1 Why Solar Cycles Occur

The solar cycle is the direct result of the Sun's very "twisted and tortured" magnetic field illustrated in Figure 1. Looking at how the Earth's stable well behaved magnetic field forms helps us to better understand the ciaos occurring on the Sun.

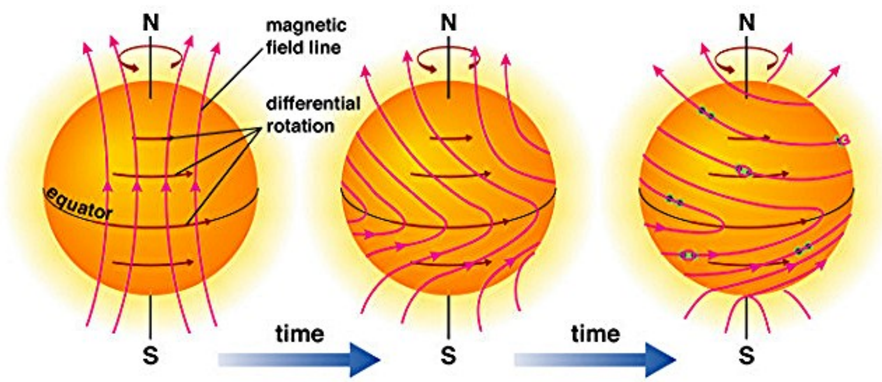


Figure 1 The Sun's twisted and tortured magnetic field (credit: skyandtelescope.com)

2 The Earth's Magnetic Field

The structure of the Earth and its internal temperature profile are shown in Figure 2 and Figure 3 respectively. The Earth's curst ranges from 5 – 70 km in depth. Below the curst the Earth's mantle extends to a depth of 2,890 km, making it the thickest part of the Earth. The mantle consists of silicate rocks rich in iron and magnesium. The outer core is composed of nickel-iron so hot that it is in a molten state. The high temperature ionizes some of the nickel-iron atoms creating an electrically charged plasma. Temperatures in the Earth's inner core are even higher. However, instead of being liquid as one would expect, the inner core is compressed into solid nickel-iron by the Earth's gravity.

Thermal convection currents within the outer core transport hot molten nickel-iron from just above the inner core to the mantle as shown in Figure 4. The molten nickel-iron cools as it rises toward the mantle, becomes more dense, and gradually sinks back toward the inner core. As it sinks it is heated by the intense thermal radiation from the inner core. The molten nickel-iron expands, becomes buoyant, and again drifts outward toward the mantle beginning a new convection cycle.

Since the hot molten nickel-iron is a plasma, with an abundance of positively charged ions and negative electrons, the convective flow of this plasma creates circulating electrical currents within the outer core.

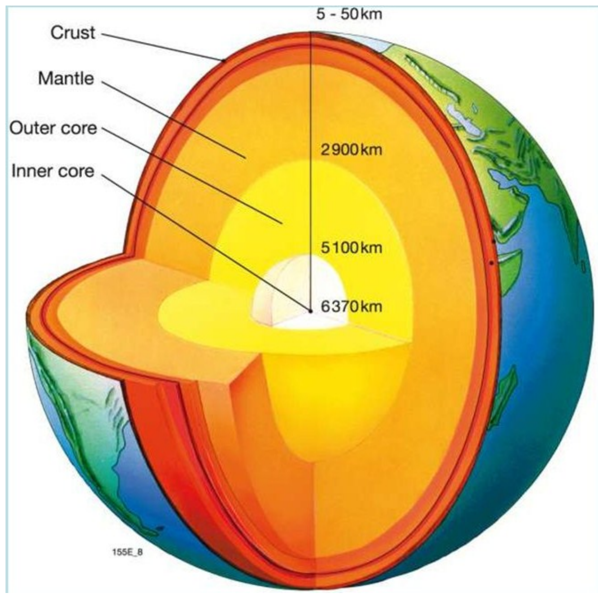


Figure 2 The Earth's Interior Structure (credit: Lakshya Geography)

