

## 1 The Sun's Solar Cycle

Early on it was known that radio signal strength and quality varied throughout the day and seasonally. By 1910 commercial and government radio operators knew that radio signals traveled further at night and were less noisy in the winter.

It was widely believed at the time that the quality and distance of radio transmissions was directly proportional to wavelength. Radio transmissions covered longer distances and were more reliable using long wavelengths instead of short ones. For this reason government and commercial radio stations operated on 50 to 1000 KHz (wavelengths of 6,000 down to 300 meters). Primarily from antenna considerations, the marine distress frequency was established at 500 KHz. A lower frequency would have been better, but lower frequencies meant longer antennas, recalling that wavelength

$$\lambda = \frac{c}{f}$$

where

c = speed of light

f = frequency

Even at 500 KHz it was difficult to get an antenna to fit aboard ship, as clearly indicated in Figure 1.

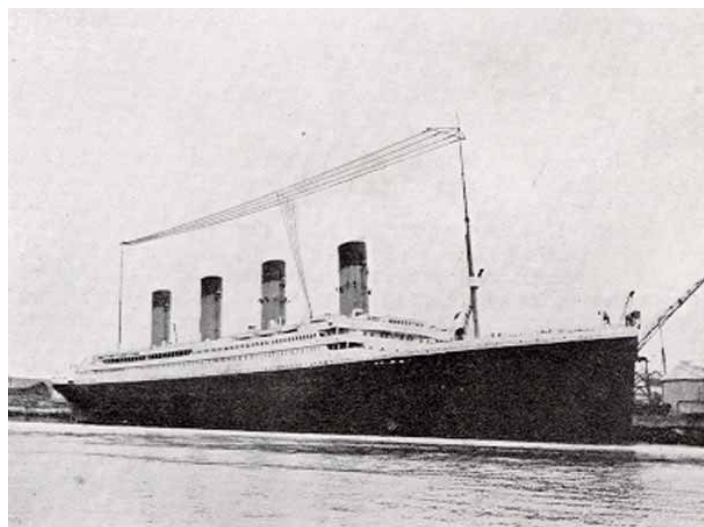
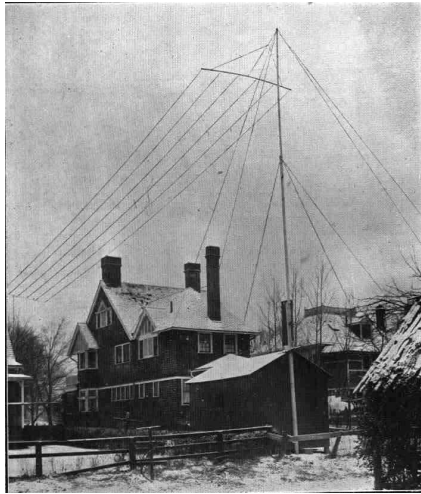
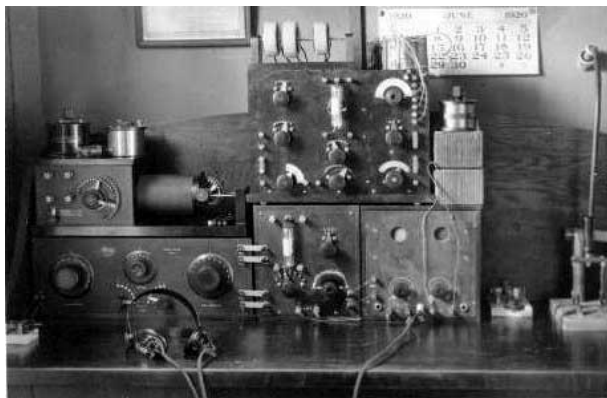


Figure 1 Shipboard antenna (credit: astrosurf.com)

Amateur radio operators were exiled to frequencies in the 200 meter band (approximately 1.5 MHz) so as not to interfere with commercial and government operations. Frequencies at and above 1.5 MHz were considered worthless from a commercial perspective. However, amateur radio operators became very successful operating at these frequencies relaying messages in short hops across country as well as communicating point to point over moderate distances.



(credit: [www.arrl.org](http://www.arrl.org))



(credit: [oldpassions.com](http://oldpassions.com))

Figure 2 Early amateur radio stations

In October 1924 amateurs were given the short wave frequency bands of 80 meters (3.5 – 4.0 MHz), 40 meters (7.0 – 8.0 MHz) and 20 meters (14.0 16.0 MHz). Since radio performance was believed to be better on longer wavelengths, these short wave frequency bands were thought to be even more worthless than 200 meters. Some amateurs reluctantly moved to these new frequencies to avoid crowding on 200 meters. The movement became a stampede when it was discovered that Europe, South America, New Zealand, Japan, and other distant places could be reliably worked on 40 and 20 meters. But the good times came to an end. By 1933 the 20 meter band was completely dead. No one knew why, it just died. Around 1935 the short wave bands came roaring back to life. It gradually became apparent that performance on the short wave bands was tracking the solar cycle.

So, what is the solar cycle? The solar cycle refers to the appearance and disappearance of sunspots over roughly a 11 year period. A cycle is arbitrarily defined to begin at sunspot minimum when few

if any sunspots are visible. Figure 3 shows the Sun at solar minimum (picture on the left) and solar maximum on the right.

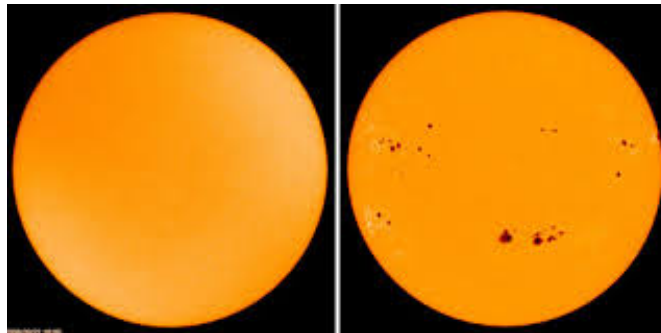


Figure 3 Sun at solar minimum and maximum (credit: springer.com)

Solar cycles from 1755 to the present are shown in Figure 4. The vertical scale on the left side of the graphs is the number of sunspots observed. Note that the

- Amplitude (the maximum number of visible sunspots),
- Shape, and
- Duration

vary considerably from one cycle to the next. For example, 87 sunspots were observed at the peak of Solar Cycle 5 in 1800 while an astounding 295 were visible during the 1957 peak of Solar Cycle 19. A solar cycle typically lasts for 11 years, but can range in duration from 8 to 15 years

Increasing numbers of sunspots appear at a fairly rapid rate as a cycle begins. The solar cycle reaches a maximum in roughly 3 to 6 years with large numbers of sunspots covering the Sun's surface. The number of sunspots then slowly decreases over the next 5 to 8 years reaching a minimum at the end of the cycle.

Continuous daily observations of sunspots began at the Zurich Observatory in 1849. Information collected from earlier observations have been used to extend the records back to 1610 when Galileo Galilei began observing the Sun with a telescope.

