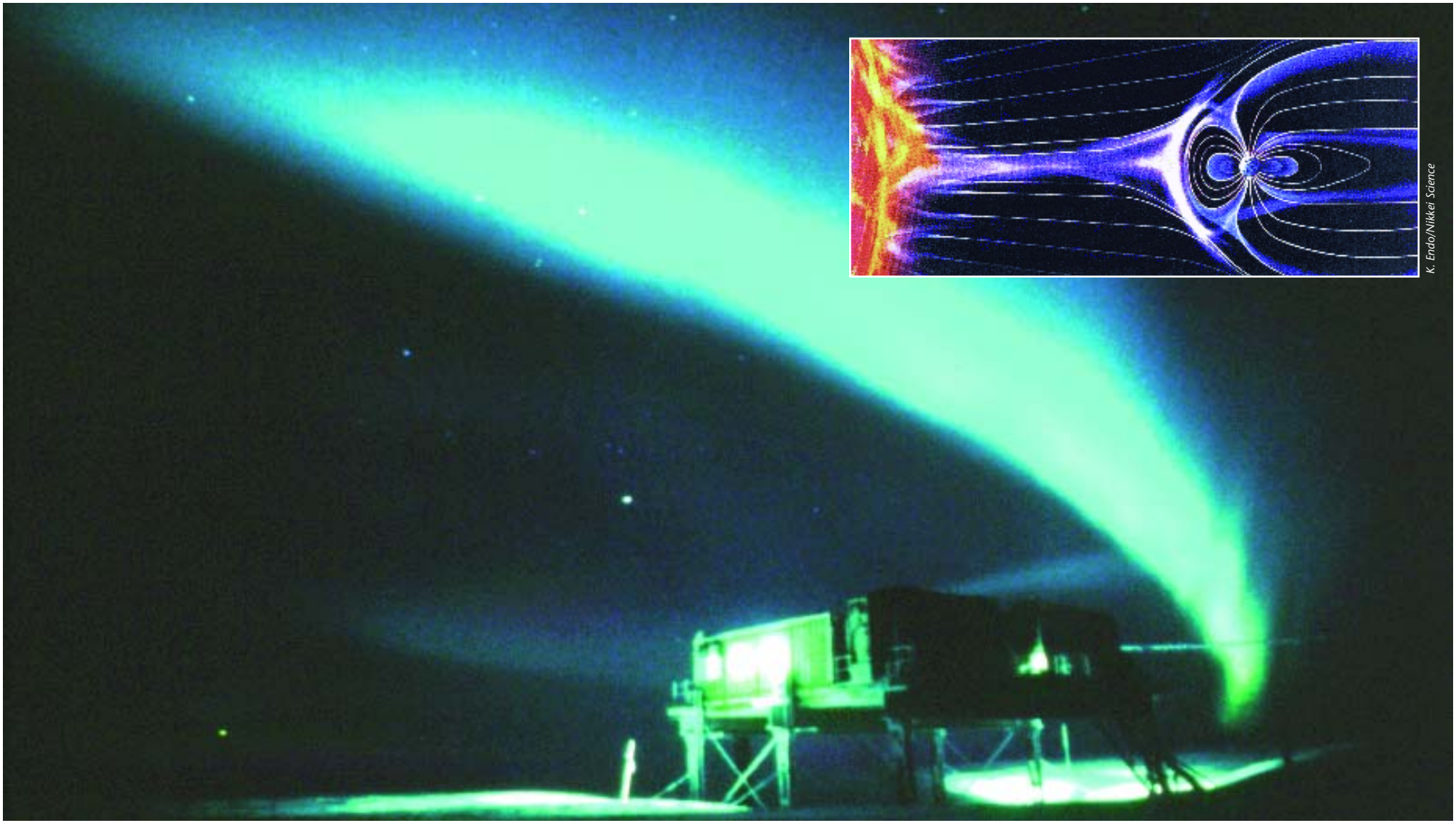
The Sun and geospace

Resource GS1

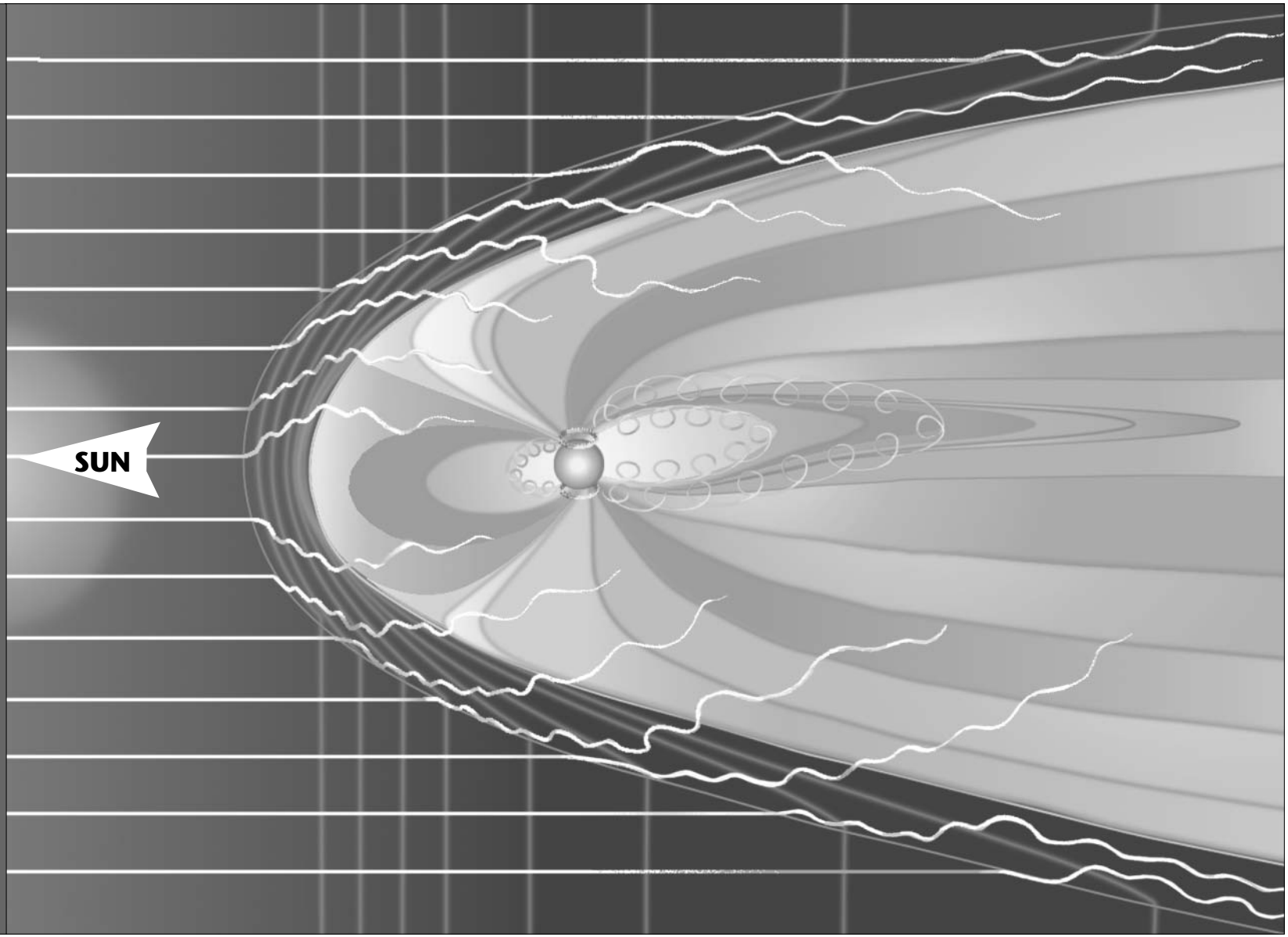


The aurora over the BAS Halley Research Station. Inset: Artist's impression of the Sun and geospace (not to scale) illustrating how particles flowing radially from the Sun are deflected by the Earth's magnetic field which forms a cavity in the particle stream, known as the magnetosphere.

