Chapter 1
What is space weather?

"Space weather" refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socioeconomic losses.

National Space Weather Program Strategic Plan, 1995.
Office of the Federal Coordinator for Meteorological Services and Supporting Research, FCM–P30–1995, Washington, DC.

1.1 Key concepts

- space weather
- climate
- meteorology
- Earth's atmosphere

1.2 Introduction

In the last 50 years, we have become a spacefaring civilization. With robotic and manned spacecraft, we have started to survey our Solar System. We have learned that we live in the atmosphere of a dynamic, violent Sun that provides energy for life on Earth, but also can cause havoc among its fleet of satellite and communications systems. **Space weather** is the emerging field within the space sciences that studies how the Sun influences Earth's space environment and the technological and societal impacts of that interaction – damage to or destruction of Earth-orbiting satellites and threats to both astronaut safety during long-duration missions to the Moon and Mars and to the reliability and accuracy of global communications and navigation systems.

Modern society depends on accurate forecasts of weather (day-to-day variability of temperature, humidity, rain, etc.) and understanding of **climate** (long-term weather trends) for commerce, agriculture, transportation, energy policy, and natural disaster mitigation. The science of understanding weather, **meteorology**, is one of the oldest human endeavors to make sense of our natural environment. Like meteorology, the field of space weather seeks to understand and predict **climate** and weather, but of outer space. For millennia, space storms have raged above our heads unknown to us. But with the advent of the space age, we have begun to notice the destructive power of severe space weather.

Like weather, space weather has its roots in the Sun. The main distinctions between the two types of weather are where it takes place and the type of energy from the Sun that influences it. For weather, we are most concerned with the troposphere, which extends from Earth's surface to the top of the highest clouds at about 10 km. Space weather science is interested in the space environment around Earth all the way to the Sun. Space begins in a region of **Earth's atmosphere** called the thermosphere, which starts at roughly 100 km. The space shuttle and space station fly at an altitude of about 350 km. Plate 1 shows a picture of Earth's atmosphere from the space shuttle. The sharp contrast between the blue of Earth's atmosphere and the blackness of space is at approximately 100 km.

The second difference between weather and space weather is the type of solar energy that influences the two regions. The Sun continuously emits two main types of energy into space – electromagnetic (EM) radiation and corpuscular radiation. Visible light, radio waves, microwaves, infrared, ultraviolet, X-rays, and gamma rays are forms of EM radiation. The Sun's EM radiation bathes the top of Earth's atmosphere with about 1400 watts[1] of power per square meter and heats the lower atmosphere, surface and oceans unevenly. Winds are driven by these differences in atmospheric temperature.

The Sun also continuously emits corpuscular (minute particle) radiation, charged atoms and sub-atomic particles (mostly protons and electrons) in what is called the solar wind. Like winds on Earth, the solar wind is driven by temperature differences, but those differences are between the Sun's upper atmosphere and interplanetary space. The solar wind, which expands out into the Solar System carrying with it the Sun's magnetic field, carves out a region of interstellar space called the heliosphere ("helios", Greek for Sun).

The solar wind is not steady or uniform, but changes constantly. These changes affect Earth's space environment in a number of ways, including creation of new corpuscular radiation that bombards Earth's upper atmosphere, causing aurorae (northern and southern lights) and

[1] A watt is the SI unit of power (energy per time) named in honor of James Watt (1736–1819), a Scottish engineer and scientist credited with making the steam engine a practical device.

large electrical currents that can disrupt communication, power grids, and satellite navigation.

Occasionally the Sun's surface erupts and sends a large part of the solar atmosphere streaming away at high speeds. These events, called coronal mass ejections (CMEs), can contain 10^{12} (or 1 000 000 000 000) kg of material (equivalent to a quarter of a million aircraft carriers) and can move away from the Sun at over 1000 km s^{-1} (over several million miles per hour) (Plate 2). If CMEs are directed towards Earth, a great space storm can develop far above our heads, crippling satellites, causing increased radiation exposure for airline crews and passengers, blacking out some forms of radio communication, and disrupting power systems on Earth.