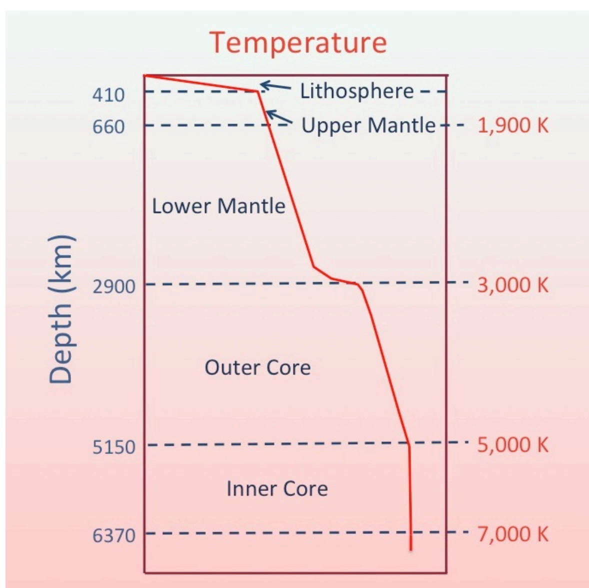


Figure 3 Temperature Profile of Earth's Interior (credit: Wikipedia)

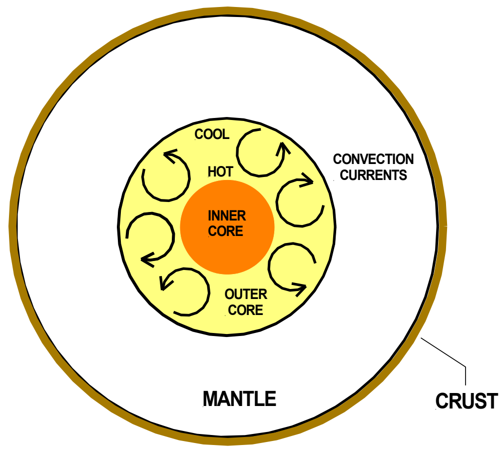


Figure 4 Outer Core Convection Currents (credit: author)

The electrical currents create a magnetic field in accordance with Ampere's Circulation Law. In this case, the Earth's magnetic field illustrated in Figure 5. Note that this field is created deep within the Earth. The Earth's magnetic field changes slowly over time, but is stable for millions of years.