Solar wind – magnetosphere interaction

Resource GS2

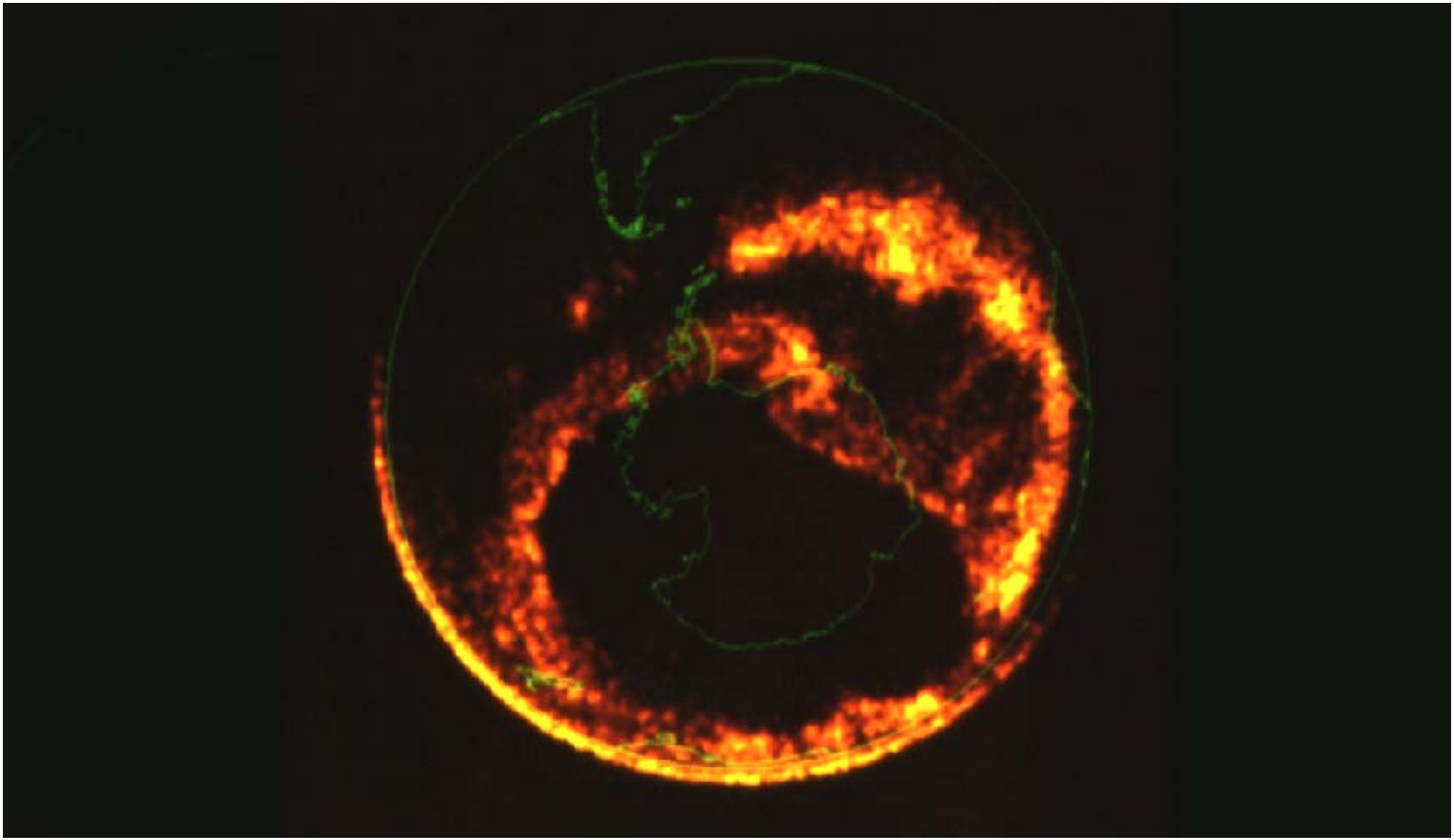
An illustration of the interaction between the solar wind and magnetosphere. Solar wind streamlines are deflected by a shock wave to flow around the magnetosphere in a turbulent layer known as the magnetosheath. Some solar wind plasma leaks inside the magnetosphere. In the magnetosphere particles are guided in spiral helical trajectories along magnetic field lines. Some of these precipitate into the atmosphere to create the aurora.



