white dwarf or a neutron star. The radio pulsar in the Crab Nebula was also found to be a powerful x-ray source.

The 1960s were the great decade of astronomy. Radio pulsars and astronomical x-rays were discovered; the radio stars discovered in the late 1950s were found to be high-redshift quasars; the microwave background radiation was discovered and correctly identified as the relic radiation of the big bang; and the foundations for gravitational wave and neutrino astronomy were laid.

The decade ended with the launch of Uhuru, a space mission dedicated to x-ray astronomy that used the detector technology developed for sounding rockets. Uhuru soon provided evidence for the subsecond variability of Cygnus X-1. On the basis of this discovery, along with the detection of its optical counterpart as a binary system with a massive, invisible companion, Cygnus X-1 became a credible candidate for a black hole. By now, a dozen such objects believed to be black holes have been found in the Milky Way.

In addition, UHURU data revealed that other x-ray sources, notably Cen X-3 and Her X-1, pulsed periodically with the same range of periods found for radio pulsars. Cyclic variations in pulse periods revealed that these objects were members of close binary systems. Pulsating x-ray sources and radio pulsars are neutron stars in different settings. The x-ray sources are in binary systems and are powered by accretion from the normal star onto the neutron star. Radio pulsars are mostly single objects that draw their power from their magnetic field and their rotation.

Today, x-ray observations are part of the arsenal of techniques used to survey the universe. The Chandra Observatory and XMM Newton, along with several other x-ray space missions, have produced imagery and spectroscopy comparable to what is obtained at other wavelengths. X-ray astronomy has virtually disappeared as a distinct discipline as observers move effortlessly from one wavelength range to the next.

The Crab Nebula provides an example of how x-ray astronomy, and astronomy more generally, has been transformed. The Crab remains one of the great laboratories for studying relativistic astrophysics. Since its discovery, it has been understood that the Crab pulsar is the engine generating the relativistic electrons that are revealed as synchrotron radiation extending from radio to ultrahigh-energy gamma rays.

The value of x-ray images can be seen by comparing a visible-light Hubble Space Telescope image (*3*) of the interior of the Crab Nebula with an x-ray Chandra image (*4*) (see the figure). The x-ray image, while not nearly at the resolution of the visible image, clearly reveals the essential features of the central engine: The pulsar itself sits at the center of equatorial bands of radiation, with a jet along the equatorial axis. These features are also present in the Hubble image in even greater detail, but one has to know that they are there because the background of visible light from elsewhere in the nebula confuses the interpretation.

These x-ray observations of the Crab and others like it yield insights not only into pulsars but also into binary x-ray sources and quasars. They begin to resolve one of the last frontiers of astronomy: the nature of phenomena in the vicinity of neutron stars and black holes.

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PERSPECTIVES: SPACE SCIENCE

# How to Cope with Space Weather

**Daniel N. Baker**

Charles Dudley Warner once famously remarked that "everybody talks about the weather but nobody does anything about it." Space weather is the latest topic of conversation, but scientists are doing more than just talk about it.

Above the troposphere—the thin atmospheric layer above Earth's surface in which normal weather occurs—lies a vast region extending into interplanetary space that is permeated by highly fluctuating magnetic fields and very energetic particles. These collective, often violent, changes in the space environment around Earth are referred to as "space weather." With observations, numerical simulations, and predictive models, scientists are now making progress toward dealing with space weather (*1, 2*).

The source of space weather is the Sun, which regularly emits giant clouds of ionized gas containing $10^{16}$ g or more of hot plasma (see the second figure, top panel). These clouds, called coronal mass ejections, move away from the Sun at speeds of 1000 km/s or more, carrying with them strong magnetic fields and highly energetic particles. The Sun also emits powerful solar flares and streams of high-speed solar wind flows.

**Aurora borealis.** This image was taken at Nome, Alaska, on 28 November 2000. For more images see http://northernlightsnome.homestead.com.

As these solar emissions reach Earth and its vicinity, they can give rise to long-lasting disturbances called geomagnetic storms. The aurora borealis, visible at high latitudes, is the most widely known manifestation of these storms (see the first figure). They can also cause substantial damage to Earth-orbiting spacecraft and to humans in space (*3*) and severely disturb electric power or communications systems.

When high-energy protons and other ions hit orbiting spacecraft, they can leave ionization tracks in microminiaturized electronics (see the second figure, bottom panel). These tracks can upset spacecraft computer memories and otherwise disrupt sensitive space electronics. As a result, satellite solar power panels may be damaged, optical tracker systems may become confused, and spacecraft command-and-control software may be scrambled. High-energy protons and ions may also hurt, and potentially kill, astronauts who are in space during a major solar particle event (*4*).

Very energetic (relativistic) electrons in the space environment can also be devastating to spacecraft. They can readily penetrate even thick spacecraft shielding and bury themselves in insulating materials, such as coaxial cables or electronics boards, deep within spacecraft systems and subsystems (see the second figure, bottom panel). As charge builds up in the insulting materials, a powerful internal electrical discharge can occur (*2, 3*), much like a miniature lightning strike. Numerous recent spacecraft failures have been attributed to this mechanism (*2, 3, 5*).