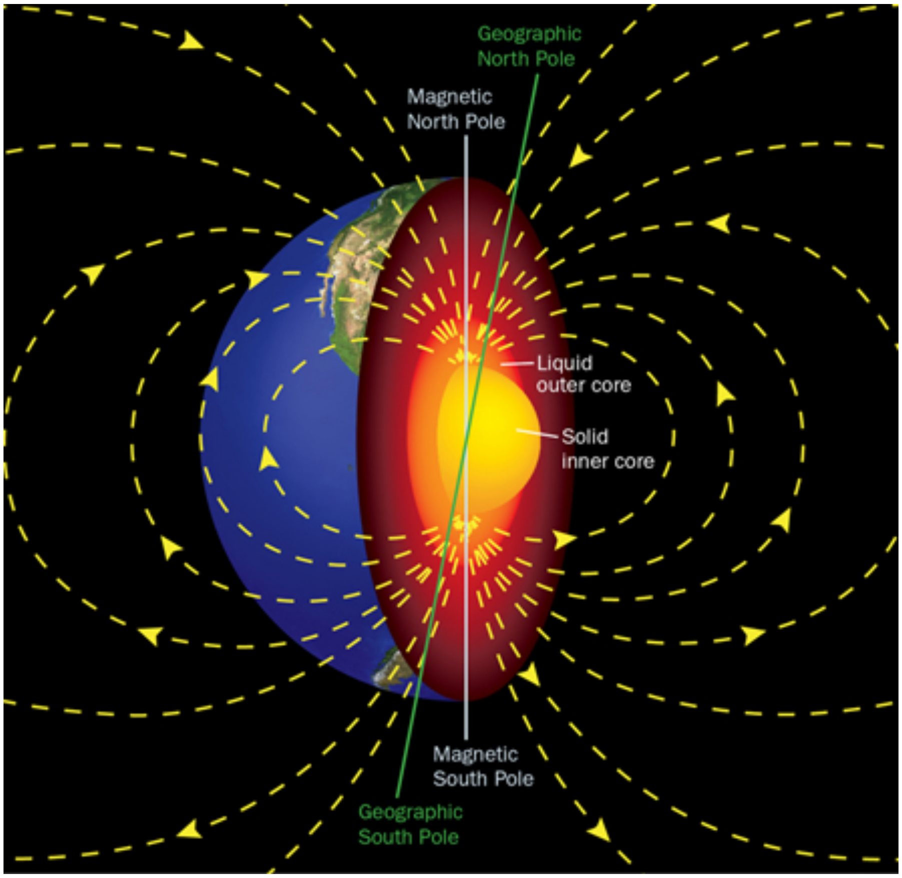


Figure 5 Earth's Magnetic Field (credit: Quora)

The Earth's magnetic field is very important to us. As shown in Figure 6, it creates a protective sheath around the Earth diverting the Sun's harsh solar winds away from Earth's surface.

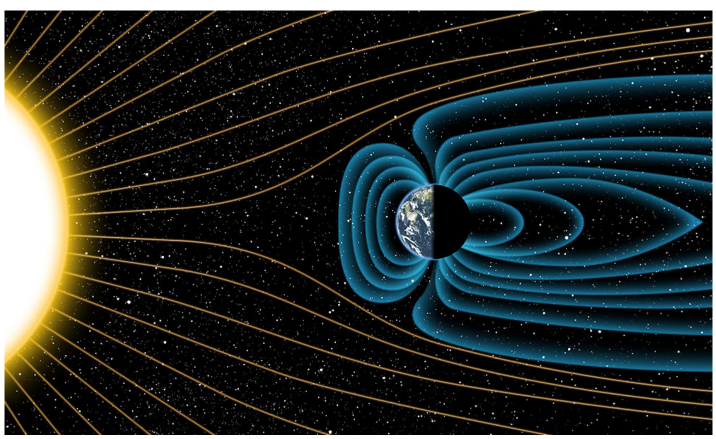


Figure 6 Earth's protective magnetic field (credit: University of Rochester)

Mars was once similar to the Earth. It had rivers, lakes, and even an ocean or two. Like Earth it too had a magnetic field created by its hot convective core. But Mars is much smaller than Earth and consequently cooled quickly. As it cooled its convective core also cooled and solidified. Once solidified the core could no longer produce the circulating electrical currents needed to generate its magnetic field. So Mars lost its magnetic field exposing the planet to the full fury of the solar winds. The winds stripped Mars of its atmosphere, dried up its lakes and oceans, and left Mars a dead planet.

This leads to an important conclusion. To have a magnetic field a planet must have a hot convective region of circulating electrical currents somewhere within the planet. This same criteria applies to the Sun as well.

3 Formation of the Sun’s Magnetic Field

The Sun consists of the 6 major regions shown in Figure 7:

- Core,
- Radiation zone,
- Convection zone,
- Photosphere,
- Chromosphere, and
- Corona