BAS

The aurora over Antarctica

Resource GS3



Professor L.A. Frank (University of Iowa)

A satellite view of Antarctica showing the aurora encircling it

The effects of space weather on human activity

Resource GS4

Effects on satellites

Satellites often operate in the space environment for many years. As a result, they can sustain long-term exposure effects in addition to special 'space storm' problems. Depending upon their orbit, satellite electronic components, solar cells, and materials degrade from the accumulated radiation dose caused by repeated traversals of the Van Allen radiation belts. Similarly, the continuous bombardment by atoms in the thin upper atmosphere can alter orbits and wear surfaces away. Some materials become brittle from long-term exposure to solar ultraviolet light above the protective absorbing atmosphere of Earth. Single penetrating energetic particles (from the Van Allen belts or cosmic rays) can change the information stored in electronics components such as spacecraft memory chips by flipping binary values that encode the information.

Telesat, Canada

Anik E1 satellite

A particular 'danger zone' for low-altitude spacecraft is in the region of the South Atlantic, where the energetic particle populations in the radiation belts can reach unusually low altitudes due to a local weakness in the Earth's magnetic field. Space weather 'storms' add new problems while exacerbating the cumulative effects. Some satellites charge up when they are suddenly immersed in enhanced radiation environments in the Van Allen belts, the auroral zone, or interplanetary space. Component surfaces can charge to very high potentials compared to the metallic surfaces of the satellite, leading to discharges between the two. Such discharges cause both material damage and electrical currents on the spacecraft. The latter can masquerade as 'phantom commands' to spacecraft systems. These events can cause a loss of control of instruments and power or propulsion systems. This appeared to happen with the Canadian ANIK E1 and E2 satellites. They experienced a loss of systems during an interval of elevated intensity of high-energy electrons in the Earth's outer magnetosphere.

EPRI

Map of power disruption in North America, due to a space weather storm in March 1989

The upper atmosphere becomes inflated if it is heated by extra energy sources such as auroral particles and enhanced resistive ionospheric currents. The resulting increased atmospheric particle densities at 300–500 km altitude significantly increase the number of microscopic collisions between the satellite and the surrounding gas particles. This increased 'satellite drag' can alter an orbit enough so that the satellite is temporarily 'lost' to communications links. It also causes the premature decay of the orbit. This can lead to early loss of the system with associated financial implications or necessitate shuttle 'boosts' for some, like the Hubble Space Telescope. These boosts again add to costs.

Effects on power systems

Electric power systems on the ground can be affected by the enhanced currents that flow in the magnetosphere-ionosphere system during geospace storms. These currents cause magnetic field perturbations on the ground that in turn induce other currents in long transmission lines, especially those located at high latitudes. The slowly varying DC part of the currents can be large enough to cause overheating and damage to systems designed for AC. Disruption of power distribution systems can adversely affect many aspects of our daily lives should a blackout result.

Effects on pipelines

Space weather-induced currents similarly flow in long conductors on the ground such as oil pipelines. These currents create galvanic effects that lead to rapid corrosion at the pipeline joints if they are not properly grounded. Such corrosion requires expensive repairs or can lead to permanent damage.

Effects on communications systems

Short wave radio communication at HF frequencies (3–30 megaHertz), which is still extensively used by the military and for overseas broadcasting in various

countries, depends upon the reflection of signals from the Earth's ionosphere. The signals are attenuated when the electron number density in the lower ionosphere increases. This affects the usable radio communication frequencies and can cause a total communications blackout. Solar flare ultraviolet and x-ray bursts, solar energetic particles, or intense aurora during geospace storms can all bring on this condition.

