Secrets of the Northern Lights

After centuries spent marveling at auroras' spectacular and fearful displays, people have solved many of their mysteries.

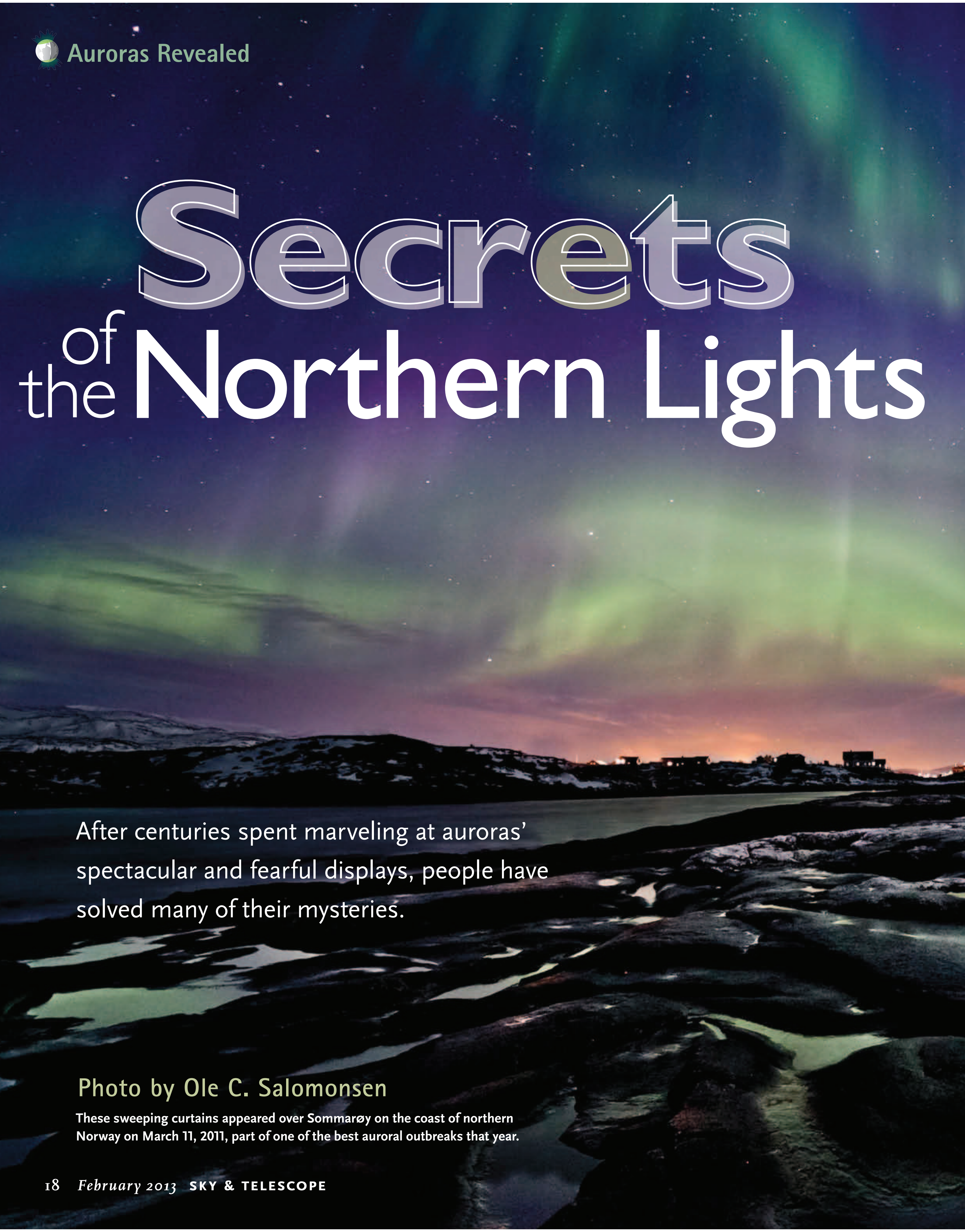


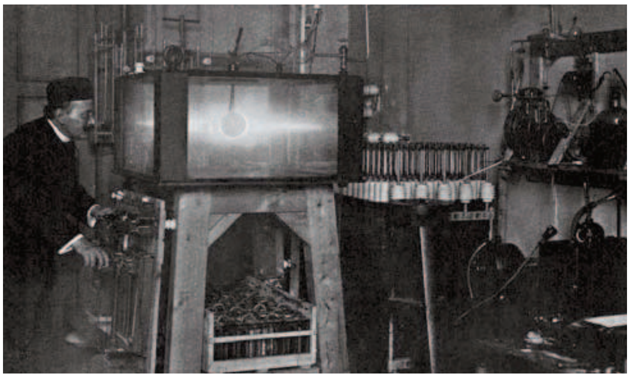
Photo by Ole C. Salomonsen

These sweeping curtains appeared over Sommarøy on the coast of northern Norway on March 11, 2011, part of one of the best auroral outbreaks that year.

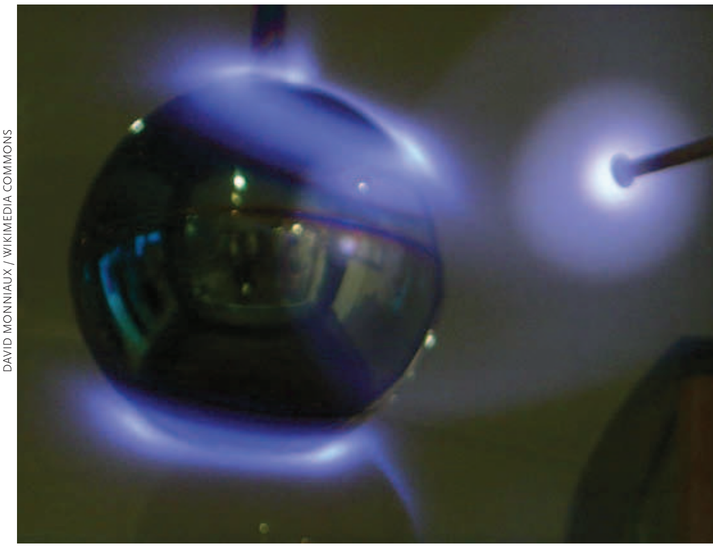
Pål Brekke

The first detailed description of the surreal sheets of light that hang in northern skies appeared in *The King's Mirror,* a Norwegian chronicle from about AD 1230 that was probably written as a prince's textbook. The author spends many lines describing the peculiar glow seen by the Vikings, but admits no one knows why the phenomenon exists. (Among the theories offered are fires at the edge of the world and gleams from the Sun, hidden beneath the horizon.)

It was only a century or so ago that people suspected a more direct connection with the Sun. Today we know that these lights, first called the *aurora borealis* or "dawn of the North" by Galileo Galilei, form when gusts of charged, energetic particles from the Sun breach Earth's protective magnetic shell and hit the planet's atmosphere. But this discovery took decades to unravel, and even today we are still grappling with the northern lights' secrets. What we have discovered about these surreal displays only heightens their beauty.



SAPERAUD / WIKIMEDIA COMMONS



DAVID MONNIAUX / WIKIMEDIA COMMONS

Left: **Kristian Birkeland studied the aurora both in nature and in his lab. He appears here with his terrella, a magnetized sphere inside a vacuum box. *Right*: Electrons shot at a terrella's magnetized metal sphere are caught by the magnetic field and channeled down to the sphere's polar regions, creating aurora-like features.**

In 1896 a breakthrough in our modern understanding of the aurora came from the Norwegian scientist Kristian Birkeland (1867–1917), who suggested that charged particles from the Sun might ignite auroras when Earth's magnetic field channels them toward the polar regions.

Birkeland was not the first to suggest a connection with solar particles, but what set his work apart was its basis in controlled experiments. To prove his theory, he built his own "world in a glass box," or a *terrella*, a vacuum chamber in which a small magnetized metal sphere (a stand-in for Earth) is bombarded by electrons injected into the box. His model planet's magnetic field captured these particles and channeled them down toward the sphere's polar regions, where they ignited aurora-like glows.