Another space weather effect is known as "surface charging" (see the second figure, part C of bottom panel). Lower energy (10 to 100 kV) electrons cannot penetrate

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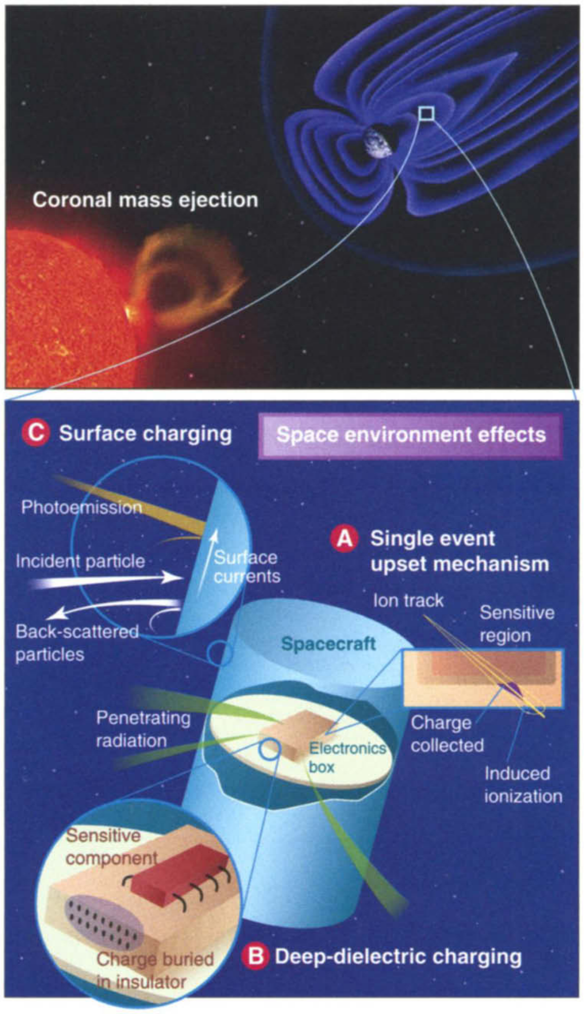
the shielding but can accumulate on insulating satellite surfaces. As with interior insulators, charge buildup on the surface may lead to a powerful, disruptive discharge, generating electrical signals in the spacecraft's vicinity that can scramble and disorient the satellite and its subsystems (*3*).

Continental-scale power generation and distribution systems are also vulnerable to space weather (*6*). Space storms can affect the operational reliability of electric power systems. In 1989, a major space storm shut down the Hydro Quebec power system in Canada for more than 8 hours. Space storms can disrupt power grids by introducing geomagnetically induced currents into the transmission network. Flowing through transformers, power lines, and grounding points, these currents can disrupt large parts of the power distribution system in North America or Europe, for example, within remarkably short periods of time (*6*).

Space weather manifests itself in many other ways. A major space storm can modify Earth's ionosphere, thereby changing the wavelengths at which high-frequency radio communication is possible. This is a problem for the military and for airlines attempting to communicate with aircraft on transpolar routes. Space weather can also cause sudden heating of Earth's thermosphere (the highest neutral layer of the atmosphere). This heating causes the thermosphere to expand and may result in a sudden increase of the drag force on low-altitude spacecraft (*3, 7*).




**Space weather and its effects. (Top)** The connected Sun-Earth system. A large coronal mass ejection propagates from the Sun toward Earth and its magnetosphere. **(Bottom)** Space weather–induced effects on an Earth-orbiting spacecraft: (A) Single-event upsets (SEUs) due to energetic ions; (B) deep-dielectric charging due to relativistic electrons; (C) surface charging due to moderate-energy electrons.

Space weather is not a new phenomenon. In an elegant and fascinating account in *The New Yorker* in 1959 (*8*), John Brooks wrote about "The Subtle Storm," a major solar flare that commenced on 9 February 1958 and played havoc with communications and other systems.

Compared to 1958, today's world is immeasurably more complex and interconnected. Earth's surface is criss-crossed by communication links, power grids, and a host of technological systems that did not exist in 1958. The satellites orbiting Earth from low to high altitudes form a complex "cyberelectric" cocoon that envelops our entire planet. Most elements of this web are susceptible to space weather effects.

Almost all modern communication systems rely on both ground and satellite links. Worldwide communication systems can therefore be disturbed by adverse space weather (*3, 5, 7*). The failure and loss of just one key communication satellite—for example, the failure of the Galaxy IV satellite on 19 May 1998—can affect tens of millions of customers relying on telephones, pagers, and other communication devices (*5*).

The first line of defense for human technology against space weather is to build robust systems that withstand any space weather onslaught. To a large extent, this has already been done: Were it not so, there would be many more space weather–induced failures. Ground communication links, national power grids, and military installations, which must withstand hurricanes, earthquakes, and floods, are very resilient and robust systems. And very few of the many hundreds of satellites in Earth orbit fail catastrophically as a result of space weather.

On the other hand, some spacecraft do fail suddenly as a result of space weather, and nearly all spacecraft eventually fail because of the rigors of the hostile space environment. We therefore need to know more about the nature of space weather and the space environment. Ultimately we want to be able to forecast the space weather environment anywhere in Earth's neighborhood many hours or days in advance. This is the goal of the U.S. National Space Weather Program (*1, 8, 9*).

Understanding and predicting space weather events is a great challenge, not least because the subject bridges the terrestrial and solar research communities (*7*). Several programs are now taking up this challenge. A new NASA initiative, "Living with a Star," aims to observe systematically the solar disturbances and follow these space weather drivers to their ultimate dissipation in Earth's atmosphere (*10*). And a consortium of universities, industry partners, and U.S. national laboratories has formed an NSF Center for Integrated Space-Weather Modeling, which will build physics-based models all the way from the Sun to Earth's atmosphere. Europe, Japan, and Australia are also actively developing major space weather programs.

Storms from the Sun are fascinating examples of energy transport and dissipation processes that are important in many cosmic contexts. The awesome splendor that accompanies space weather and the danger from these powerful events inspire popular accounts (*11*). We have come to a new appreciation of how the Sun affects human technology. In the next few years we may be able to predict such effects with accuracy and confidence.

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