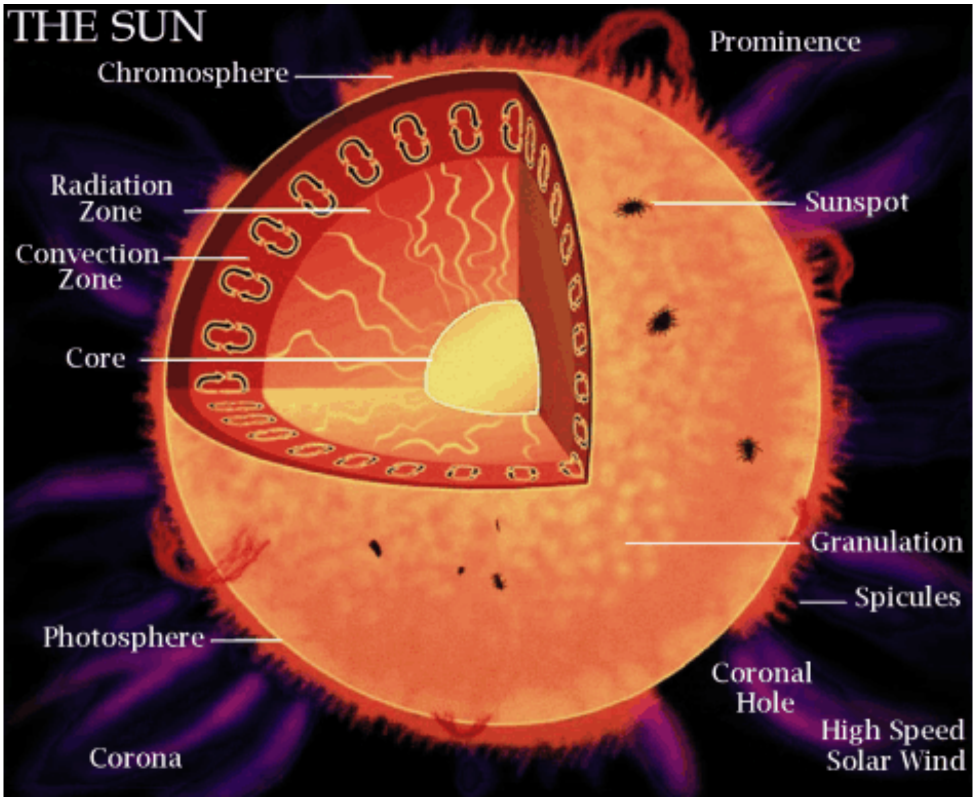


Figure 7 The Sun (credit: NASA).

The photosphere is the visible surface of the Sun, the part of the Sun that radiates the light that we see. The photosphere emits 99% of the Sun's light and heat. The intensity of this radiation decreases rapidly from the base to the top of the photosphere, a distance of only 500 km. The rapid change in intensity over a such a short distance gives the Sun a sharp well defined outer edge, instead of a fuzzy edge that one might expect from a large ball of gas. The fact that the photosphere is the furthest that we can see into the Sun, coupled with the Sun's sharp edge, gives the impression that the photosphere is the Sun's surface.

We assume that the photosphere is a very dense, almost "hard", layer of gas since we perceive it to be the Sun's surface. However, that is not the case at all. The photosphere's density is about 10,000 times less than Earth's atmosphere at sea level. Since the density of the photosphere is so low, why can we not see through the photosphere? We actually can. In Figure 8 we can see a sunspot and granules at the boundary between the photosphere and the underlying convection zone. The granules are hot plasma bubbling up from deep within the convection zone. The convection zone is so hot that it is opaque, preventing us from seeing any further into the Sun.

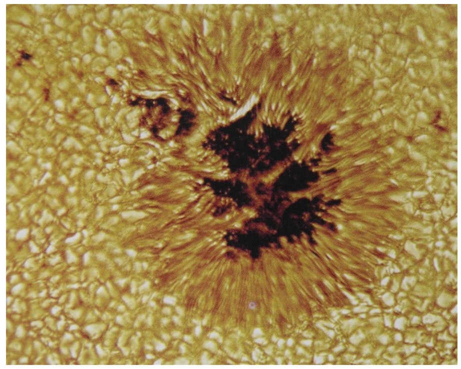


Figure 8 Sunspot and granules at base of the photosphere (credit: spaceweatherlive.com)

We think of the corona and chromosphere as the Sun's "atmosphere" since we can see through both of these regions to the photosphere below. The photosphere is so bright that we can only see the chromosphere and the corona during a full solar eclipse. The thin red ring seen around the edge of the Sun in Figure 9 is the chromosphere while the white halo is the corona. The white appearance of the corona is formed by intense sunlight from the photosphere reflecting off dust particles in interstellar space surrounding the Sun.

