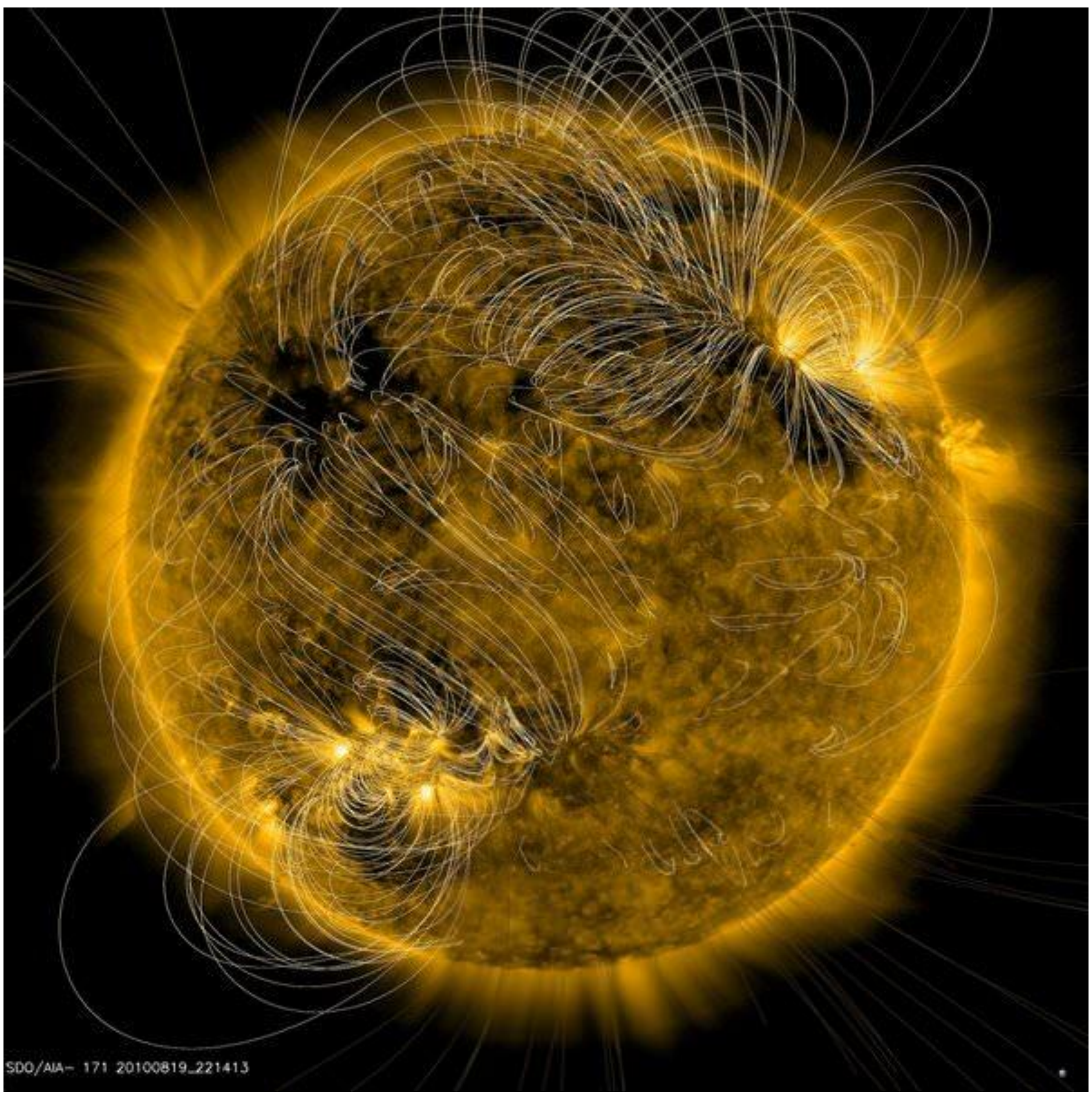
National Aeronautics and Space Administration

What is Magnetism?

An Introduction



Contents

1. A Brief History

When was magnetism first discovered?
How was magnetism discovered?
How have scientists described magnetism?

Magnetism is a force in nature that has been clouded in mystery for thousands of years. But in truth, magnetism is no more mysterious than gravity. Everyone has refrigerator magnets, and everyone at one time or another has played with a compass. But magnetism remains a mysterious force because it demonstrates how something invisible can reach out through space and affect something we see like paperclips or nails. It is the ultimate magician's trick that every one of us can experience and play with. Beyond that, the study of magnetism has a history as old as human history.

The earliest Chinese mention of magnetism can be found during the 4th century BCE in the writings of Wang Xu where he says, "*The lodestone attracts iron."* The book also says that the people of the state of Zheng always knew their locations by means of a "south-pointer", which was a spoon-like device whose handle pointed south. The earliest known mention of the magnetic compass in Europe was by the Englishman Alexander Neckam in his 1180 textbook *De Utensilibus* (On instruments). By the mid-1200s, compasses were being used by the Vikings as they traveled the North Sea, and by Arab merchants on land. Compasses were considered the highest technology of the Middle Ages, like the telegraph of the 1800's and the computer of the 20th century.

But what was magnetism? It seemed to be an invisible zone of influence surrounding some kinds of objects. This influence attracted sometimes and repelled others, but when you looked closely, there was nothing there to show why! Then, in 1644, René Descartes made invisible magnetic forces visible by inventing the iron filing method. In his book Principles of Philosophy, he explained that *the filings will arrange themselves in lines, which display the curved paths of the filaments around the magnet.*

Descartes' drawing in Figure 1 showed the magnetic field of the Earth attracting several round lodestones *(I, K, L, M, N)* and illustrated his theory of magnetism. Descartes thought that magnetic attraction was caused by tiny screw-shaped particles that circulated through parallel threaded pores in magnets. They passed in through the South Pole *(A)*, out through the North Pole *(B)*, and then through the space around the magnet *(G, H)* back to the South Pole.