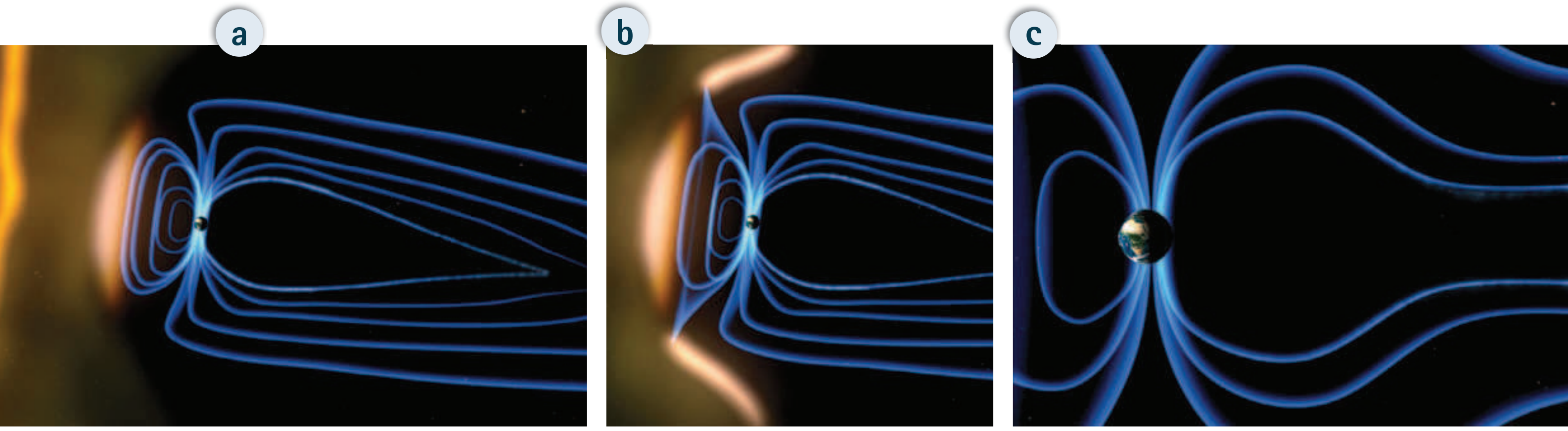
Based on this work, as well as extensive geomagnetic expeditions that showed nearly uninterrupted auroral activity around the poles, Birkeland concluded that "rays of electric corpuscles emitted by the Sun" continually bombard our planet. Today we call these charged particles the solar wind. But despite the importance of this work in retrospect, many of Birkeland's ideas were not confirmed until the Space Age. Since then, we have solved many of the aurora's secrets.

Message from the Sun

The northern lights display a variety of shapes and structures that can shift dramatically in a matter of minutes. The most common shape is the curtain-like sheet that moves and flickers like fluorescent folds of silk in the sky. These patterns are a visible manifestation of the solar wind buffeting Earth's magnetic field.

The solar wind mainly consists of electrons and protons that stream out from the Sun's outer atmosphere into space. These particles blow into the solar system at a typical speed of 1.5 million kilometers per hour (930,000 mph), nearly 40 times faster than the speed a spacecraft would need to escape Earth's gravity. Strong gusts of solar wind can zoom twice as fast as that.

A substorm occurs when Earth's magnetic tail pinches off. First, a coronal mass ejection slams into the dayside magnetosphere (a). This collision sends particles and magnetic energy around to the planet's nightside (b). The changes compress the magnetic tail (c), ultimately resulting in magnetic reconnection, which releases heat and energy (d). This reconnection sends particles shooting toward



NASA / GSFC CONCEPTUAL IMAGE LAB (6)

These gusts are sometimes joined by large solar gas eruptions called coronal mass ejections, or CMEs, that eject gigantic bubbles of ionized gas into space. These bubbles can reach velocities up to 8 million kph.

Earth's invisible, protective magnetic shell shields us against these particles. The solar wind hammers on this *magnetosphere*, compressing it toward Earth on the dayside and stretching it out in a long tail on the nightside to form a magnetic cocoon shaped like a planet-scale comet.

The weakest sites in this shield are the polar cusps, two regions above the planet's magnetic poles. Through the cusps, particles from the solar wind can access the upper layer of Earth's atmosphere directly, creating dayside auroras that are invisible to us. Some particles will also enter the tail of the magnetosphere (on the nightside) and get pushed back toward Earth, where they generate the "everyday" aurora circling the magnetic poles.