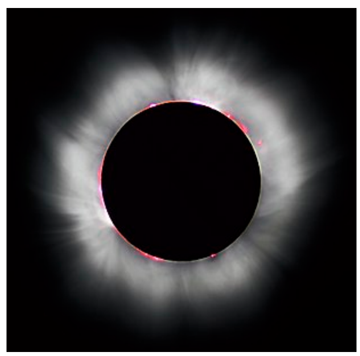


Figure 9 Full solar eclipse (credit: Wikipedia)

The chromosphere can be directly seen by observing the Sun through a telescope equipped with a hydrogen-alpha filter. Figure 10 shows the intricate structure visible in the chromosphere.

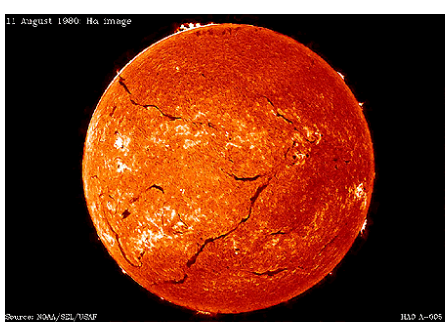


Figure 10 Chromosphere seen in H-alpha light (credit: NOAA)

Unlike the Earth, the Sun is composed almost entirely of hydrogen and helium gas.

	% By Mass	**% By Abundance**
Hydrogen	71	92.1
Helium	27	7.8
All Other	2	0.1
Oxygen		*0.061*
Carbon		*0.030*
Nitrogen		*0.0084*

Table 1 Sun's Composition

The Sun contains trace amounts of all elements in the periodic table.

Gravity resulting from the Sun's immense size squeeze the hydrogen and helium gas into a core where temperatures reach over 15 million degrees kelvin. At these temperatures and pressure thermal nuclear reaction spontaneously occurs converting hydrogen into helium and releasing an enormous amount of energy in the process. The outward flow of energy just balances the inward force of gravity, maintaining the Sun in a stable configuration for billions of years.

The interior of the Sun, shown in Figure 7, is radically different from that of the Earth. Instead of being surrounded by a hot molten outer core of circulating plasma like the Earth, the Sun's core is encapsulated in the radiation zone. A zone which is in essence a very hot thick blanket of hydrogen and helium gas 348,000 km deep. Temperature gradients within the radiation zone guarantee that its plasma of hydrogen and helium ions are frozen in place. There are no circulating electrical currents within the radiation zone to create a magnetic field.

Instead, the radiation zone transports heat in the form of high energy photons away from the core. The density of hydrogen and helium ions in the radiation zone is so high that photons only travel a very short distance before colliding with plasma particles. Because of the continuous collisions and scattering, it takes a photon on the order of 170,000 years to traverse the radiation zone. Photons travel quickly through the convection zone and take only 8 minutes to travel from the Sun's photosphere to Earth. Today's sunlight began its journey in the Sun's core about the time modern man (homo sapien) first appeared on the planet 200,000 years ago. After traveling through all of human history, that sunlight finally arrived today.

The convection zone is much different. The convection zone is similar to Earth's outer core. Hot plasma around 2 million degrees in temperature floats outward from just above the radiation zone, appears as granules at the Sun's surface, cools and sinks back toward the radiation zone. The bright granules shown in Figure 11 is hot plasma "boiling up" from deep within the convection zone. The dark channels around the granules are formed by cool plasma slinking back into the convection zone.

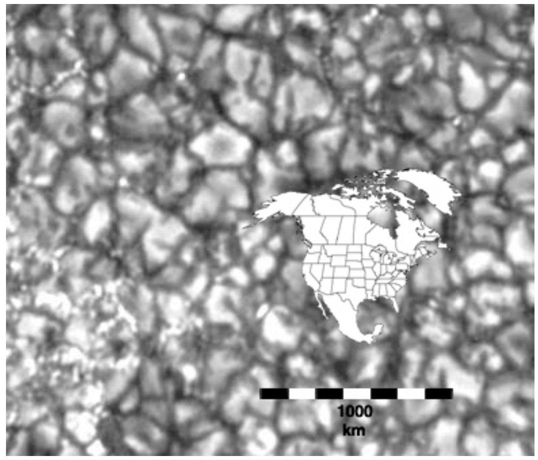


Figure 11 Thermal cells (granules) reaching the photosphere and sinking back into the convection zone. North America superimposed as a reference (credit: Wikipedia)