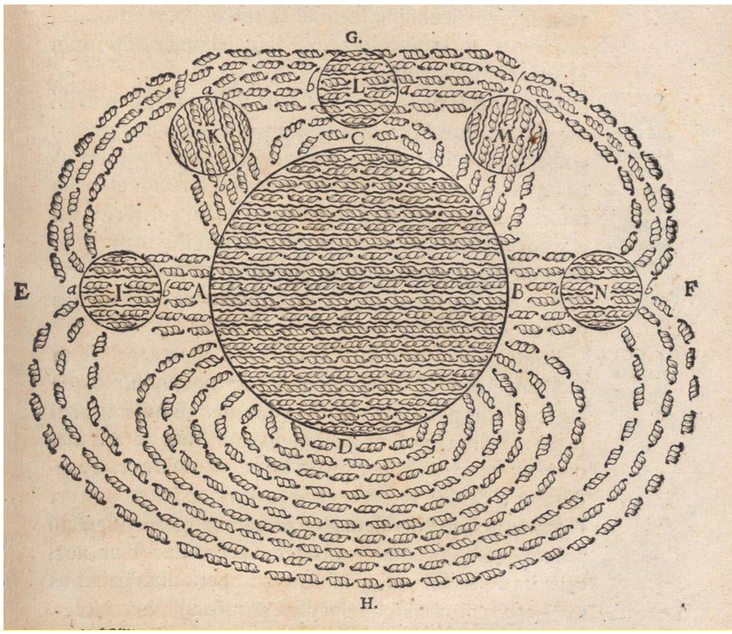


Figure 1. Drawing of a magnetic field by French philosopher René Descartes
(Credit: Principia Philosophiae, 1644)

In 1666, Sir Isaac Newton discovered that gravity follows an inverse-square law. This means that if you doubled the distance between two bodies, the force would diminish by one fourth. If you tripled the distance the force of gravity would only be one ninth as strong, and so on. A similar inverse-square law was discovered for magnetism in 1750 by John Mitchell. About 35 years later, Charles de Coulomb found that the electrostatic forces between two charged bodies also followed this same law. Astoundingly enough, although gravity controls the movement of the planets around the Sun, as a force it is over 2000 trillion, trillion, trillion times *weaker* than the magnetic or electrostatic forces between the same two bodies!

Because it is so weak, it is extremely hard to study gravity in the laboratory. For magnetism, though, it is very simple. You can make magnets in a variety of ways, or by collecting a mineral called magnetite (also known as lodestone). In the early-1800s, Andre Ampere discovered something remarkable. He suspended two wires side-by-side and then let an electrical current from a battery flow through the wires in the same direction. They immediately repelled each other just like the south poles of two magnets placed next to each other. When currents were flowing in opposite directions the wires attracted. In 1820, Danish scientist Hans Christian Ørsted discovered by accident that an electric current flowing through a wire would cause the needle of a compass to move. Ørsted correctly theorized that electricity created a magnetic field, an observation that was built upon by other scientists who endeavored to use electricity to create magnets. These discoveries would have remained laboratory curiosities had it not been for a discovery by Michael Faraday, which would single-handedly change the face of human society and unleash the modern age of electricity!

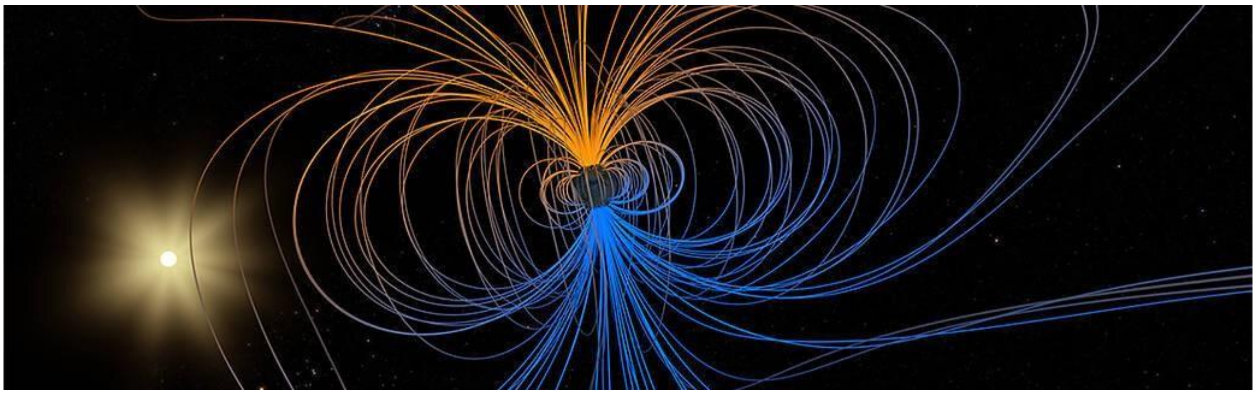


Figure 2. This visualization shows a simple model of Earth's magnetic field. It is very similar to the magnetic field of a bar magnet. (Credit: NASA's Goddard Space Flight Center)

After many years of painstaking research, Faraday finally demonstrated the existence of a new electric phenomenon in 1831 that he called induction. Each time the electrical current in a wire was switched on or off, or abruptly changed in strength, a weak current would begin to flow in the neighboring wire. This led to a second discovery that a moving magnet could also produce such currents. The practical consequences of this new induction phenomenon spawned entirely innovative technologies, including the invention of the electric dynamo and its cousin the electric motor.

Faraday built a hand-cranked dynamo that generated electricity. When the Prime Minister of England paid his lab a visit one day and saw Faraday demonstrate how it worked, he said. "*Of what value is this?"*. Faraday replied, *"I know not. But I am certain that you will find a way to tax it!"*. Faraday's comment came true as the electrification of England began in earnest, and the use of the electric light invented by Thomas Edison became widespread as the 20th century was about to dawn. A dynamo consisted of a magnet on a shaft that rotated inside a large loop of wire, and as it rotated it created an electrical current in the wire. This is useful to our modern, electrified society because scientists soon realized they could attach the dynamo to a water wheel to generate hydroelectric power or to a steam turbine to create electricity by burning coal to make the steam!

The origin of magnetic fields from currents of electricity soon led to an explanation of why Earth has a magnetic field. Deep inside, the core of our planet is a solid sphere of iron and nickel a thousand miles across but on its surface the temperature and pressure allow the iron and nickel to remain molten. It circulates around the core of Earth as Earth rotates, and this movement creates an electrical current that generates the magnetic field. Unlike the steady current and smooth magnetic field created in a wire, Earth's current is not steady and the magnetic field it creates can 'flip over' in polarity. Right now, Earth has a south-type pole in the Arctic and a north-type pole in the Antarctic, but 800,000 years ago the polarity was opposite, with a north-type pole in the Arctic and a south-type pole in the Antarctic. Today, the magnetic field is decreasing in strength, and some scientists think that in another 10,000 years it will once again reverse its present polarity. Magnetic pole reversals have been common over the billions of years of Earth's history. They have no effect on living organisms, do not produce extinctions of animals, and so the effect will be harmless to humans living in the distant future.