Solar wind particles also gain access through more violent means, when CMEs crash into the magnetosphere. This impact generates *geomagnetic storms*, worldwide disturbances in which the CME compresses the field, reducing its dayside size by roughly 40%. The entire magnetosphere is disturbed during one of these storms, and even a compass needle will deviate from its correct position.

But solar particles by themselves don't cause severe space weather. They need energy from magnetic processes. A geomagnetic storm's severity depends on the density of the gas and the structure of the magnetic field embedded in the CME. The Sun's magnetic field isn't confined to the immediate vicinity of our star: the solar wind carries the field with it throughout the solar system. We call the Sun's extended magnetic field the Interplanetary Magnetic Field (IMF). Because the Sun rotates (one revolution every 25 days at the equator), the IMF actually has a spiral shape — named the "Parker spiral" after Eugene Parker, the American astrophysicist who first described it. The Sun sits at the center of this spiral.

The IMF meets up with Earth's magnetic field at the *magnetopause*, and it's here that a storm's power is determined. Earth's magnetic field points north on the dayside, but the IMF's orientation often changes. If the IMF points north, there will be little interaction with Earth's magnetic field: two aligned bar magnets repel each other, so the CME basically slides around Earth's magnetosphere.

But if the IMF points south, opposite Earth's magnetic field, the two fields will link up. This linking is called *magnetic reconnection*, and it happens when magnetic lines of force snap into new arrangements, releasing heat and energy (see the time series below). The process opens Earth's field on the dayside, allowing particles and magnetic energy to enter the magnetosphere. This energy then travels to the nightside and stretches the magnetic tail, eventually causing it to pinch off and snap back toward the planet in an event called a substorm. When this substorm happens, it sends solar wind particles zooming to Earth's polar regions.

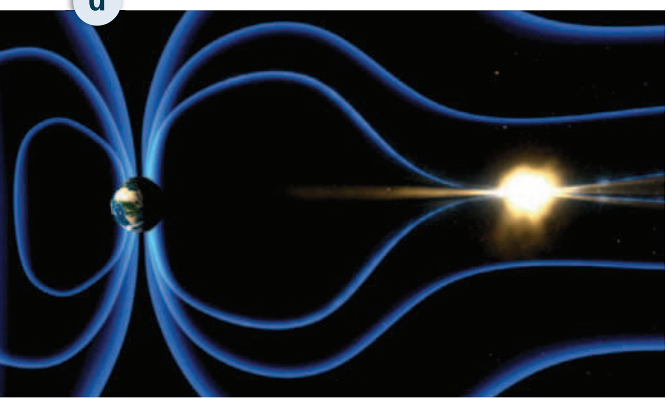
By themselves, substorms do not create the bright aurora we see. Large sheets of electric current above Earth's atmosphere accelerate the particles further; this acceleration is related to how the magnetic tail snaps back and slams into Earth's field near geosynchronous orbit (6.6 Earth radii, much closer than the substorm pinch-off, which happens at roughly 20 Earth radii). The process is similar to an old cathode-ray tube television: an electrical wire brings in electrons (the magnetic snapback phenomenon) to an electron gun (the current sheets), which shoots the electrons at the TV screen (the atmosphere).

These souped-up particles create the northern lights by colliding with atoms, primarily nitrogen and oxygen. These collisions typically occur at altitudes between 80 and 300 km — far above weather phenomena, which mostly happen within the first 20 km above the surface. The collisions transfer energy to the atoms, causing them to emit light of a certain wavelength.

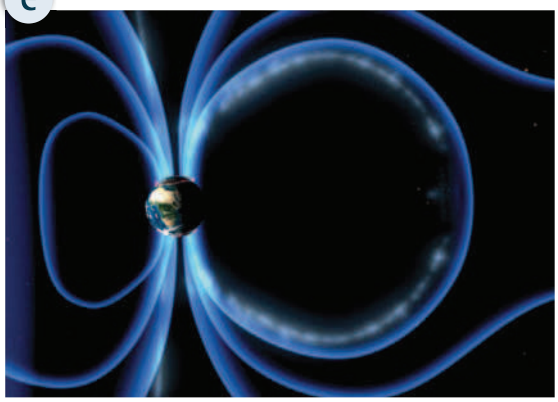
Oxygen atoms cause green and bright red light, the two most prominent colors of the aurora. Red oxygen emission occurs at high altitudes, so the highest part of

Earth, where they form a plasma sheet (e). From there, the particles interact with Earth's upper atmosphere, creating auroras (f). Watch the video at skypub.com/aurorasci.

d



e



f

the auroral curtain is usually red. Nitrogen molecules produce bluish light and deep red.