These space storms, like weather storms such as Hurricane Katrina in 2005, have caused severe damage to technological systems in the past. In March 1989, a large CME slammed into Earth causing massive power outages in eastern Canada. The emerging science of space weather is attempting to understand the causes of space storms and their impact on Earth's technological infrastructure with the hope that we can forecast space weather and mitigate damage.

1.2.1 It's Greek to me. The origin of technical names in science

The ancient Greeks envisioned the heavens as being on concentric spheres around Earth, with the planets (Greek for the wanderers), Sun and Moon moving on their own celestial spheres, while the stars moved in lock-step behind them on their own sphere. Science borrows from this worldview by giving concentric regions in and around the planets and the Sun a Greek prefix and the suffix "sphere". The rocky surface of Earth is often called the lithosphere ("litho", meaning stone), the water part the hydrosphere ("hydro", meaning water), the place where life is found the biosphere ("bio", meaning life). The region above Earth's surface is called the atmosphere ("atmos", meaning vapors). The atmosphere is further divided into sub-regions, which are listed in Table 1.1. The boundaries between the spheres are called "pauses" (e.g., the boundary between the troposphere and stratosphere is the tropopause). Several more "spheres" and "pauses" will be introduced in the following chapters. Figure 1.1 shows the layers of the atmosphere as a function of height. Note that each layer or sphere has a different temperature profile with height. (For example, the troposphere has temperature decreasing with altitude, while the stratosphere has temperature increasing with altitude.)

Table 1.1 *Greek prefixes for regions of Earth's atmosphere*

Prefix	English translation	Height	Characteristic
tropo	mixing or changing	0–10 km	where weather takes place
strato	layer	10–50 km	where ozone layer is located
meso	middle	50–80 km	coldest region
thermo	heat	80 km–	where space begins
iono	to go	80 km–	where aurorae occur

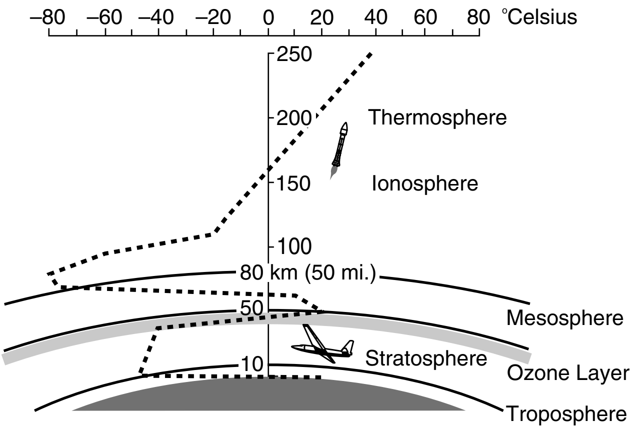

Figure 1.1 The vertical temperature scale of Earth's atmosphere. The dashed line represents the temperature as a function of height. Each region is defined by how the temperature changes with height (courtesy of Cislunar Aerospace, Inc.).

1.3 Brief history

The study of space weather began with systematic observation of three natural phenomena: the aurorae (also called the northern or southern lights), Earth's magnetic field, and sunspots (dark regions observed on the surface of the Sun). Because aurorae can be seen with the unaided eye, they have been observed for thousands of years, though the systematic study of the aurorae didn't begin until the sixteenth century. Development of the sensitive compass and telescope in the early seventeenth century made possible the discovery of the nature of Earth's magnetic field and sunspots.

The understanding of space weather traces its roots to connections between these three phenomena. The first tentative connections were made in the middle of the nineteenth century. For the last 150 years, we have slowly expanded our knowledge of the Sun and Earth's space environments and, in so doing, have begun to develop a physical model of the Sun–Earth connection. This section gives a brief history of the discoveries and an introduction to some of the scientists who have led us to our current understanding of the solar–terrestrial relationship. As with all areas of science, the field of space weather developed in concert with our understanding of physics and chemistry and new technologies that allowed us to "see" the "invisible" – things too small or far away to be seen with the unaided eye or beyond our sensibilities and capabilities to see, hear, or feel, such as radio waves and magnetic fields. A website has been developed to provide a detailed timeline of our understanding of space weather. The web address is given in Appendix A.