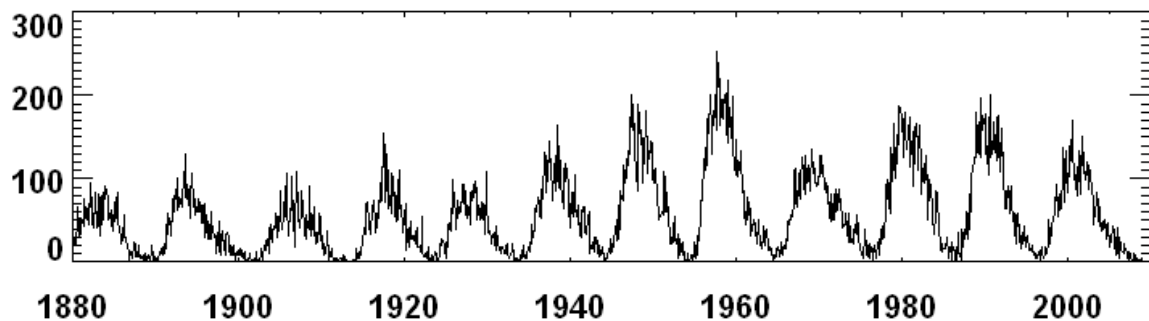
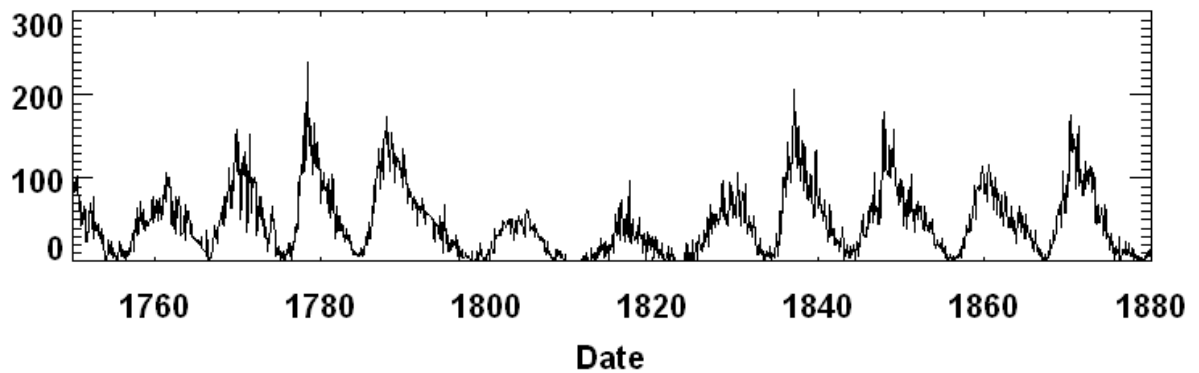
Table 1 lists the solar cycles from 1755 through the present. The solar cycle beginning in 1755 is defined as Solar Cycle – 1.

The table list:

- the year in which a cycle began,
- when it reached solar maximum, and
- when the cycle ended.

The table also shows

- the number of sunspots observed at solar minimum (SN min),
- the number at solar maximum (SN max),
- the number of years to reach solar maximum (T rise years),
- the number of years to again reach solar minimum (T fall years), and
- the total duration of the cycle (Total years).



Solar cycle number 16 peaked in 1928 with excellent long distance communications on 40 and 20 meters. But 20 meters was dead by 1933. In 1935 short wave communications on 20 meters came back, suggesting that short wave radio performance was tied to the solar cycle.

Figure 4 Solar cycles from 1755 to 2010 (credit: SpaceWeather.com)

Solar Cycle #	Begin	Maximum	End	SN min	SN max	T rise years	T fall years	Total years
1	May 1755	Jun 1761	Aug 1766	11.3	150.7	6.08	5.17	11.25
2	Aug 1766	Oct 1769	Jun 1775	16.0	208.9	3.17	5.67	8.83
3	Jun 1775	May 1778	May 1784	11.7	269.6	2.92	6.00	8.92
4	May 1784	Nov 1787	Jun 1798	15.2	239.0	3.50	10.58	14.08
5	June 1798	Dec 1804	Aug 1810	4.6	87.5	6.50	5.67	12.17
6	Aug 1810	Mar 1816	Apr 1823	0.0	84.6	5.58	7.08	12.67
7	Apr 1823	Jun 1829	Aug 1833	0.2	119.2	6.17	4.17	10.33
8	Aug 1833	Feb 1837	Jun 1843	12.4	254.7	3.50	6.42	9.92
9	Jun 1843	Dec 1848	Jan 1856	17.8	223.6	5.42	7.08	12.50
10	Jan 1856	Jul 1860	Apr 1867	6.3	187.1	4.50	6.75	11.25
11	Apr 1867	Jul 1870	Dec 1878	8.2	241.5	3.25	8.42	11.67
12	Dec 1878	Jan 1884	Feb 1890	3.2	130.1	5.08	6.08	11.17
13	Feb 1890	Aug 1893	Sep 1901	6.6	149.1	3.50	8.08	11.58
14	Sep 1901	Oct 1905	Jun 1913	4.8	106.6	4.08	7.67	11.75
15	Jun 1913	Aug 1917	Apr 1923	1.8	186.8	4.17	5.67	9.83
16	Apr 1923	Jun 1928	Sep 1933	9.3	136.7	5.17	5.25	10.42
17	Sep 1933	May 1937	Apr 1944	4.9	199.7	3.67	6.92	10.58
18	Apr 1944	Jun 1947	Apr 1954	10.8	228.3	3.25	6.75	10.00
19	Apr 1954	Nov 1957	Aug 1964	4.7	295.0	3.58	6.75	10.33
20	Aug 1964	Feb 1969	Mar 1976	12.6	157.9	4.50	7.08	11.58
21	Mar 1976	Nov 1979	Sep 1986	18.1	236.6	3.67	6.83	10.50
22	Sep 1986	Sep 1989	May 1996	14.1	217.9	3.00	6.67	9.67
23	May 1996	Nov 2001	Dec 2008	11.1	185.1	5.5	7.08	12.58
24	Dec 2008	Mar 2014		2.2	118.2	5.25		
25								
			<b>Average</b>	8.7	183.9	4.38	6.69	11.03

Table 1 Table of Solar Cycles (adapted from D. Hathaway)

Sunspot numbers are more difficult to determine than might be expected. If you look at the Sun through a low power home telescope, **with a strong solar filter carefully attached to the telescope to protect your eyes**, you might see three or four large sunspots. A high powered observatory telescope may see 10 to 20 sunspots, while a solar telescope in orbit could observe perhaps 50 to 100 sunspots.

So what is the correct number of sunspots, and more importantly, how do we correlate today's numbers with sunspot observations made more than a hundred years ago? The equation used today

in determining daily sunspot numbers (the number of sunspots seen on a given day) is based on a formula derived by Rudolph Wolf in 1848. This equation is

$$R = k(10g + s)$$

where

$R$  = the relative sunspot number

$g$  = the number of sunspot groups observed on the solar disk

$s$  = the total number of individual spots observed, including those in sunspot groups

$k$  = a variable scaling factor

The scaling factor  $k$  accounts for observing conditions and the particular telescope used. Wolf set  $k = 1$  for the observations he made with his telescope at the Zurich observatory in 1849. Each observatory has its own assigned value of  $k$  which scales its observations to what Wolf would have observed using his 1849 telescope. Today  $k < 1$  for most observatories, generally much less than 1.

Data from many different observatories, each with their own value of  $k$ , are combined together to arrive at a daily sunspot number. Two official sunspot numbers are in common use:

1. The daily “Boulder Sunspot Number” computed by the NOAA Space Environment Center
2. The “International Sunspot Number” published by Solar Influences Data Center in Belgium.

Two other sunspot numbers are important in addition to the daily sunspot number. These are

- The monthly mean sunspot number  $R_m$ , and
- The smoothed monthly sunspot number  $R_s$ .

The monthly mean sunspot number is the average number of sunspots for the month. That is, the monthly mean sunspot number is

$$R_m = \frac{R_1 + R_2 + R_3 + \cdots + R_n}{n}$$

where

$R_1$  = the daily sunspot number for the first day of the month

$R_2$  = the daily sunspot number for the second day of the month, etc.