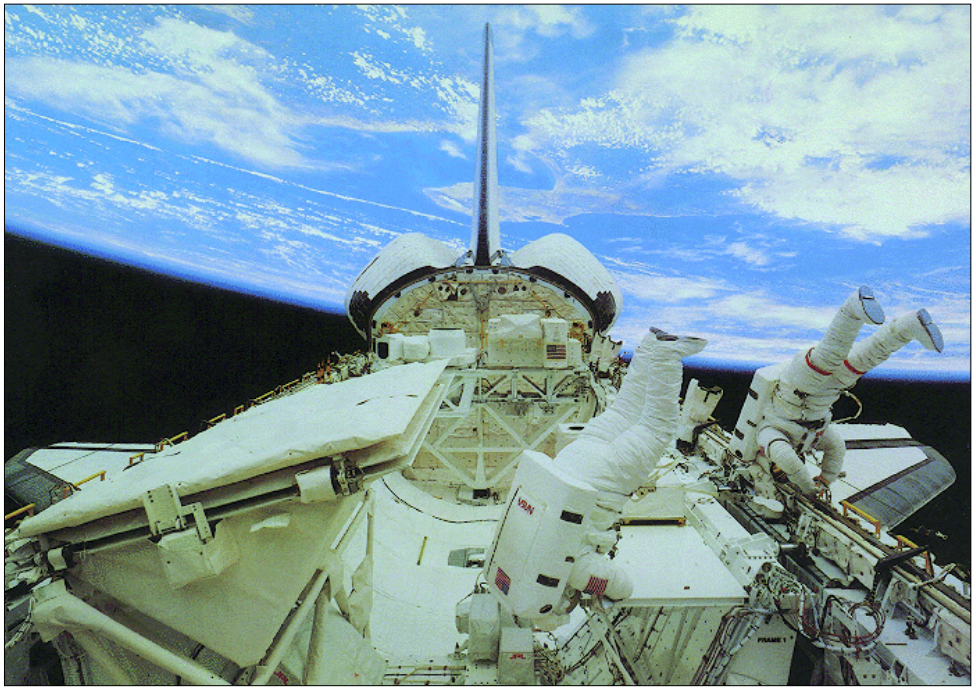
The changes in ionospheric attenuation and reflection of electromagnetic waves also affect the use of 'over-the-horizon' HF radars used to detect and monitor aircraft and sea conditions. Ionospheric electron density irregularities also produce noise or 'clutter' in the radar signals.

Effects on navigation systems

The same disturbance-related changes in the Earth's ionosphere that affect communications introduce changes in the time it takes signals to traverse the ionosphere. The abnormal time delays introduce position errors and decrease the accuracy and reliability of the Global Positioning System (GPS), which is used for many range-finding and navigational purposes.

Effects on geomagnetic surveys

Geomagnetic surveys are important tools in the commercial exploration of natural resources. However, space weather-related perturbations can create signals in survey data that can be mistaken for signatures of subsurface resources. Survey schedules or operations must be modified, often suddenly and with significant costs, to avoid errors in the survey data.



NASA

View of Earth across the cargo bay of the Space Shuttle

Hazards to humans in space

The principal space weather hazard to humans is radiation exposure to astronauts and passengers in high-altitude aircraft. Although the residual atmosphere above an aircraft provides a measure of protection from cosmic rays and solar energetic particles, there is still concern for flights on polar routes during major solar particle events. The primary means of reducing this hazard is to modify flight paths as necessary and to limit the flight time of personnel on high-altitude aircraft such as Concorde. It is clear that in this case early warnings of solar energetic particles are extremely desirable. While some sources (solar flares) can be monitored at least on the visible disk of the Sun, indications of solar events likely to produce a geospace storm (such as a coronal mass ejection) are less apparent.

Astronaut radiation exposure is a major concern for manned space flight. Most manned missions occur in orbits that are below the regions where the Van Allen belt radiation is most intense. Spacewalks in the region of anomalously high radiation over the South Atlantic need to be avoided. However, the Mir space station and the International Space Station (ISS) have orbits sufficiently inclined from the equator to bring them into the expanded auroral zones that occur during geospace storms. The likelihood of a frequently disturbed magnetosphere and presence of solar energetic particles is considerable given the phasing of the ISS construction with the next solar maximum.

