Daleel Lilla

SuperDARN

Judy Stephenson tells us about the radar network's contribution to space weather prediction and warning

Space weather, as the name implies, originates in space and can often be traced to physical processes in the Sun. Like its meteorological counterpart, it is hard to predict accurately due to its complexity, but over the last half-century it has become better understood thanks to improved instrumentation, data sharing and international collaboration. Scientists have learnt to trace space weather from its origin in plasmas below the solar surface, through the plasmas of interplanetary space to approximately 100 km above the Earth's surface, where they can detail its impacts.

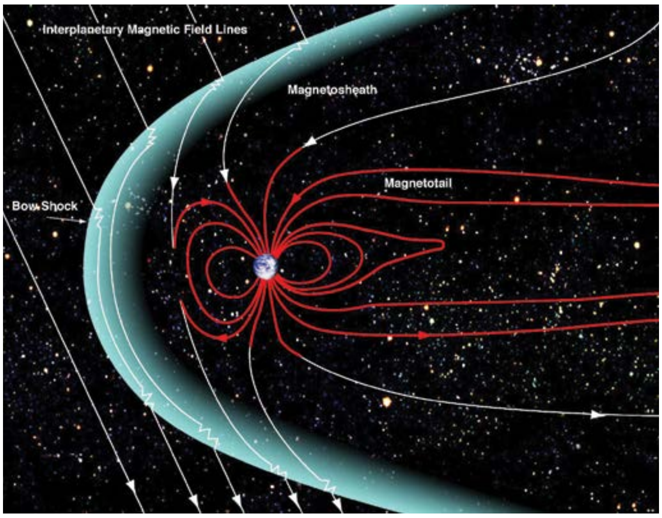
In physics, a plasma is a gas consisting of a mixture of ions and electrons that have been freed from atoms or molecules by high temperatures

The science behind space weather

The Sun's ultraviolet radiation takes approximately eight minutes to reach the Earth's 'day side', where it ionises the upper atmosphere to form a charged layer called the ionosphere. This layer extends from around 60–1 000 km in altitude and, at its lower ranges, overlaps with the neutral atmosphere. The ionosphere has for many years been used for shortwave radio communication.

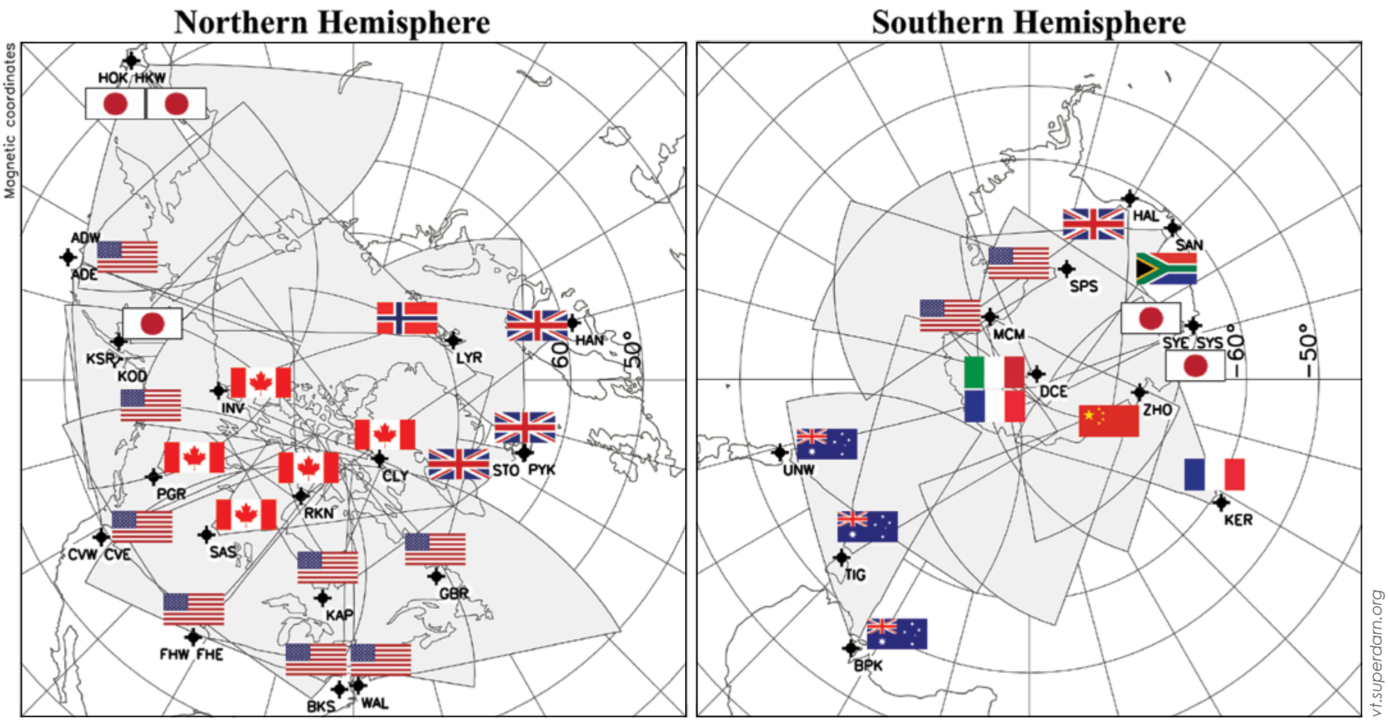
Apart from this radiation, the solar surface exhibits two phenomena important in the origin of space weather: solar flares and coronal mass ejections (CMEs). Both are caused

