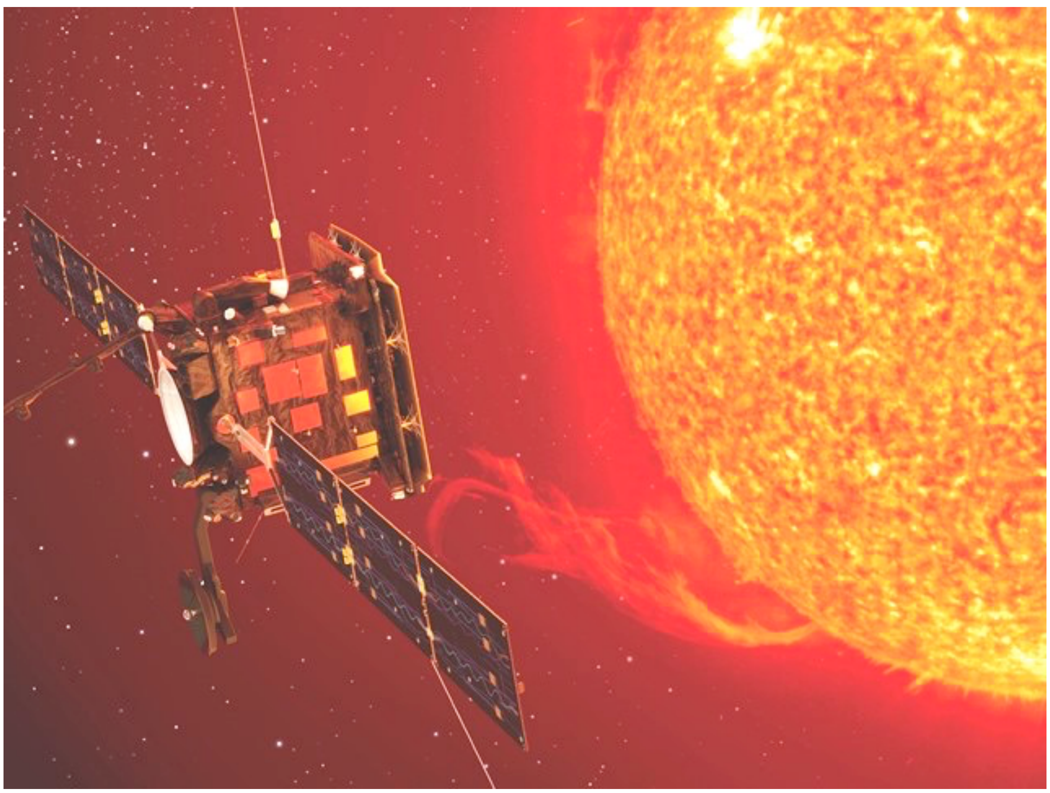
Chapter 3

The Sun's Atmosphere



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3 The Sun's Atmosphere

The photosphere, chromosphere, and corona illustrated in Figure 1 are referred to as the solar atmosphere since we are able to see through these regions to the top of the convection zone. High temperatures in the convection zone cause it to be opaque. Consequently, the boundary between the convection zone and the photosphere is the furthest that we can see into the Sun.

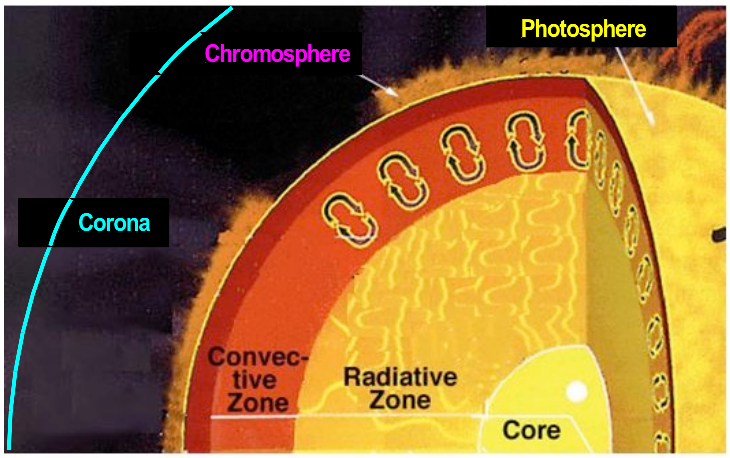

Figure 1 The Sun's atmosphere (credit: socratic.org)

The characteristics of the photosphere, chromosphere, and corona regions are summarized in Tables 1 and 2.