1.3.1 The aurorae

Our earliest ancestors observed the aurorae. Until the eighteenth century most treatises on aurorae were based on speculation about their origin by men who may have never observed them. These speculations usually followed Aristotle's (384–322 BC) view of aurorae as burning flames, or René Descartes' (1596–1650) idea that aurorae were moon- or sunlight reflected off ice or snow crystals. Systematic observations of aurorae were first made in the sixteenth century. One of the greatest astronomers of all time, Tycho Brahe (1546–1601), recorded the occurrence of aurorae between 1582 and 1598 from his Uraniborg observatory in Denmark. He found that the number of aurorae varies from year to year, but did not note any systematic or regular variation. On September 12, 1621, the astronomer Pierre Gassendi (1592–1655) from the south of France and Galileo[2] in Venice observed the same aurorae. Gassendi called the lights aurorae borealis (Latin for northern dawn), a name that has been associated with polar lights ever since. He noted that the aurorae must occur high in Earth's atmosphere for observers at distant locations to be able to observe the same phenomena.

In the eighteenth century a number of observations began to illuminate the origins of aurorae. Frenchman Jean-Jacques d'Ortour de Mairan (1678–1771) made the first rough measurements of auroral height in 1726; these were consistent with Gassendi's observation that aurorae occur in the upper atmosphere. Using the triangulation method, English scientist Henry Cavendish (1731–1810) correctly estimated auroral height to be between 80 and 112 km in 1790. However, estimates of auroral height continued to have large uncertainties until around 1900, when Norwegian scientist Carl Størmer (1874–1957) measured the height accurately using photographic techniques.

[2] Galilei, Galileo (1564–1643), Italian physicist and astronomer and founder of the modern scientific method. The first to use a telescope for astronomical observations, he discovered the moons of Jupiter (named the Galilean moons in his honor); that Venus has phases, which offered direct support for the Copernican heliocentric theory; that the Milky Way is made up of individual stars; and that the Moon has mountains.

Captain James Cook was the first European to observe the southern lights (which he called aurora australis) while in the Indian Ocean near latitude 58°S on February 17, 1773. He wrote in his ship's log:

> lights were seen in the heavens, similar to those in the northern hemisphere, known by the name of Aurora Borealis.

In the nineteenth century, as reports from polar explorers were compiled, it became clear that aurorae appear in large ovals centered near the North and South Poles. Captain John Franklin, who later perished with his crew as they attempted to find the Northwest Passage, determined that the number of auroral sightings decreases nearer the Pole, suggesting an auroral zone. In 1833, the German geographer Georg Wilhelm Muncke (1772–1847) noted the existence of a zone of maximum auroral occurrence that is limited in latitude. In 1860, Professor Elias Loomis (1811–1888) of Yale University published the first map of the north polar region showing the zone where aurorae had been most commonly observed (see Figure 1.2).

So, by the middle of the nineteenth century a number of facts about aurorae were known: they occur in an oval around the north and south polar regions, and they are high in the upper atmosphere. The search was still on for the cause of the aurorae.