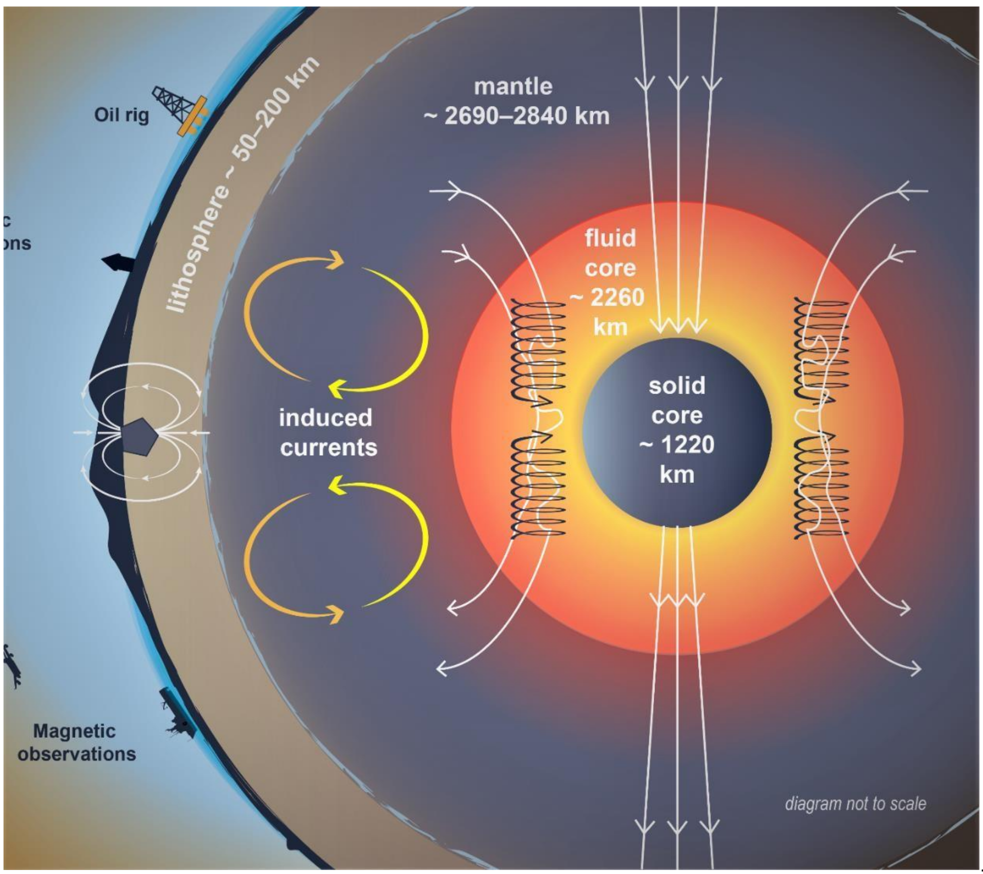


Figure 3. A diagram showing how Earth's magnetic field is generated from electrical currents flowing in the molten outer core of Earth. Physicists use supercomputers to calculate how Earth's magnetic field changes over thousands of years. (Credit: NOAA/National Centers for Environmental Information).

Magnetism is found on the Sun because as the Sun rotates, the charged plasma circulates like a current in a wire and creates magnetic fields at many different scales from a few kilometers to nearly the full million-kilometer size of the Sun itself. Plasma is the fourth state of matter. You can produce plasma by heating ordinary gas to thousands of degrees.

The atoms begin to lose their electrons, creating a mixture of charged electrons and charged atoms. Sunspots are a common example of magnetic fields on the Sun being so intense that they literally pop through the surface of the Sun to create pairs of spots: One with a north-type and one with a south-type polarity. Because some plasma can act like iron filings, you can often see the magnetic 'lines of force' emanating from the Sunspots to create fields like those you see in bar magnets in your classroom. Magnetic fields mixed up in charged plasma can also change their shapes in a process that is called reconnection. When this happens, energy stored in the magnetic field is released to create a burst of x-ray light called a solar flare. Sometimes these reconnection events release so much energy that they eject billion-ton clouds of plasma into space. These coronal mass ejections can sometimes be directed at Earth and when they arrive a few days later can cause changes in Earth's magnetic field. These are usually accompanied by spectacular Northern and Southern Lights (also called auroras).

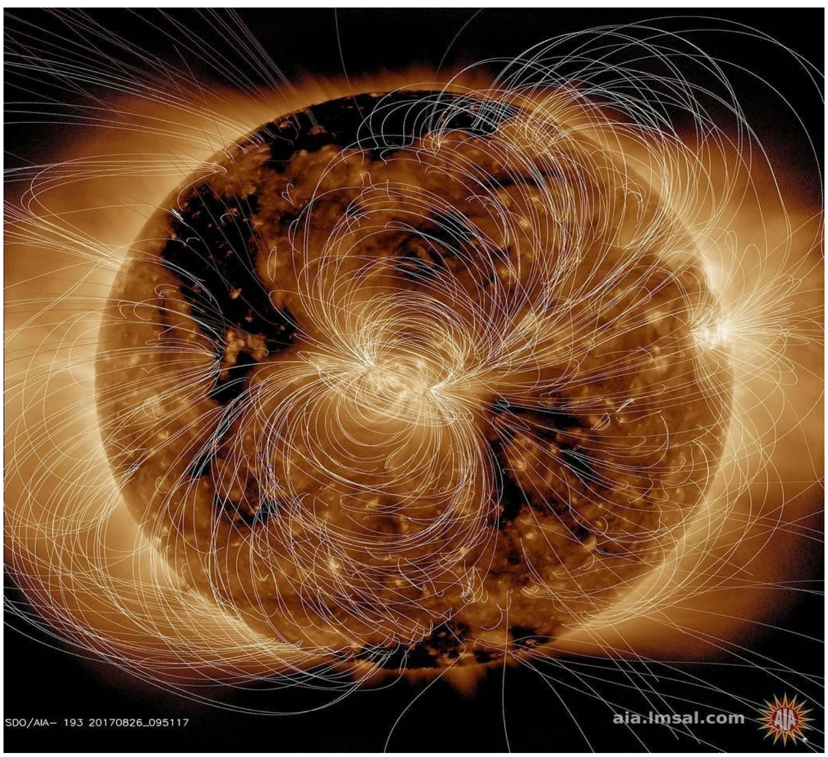


Figure 4. NASA's Solar Dynamics Observatory (SDO) scientists used their computer models to generate a view of the Sun's magnetic field on August 10, 2018. The bright active region right at the central area of the Sun clearly shows a concentration of field lines, as well as the small active region at the Sun's right edge, but to a lesser extent. Magnetism drives the dynamic activity near the Sun's surface. (Credit: NASA/SDO)