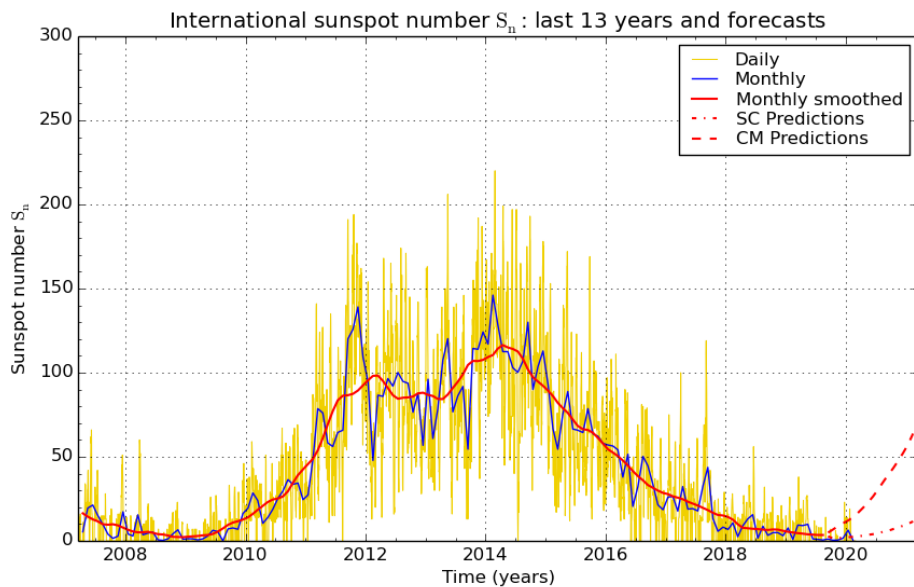
$n$  = the number of days in the month

The smoothed monthly sunspot number  $R_s$  is the average of the monthly mean sunspot numbers over 13 months from 6 months before to 6 months after the month of interest  $m$ . All months have the same weighting except for the first and last months in the series ( $R_{m-6}$  and  $R_{m+6}$ ) each of which is given a weighting of one half (0.5). Thus the smoothed monthly sunspot number

$$R_s = \left( \left[ \sum_{m-5}^{m+5} (R_m) \right] + 0.5R_{m-6} + 0.5R_{m+6} \right) / 12$$

The smoothed monthly sunspot number is one of the most widely used index in ionospheric work.

Figure 5 compares the daily (yellow), monthly mean (blue), and smoothed monthly (red) sunspot numbers for Solar Cycle 24.



SILSO graphics (<http://sidc.be/silso>) Royal Observatory of Belgium 2020 March 2

Figure 5 Solar sunspot numbers for Solar Cycle 24 (credit: SILSO graphics <http://sidc.be/silso>)

While the Wolf equation is simplistic, it compares remarkably well with more complex measurements of solar activity based on current technology.

One of the techniques extensively used today is background radio noise known as the Solar Flux Index (SFI). Random collisions of electrons with heavier particles produces this continuous solar radio noise which is measured by observatories every day at a frequency of 2,800 MHz (10.7 cm wavelength). The Solar Flux Index correlates well with measured levels of solar X-ray and Extreme

Ultra Violet (EUV) radiation. It also correlates remarkably with sunspot numbers as illustrated in Figure 6. In addition, Solar Flux Index is an excellent indicator of ionospheric conditions, including HF radio propagation through Earth's upper atmosphere. SFI numbers vary from a low of about 65 during solar minimum to around 225 at the peak of a solar cycle.

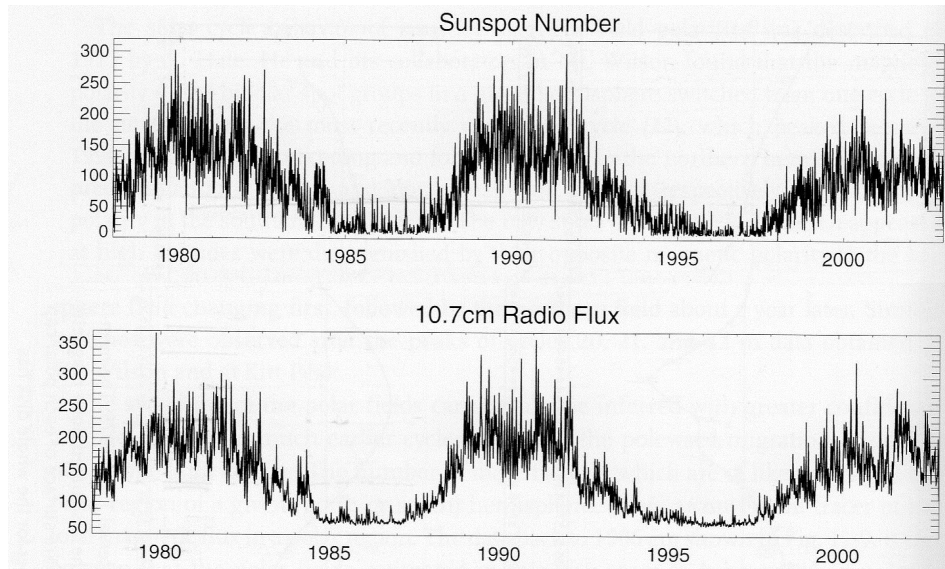


Figure 6 Radio flux vs Sunspot number (credit: G. deToma)

## 2 HF Skywave Propagation

In 1924 Edward Appleton proved that HF communications occurred by skywave propagation through Earth's upper atmosphere as illustrated in Figure 7

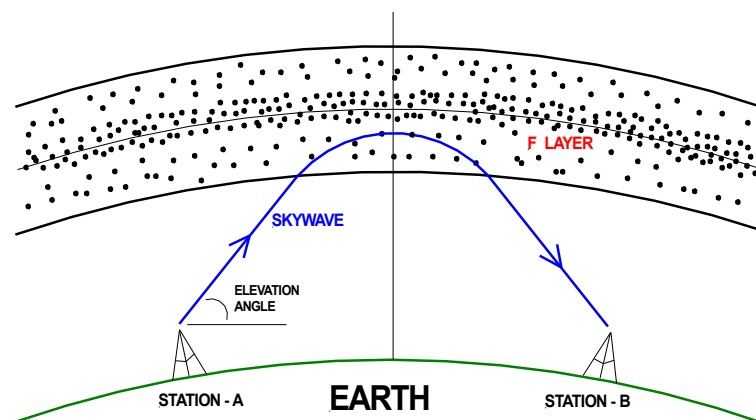


Figure 7 Skywave propagation (credit: author)



Prior to Appleton's experiments, no one really knew how radio communications occurred. It just did. There were many theories proposed by renowned scientists at prestigious universities, but none of the theories actually matched what was happening. For some time there had been suggestions that an electrified layer existed in Earth's upper atmosphere which radio waves reflected off of. But there was no experimental evidence that such a layer actually existed.

In April 1924 Appleton studied the strength of radio signals received at Kings Collage, located in Cambridge, from the powerful London BBC radio station. Cambridge is about 80 km north-east of London. Appleton discovered that signal strength was constant during the day but varied at night. He theorized that at a night he was receiving two signals, one traveled along the ground and the other reflected from the upper atmosphere. The variation at night he concluded was the result of interference between the two signals. During the day only one signal was being received, the signal traveling along the ground. The other signal was absorbed by the upper atmosphere and thus could not be heard. Further investigations showed that at night the long wavelength signal transmitted by the BBC station was reflected from atmospheric ionization about 90 km above the Earth. Appleton referred to this electrified region as the E-layer, E standing for electrified. Appleton later discovered that short wave radio signals passed through the E-layer and were reflected from what he called the F-layer about 200 km above the Earth.