1.3.2 The geomagnetic field

In 1088, Chinese encyclopedist Shen Kua (1031–1095) wrote the first description of compasses, magnetized pins floated on a small cork in a bowl of water. Alexander Neckham of St. Albans (1157–1217) was the first European to describe a compass in his work *On the Nature of Things* published in 1187. Neckham had probably heard of the Chinese compass through the silk-road trade routes from China to Western Europe. In 1576, Robert Norman discovered that Earth's magnetic field has a vertical component called dip. Combining this discovery with his own work with a model magnetic field called a terrella, William Gilbert[3] (later the personal physician of Queen Elizabeth I) wrote a book called *De Magnete* in 1600. In this book he demonstrated that Earth's magnetic field behaves like a magnet, which led to the systematic study of magnetic field orientation as a function of position on Earth. These magnetic maps allowed the use of compasses for navigation. In 1722, George Graham (1674?–1751) built a compass sensitive enough to observe slight (usually

[3] Gilbert, William (1544–1603), English physicist and physician who pioneered the field of geomagnetism. The first English scientist to accept the Copernican view of the Solar System, he suggested that habitable worlds might be in orbit around other stars.

Cambridge University Press
978-0-521-86149-6 - An Introduction to Space Weather
Mark Moldwin
Excerpt
More information

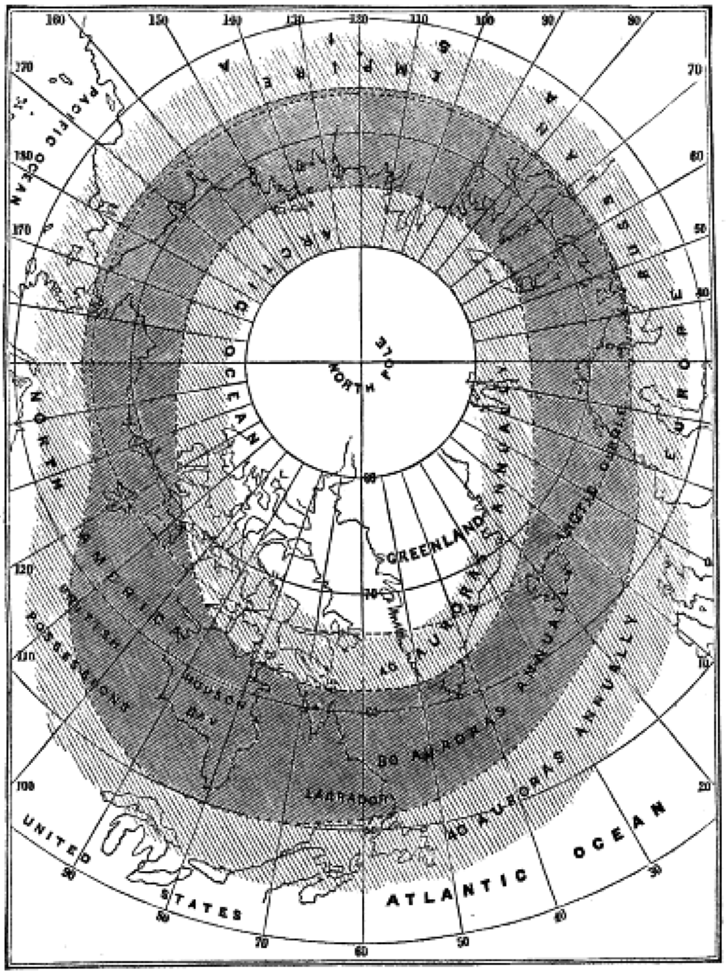

Figure 1.2 The auroral oval from Professor Loomis' late nineteenth century study. Note that the aurora has a zone of occurrence centered around, but not at, the pole (from Loomis, 1869).

less than 1°) irregular variations of the geomagnetic field that caused the compass needle to "wriggle" slightly.

Thus the basic fact about geomagnetism known by the early eighteenth century was that Earth has a magnetic field like that of a regular magnet (called a dipole magnetic field) with both regular and irregular variations. The search was on for the cause of these geomagnetic fluctuations.