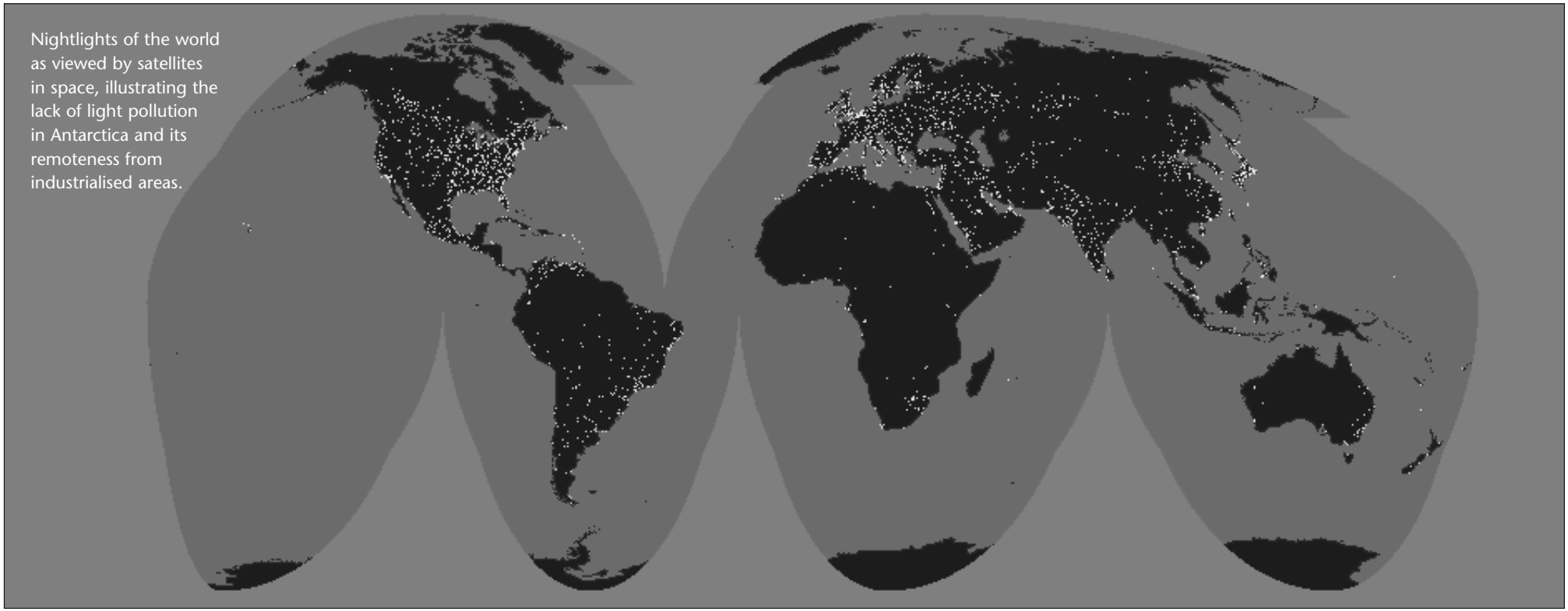
For missions that leave low-Earth orbit, like the Apollo missions to the Moon, the ability to rapidly traverse the radiation belts and to predict the occurrence of solar energetic particle events is essential. While proposed manned spacecraft for future missions to Mars will generally be equipped with shielded astronaut shelters, adequate warning is necessary for these to be useful.

An astronaut on the lunar surface would be in danger of a lethal dose of radiation from solar energetic particles were a major coronal mass ejection to occur unnoticed.

This article is drawn from the views of the US National Academy of Sciences as expressed on their World Wide Website (http://nas.edu/ssb/spwptSnw.html)

Why study geospace in Antarctica?

Resource GS5



Nightlights of the world as viewed by satellites in space, illustrating the lack of light pollution in Antarctica and its remoteness from industrialised areas.

NOAA/USAF

There are six compelling reasons for conducting frontier experimental research on geospace physics in the Antarctic:

• The ionosphere above the Antarctic provides a viewing window through which to remotely sense nearly all regions of geospace. A small region of the high latitude polar ionosphere senses large volumes of geospace via geomagnetic field lines that diverge from the Earth's surface.

• The Antarctic is a preferred region for energetic electron precipitation into the upper atmosphere. Most of the solar wind energy transferred into the magnetosphere and ionosphere is deposited in the high latitude regions, owing to the configuration of the Earth's magnetic field. One manifestation of this is the aurora.

• The geospace environment deposits energy into both north and south polar regions, but often in different amounts. Simultaneous observations in both polar regions provide critical data to study this. Comprehensive instrumentation in Antarctica complements the similarly extensive instrumentation in the geomagnetically conjugate region of Greenland, eastern USA and Canada.

• There are also significant north-south differences between the energy input to the upper atmosphere from below, due to the different topography and albedo of the two hemispheres.

• The effects of the separation of the geographic and geomagnetic poles is most apparent in the Antarctic Peninsula region compared to anywhere else on Earth. For this reason, solar and geomagnetic effects on the upper atmosphere can be distinguished more readily here.