After the 40 and 20 meter rollercoaster experience from 1924 – 1935, the question became: why the number of sunspots on the Sun, or lack there of, had such a tremendous impact on skywave radio communications? To answer this question we first need to know two things:

1. How the ionosphere forms in the Earth's upper atmosphere
2. Why the ionosphere causes radio signals to bend back to Earth.

## **2.1 Formation of the Ionosphere**

Extreme Ultra Violet (EUV) and X-ray radiation from the Sun ionizes atoms in the upper atmosphere. How does that occur? Solar radiation is absorbed by a neutral atom transferring energy to its electrons. Occasionally, an electron is sufficiently energized that it breaks away from its parent atom forming a free electron and a positive ion (an atom that has lost one of its electrons) as illustrated in Figure 8.

Occasionally is the operative word. There are 1,000 times more neutral atoms in the upper atmosphere than ions. Consequently, the ionosphere is very thin and wispy.

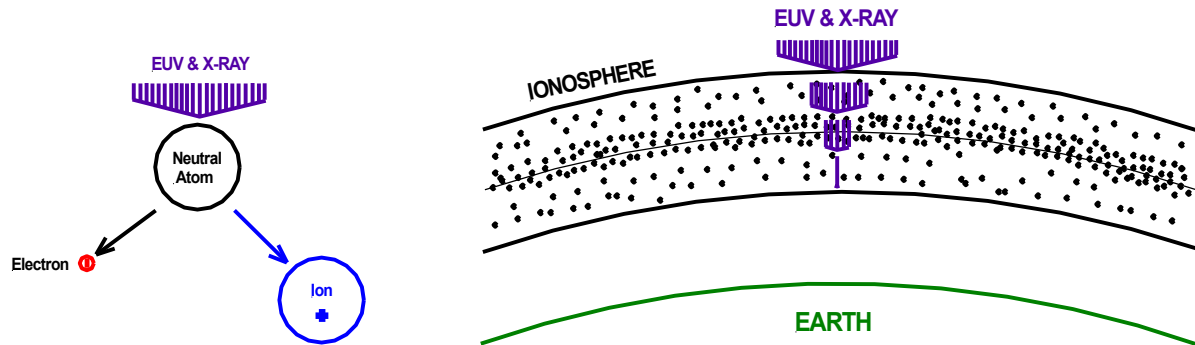


Figure 8 Ionization of atoms in Earth's upper atmosphere (credit: author)

Solar radiation is intense at the top of the atmosphere, as shown in Figure 8, but there are few atoms available to ionize. As the radiation penetrates deeper into the atmosphere, it encounters more and more atoms (mostly nitrogen and oxygen) resulting in higher levels of ionization. However, the ionization process absorbs energy from the EUV and X-ray radiation. The number of atoms keeps increasing as the radiation penetrates further into the atmosphere, but ionization levels decrease due to weakening radiation. Ionization continues to drop as the radiation weakens further and finally disappears. The point at which the radiation disappears marks the bottom of the ionosphere.

There are two additional things to note in Figure 8. Ions are way too massive to be affected by our puny radio waves. But tiny electrons interact readily with our radio waves. Thus it is electron densities that are so important to us.

## 2.2 How Skywave Propagation Works

The highest levels of ion and electron densities occur roughly in the middle of the ionosphere as shown in Figure 9.

A radio wave travels in a straight line from the transmitting antenna to the ionosphere. However, it begins immediately bending as it enters the ionosphere. The direction that it bends in is important.

- Radio waves bend toward the Earth as electron densities INCREASE.
- Radio waves bend away from the Earth when electron densities DECREASE.

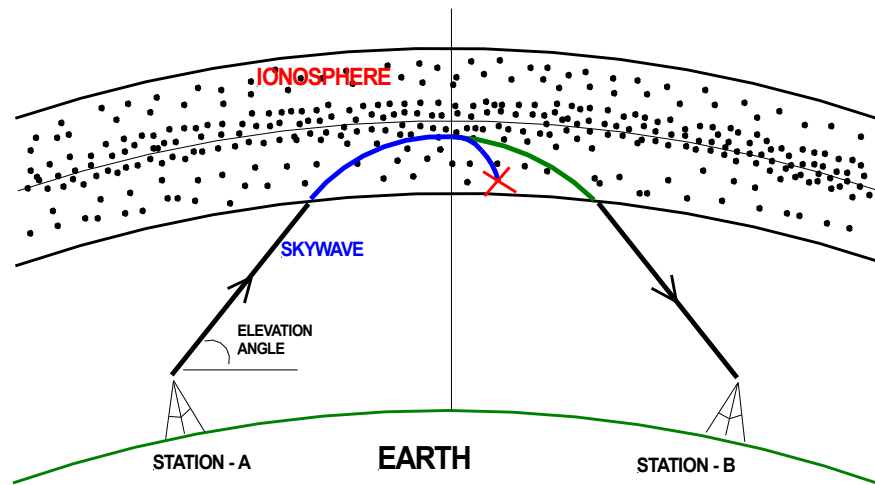


Figure 9 How skywave propagation works (credit: author)

Electron densities increase from the point of entry into the ionosphere, reaching a maximum near the middle of the ionosphere. Consequently a radio wave begins bending back toward Earth as soon as it enters the ionosphere. Bending eventually reach the point where the radio wave is traveling parallel to the Earth. If it continued to bend in the same direction, at the same accelerating rate, it would exit the ionosphere near the red X in Figure 9. But that is not what happens. Electron densities decrease as the radio wave travels back toward Earth. As electron densities decrease, the radio wave bends away from the Earth causing it to straighten out and exit the ionosphere at the point shown. It then travels in a straight line from the bottom of the ionosphere to the receiving antenna.

### 2.3 Trends in HF Communications During Solar Maximum

Radiation from the Sun is intense during solar maximum when large numbers of sunspots are visible on the Sun. The ionosphere becomes heavily ionized during the day, including a heavily ionized D - Layer. 80 meter signals are quickly absorbed in the D – Layer following sunrise and remain absorbed all day long until just after sunset, as illustrated in Figure 10. 40 meter signals are also absorbed in the D – Layer during mid day. But communications on 40 meters is often possible for an hour or so after sunrise and in the late afternoon. 20, 15, and 10 meter signals are all bent back to Earth with little absorption providing excellent long distance DX contacts all day.

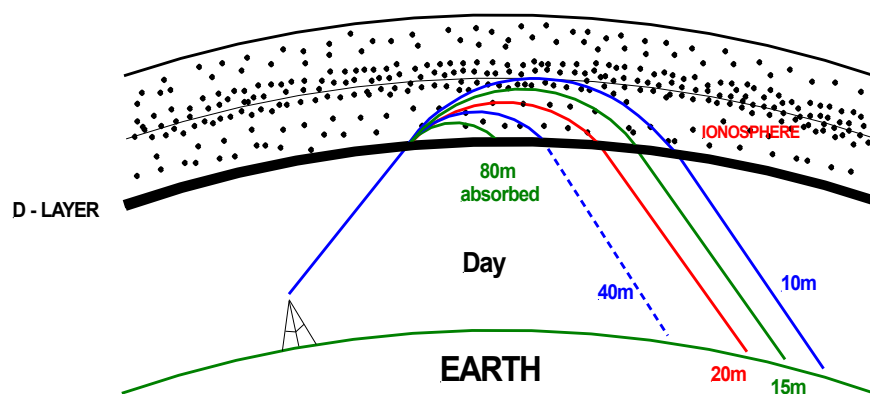


Figure 10 Daytime radio wave propagation solar maximum (credit: author)

At night levels of ionization drop, due to lack of sunlight, as electrons and ions recombine into neutral atoms. The D – Layer disappears an hour or so after sunset providing excellent night time communications on 80 and 40 meters. 80 meter communication typically lasts all night, disappearing just as the Sun rises. 40 meter communications usually dies out in the early morning hours when ionization is at its lowest level. Notice 20 meters in Figure 11. In this figure a 20 meter signal is right in the densest part of the ionosphere. In the early evening, communications on 20 meters is still possible. But as the evening wears on, ionization levels continue to drop resulting in the 20 meter signal passing through the most dense part of the ionosphere without being bent back to Earth. Once that happens the 20 meter signal enters a region of decreasing electron density meaning that the signal bends away from Earth and is lost to outer space. The same thing happens to 10 and 15 meter signals, but much faster. They are lost to outer space shortly after sunset.