1.3.3 Sunspots

In 1610, Galileo turned his telescope to the Sun and observed sunspots by focusing the image onto a piece of paper (see Figure 1.3). Several other observers – Johannes Fabricius, Thomas Harriot and Christoph

Scheiner – essentially simultaneously observed sunspots with the newly developed telescope. But what were they? Scheiner argued that they were moons or planets (Mercury, Venus, or the mythical planet Vulcan) orbiting between the Sun and Earth, while Galileo argued that they were on the surface of the Sun. The first regular daily (when weather permitted) observations of sunspots began in 1749 at the Zurich Observatory in Switzerland. Using data from Zurich, Samuel Heinrich Schwabe (1789–1875) recognized the occurrence of an 11-year solar cycle in about 1844. His original goal had been to find intra-mercurial planets such as those conjectured in Galileo's time. He began to systematically look for "transits" of these hypothesized planets across the Sun. In so doing, he meticulously recorded the position of every sunspot for 18 years. With this data set he discovered the 11-year sunspot cycle. He never did discover a planet crossing the Sun.

So by the mid-nineteenth century, it had been clearly demonstrated that sunspots exist on the Sun and they have an 11-year cycle during which their number waxes and wanes. The question of what sunspots are and what if any effect they have on Earth still remained.

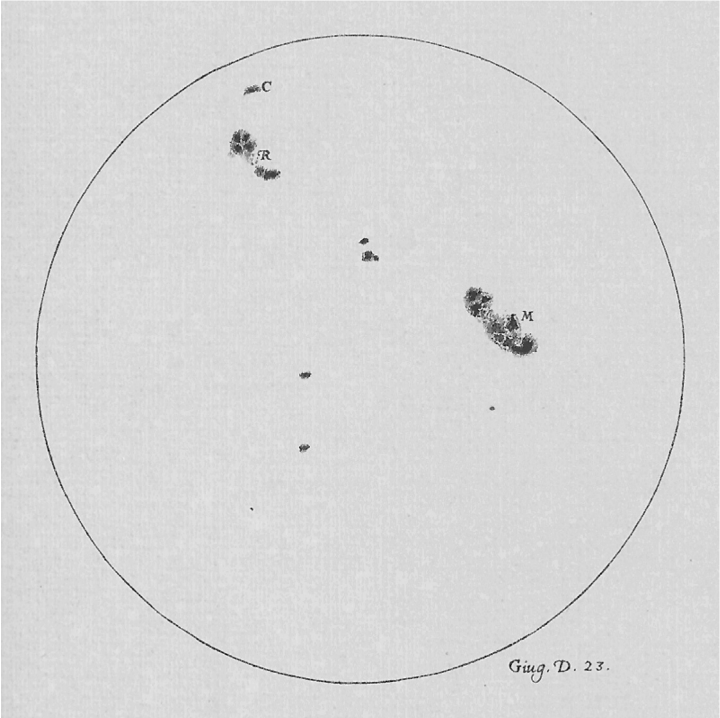

Figure 1.3 Sunspot drawings from Galileo made in about 1610 (from Galileo Galilei, 1613, courtesy of Owen Gingerich).

1.3.4 Making the connection between aurorae, the geomagnetic field, and sunspots

English astronomer Edmond Halley (1656–1742), of Halley's Comet fame, noted that the aurorae that occurred on March 16, 1716 over London appeared to have rays converging toward Earth similar to Earth's magnetic field lines. He drew the magnetic field lines outside Earth by extrapolating from the shape that iron filings make around a magnet. This hint that auroral rays are aligned with Earth's magnetic field was not confirmed until 1770 when the Swedish scientist Johann Wilke observed that auroral rays actually lie along the geomagnetic field lines. In 1722, the British instrument maker George Graham observed slight magnetic fluctuations with his compass, which later were observed to be correlated with observations of aurorae by Anders Celsius (the scientist whose name was given to a temperature scale) and his student (and brother-in-law) Olaf Hiorter in Uppsala, Sweden in 1747. Professor Celsius' instrument was obtained from Graham, and through regular correspondence Celsius and Graham found that days with geomagnetic activity (the name given to magnetic fluctuations) in London were also days with geomagnetic activity in Uppsala. This established that geomagnetic activity and hence aurorae occur over large distances. Hiorter wrote "That aurorae must be the highest phenomena of our atmosphere, so high and extensive, that they can simultaneously, here and in England, at Uppsala and London, . . . disturb the magnetic needle." They and others then began to observe periods of very large geomagnetic fluctuations – many degrees of magnetic needle fluctuation in several minutes. These large geomagnetic disturbances are now called geomagnetic storms.