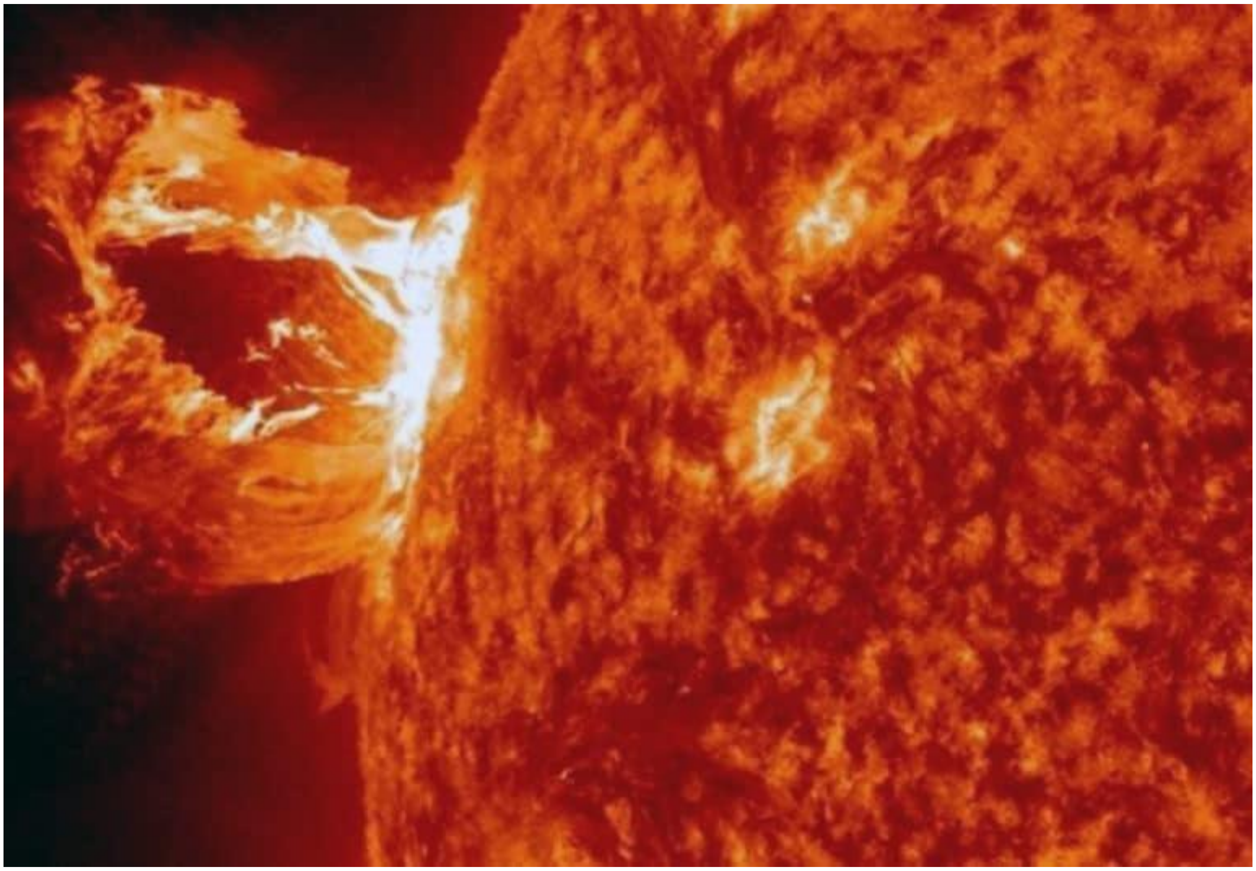


Figure 5. A coronal mass ejection produced by magnetic fields on the Sun reconnecting to form a cloud over 100,000 kilometers in diameter and traveling at 1,000 km/sec. (Credit: NASA/SDO).

2. Basic Magnetism

How do we measure magnetism?
What is magnetic polarity?
What are some common sources of magnetism in the universe?

Magnetism is a force found across the universe in a variety of objects from stars and planets to galaxies. All forms of magnetism are produced by currents of electrons or charged particles flowing somewhere in space. In the mineral magnetite (also called lodestone), these currents are produced by the electrons whirling within the atoms where enough of the atoms are lined up to create the overall field. Magnetic fields can be complex depending on how the electrical currents are flowing. For example, on the surface of the Sun, currents just below the surface produce complex magnetic fields that extend millions of kilometers into space and speckle the surface in sunspots.

Magnetic fields and their forces are complex because currents can flow in many different directions and with many different intensities. But the simplest magnetic fields always have exactly two poles, which we call the North and South poles. This feature of magnetism is called its polarity. They can produce two types of forces that are repulsive when like poles are placed close together, or attractive when opposite poles are combined. Compare this in Figure 6 to gravity, which is a force that operates only in one direction along the line connecting the centers of two bodies. It is only attractive, and it has only one polarity.

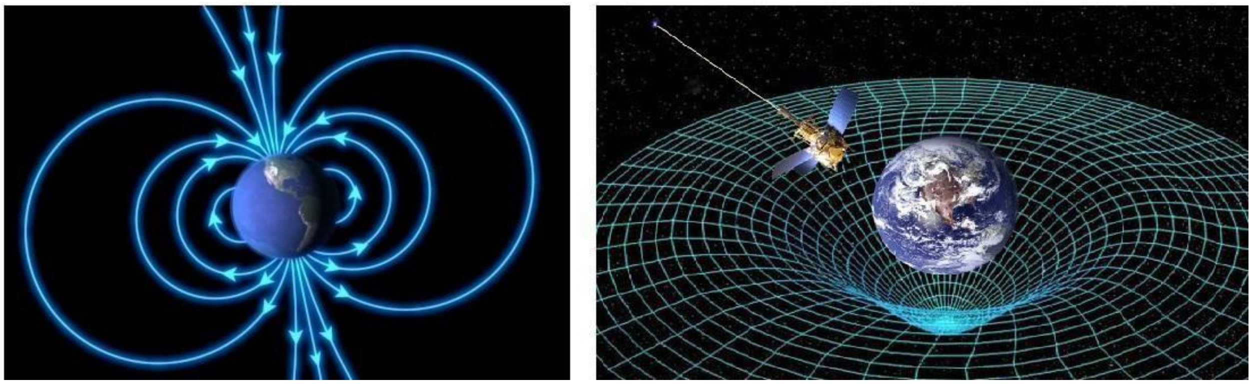


Figure 6. Magnetism has two poles (attractive and repulsive) and is called dipolar (left). Gravity is caused by the warpage of space near matter, has only one polarity (attractive) and is called unipolar (right).
(Credit: The COMET Program/UCAR and NASA)

The basic unit of magnetism in the SI (meter-kilogram-second or MKS) system is the Tesla. Some common things and their magnetic field strengths are listed in Table 1. In addition to Tesla, the prefixes milli, micro, nano, kilo and giga may also be used. For example, one milliTesla (mT) is 0.001 Tesla while one kiloTesla (kT) is 1,000 Tesla.

For smartphone measurements, the common magnetic unit is the microTesla, which is 0.000001 Tesla, and is commonly abbreviated as μT. Another unit used in describing magnetic storms is the nanoTesla abbreviated as nT and where 1 nT = 0.001 μT.