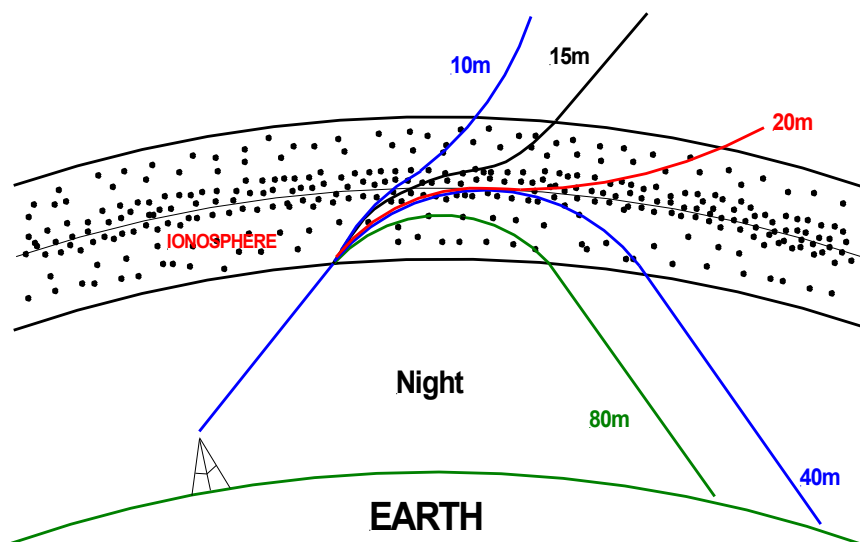


Figure 11 Night time radio wave propagation solar maximum (credit: author)

## 2.4 Trends in HF Communications During Solar Minimum

The Sun's radiation is weak during solar minimum when few if any sunspots are visible. The Earth's ionosphere is in turn weakly ionized. However, there is still a D – Layer which absorbs 80 meter signals during the day. While present, the D – Layer is weaker during solar minimum permitting regular communications on 40 meters during the day. 20 meter communications is erratic during solar minimum. On some days it is good, but on other days the band is dead. 10 and 15 meter signals are usually lost to outer space most of the time during solar minimum resulting in poor long distance DX.

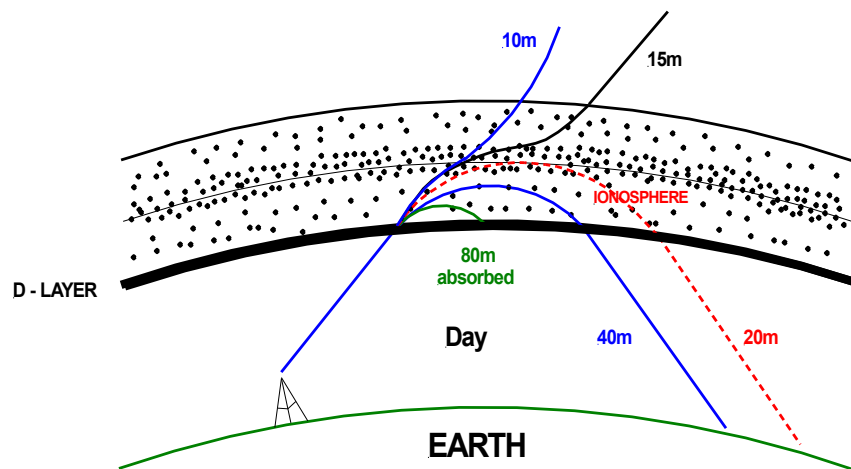


Figure 12 Daytime radio wave propagation solar minimum (credit: author)

At night levels of ionization drop even further, due to lack of sunlight, as electrons and ions recombine. The D – Layer disappears around sunset providing excellent night time communications on 80 meters. Communications on 40 meters lasts into the early evening but then dies out. There is no communications on 20 through 10 meters. These signals are lost to outer space.

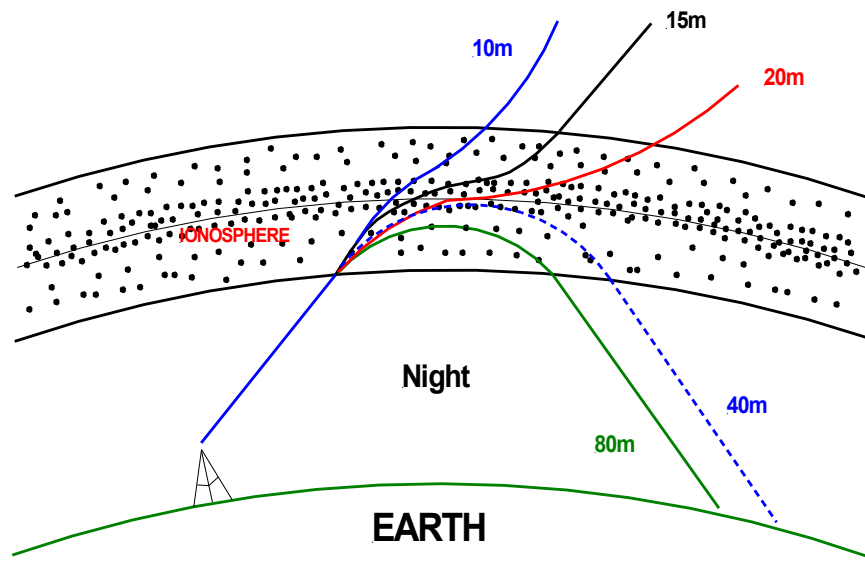


Figure 13 Night time radio wave propagation solar minimum (credit: author)

### 3 Long Term Solar Cycle Observations

Solar sunspot cycles have been observed for a long time. Figure 14 shows the solar cycles recorded from 1610 through the present.

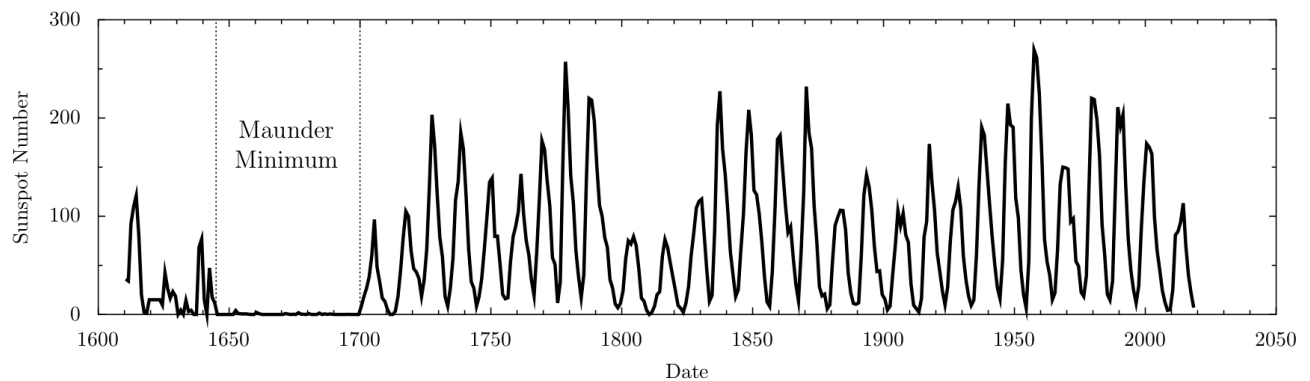


Figure 14 400 years of solar cycle observations (credit D Hathaway)

What is interesting in Figure 14 is the Maunder Minimum plus more subtle periodic dips in the amplitude of solar cycles.