• Antarctica is relatively free from radio and light pollution and is therefore ideal for operating sensitive instruments.

Geospace

Worksheet 10

Many of you will be unfamiliar with the concept of geospace. This is not surprising, as its study is a relatively new science. Although in earlier centuries there was an awareness of geospace phenomena such as the aurorae, it is only with the arrival of radio communications and the development of space travel and satellite systems that the significance of geospace has emerged. This worksheet examines the nature of geospace, its influence on human activity and the reasons why Antarctica is an ideal location from which to study it.

What is geospace?

Geospace is where the atmospheres of the Sun and Earth meet. It is a comet-like area of space around the Earth which includes the magnetosphere, a region of space above the atmosphere dominated by the Earth's magnetic field. Geospace extends for over a million kilometres although it is only populated by particles at a very low density. If all the particles were brought down to the Earth's surface they would occupy no more space than that in a typical supermarket.

BAS

High frequency radar aerials at the BAS Halley Research Station used for investigating geospace

Resource GS1 contains an inset showing an artist's impression of geospace illustrating the flow of particles from the Sun and what happens to them when they encounter the Earth's magnetic field.

Task 1 What shape does the stream of particles from the Sun form around the Earth? Suggest reasons for this pattern.

The solar wind

The particles involved in the interactions with the Earth's magnetic field are known as the solar wind. They originate in the outer atmosphere of the Sun, the corona, where the high temperatures (over 1,000,000°K) generate an outward flow of ionised, coronal gas. Such a gas is known as a plasma. The gas comprises charged ions and an equal number of electrons so that the overall electrical charge is neutral. The plasma ions are largely hydrogen though there is some helium and heavier elements. A million tonnes of this solar wind plasma flows out from the Sun every second at speeds ranging from 300 to 800 km/second. By the time the plasma reaches the Earth every cubic centimetre contains an average of eight ions and eight electrons.

Task 2 Given a distance between the Sun and Earth of 150 million km and an average speed of 600 km/second calculate the time taken for the solar wind to flow from the Sun to the Earth.

The solar wind is not constant. Its outflow is strongly influenced by the solar magnetic field which varies with the so-called 'sunspot cycle' of 11 years. When there are few sunspots (solar minimum) the solar magnetic field is like that of a bar magnet with a north and south pole. When there are many sunspots (solar maximum) the solar magnetic field is very disorganised. Magnetic structures in the corona can spontaneously erupt to throw out plasma at high speed in a 'coronal mass ejection'. These cause magnetic storms in geospace. There was a solar maximum in 1989. In March of that year a magnetic storm knocked out the power supply to six million people in the Canadian province of Quebec.

The interaction of the solar wind with the Earth's magnetic field

Just as the solar wind is initially influenced by the solar magnetic field so it is also affected as it approaches the Earth's magnetic field. The Earth can be regarded as a dipolar bar magnet with North and South magnetic poles close to the geographic poles but moving from year to year. What happens to the solar wind when it approaches the Earth is shown in the diagram in Resource GS2.

Task 3 With reference to Resource GS2 create your own annotated diagram to explain the key characteristics of the magnetosphere.

The aurorae

While most of the solar wind plasma is diverted around the magnetosphere, some of it 'leaks' inside. Particles are trapped on magnetic field lines in doughnut shaped layers around the Earth called radiation belts. Some particles are 'precipitated' into the Earth's atmosphere, along magnetic field lines. As they collide with neutral atoms of oxygen and nitrogen, light is emitted. This is known as the aurora. It is concentrated in the polar regions.

Analysis in the 19th century of the Northern Lights revealed an early insight into geospace. Measurements were taken of the frequency of sightings of the aurora at various locations and a map compiled to show isolines of equal numbers of sightings. These turned out to be

aligned with lines of magnetic rather than geographical latitude. Current magnetic co-ordinates can be seen in the diagram on this page. It was thus assumed that the phenomena were related to the Earth's magnetic field. Nowadays we can see the whole auroral 'oval' with the aid of satellites, as can be seen in the image shown in Resource GS3.

Task 4 Compare the image in Resource GS3 with the map of geomagnetic latitude and comment on the relationships between them. Explain with reference to Resource GS2 why aurora are found mainly in the polar regions.