Table 1. Examples of magnetic fields and their strengths

Object	Size	B (Tesla)
Magnetar Star	20 km	100 billion
Neutron Star	20 km	100 million
Record pulsed magnetic field	1 meter	2,800
Strongest continuous artificial field	1 meter	45
Electromagnet of an MRI medical imager	10 cm	9.5
Magnet used in a large ‘atom smasher’	1 meter	8.3
Electromagnet used in a junk yard	2 meters	1
Sunspot magnetic field	1,000 km	150 milliTesla
Refrigerator magnet	1 cm	5 milliTesla
Jupiter’s magnetic field	10,000 km	417 microTesla
Earth’s magnetic field at ground level	5,000 km	58 microTesla
Residential 34,500-Volt power line at 1 foot	1 cm	500 nanoTesla
Solar wind magnetic field	100 million km	15 nanoTesla
Human brain neuron	1 micron	1 picoTesla

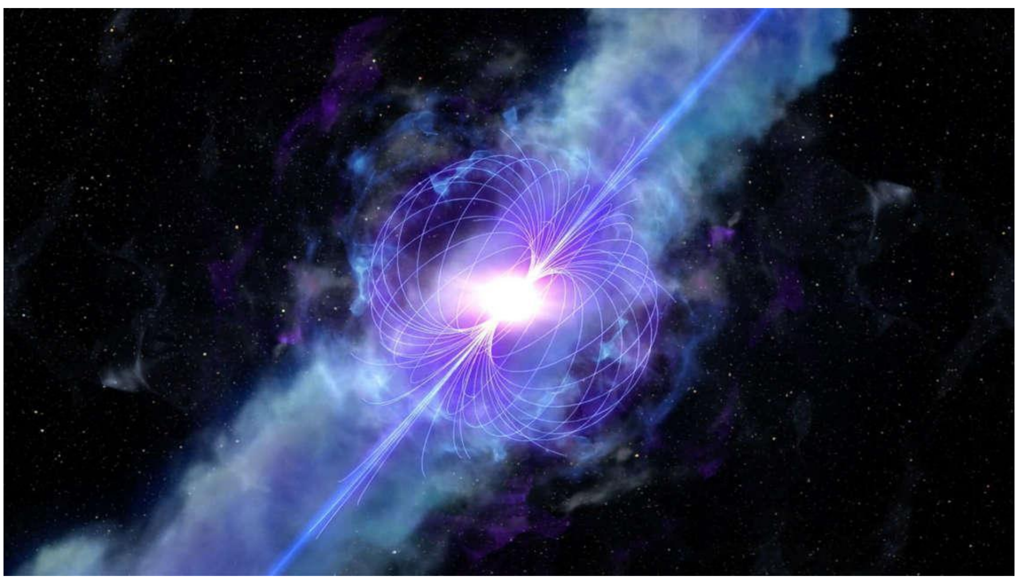


Figure 7. A magnetar is all that remains of a very massive star after it becomes a supernova. These stellar objects are denser than an atomic nucleus, no more than 60 km across, and spin over 30 times a second. Their magnetic fields are the strongest known ones among all the kinds of objects in our universe. At the distance of the moon, a magnetar could possibly disrupt the flow of blood in every human on earth! (Credit: NASA/ESA /D. Player)

The strongest known magnetic fields in the universe occur on the surfaces of objects called magnetars. These are created when massive stars explode as supernovae and their dense cores collapse into neutron star remnants. During this compression, magnetic fields within the star are amplified by trillions of times and become locked into the solid surface of the neutron star. If a magnetar were to enter our solar system with a mass equal to our Sun, it would only be 20 km in diameter. At a distance from Earth of a million kilometers, a magnetar’s magnetic field could rip the red blood cells from your body because of hemoglobin's iron content. But a magnetar that close has such intense gravity that it would shatter Earth instantly, so there's no need to worry!

3. How NASA spacecraft use magnetometers

Why do scientists use magnetometers in space?
Why are they difficult to use in space?

Next to camera systems, magnetometers are the most widely used scientific instruments in exploratory spacecraft. Engineers use them to estimate the orientation of a satellite or spacecraft. Scientists use them to determine whether a planet or other solar system object has a magnetic field, and to map out the size and shape of this field in space. For planets, the presence of a magnetic field usually means that the planet has a circulating electrical current in a molten core. The Sun's magnetic field is also of particular interest in studying sunspots and space weather events.

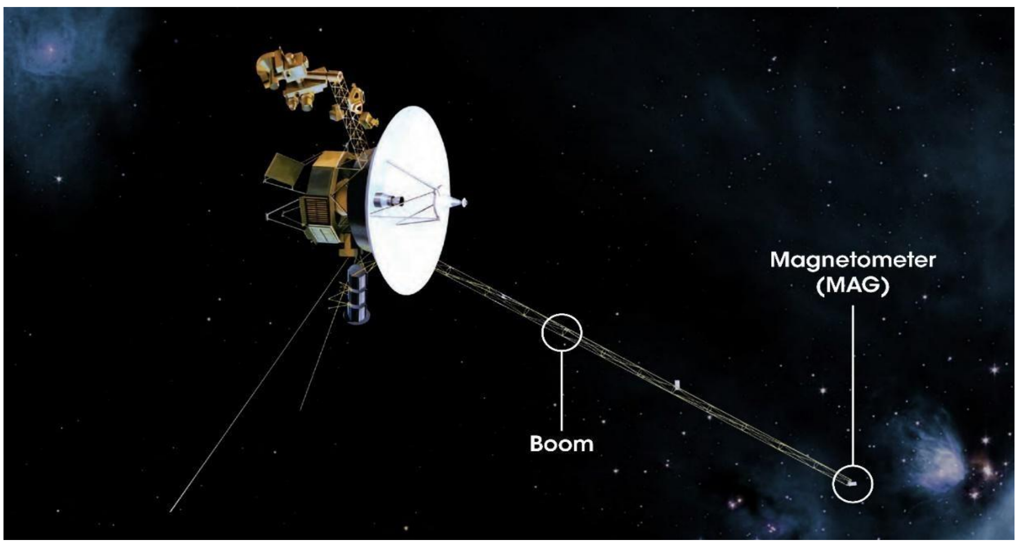


Figure 8. The Voyager spacecraft used magnetometers on long booms to minimize spacecraft noise (Credit: NASA/JPL)

To make high-precision measurements of the magnetic fields that are often very weak, the magnetometer instrument must be placed on a boom that can place it far from the spacecraft's interfering currents and magnetic fields. For example, the magnetometer on each of the Voyager spacecraft shown in Figure 8 was located at the end of a 13-meter-long boom. This was especially important in detecting the very weak magnetic field of interstellar space beyond the orbit of the dwarf planet Pluto.

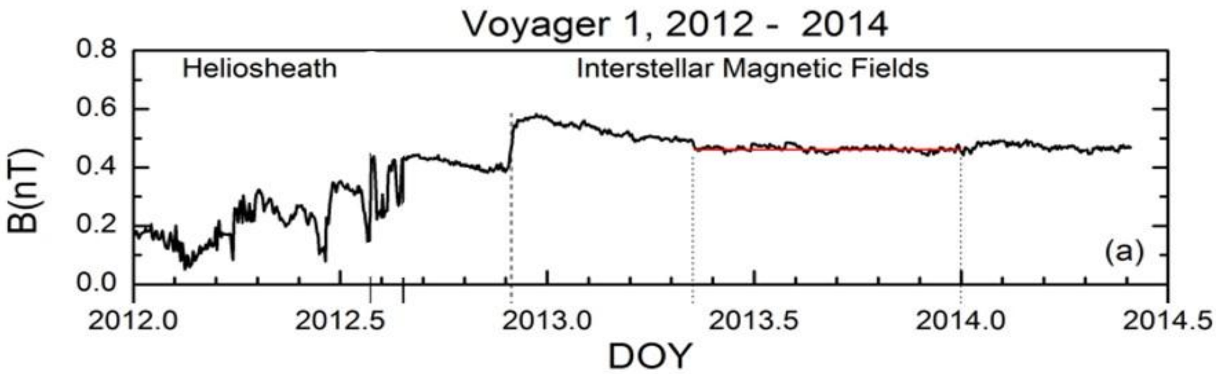


Figure 9. Voyager 1 measurements of very weak interstellar magnetic fields require noise-free conditions, so the magnetometer is placed far from the spacecraft using a boom. (Credit: NASA/JPL)