We do not fully understand why auroras have the shapes they do. We do know that auroral curtains and beadlike structures appear after a magnetic tail pinch-off. The thick auroral curtains, which often stretch tens of kilometers across, come from the large-scale sheets of electric current that accelerate particles downward. Auroras' lengths probably relate to activity in the magnetosphere, and smaller magnetic waves might energize particles to create the narrower (1-km-wide) curtains. But other than that, these shapes are still a mystery.


FRED SIGERNES / KJELL HENRIKSEN OBSERVATORY

Instruments peer out at the aurora from inside 30 domes that are nestled among mounds of snow and ice at the Kjell Henriksen Observatory on Svalbard.

Putting Auroras to the Test

Today we study the northern lights from both ground and space. A large number of all-sky cameras and instruments study the phenomenon from many northern countries. These surveys include incoherent scatter radars, such as the large European Incoherent Scatter Scientific Association's antennas on the Norwegian archipelago Svalbard. Also on Svalbard sits the new Kjell Henriksen Observatory, opened in 2008 and the largest aurora observatory of its kind, with 30 dome-topped instrument rooms. Here, scientists around the world can remotely operate their instruments from their home institutions.

What makes Svalbard special is that during the day it sits right under the northern polar cusp. Here, solar wind particles can enter directly into the atmosphere without being routed via the magnetic tail, as is the case for nighttime auroras.

For decades, ground-based observations have revealed a complex and dynamic aurora. New camera technology has allowed researchers to obtain high-resolution time series images that reveal thin structures less than 100 meters wide, as well as patterns that can appear and disappear in a fraction of a second. There is still no consensus about the processes behind these small-scale shapes.

Rockets launched from Fairbanks in Alaska, Svalbard, and Andøya (off mainland Norway) spear the aurora and can actually measure its physical properties. And from even higher up, satellites provide a global view of the auroral oval, the ring of light circling each geomagnetic pole. In 2009 scientists at the University of Bergen in Norway presented satellite images of the aurora taken simultaneously above the Northern and Southern Hemispheres. These images reveal that the auroras in the two

A coronal mass ejection released from the Sun on January 23, 2012 created spectacular auroras the following night, when the author took this picture of the Norwegian city Tromsø.

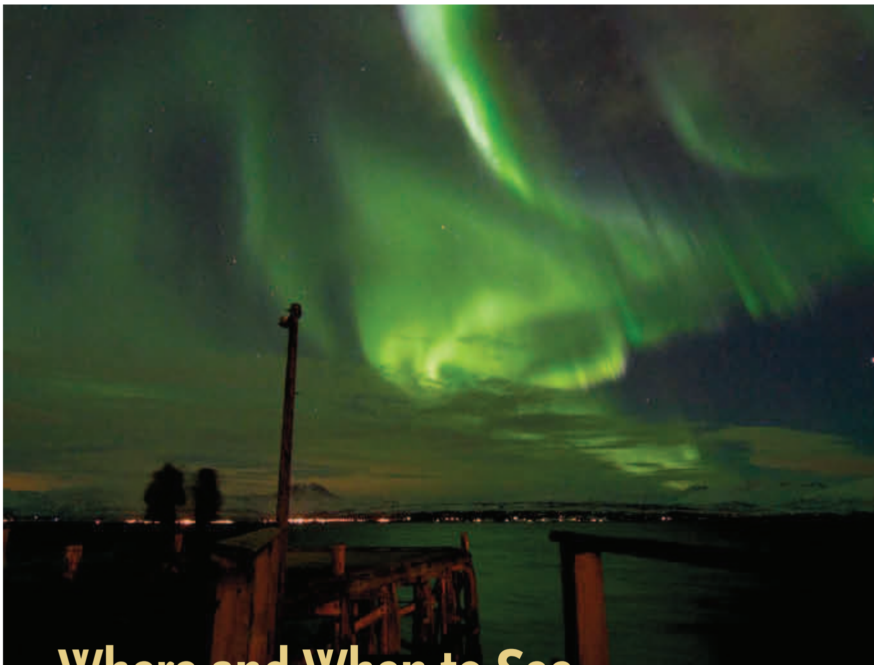
hemispheres can be totally asymmetric, contradicting the common assumption (which Birkeland and others held) that the aurora borealis and aurora australis are mirror images of each other.