Dips seem to occur every 80 to 120 years. The most recent dips occurred around 1816 (Solar Cycle 6) and 1905 (Solar Cycle 14). Referring to Table 1 shows that the amplitude of the 1816 solar cycle was slightly less than that of the solar cycle that preceded it and considerably less than the earlier and following cycles. Similarly, the amplitude of the 1905 solar cycle was less than that of solar cycles on either side of it. It is possible that the up coming Solar Cycle 25, expected to peak around 2025, may be another amplitude dip.

For 70 years, from 1645 to 1715, there were few if any sunspots visible on the Sun. That was a long time ago. One could speculate that astronomers and scientists at the time were simply not vigilant in their observations of the Sun. However, that is not so. Records indicate that the Sun was continuously and carefully observed throughout that period by noted astronomers including Hevelius, Boyle, Fogelius, Picard, and Cassini. At the Paris Observatory daily observations of the Sun were made from 1667 on. Between 1670 and 1700 there were never more than eight spots visible at one time. Only a single short-lived sunspot was seen for the entire decade from 1690 to 1700. Sunspots were so rare that the appearance of a sunspot created considerable excitement in the astronomical community. Interestingly, from 1660 to 1715 almost all the sunspot that did appear were in the southern hemisphere. It was not until 1715 that sunspots began appearing again in significant numbers, and in both hemispheres.

This long period of little or no sunspot activity is known as the Maunder Minimum. Ernest Maunder published two papers in 1890 and 1894 drawing attention to the absence of sunspots during the late seventeenth century. However, his papers as well as earlier research by Gustav Sporer were generally ignored. It was not until the landmark 1976 paper by John A. Eddy, published in the periodical Science, that interest was finally focused on the 1645 to 1715 solar minimum. It was Eddy who referred to this lack of sunspot activity as the Maunder Minimum. Eddy also suggested a possible connection between the solar minimum and a cool period throughout Europe that occurred about the same time termed the Little Ice Age. In addition, Eddy pointed out that a Medieval Warm Period from roughly 900 to 1300 occurred at a time of enhanced solar activity. Throughout this period Greenland was warm enough to be settled by Vikings and good wine was produced in England.

It is sobering to think what impact such a long solar minimum would have today on HF radio communications

It turns out that there have been other prolonged solar minimums throughout history. Figure 15 shows that two additional prolonged minimums, the Wolf and Sporer minimums, occurred from approximately 1290 through 1340 and 1410 through about 1520 respectively.

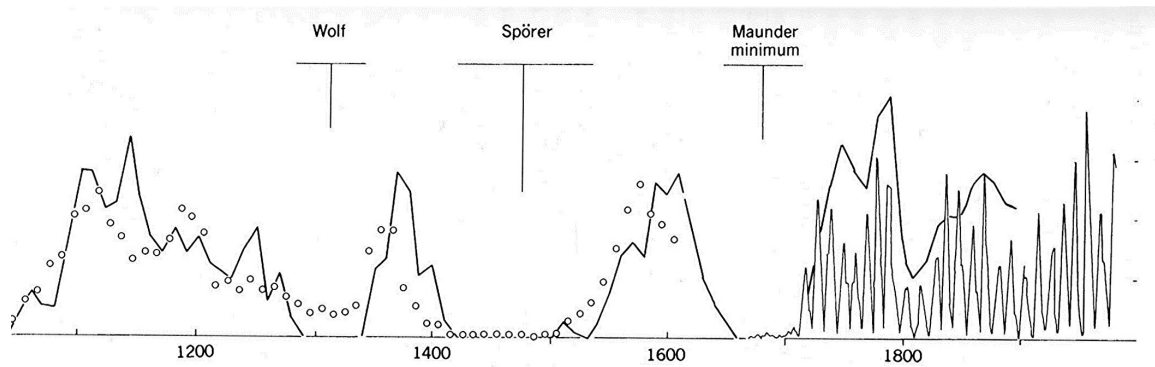


Figure 15 Prolonged Solar Cycle Minimums (credit: J. Eddy)

Evidence of these earlier prolonged minimums are found in the measurement of carbon-14 in tree rings. Carbon-14 is a radioactive isotope of carbon that is produced by energetic cosmic rays colliding with nitrogen atoms in Earth's upper atmosphere. The carbon-14 makes its way down to the lower atmosphere, is absorbed by tree leaves as part of the photosynthesis process, and ends up in tree rings as trees grow. During solar maximum the Sun's intensified magnetic field partially shields the Earth from cosmic rays resulting in less carbon-14 being produced. Thus:

- Solar Maximum = Low levels of carbon-14 in tree rings
- Solar Minimum = High levels carbon-14.

Tree ring data has provided a reliable record of fluctuations in the amount of carbon-14 present in Earth's atmosphere over the last 7,000 years.

The solid line in Figure 15 shows carbon-14 tree ring measurements from roughly 1000 to 1900. Note that the carbon-14 curve in Figure 15 is inverted. Peaks in the curve represent low levels of carbon-14 in tree rings coinciding with solar maximums. Dips or valleys occur in the curve during solar minimums when high concentrations of carbon-14 are found in tree rings.

Records of northern hemisphere auroral sightings are also useful in identifying long term solar minimums and are more reliable than one might expect. Auroral activity is much more frequent during solar maximum. Thus a prolonged period of little auroral activity corresponds to a prolonged solar minimum. The circles in Figure 15 represent the number of auroral sightings over the period from 1000 to 1600. Telescope sunspot observations are shown in Figure 15 from 1700 to present.

The fairly regular behavior of solar cycles over the past 300 years (from roughly 1700 to the present) may NOT be the norm. It appears that prolonged solar minimums occur at regular intervals of 150 to 250 years. We may be over due for the next prolonged minimum!

Figure 16 shows that the amplitudes of solar cycles were relatively consistent from 1880 to 1928. Sunspot activity increased from 1928 to 1964, peaking in 1957. Since 1980 sunspot activity has slowly declined as illustrated in Figure 17. Sunspot activity during Cycle 24 was about the same as



it was during the early days of radio. Solar cycle 25, shown in Figure 18 peaking in 2025, is expected to be about the same amplitude as Cycle 24, or perhaps slightly smaller. Based on this information, Solar Cycle 25 could be the next amplitude dip.