The hot highly ionized circulating plasma creates strong electrical currents in the convection zone. These electrical currents produce the Sun's magnetic field. But, unlike the Earth, the Sun's magnetic field is formed in the outer part of the Sun, near its surface, instead of deep within the Sun.

That is part of the problem!

The Sun is not solid. It is a huge rotating ball of gas. Furthermore, the gas does not rotate at the same rate. The Sun's equator rotates in 24.5 days while the poles rotate in 34 days. The Sun's rotational rate in days as a function of solar latitude is shown in Figure 12. In contrast, the Earth is solid forcing every point on the Earth to rotate at the same rate, one revolution every 23 hours, 56 minutes, and 4 seconds with respect to distant stars.

Variations in the Sun's rotational rate with latitude is technically referred to as differential rotation. The differential rotation is not just a surface phenomena, it extends down all the way through the convection zone. The radiation zone, on the other hand, appears to rotate rigidly. Its rotational speed is about the same as the photosphere middle latitude rotational rate. A thin layer known as the tachocline forms the transition between the differentially rotating convection and the rigidly rotating radiation zones.

The Sun's differential rotational rate is the other part of the problem.

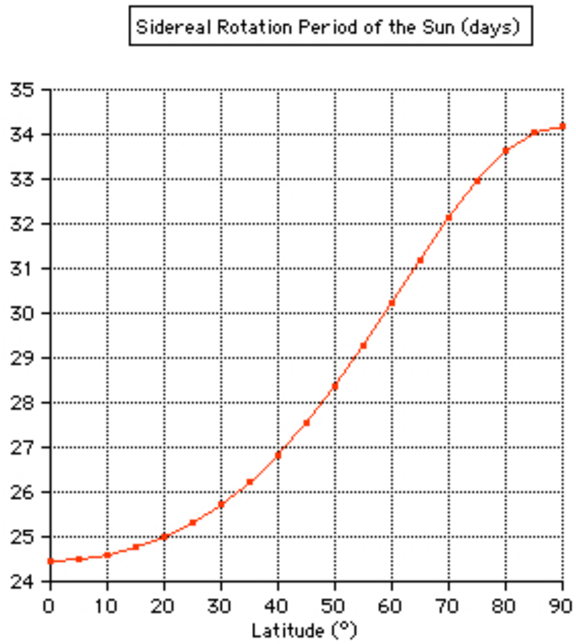


Figure 12 Rotational rate of the Sun (credit: jgiesen.de)

The fact that the Sun's magnetic field is created near its surface, instead of deep within the Sun, coupled with the Sun's differential rotation, causes the Sun's magnetic field to become badly twisted and distorted.

At solar minimum the Sun's magnetic field, shown in Figure 13, is a "quiet" north – south bipolar field similar to that of Earth's magnetic field. The strength of Earth's magnetic field is around 0.2 gauss. At solar minimum the strength of the Sun's magnetic field is about 1.0 gauss. The Sun's quiet magnetic field is not that much different from Earth's magnetic field.

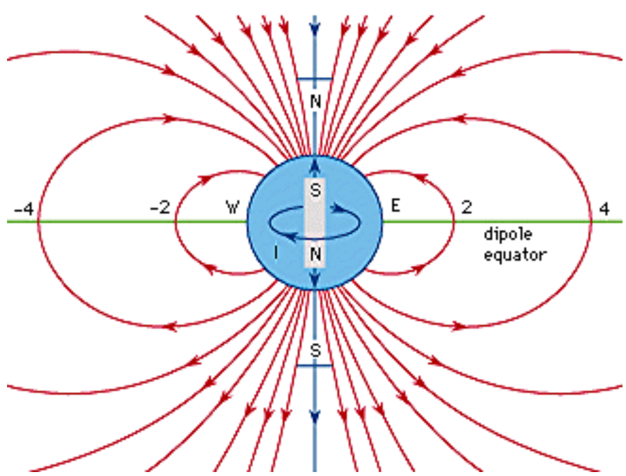


Figure 13 Sun's magnetic field at solar minimum (credit: Encyclopedia Britannica)