Satellite studies have also produced a lot of new knowledge about interactions between the solar wind, the magnetosphere, and the atmosphere. In 2007 NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft fleet, together with a chain of ground-based cameras, made several new discoveries about auroral eruptions caused by energy released when the magnetosphere's tail pinches off. Scientists have studied these events for more than a century, but the new observations surprised them. The aurora brightened and moved twice as fast as was thought possible, surging westward through the atmosphere to cross an entire time zone in less than 60 seconds. The electrical power dissipated by the currents of energetic electrons was also impressive — 500 trillion joules, equivalent to the energy of a magnitude-5.5 earthquake.

THEMIS also helped unravel a long-standing mystery in the magnetosphere. We have wondered in the past how so many energetic particles sneak inside the magnetosphere, because the cusps' weakness should not allow so many in. Observations by the five THEMIS spacecraft found evidence that connections between the magnetosphere and solar wind form in short bursts. These are gigantic, twisted, ropelike bundles of magnetic field that connect Earth's upper atmosphere directly to the solar wind. When these ropes connect with the wind — on average every 8 minutes — the particles can sneak into the magnetosphere. The ropes then drag over and under Earth to the nightside, where their energy is released about 30 minutes later during a substorm. Recent observations with the ESA's Cluster satellites also suggest that the magnetosphere is more like a sieve than a shield, often allowing the solar wind to flow in.

THEMIS has also helped us understand where solar particles entering through the magnetosphere's tail receive their energy boost. In 2011 researchers found that most of the particles' acceleration happens much closer to Earth than the tail pinch-off that first shoots the particles at the planet. Instead, the particles grab energy as they cross changing magnetic fields along their path, boosting the particles' energy 10 times. But the electric currents above Earth still provide the final thrust that leads to auroras.

Modern observations have reached beyond light to auditory studies as well. Many people say that they hear crackling sounds during auroral displays, often synchronized with the phenomena's movements. Indeed, the Sami people of Norway called the northern lights *guovssahas* — the light you can hear. Since the aurora occurs at least 80 km above the surface and in a near-vacuum, it should be impossible for sound to travel from the site of emission down to the ground.



Where and When to See the Northern Lights

Auroras occur within an oval about 500 to 1,500 kilometers wide that's centered on the geomagnetic poles. They happen day and night during the entire year but are only visible from the ground during clear, dark nights because daylight outshines them. The width of the oval expands during geomagnetic storms, moving the edge farther south.

In parts of northern Norway you can see aurora almost every clear night. But the north part of Norway is at the same latitude as Barrow, Alaska, so you'll need to travel quite far north in North America to see the aurora frequently. When the Sun is active (like now), the northern lights should appear 10 to 15 times each year in the upper continental U.S., and a few times in the mid states. Very strong solar storms have sometimes pushed the aurora all the way down to Florida, such as in July 2000.

The strongest auroras often occur between 8 p.m. and 2 a.m. local time in Europe and more like midnight to 4 a.m. in North America. The best period is from September to April, when nights are dark. Strong auroras happen more often around the equinoxes, making the best time to watch September and October, March and April. Researchers don't agree on why the equinoxes are prime aurora time, but the answer could involve how the yearly wobble of Earth's spin axis toward and away from the Sun affects the interaction of the solar and terrestrial magnetic fields.

This winter should be good for aurora hunters, since solar activity is expected to peak in 2013, but the two years following solar maximum often produce the strongest auroras. That means that there should be several possibilities to experience auroras at lower latitudes in the next three years.