Figure 9 was created from data taken with the Voyager 1 magnetometer as it traveled away from the Sun between January 2012 and June 2014. Astronomers interpret the data as showing how the magnetic field of the Sun's heliosphere was rapidly changing in intensity up until August 2013 when the Voyager spacecraft reached 121 AU, where 1 AU is the average distance between Earth and the Sun or 150 million km. At this point, all the rapid changes in the magnetic field subsided but reached a considerably higher level near 0.4 nanoTesla. The transition region encountered in August 2012 is called the heliopause. This is where the pressure from the outflowing solar wind and magnetic fields from the Sun are balanced by the pressure of the interstellar medium (ISM). The ISM is a dilute gas of hydrogen atoms and magnetic fields that surrounds all the stars in the Milky Way.

4. Variations in Earth's Magnetic Field

Detecting Geomagnetic Storms

A geomagnetic storm is caused by a cloud of plasma ejected by the Sun called a coronal mass ejection or CME. If CMEs are directed towards Earth in its orbit, they can arrive within two to three days and compress Earth's magnetic field. This causes disturbances in the geomagnetic field that can be detected at ground-level by sensitive magnetometers. Although Earth's ground-level field has a strength of about 50-60 microTesla (μT), geomagnetic 'storms' caused by CMEs can cause changes up to 2.0 μT, especially at northern and southern latitudes near the Arctic and Antarctic Circles.

The typical magnetic signature during a geomagnetic storm will be a change by about 1 μT over the course of three to six hours. This measurement can be challenging to make but is a valuable exercise to help students learn about local sources of magnetic noise and the sensitivity of smart device systems. In previous experiments, students have explored environmental variables that can affect magnetic field measurements, including common household electric devices, magnetite/lodestone deposits, and high-voltage power lines.

Scientists track the severity of a geomagnetic storm by using the global, planetary K index called the Kp index. This index is created by measuring the changes in Earth's magnetic field at dozens of magnetic observatories around the world. These changes are indicated on a 10-point scale from 0 to 9 and averaged at each observatory every three hours. When the individual observatory data is combined and averaged from around the world, the result is the Kp index. Figure 10 shows the changes in the Kp index during a severe geomagnetic storm on October 30, 2003. Figure 11 shows the actual magnetic observatory data for this storm recorded at the Sitka Magnetic Observatory in Alaska.

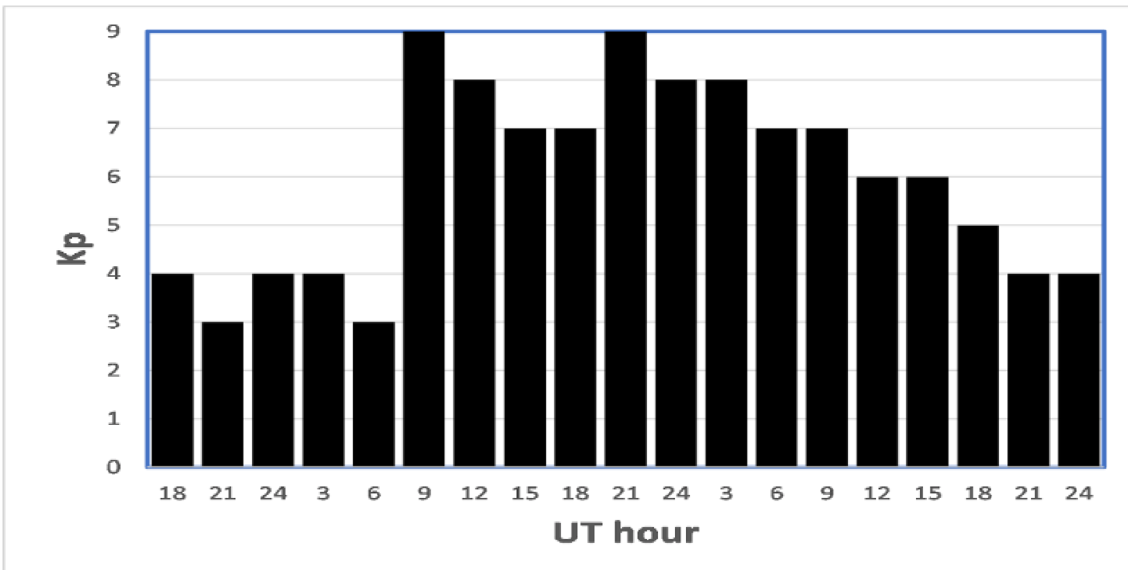


Figure 10. Kp index of the October 28-31, 2003 storm. Values near 1-2 are for quiet conditions but values above 7 indicate severe geomagnetic storm conditions. The data is averaged in 3-hour intervals.

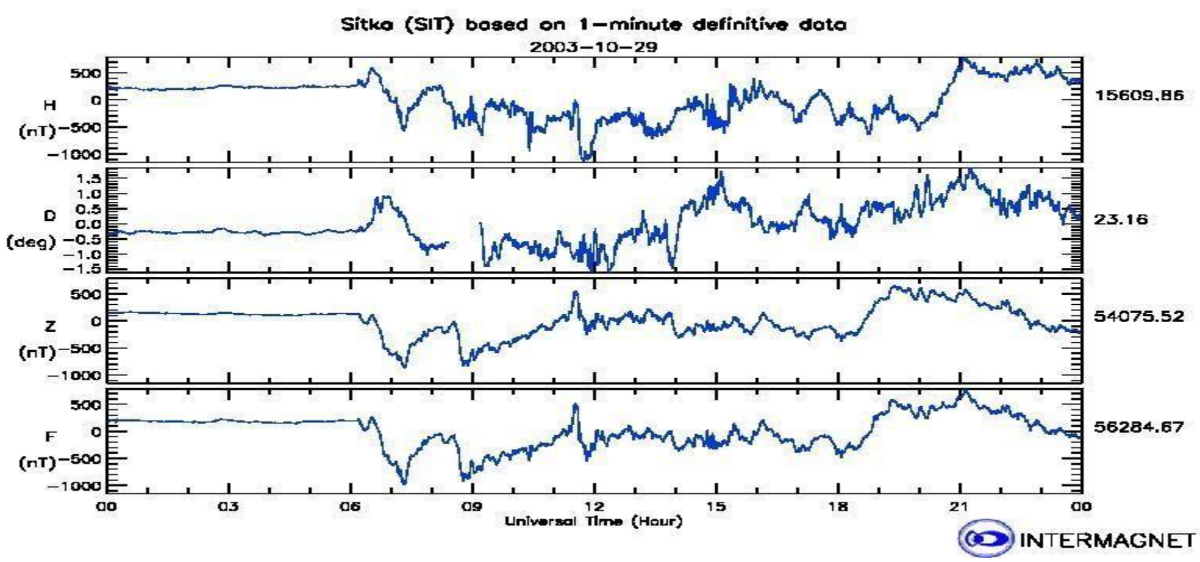


Figure 11. Magnetic trace of the October 28-31, 2003 storm. The 'D' value gives the magnetic compass deviation caused by the storm, which can be as large as 1.5 degrees of error in the bearing. (Credit: INTERMAGNET).