The southern lights, or aurora australis, form a spectacular backdrop to the South African Antarctic base, SANAE IV. These curtains of light – called aurora borealis in the northern polar regions – appear in the sky when high-energy particles from the Sun enter the Earth's atmosphere during a geomagnetic storm.



NASA/Goddard/Aaron Kaase

Schematic showing a 2D cut through the Earth's magnetosphere. The solar wind blows from the Sun (out of view on the left) towards and beyond the Earth, forming a supersonic shock wave called the bow shock on the 'day side' of the magnetosphere. Magnetic field lines from the solar wind are shown in white, while those originating from the Earth are in red. The point where the two meet is the magnetopause, which is the outer boundary of the Earth's geomagnetic field.



The Super Dual Auroral Radar Network (SuperDARN) circa 2018. Another radar has since been added in the Antarctic. Each radar has a limited field of view (shaded shapes), but together they monitor a substantial portion of the southern and northern polar regions for the effects of space weather.

by a conversion of magnetic energy – magnetic field lines on the Sun's surface become so twisted that they 'snap' like elastic bands. This can create a burst of radiation, evident as a solar flare, which accelerates very high-energy particles towards Earth. More problematic are the CMEs, which can be likened to plasma bubbles with an associated magnetic field being 'coughed' out of the Sun and typically taking around three days to reach Earth. In addition, there is at all times a steady stream of particles and magnetic field escaping from the Sun, called the solar wind.

The plasmas from the CMEs and flares interact with the plasmas of the Earth's magnetosphere – the area of space controlled by our planet's geomagnetic field, formed by swirling currents of molten lava above its core. The interaction is particularly strong if a component of the magnetic field in the solar wind and the geomagnetic field at the magnetopause boundary are oppositely directed, which is similar to what happens if the north and south pole of two magnets are brought together. This allows the CME plasma to enter the magnetosphere, and since the geomagnetic field and the solar wind magnetic field are now connected, the plasma within the magnetosphere is dragged along with the speed of the solar wind, significantly enhancing the circulation rate in the magnetosphere.

This interaction is transferred throughout the magnetosphere and down into Earth's ionosphere. The 'day side' of the magnetosphere becomes highly compressed, while on the 'night side' it is stretched out to form the magnetotail. Similar to the letting go of a stretched elastic band, when this stretched magnetotail relaxes, it leads to acceleration of charged particles associated with these field lines into the polar ionosphere – one result of which is an auroral display. In addition, many associated plasma processes are excited, such as different types of waves, instabilities and wave-particle interactions. Such a description is referred to as a geomagnetic storm, which is the most dramatic form of space weather, comparable to a cyclone or tornado in atmospheric weather.

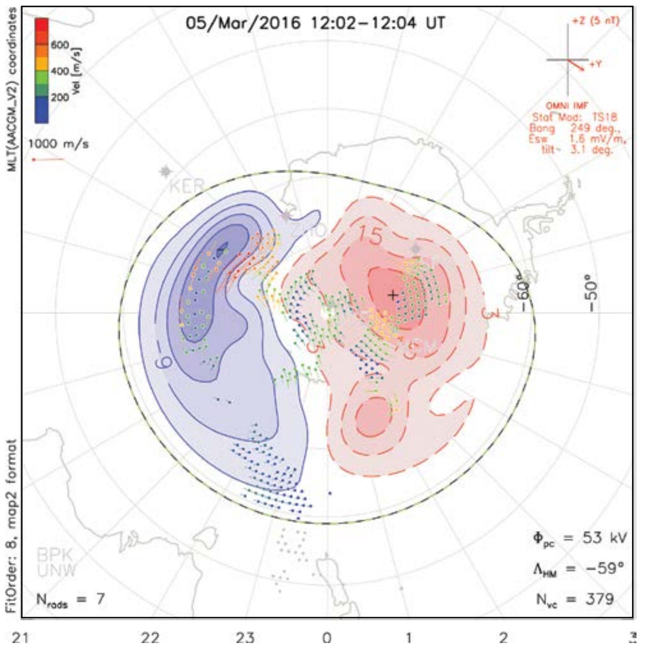
The need for monitoring

Estimates of damage to technological infrastructure from an extreme space weather event are around US$2 trillion. Land-based and Earth-to-satellite communications can be disrupted by the perturbing effects on the ionosphere, while lags and disruptions in signals to and from GPS satellites may cause errors in positioning. Space weather can even destroy power-grid transformers by creating geoelectric fields that cause strong underground currents, in the past resulting in power outages for more than 100 million people over several months. It can also disrupt or destroy electronic systems in Earth-orbiting spacecraft and in aircraft, or expose astronauts, pilots and crew to unsafe levels of radiation.