When planning your expedition, avoid city lights and the full Moon and find a dark place with a clear view of the northern horizon. Check predictions for solar activity before you go. Several satellites observe the Sun 24 hours a day, and by monitoring the Sun and measuring the speed of solar wind particles just outside the magnetosphere, scientists can predict the strength and location of aurora up to a couple of days in advance.

Top of page: **The southernmost part of the island of Tromsøya is a popular place in Norway to view the aurora (skygazers appear as black blurs on the dock). The author captured this shot of the northern lights on January 24, 2012.**

JESSE ALLEN AND ROBERT SIMMON / NASA EARTH OBSERVATORY / NOAA / GSFC / SUOMI NPP

This visible and infrared image by the Suomi National Polar-orbiting Partnership satellite reveals a scalloped auroral curtain seen above the Great Lakes region of North America on October 8, 2012, a few days after the Sun unleashed a coronal mass ejection.

Find aurora forecast resources, animations, and sounds of the northern lights at skypub.com/aurorasci.

Long-Term Ups and Downs

The northern lights vary on several timescales. The frequency of strong auroras depends on the general level of solar activity, which follows an 11-year cycle. The Sun also displays longer cycles that affect the aurora, and the last few centuries have seen an increase in solar activity. Thus, people see more northern lights today than in earlier centuries.

Whether the northern lights will be more or less frequent in the future is unknown. It depends on what the Sun does in the next century. Recent studies suggest that we have reached a grand maximum in solar activity, and that the Sun is heading toward a quieter period again — although not necessarily as severe a lull as the famous Maunder Minimum, a period from 1645 to 1715 when sunspots rarely appeared and when aurora may have disappeared entirely from many people's skies.

But even if the Sun goes quiet, there should still be good auroras. During quiet periods, holes often appear close to the solar equator in the Sun's outermost atmospheric layer, called the corona. In these holes, the Sun's magnetic field lines stretch out into space, allowing the solar wind to escape more easily and with higher velocity. If a coronal hole points toward Earth, a gust of solar wind should hit us a few days later.

No real change in auroral activity should come from Earth's magnetic field, either. The auroral oval forms a ring around Earth's *geomagnetic* pole. Unlike the magnetic pole, which is where magnetic needles become vertical, the geomagnetic pole is the intersection of Earth's surface with the imaginary bar magnet

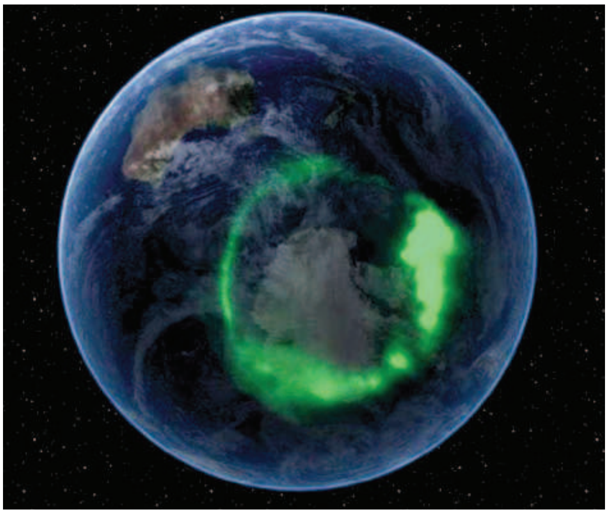
Recently, a group of Finnish scientists claimed they have found the explanation to this paradox. They used three microphones on the ground during high auroral activity to triangulate the source of the crackling. Their observations point to an origin only 70 meters above the ground, although they concluded the sounds are made by the same solar particles that generate the aurora. The team is still unsure what mechanisms are involved, since there are many types of sounds, and different mechanisms might explain each.

Still-Mysterious Lights

Despite these advances, many questions remain. Satellites and ground-based radars reveal that there is a surprising outflow of ionized oxygen atoms from the auroral zone into space. This flow points in the opposite direction from the streams of solar particles that whiz down to cause the aurora. In addition, these regions are often filled with highly energetic particles, and there has been a long-standing debate concerning how and where these particles are accelerated. New observations by NASA's Cluster mission suggest that these particles are accelerated within the cusps themselves, also by magnetic reconnection.

