunjammer is derived from a previous instrument that has flown in low Earth orbit on a CubeSat called Cubesat for Ions, NEutrals and MAGnetic fields (CINEMA), and is described in more detail by Eastwood *et al.* (2014b). A number of instrument developments have been made, such as the use of two boom-mounted sensors so as to better characterise the spacecraft magnetic field and remove its effects. The design is also more robust in the use of high reliability components where possible.

The SWAN plasma detector is designed to measure the properties of the solar wind plasma itself (Kataria *et al.*, 2014). SWAN is an electrostatic analyser; such instruments use electric fields to bend incoming particles onto a detector plane, and by rapidly stepping the voltage, one can quickly measure the flux of particles as a function of energy. MSSL has considerable heritage and experience in developing such instruments, having built similar instruments flying on both the Cluster and Cassini spacecraft. SWAN is based on both the ChaPS plasma detector which launched on the TechDemoSat technology demonstrator satellite earlier this year, and the solar wind experiment that will fly on European Space Agency's (ESA's) Solar Orbiter. SWAN also contains a solid state detector for energetic particles (ions > 5MeV, electrons > 250keV).

Any in-flight sail demonstration must initially aim to understand and evaluate the sail performance and the performance of novel miniaturised space weather instrumentation. For example, the photoelectric effect means that the sunward facing side of the sail will tend to become positively charged relative to the anti-sunward side. In the knowledge that this could lead to electric currents, magnetic

fields and capacitive charging, which could contaminate the space weather measurements, the sail design includes numerous 'grounding' devices to reduce this possibility. Successful in-flight demonstration will open a path to an operational mission using space weather technology.

Summary

Of all the space weather phenomena that pose a risk to our technology and activity in space and on the ground, geomagnetic storms are perhaps one of the most important. The strongest storms are associated with CMEs. However, as we have seen, their 'geoeffectiveness' fundamentally depends on their internal plasma structure and magnetic field, which must be measured *in situ*. To increase warning times, monitoring platforms operating further upstream of the Earth than existing satellites are needed.

Solar sail missions are a potential game-changer for space weather monitoring because they can station-keep further upstream of the Earth than existing satellites such as ACE. The Sunjammer mission concept sees as part of its payload two UK-built instruments that measure the solar wind and its magnetic field, and is founded on UK innovations in orbital dynamics and mission design. This payload is highly miniaturised and thus optimised for solar sail applications. Ultimately, key goals include investigation of the feasibility of using solar sail platforms for making operational space weather measurements, and conducting scientific studies of the solar wind and its magnetic field to better understand the fundamental sources and causes of space weather. Finally, although solar sails will pave the way for future space weather monitoring systems, this technology has applications in many diverse areas of space exploration and exploitation, ranging from interstellar probes to Earth observation.

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