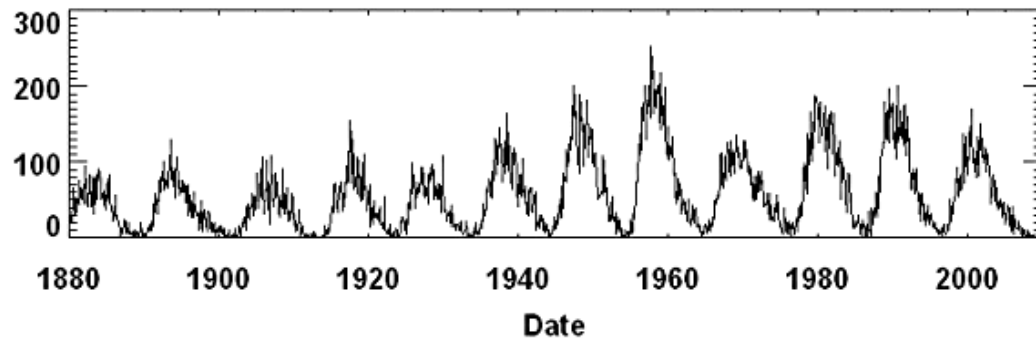


Figure 16 Solar cycles from 1880 to 2010 (credit: SpaceWeather.com)

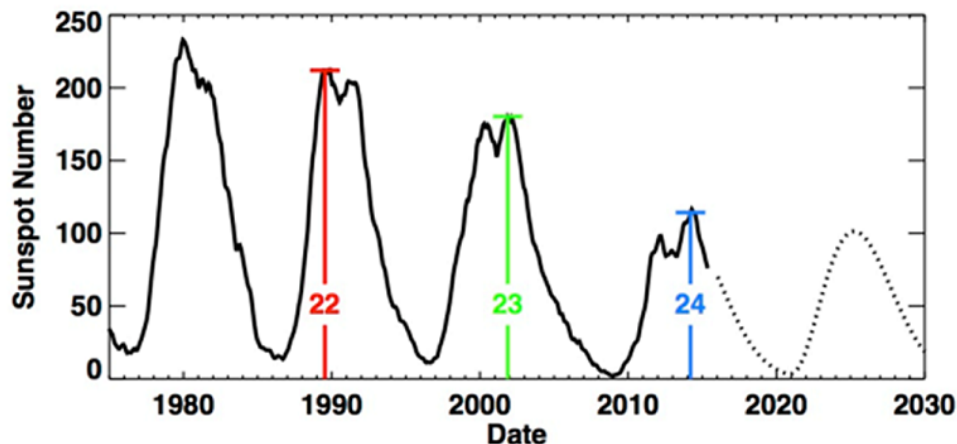


Figure 17 Solar Cycles 21 through 25 (credit: D. Hathaway)

It is interesting to look at Solar Cycle 17 in Figure 16. Cycle 17 peaked in May 1937, resulting in excellent world wide HF radio communications just as WW-II began. HF communications deteriorated throughout the war with a solar minimum occurring in 1944. The solar minimum persisted through 1945, the last year of the war. Despite deteriorating conditions, radio operators learned how to deal with the situation and got their radio traffic through. They had to! At the time HF radio was the only means available for long distance communications, not only between land based stations (since all telephone and telegraph lines had been cut in the war zone) but with ships at sea and aircraft as well.

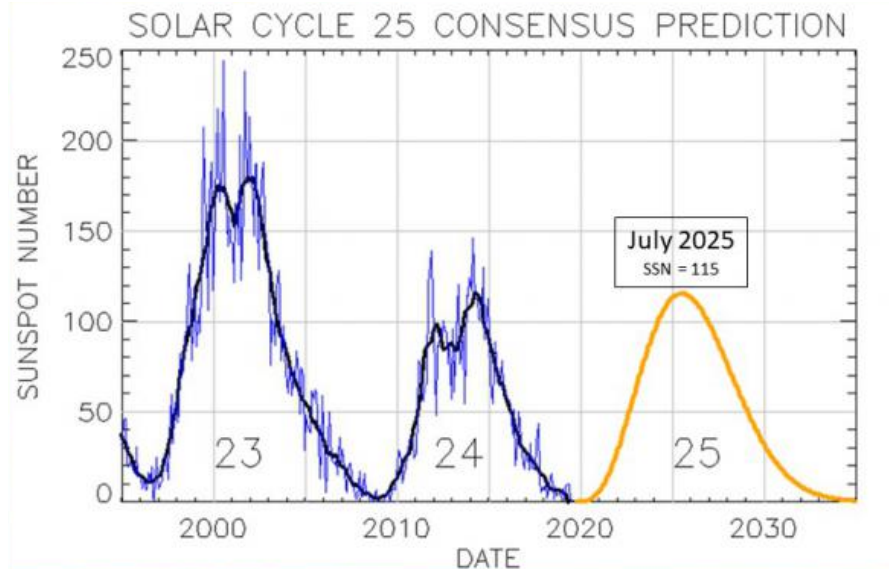


Figure 18 Projections for Solar Cycle 25 (credit: NOAA Space Weather Prediction Center)

#### 4 A Closer Look at Sunspots and Solar Cycles

Figure 19, known as the butterfly diagram, shows the density of sunspots at each solar latitude for the years from 1880 through the present. At solar minimum, few if any sunspots are visible on the Sun. The first sunspots of a new cycle appear at  $30^\circ$  to  $40^\circ$  latitude in both hemispheres as clearly occurred in the year 1903. During its lifetime a sunspot remains at the same latitude. Increasing numbers of sunspots appear at progressively lower latitudes as the solar cycle continues while the sunspots at higher latitudes die out. The largest number of sunspots occur during solar maximum at a latitude of  $10^\circ$  to  $20^\circ$ . Following solar maximum, these sunspots die out while new sunspots form closer and closer to the equator. By 1910 most of the sunspots were clustered near the equator. However, a problem develops. Sunspots in the southern hemisphere have the opposite magnetic polarity of those in the northern hemisphere. Consequently, sunspots forming in close proximity on opposite sides of the equator obliterate each other resulting in the absence of sunspots at the equator. High latitude sunspots of the next cycle can often begin to form while sunspots of the previous cycle are still visible near the equator, creating a cycle overlap. This phenomenon is quite pronounced during the transition from Solar Cycle 19 to 20.

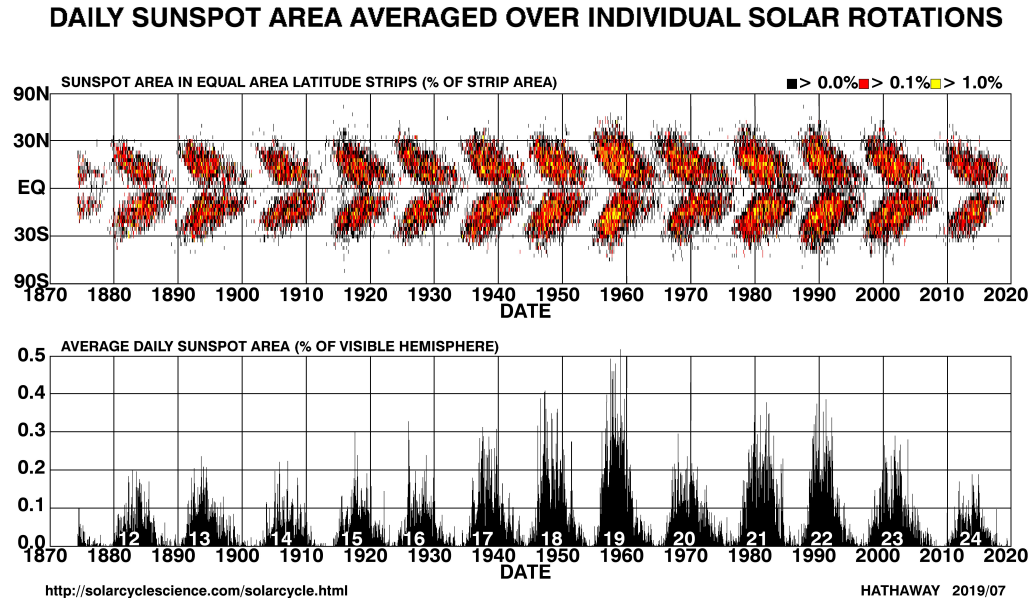


Figure 19 Sunspot butterfly diagram (credit D. Hathaway)

A sunspot has a black center called the umbra and an outer lighter colored penumbra as shown in Figure 20. The umbra is the lowest temperature (blackest) part of a sunspot. The temperature of the umbra usually ranges from about 3,800 to 4,100 degrees kelvin compared to 6,500 K for the photosphere. The penumbra around the outer edge of the sunspot is warmer than the umbra and not as black. The penumbra is characterized by large numbers of elongated dark and bright filaments that extend outward from the umbra. Out flows of material occurs in the penumbra, beginning at the umbra, reaching a maximum speed of 2 – 6 km/s, and then dissipating outside the penumbra.