NASA plans to launch the Magnetospheric Multiscale (MMS) mission in 2014, a suite of four identical spacecraft variably spaced in Earth orbit, to make three-dimensional measurements of the boundaries of Earth's magnetic field and examine this reconfiguration process. Magnetic reconnection converts the energy stored in magnetic fields into both heat and the impulse energy that drives solar wind particles toward Earth, and it lies behind nearly every space weather phenomenon, including solar flares, CMEs, and geomagnetic storms. But despite how common it is, we don't fully understand it. MMS will test prevailing theories of these space-weather events to help us decipher what is going on.

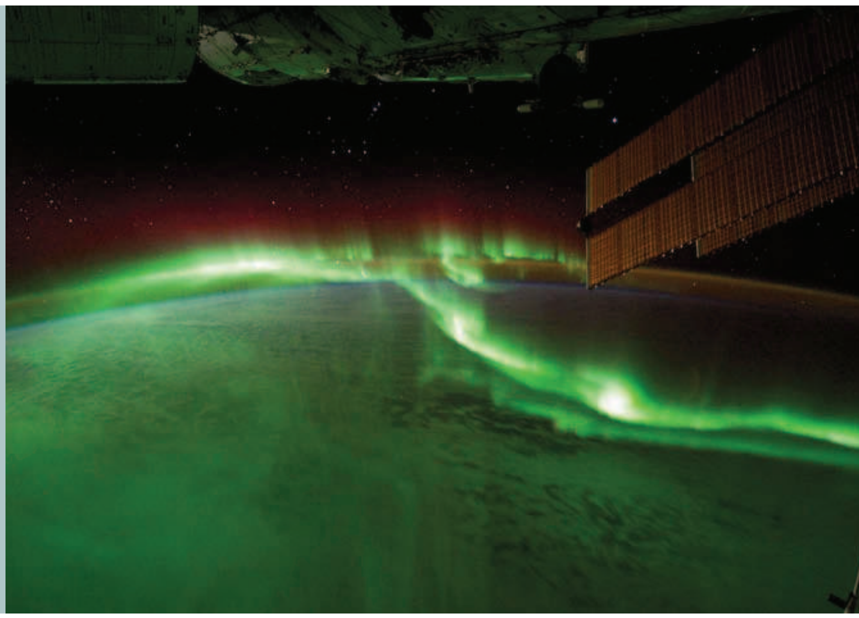
These studies are not just aimed to figure out the aurora. Solar storms affect our technology-based society more and more. They can induce electric currents in power lines, causing voltage variations that trigger safety cutoffs or damage transformers and leave communities without electricity (*S&T*: February 2011, page 28). Solar storms can also damage satellites on which our civilization depends and pose a hazard for space exploration. Thus, studying the interaction between these phenomena and Earth's space environment has a practical use that goes beyond predicting the mesmerizing aurora. As we continue to advance technologically, we will need a better understanding of the Sun-Earth connection to protect ourselves. ✦



NASA's IMAGE satellite captured this ultraviolet view of the southern lights on September 11, 2005, four days after a record-setting solar flare. The auroral oval created over Antarctica appears here overlaid onto NASA's Blue Marble image.

***Pål Brekke** is a solar physicist and a senior advisor at the Norwegian Space Centre, as well as an adjunct professor at the University Centre at Svalbard. His recent books,* Our Explosive Sun *and* The Northern Lights — A Guide, *explore our stormy Sun and the aurora.*

the *geomagnetic*, not the magnetic, pole that controls the aurora. The geomagnetic pole is calculated by a mathematical analysis of Earth's overall magnetic field, assuming that the field acts as a perfect bar magnet. The north geomagnetic pole is more static and is currently located in Kane Basin, between Ellesmere Island and Greenland. (The north magnetic pole, on the other hand, is in the Arctic Ocean north of Canada.) You cannot detect the geomagnetic pole with a compass, but if you view Earth from space, the geomagnetic pole marks the center of the aurora oval.



Astronauts aboard the International Space Station caught this view of the southern lights while passing over the Indian Ocean on September 17, 2011. The ISS's solar panels poke in from the right.

IMAGE SCIENCE AND ANALYSIS LABORATORY / NASA JSC