In the mid-nineteenth century, Col. Edward Sabine and Prof. Rudolf Wolf independently were the first to publish results showing the correlation between sunspots and geomagnetic activity. Sabine was a British military officer (later knighted) in charge of British observatories around the world at which surface weather and changes in the geomagnetic field were monitored. Understanding the geomagnetic field was important for navigation because of the use of magnetic compasses. Rudolf Wolf was director of the Zurich Observatory and therefore had access to the longest record of sunspot occurrence in the world. The studies of Graham and Celsius now linked aurorae with geomagnetic activity, and the studies of Sabine and Wolf linked geomagnetic activity with solar activity. Because of the unreliable reporting of the occurrence of aurorae (summer time, clouds, limited populations at high latitudes), it was several years before the occurrence of aurorae was also clearly shown to be linked with solar activity.

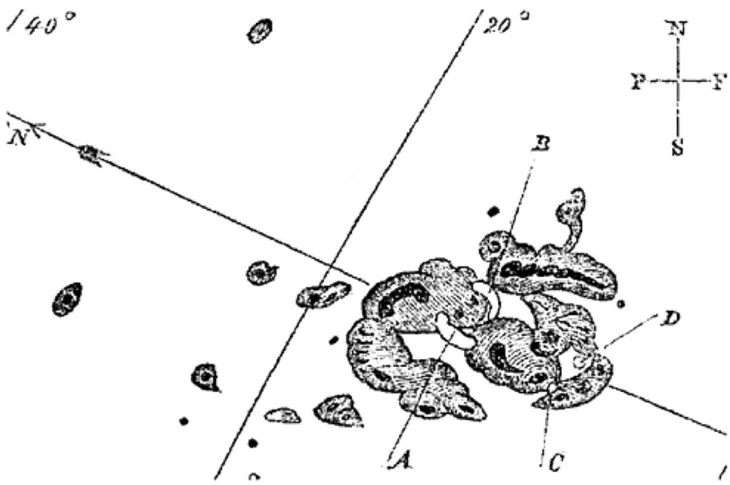

Figure 1.4 Carrington's 1859 drawing of a white light solar flare associated with a sunspot group (from Carrington, 1860).

Immediately the question was raised: what connected sunspots with Earth's magnetic field? In 1859 when Richard Carrington, who worked as an astronomer at Greenwich Observatory, observed a white light flare above a sunspot, he remarked in a letter to the British Royal Society that the flare was followed within a day by a geomagnetic disturbance. (Figure 1.4 shows Carrington's drawing of the flare.) In this letter he suggested that perhaps there was a causal relationship. However, in 1859 it was assumed that space was a complete vacuum and the discovery of electrons and the other sub-atomic particles was 40 years away. In fact, in 1859 there was still not a clear understanding of electromagnetic radiation (such as light). In 1863 Lord Kelvin,[4] one of the dominant physicists of the nineteenth century, cast strong doubt on the connection between sunspots and geomagnetic activity after calculating that the solar magnetic field could not possibly impact Earth's magnetic field over the tremendous distance between the Sun and Earth. He later expressed these thoughts in his Presidential Address to the Royal Society in 1892 as: "It seems as if we may also be forced to conclude that the supposed connexion [sic – old British spelling] between magnetic storms and Sun-spots is unreal, and that the seeming agreement between periods has been mere coincidence."

[4] Kelvin, William Thomson (1824–1907), Irish-born Scottish physicist and one of the greatest scientists of the nineteenth century. His work included studies in thermodynamics and electricity and magnetism. He was also an entrepreneur and became wealthy with inventions that made the first transatlantic telegraph successful. Proposed the absolute temperature scale, whose degree is now called the kelvin (K) in his honor.