Zone	Altitude	Depth	Temp °K	Intensity	Density g/cm^3
Convection Zone	↕		↕		
	0 km		6,500 K		$2.78\ x\ 10^{-7}$
Photosphere	↕	500 km	↕	I_0	
	500 km		4,400 K		$6.22\ x\ 10^{-9}$
Chromosphere	↕	1,800 km	↕	$10^{-4} I_0$	
	2,300 km		25,000 K		$7\ x\ 10^{-13}$
Transition Zone	↕	300 km	↕		
	2,600 km		$1\ x\ 10^6\ K$		
Corona	↕	$2\ x\ 10^6$ km	↕	$10^{-7} I_0$	$1\ x\ 10^{-16}$
	$> 2\ x\ 10^6$ km		$> 2\ x\ 10^6 K$		

Table 1 Characteristics of the photosphere, chromosphere, and corona

Zone	Altitude	Temp °K	Density g/cm^3	Hydrogen Atoms $/cm^3$	Electrons $/cm^3$
Convection Zone	↕	↕			
	0 km	6,500 K	$2.78 x 10^{-7}$	$1.19 x 10^{17}$	$7.68 x 10^{13}$
Photosphere	↕	↕			
	500 km	4,400 K	$6.22 x 10^{-9}$	$2.65 x 10^{15}$	$3.04 x 10^{11}$
Chromosphere	↕	↕			
	2,300 km	23,000 K	$7 x 10^{-13}$	$1.38 x 10^{10}$	$1.44 x 10^{10}$
Transition Zone	↕	↕			
	2,600 km	$1 x 10^6 K$	$5 x 10^{-13}$	$8 x 10^9$	
Corona	↕	↕			
	$> 2 x 10^6$ km	$> 2 x 10^6 K$	$1 x 10^{-16}$	$1 x 10^5$	

Table 2 Additional characteristics of the photosphere, chromosphere, and corona

Altitudes listed in these tables are the distances outward from the top of the convection zone.

3.1 Photosphere

The photosphere shown in Figure 2 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.

Figure 2 Photosphere (credit: NASA Goddard Space Flight Center)

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 10,000 times less than Earth's sea level atmosphere. The density at the base of the photosphere is $2.78\ x\ 10^{-7}\ g/cm^3$ while the density of Earth's atmosphere at sea level is $1x10^{-3}\ g/cm^3$. Since the density of the photosphere is so low, why can't we see through the photosphere? We actually can. In Figure 3 we 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 photosphere's density drops two orders of magnitude from $2.78\ x\ 10^{-7}\ \text{g/cm}^3$ at the base to $6.22\ x\ 10^{-9}\ \text{g/cm}^3$ at the top of the photosphere. Over this same distance the number of $\text{hydrogen atoms/cm}^3$ (the number density) drops from $1.19\ x\ 10^{17}$ to $2.65\ x\ 10^{15}$. Both of these densities are similar to those in Earth's Mesosphere 50 to 90 km above Earth's surface. The structure of Earth's atmosphere and its density from sea level to an altitude of 450 km is shown in Figure 4, Figure 5, and Table 3 for reference.

The photosphere is hot, twenty times hotter than the surface of the Earth (6,500 °K verses 300 °K for the Earth), and the chromosphere and corona are much hotter yet. In addition, the photosphere is highly charged. Its electron density is a million times greater than Earth's ionosphere.

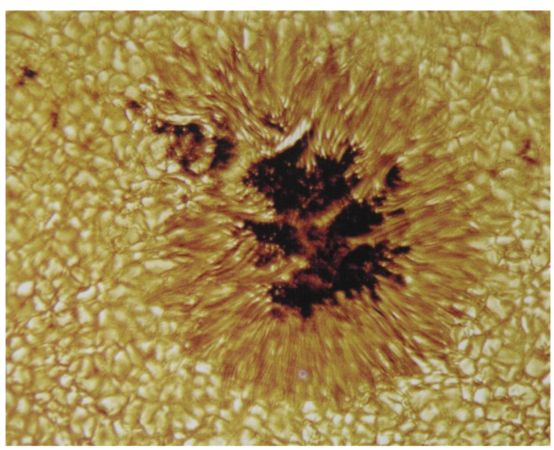

Figure 3 Sunspot and granules at base of the photosphere (credit: spaceweatherlive.com)