Given these hazards, the South African National Space Agency's (SANSA) space science division in Hermanus hosts a regional warning centre, which monitors cameras on satellites placed in different orbits around the Sun. As space weather phenomena are spotted, models are run and predictions are made of their impacts on Earth. Alerts are provided to stakeholders in the defence, aeronautics, navigation, energy generation and communication sectors.

The role of SuperDARN

SuperDARN is the Super Dual Auroral Radar Network, an international scientific network of high-frequency (HF) radars, 33 of them currently active. The radars are located in the polar and mid-latitude regions, where they



vt.superdarn.org

An example of a southern hemisphere SuperDARN convection map. It represents a snapshot of the space weather over Antarctica (as seen looking from inside the Earth outwards) for the two-minute period 12:02–12:04 UT on the 5th March 2016. The Sun (and local midday) is at the top, which implies that the solar wind flows from top to bottom (local midnight) of the map.

observe the ionosphere directly. The polar ionosphere may be understood as a screen onto which space weather processes are projected, because magnetic field lines at the poles connect to remote parts of the magnetosphere. Since space plasma processes are aligned with the magnetic field, these field lines act as a funnel, focusing the effects of phenomena in the distant magnetosphere onto this small part of Earth's ionosphere.

The first SuperDARN radar came online in 1984 at Goose Bay in Labrador, Canada. After 1994, when political conditions in South Africa made it possible, Prof. ADM (David) Walker of the University of KwaZulu-Natal was approached by American and British space scientists to join the network. A SuperDARN radar was assembled by the University of Potchefstroom – now part of the North-West University – and deployed at the South African National Antarctic Expedition (SANAE) base in 1997.

SuperDARN radars transmit in the 8–20 MHz band. Electromagnetic radiation at these frequencies is refracted in the ionosphere. Most of the time, after some refraction, the radiation from the radar encounters plasma instabilities (corrugations) in the ionosphere, and it is reflected from them back to the radar. These instabilities are the main targets of SuperDARN radars. By knowing the timing of the pulse of transmitted radiation as well as characteristics of the pulse, the backscattered power (from the target), Doppler velocity (speed of target away and towards the radar) and spectral width (how many frequency components make up the target) can be determined. These parameters allow a wide range of space phenomena to be traced and studied. There are times when ionospheric plasma conditions are such that the transmitted ray is refracted so much that it is bent back towards the ground some distance from the radar, making it possible for two to three hops (ground reflections) to take place. This allows the radar to observe over ranges of several thousand kilometres.

The main product of the SuperDARN network is the ionospheric convection map, which is produced for each hemisphere at two-minute intervals. This 'space weather map' is similar to a meteorological weather map, but instead of temperature and pressure differences driving wind speed, here plasma convection (or velocity) is determined by the movement of the magnetic fields (due to solar wind and other plasma processes) and electric fields. The resulting convection velocity is shown by red and blue contour lines, equivalent to isobars on a weather map. Using such maps, skilled interpreters can provide detailed accounts of the prevailing space weather and its potential impact.

Information from the maps also improves our understanding of space processes, which allows scientists to advise design engineers on how to incorporate protection in devices. Furthermore, SuperDARN data is valuable as an input into models that combine physics knowledge and data for forecasting and prediction purposes. The model outputs essentially serve as an early warning system, enabling potentially affected systems to be configured to improve resilience. For example, within about 10 seconds of space weather impacts, satellite navigation systems can correct for most of the positional errors that arise from the effects of solar flares on the ionosphere. Predictive capability is vital considering that, for every year that goes by, our rapid advance in technology increases our vulnerability to space weather dramatically.

Apart from operational uses, SuperDARN's data is an important contributor to understanding how energy is transported around the magnetosphere. This comes from its ability to monitor and be a diagnostic tool for space plasma processes such as ultra-low frequency waves, plasma instabilities and wave-particle interaction. It can also track the boundaries of many different plasma regions, increasing understanding of how the different regions of space respond to space weather. There are well over 600 papers in the scientific literature utilising data from SuperDARN, which has won awards for its valuable contribution to space physics, most notably from NASA and the Royal Astronomical Society.

As a collaborative programme where data is shared between all investigators and the general science community, SuperDARN is a shining example of the international cooperation that is key to furthering our knowledge in the field of space physics.

- For more information on space weather and its prediction, see SANSA's webpage: https://www.sansa.org.za/products-services/space-science-2/

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