Auroral colours are determined by the neutral atoms that the precipitating particles are interacting with, green for nitrogen and red for oxygen. A photograph of an aurora over Halley Research Station is shown in Resource GS1. A typical aurora involves 10^{26} plasma particles per second yet it can generate from 10^{8} to 10^{13} watts of electricity, making it possible to read by its light.

Task 5 Compare this output to the generating capacity of a power station. For example, Didcot 'A' power station near Abingdon has a generating capacity of 2000 megawatts. How many such stations would be needed to produce the electricity found in a 10^{13} watt aurora?

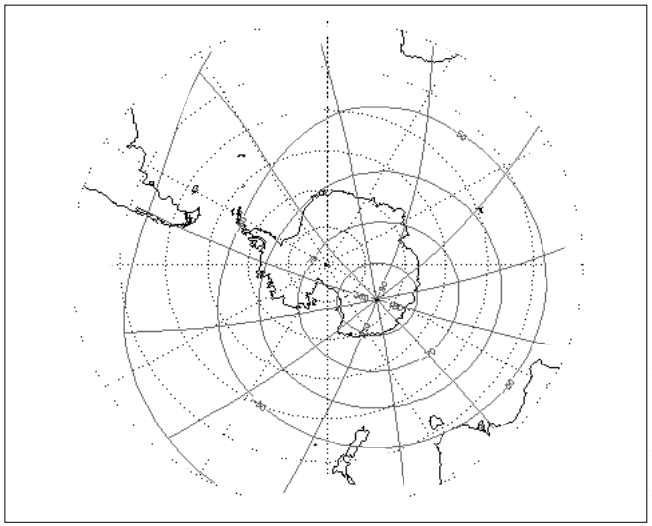
What is the significance of space weather?

You may be wondering if the solar wind has any relevance to everyday life. In centuries past it would not have. Now, however, an understanding of space weather is extremely important not only to manned space flight but also to satellite and other telecommunications, power grids, pipeline networks, geomagnetic surveys and complex navigation systems. Resource GS4 summarises some of these potential impacts and their financial and other implications.

Task 6 Using the information provided in Resource GS4 create a space weather impact table. In the first column identify the systems under threat (e.g. power supplies). In the second briefly describe the nature of the hazards (e.g. geomagnetically induced electrical currents). The third column should outline the impact of the hazard (e.g. failure of transformers at power stations and substations). The fourth column should indicate any costs attaching to the impacts (e.g. replacement of the iron core of a transformer). A final column could suggest preventative or other measures that might be implemented to minimise impacts (e.g. new electrical monitoring equipment to warn operators). In some cases such measures may not be possible.

Space weather forecasts

It is possible to provide both long and short-term space weather forecasts. The sunspot cycle is well known but other fluctuations can also be anticipated.



Redrawn from NASA/GSFC

A map of Antarctica showing lines of geomagnetic latitude and longitude (solid) compared to lines of geographical latitude and longitude (dotted).

Task 7 Refer back to your calculations regarding the solar wind. How much warning could be given of an approaching magnetic storm to an astronaut if he or she was on a space walk in Earth orbit? If you were 'Mission Control' what would you tell the astronaut to do?
How might military strategists make use of space weather forecasts?

Task 8 Working in small groups use your imagination, knowledge of current weather forecasting and the information provided in this worksheet to prepare an Earth space weather forecast for broadcast on TV in the late 21st century. You should assume that by then space flight is common and includes shallow space flight to distant parts of the world (e.g. UK to Australia), tourist flights on the space shuttle and short holidays on the Moon. You should outline a 'storyboard' for the broadcast, which should not exceed two minutes. You should indicate what maps or other graphics you might use to support your forecast.

Why is Antarctica so important to geospace science?

You may have already guessed some of the reasons why Antarctica is a highly suitable place to study geospace. Resource GS5 lists the key reasons.

Task 9 In what fundamental ways does the use of Antarctica by geospace scientists differ from those of other scientists such as biologists, geologists?
In your view does geospace science have a significant impact on the environment?
In what ways does the Antarctic Treaty System (see the Worksheet 5 on the Antarctic Treaty System) in particular the Environmental Protocol, provide protection for geospace science?