However, over a period of 3 to 6 years the Sun's differential rotation slowly drags and winds the magnetic field around the Sun as shown in Figure 14 "a" through "c". The magnetic field at the equator is dragged around the Sun faster than the magnetic field at the poles winding the original bipolar field in Figure 14a into the toroidal field shown in Figure 14c. In addition, convection zone turbulence twists the magnetic field lines into ropes some of which become knotted.

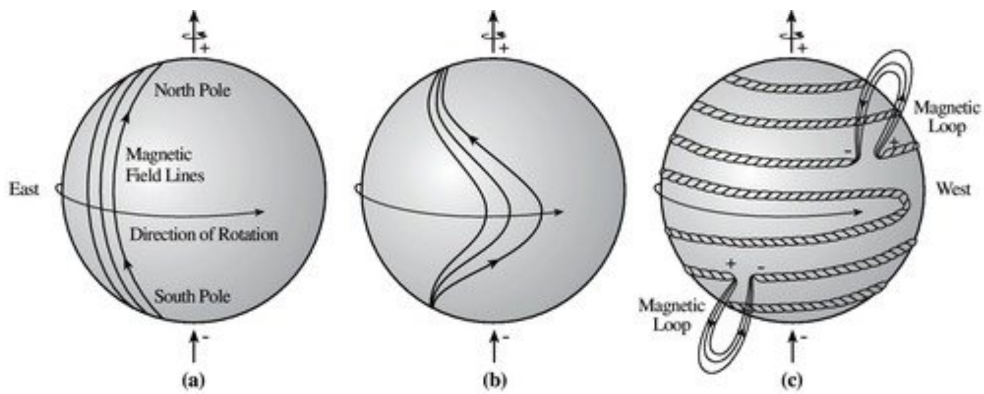


Figure 14 Magnetic field lines become wrapped and twisted around the Sun
(credit: NASA's Cosmos – ase.tufts.edu)

Winding the magnetic field around the Sun in tighter ever increasing number of turns is not a sustainable process. Something has to break, and it does!

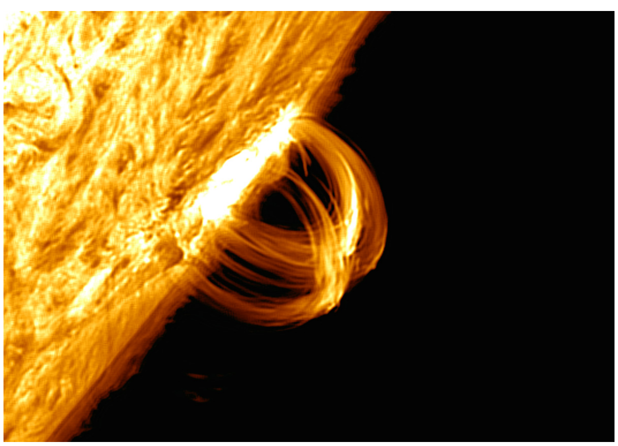


Figure 15 Prominence (credit: Astronomy Magazine)

Continued winding, twisting, and knotting creates tremendous stress in the magnetic field driving field intensities to well over 3,000 gauss.

The enormous stress eventually causes the field to rupture. As it does so high arching prominences, sunspots, and solar flares erupt from the Sun. The Sun reaches solar maximum during this very turbulent phase of the solar cycle with large numbers of sunspots visible on the solar surface.