Sunspots can be huge. Large sunspots (including both the umbra and penumbra) can be 50,000 km or more in diameter. More typically, the umbra is around 10,000 km in diameter, about the same size as the Earth. The Earth's diameter is 12,756 km. Sunspots appear, last several days, and then disappear. Some sunspots may last for several weeks.

While individual sunspots do form, most of the time they occur in pairs or more frequently in groups as shown in Figure 21.

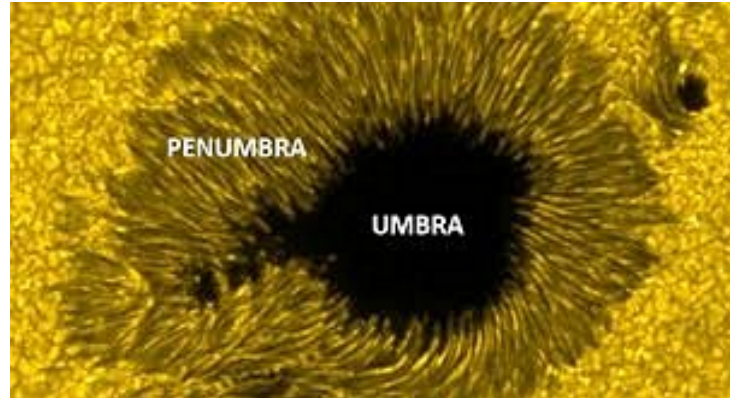


Figure 20 A closer look at sunspots (credit: spaceweatherlive.com)

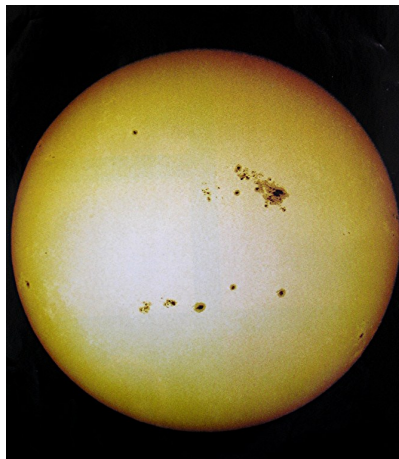


Figure 21 Sunspot groups on face of the Sun ( credit: NASA Goddard Space Flight Center)

A sunspot develops at a point where the Sun's magnetic field erupts through the photosphere (the Sun's visible surface) as shown in Figure 22. A second sunspot occurs where the magnetic field plunges back into the photosphere. Notice that sunspots have magnetic polarities created by the magnetic field's direction of flow. The field flows out of a magnetically north (N) sunspot and into a south (S) magnetic spot. North and south are often represented as "+" and "-" respectively.

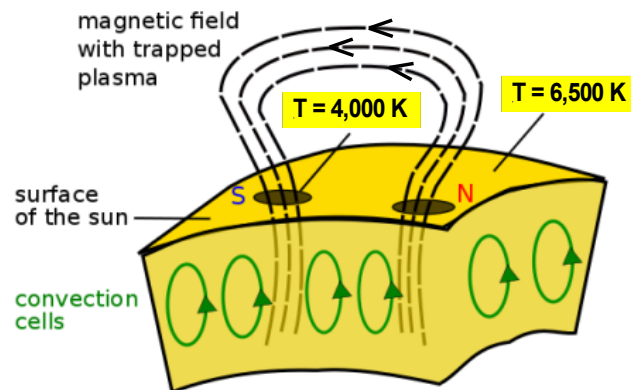


Figure 22 Sunspot formation (credit: Sky Maps with Pierre Auger Data)

The peak intensity of the field emanating from a sunspot is in the neighborhood of 3,000 to 4,000 gauss. This field is so intense that it suppresses the upward flow of hot plasma below the sunspot location, causing the sunspot site to be 2,500 degrees cooler than the surrounding photosphere. The sunspot's lower temperature is why it appears black in color.

Sunspots are part of the Sun's photosphere and thus rotate with the Sun. In Figure 23 sunspots move from left to right as the Sun rotates. Sunspots that disappear around the Sun's right limb may reappear about 13 days later on the left side of the Sun.

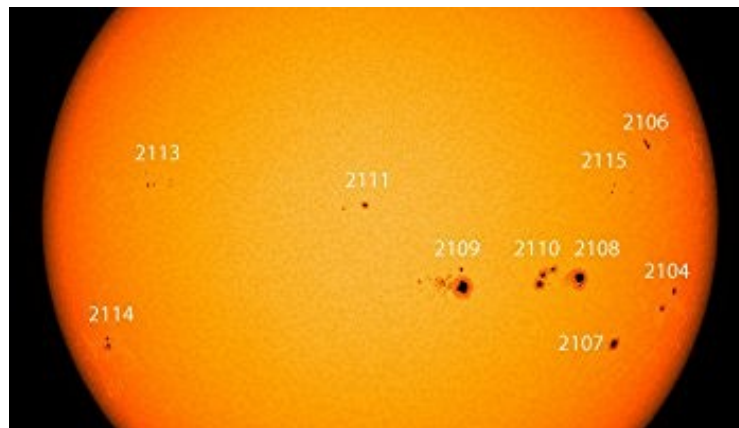


Figure 23 Sunspots on the face of the Sun (credit: NOAA Space Weather Prediction Center)

While there is a strong correlation between sunspots and the quality of long distance radio communications, it turns out that sunspots have little to do with HF propagation. Sunspots are far too low in temperature to generate the EUV radiation needed to ionize Earth's upper atmosphere. The required EUV radiation is primarily produced by plagues.

Plages are hot bright irregularly shaped areas easily visible in the image of the chromosphere shown in Figure 24. Plages are formed in the chromosphere by intense magnetic fields radiating out from the underlying photosphere. Plages occur in active sunspot regions of the Sun and usually form several days prior to sunspots in the area. Plages typically last long periods of time, longer than their associated sunspots, and emit copious amounts of EUV radiation.

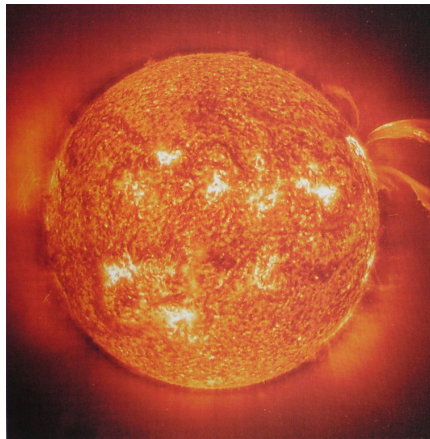


Figure 24 Sun's chromosphere shown in H alpha ( $H_{\alpha}$ ) light (credit: universitytoday.com)

The problem is that plages can not be seen in normal sunlight because the photosphere too bright. But sunspots, like those shown in Figures 21 and 23, can easily be seen. Thus sunspots become markers for plages. A large number of sunspots means a large number of plages, high EUV levels, strong ionization of the Earth's ionosphere, and good HF radio communications.

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