Variability on many timescales

Changes in Earth's magnetic field occur at many distinct intensities and durations in time. Table 2 shows some examples of the kinds of changes that are the most common. The Kp scales are related to the variability detected at the magnetic observatory in Boulder, Colorado at mid-latitudes (technically called the local K index for that observatory), but the magnetic measurements given in units of nanoTeslas would be 2-3 times stronger at higher latitudes such as Alaska. Also shown by the geomagnetic storms is how often they will be seen during a typical Sunspot cycle. For example, in the case of the Kp = 9 Extreme Storm events, the third column indicates '4/c' which means four events per 11-year sunspot cycle.

From Table 2 we see that many of the strong magnetic changes detectable with simple magnetometer technology will only be seen every few weeks (Kp> 5) but during Sunspot maximum, the weaker storms below Kp = 4 are so numerous they will be seen every few days. These conditions commonly occur due to irregularities in the solar wind, which cause a varying pressure on the geomagnetic field that leads to magnetic field changes.

Table 2. Common types of geomagnetic variability

Type	Intensity change (nT)	Frequency (Storms per cycle)	Time interval
Kp=9 (G5) Extreme storm	**>500**	**4/c**	**Yearly**
Kp=8 (G4) Severe storm	**300 – 500**	**100/c**	**Few months**
Kp=7 (G3) Strong storm	**200 – 300**	**200/c**	**Monthly**
Kp=6 (G2) Moderate storm	**100 – 200**	**600/c**	**Few weeks**
Kp=5 (G1) Minor storm	70 – 100	2000/c	Few weeks
Kp = 3-4 Disturbed conditions	40 – 70		Few days
Kp = 0-2 Calm conditions	10 – 40		Daily
High-voltage transmission line	Up to 5000	50-60 cycles/sec	0.02 seconds
Geomagnetic pulsations[1]	1 to 500	5 to 600 seconds	Daily
Ionospheric Sq current (By)	20 to 100	24 hours	Daily
Lightning [2]	0.1 to 2	100-1000 per storm	Seasonal

[1] https://www.researchgate.net/figure/Classification-of-geomagnetic-pulsations_tbl2_252545529

[2] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020GL091507

5. How often do strong storms occur?

How often should you expect to see a strong geomagnetic storm that your soda bottle magnetometer can detect? It all depends on how active the Sun is.

Magnetic storms are spawned by violent events in the solar corona that send clouds of plasma called Coronal Mass Ejections (CMEs) into interplanetary space. If Earth happens to be in the wrong place in its orbit, within a few days, these million-kilometer-per-hour plasma clouds reach Earth and impact its magnetic field. Many physical processes are then caused as the CME particles and magnetic fields invade Earth's magnetic field. Magnetometers on the ground then notice complex magnetic field changes that last until the CME plasma passes Earth. The magnetic field then returns to normal. Major magnetic storm events also lead to spectacular auroral displays even at low geographic latitudes.

As we approach the maximum of sunspot cycle #25 (SC25) between 2024 – 2025 shown in Figure 12, there will be many opportunities for observing magnetic storms and auroras, provided you are equipped to do so. The current sunspot cycle called SC25 is now predicted to be a strong cycle. Predictions based on the change in sunspot counts by March 2024 suggest it could be as strong as cycle SC23.

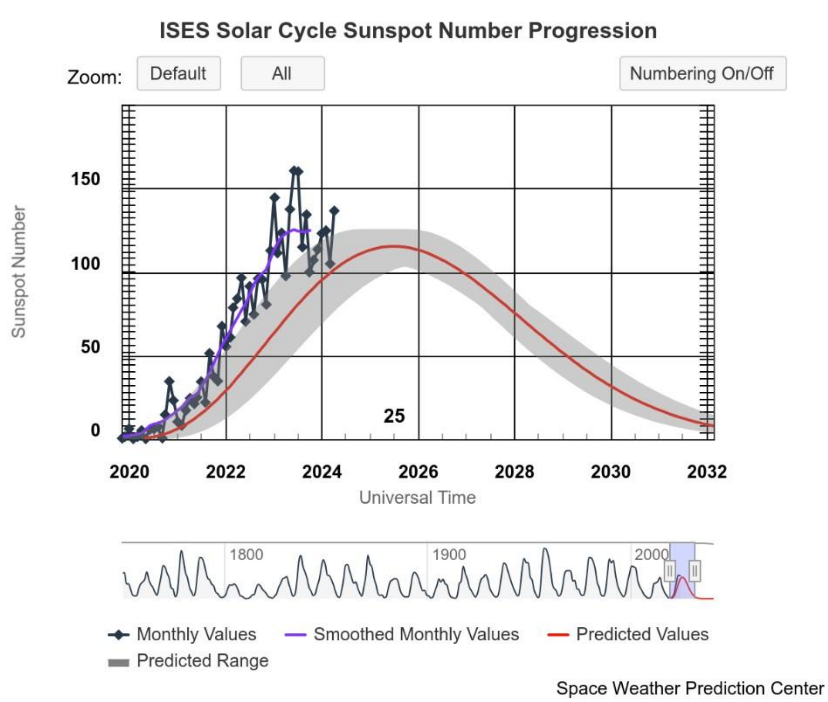


Figure 12. The current and predicted status of sunspot cycle 25. (Credit: NOAA/SWPC)

A complete archive of Kp indices going back to 1932 covers the last 8 sunspot cycles with measurements recorded every 3 hours through the present time. From this archive we can calculate for other strong cycles such as SC17, SC20 and SC23, how frequent storms are at the various levels. A soda bottle magnetometer is sensitive enough to detect events with Kp > 5. Table 3 summarizes the number of these 3-hour events averaged for the three sunspot cycles during each year of their 11-year sunspot cycles.