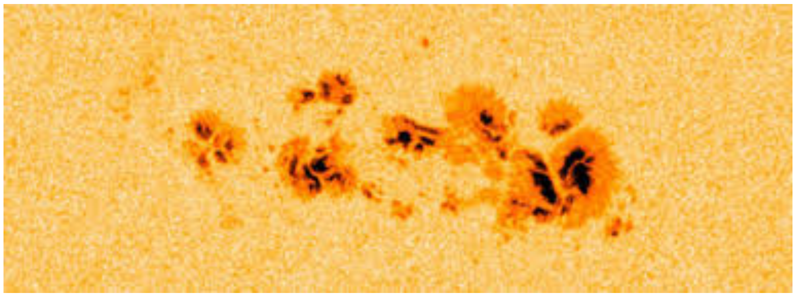
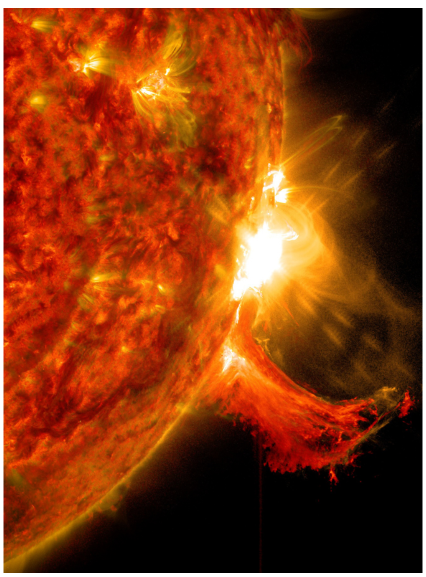


Figure 16 Sunspot Group (credit: SpaceWeatherLive.com)



As the magnetic field disintegrates, sunspots gradually disappear and the Sun again approaches solar minimum with a quiet north-south magnetic field.

However, as the field unwinds, the Sun's magnetic poles flip. What was the north magnetic pole becomes the magnetic south pole, and visa versa. The poles flip again at the end of the next solar cycle producing the 22 year cycle illustrated in Figure 18.

Figure 17 Solar flare (credit: NASA/SDO)

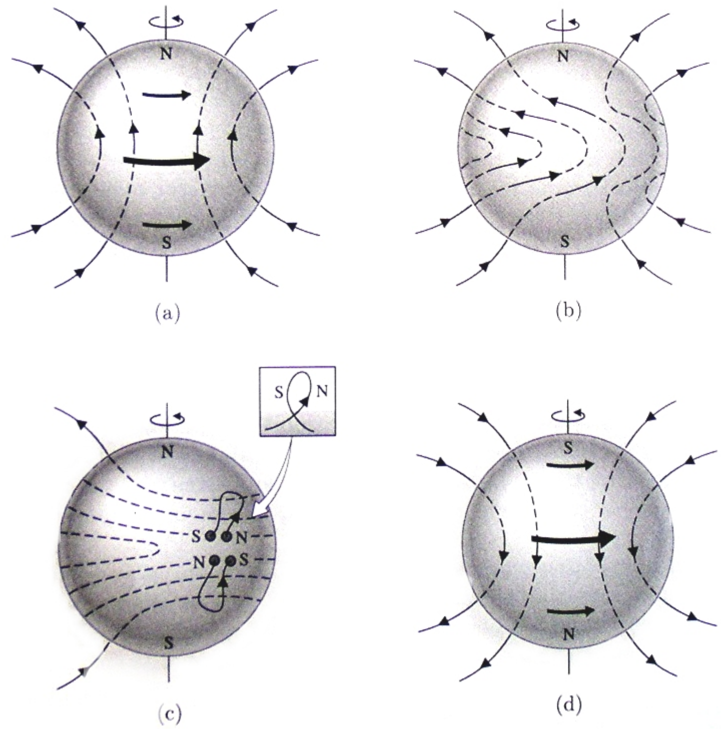


Figure 18 22 Year Solar Cycle (credit: B. Carroll, Modern Astrophysics)

Reversal of Earth's magnetic poles also occurs (the Earth's north and south magnetic poles flip). But, geological evidence, based on magnetic orientation within rocks when they solidified, indicates that reversals occur randomly over periods from 100,000 to 50 million years.

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