Table 3. The number of 3-hour events exceeding specific Kp levels.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
NOAA =	**Calm**			**Mild**	**G1**	**G2**	**G3**	**G4**	**G5**
Year	**Kp≥1**	**Kp≥2**	**Kp≥3**	**Kp≥4**	**Kp≥5**	**Kp≥6**	**Kp≥7**	**Kp≥8**	**Kp=9**
0	931	755	548	247	91	21	5	1	0
1	1034	717	426	189	60	19	6	1	0
2	958	668	456	202	71	42	15	4	1
3	876	706	495	264	111	40	12	4	1
4	748	754	589	305	107	60	19	8	1
5	849	799	533	255	85	70	30	8	1
6	801	763	605	286	113	79	31	8	2
7	619	722	648	416	205	95	34	11	3
8	748	777	619	310	105	74	42	19	4
9	722	699	618	371	175	98	33	13	5
10	711	666	594	380	170	63	15	3	0
11	756	671	561	357	156	50	9	1	0
	Too weak for soda bottle				**Strong enough for soda bottle detection**				

For example, the cell corresponding to Column 7 for the year '2' says that there was an average of 42 events during sunspot cycle year 2 for which Kp was at a level of 6 or higher (Kp ≥6). A Kp of 6 corresponds to the NOAA geomagnetic storm scale of G2, which means a Moderate storm event. According to the G2 scale, high-latitude power systems may experience voltage alarms, and long-duration storms may cause transformer damage. Corrective actions to spacecraft orientation may be required by ground control, changes in drag affect orbit predictions. High-frequency radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho. [NOAA Scales: https://www.swpc.noaa.gov/noaa-scales-explanation]. Another way to look at the data in Table 3 is to calculate the average time between these events by dividing 365 days by the number in each cell. For example, with 42 events at Kp≥6, the average time between events during Year 2 was 365d/42 = 9 days. This means your magnetometer will see about one of these during a typical week in Year 2 of the Sunspot cycle.

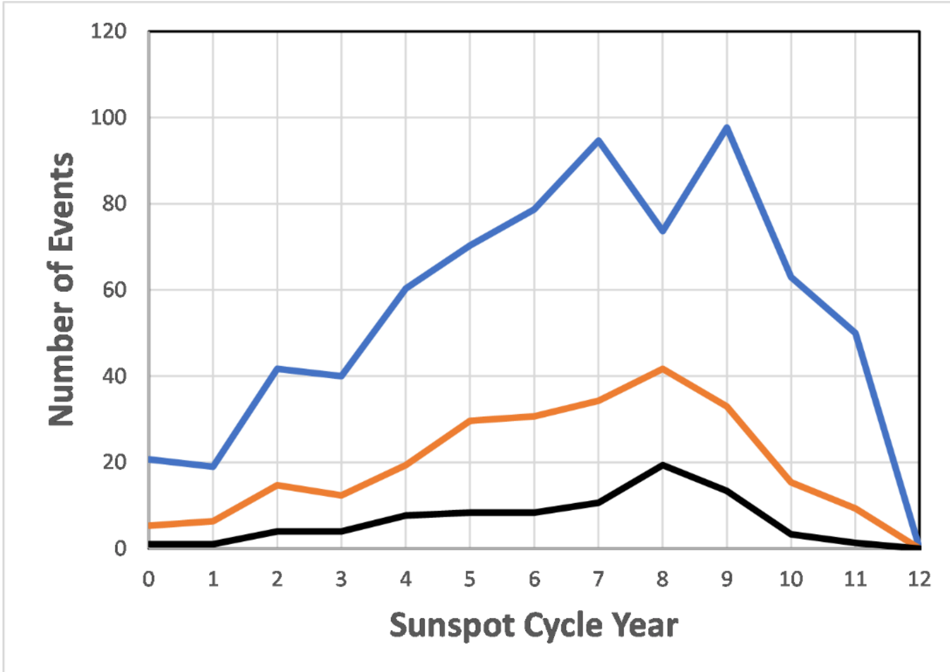


Figure 13. Average event frequency for strong geomagnetic storms. Blue line = Kp≥6; Red line = Kp ≥7; Black line = Kp≥8

Figure 13 also presents this data graphically. The typical time between these events is found by dividing 365 days by the value on the Y-axis. Note that a Sunspot cycle starts out with these events few and far between, but by Year-8 of the Sunspot cycle, typically 1-2 years after Sunspot maximum, these events are near their maximum frequency. For the current Sunspot SC25, it began in December 2019, so in April 2023 we are currently in Year 4 of the cycle. The graph shows that we might expect to see 8 events with Kp≥8 (black line) and about 60 events with ≥6 (blue line).

A geomagnetic storm consists of multiple Kp events. In terms of actual storms, there are typically 2 events per storm with Kp≥8, so we might expect to see 8/2 = 4 of these Kp≥8 storms during the year for an interval between storms of about 3 months. For the weaker Kp≥6 events, the 60 events expected for Year 4 correspond to approximately 15 storms for an interval of about 1 month between these storms. This means that during any given week of Year 4, you only have a one-in-four chance of seeing your soda bottle magnetometer react to a geomagnetic storm. To improve your odds, it is best to use a space weather service such as *NOAA's Space Weather Prediction Center* shown in Figure 14 to see if there are any storms brewing in the next few days, then target your measurements to the time when an aurora event is being predicted for your area. There are also apps available for your smart device that will alert you when the Kp index reaches specific storm thresholds.

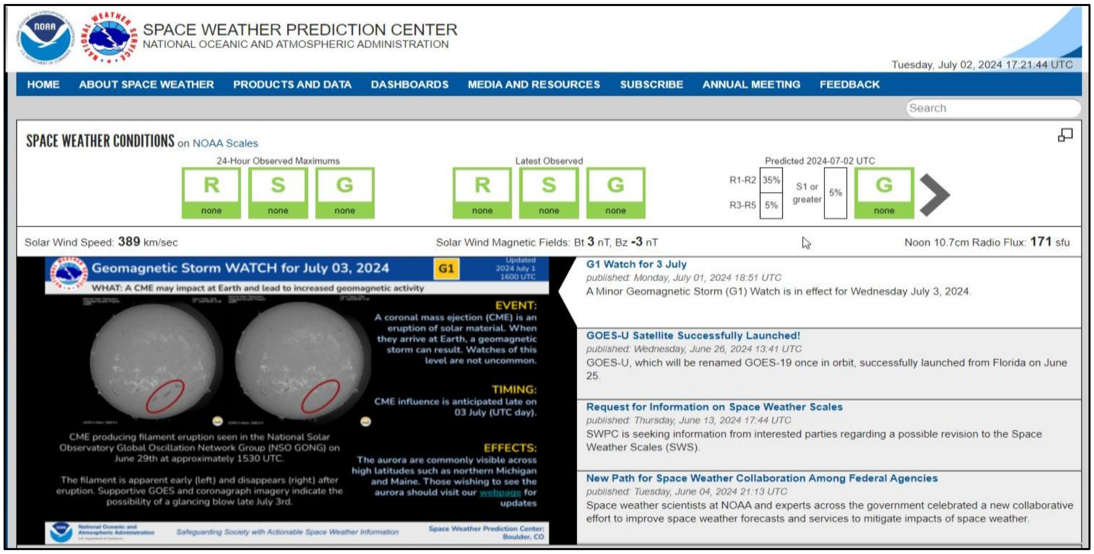


Figure 14. Example of an announcement for July 2, 2024.