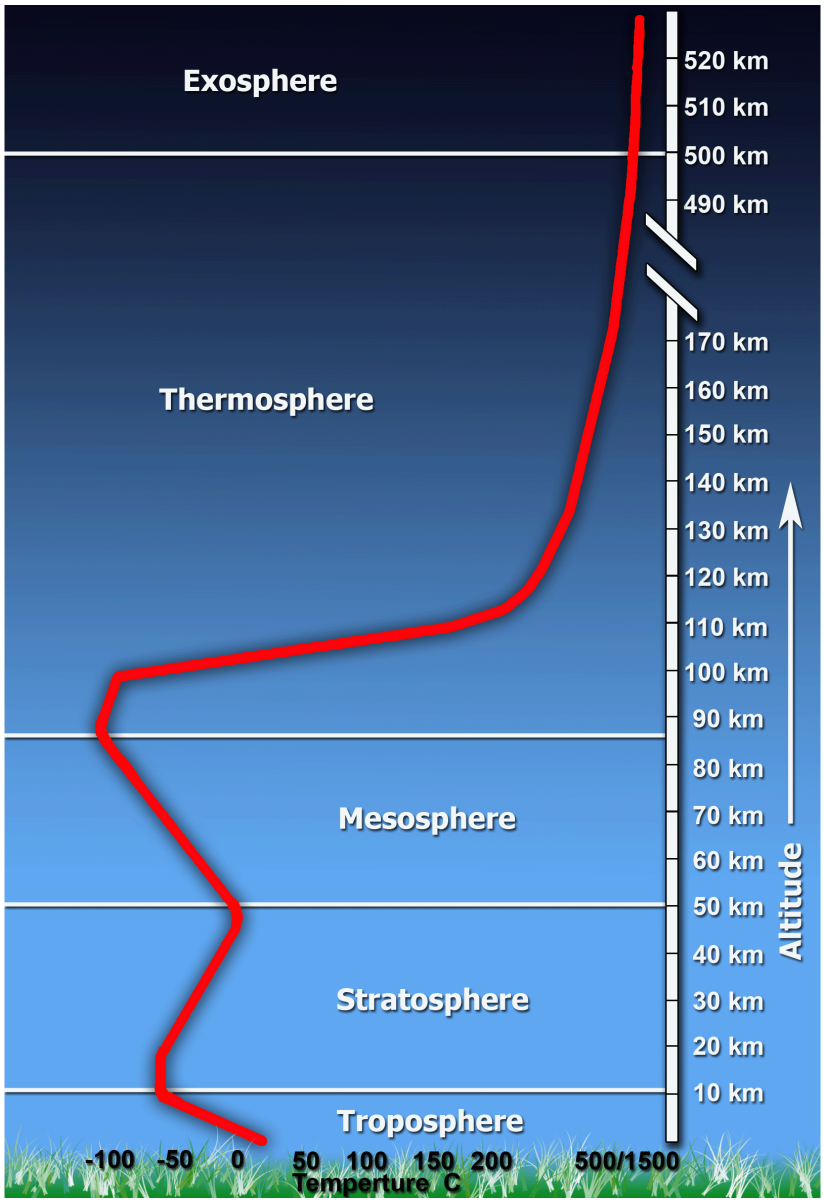

Figure 4 Structure of Earth's Atmosphere (credit: NASA Climate Science Investigations)

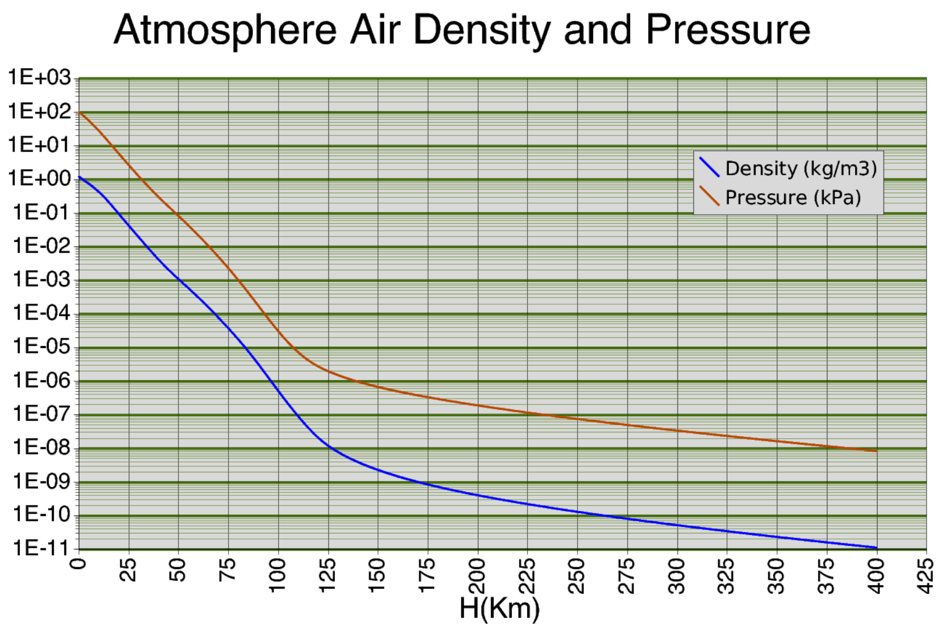

Figure 5 Density of Earth's Atmosphere (source: Wikimedia Commons)
Note: $g/cm^3 = (10^{-3})[kg/m^3]$

Altitude (km)	Mass Density g / cm³	Number Density (atoms + molecules / cm³)	Electron Density (electrons / cm³)
450	$8x10^{-15}$	$4.5\ x\ 10^7$	$5x10^3$
425	$9x10^{-15}$	$6.0\ x\ 10^7$	10^4
400	$1x10^{-14}$	$1.0\ x\ 10^8$	$5x10^4$
375	$1.5x10^{-14}$	$1.5\ x\ 10^8$	10^5
350	$2x10^{-14}$	$2.5\ x\ 10^8$	$5x10^5$
325	$4x10^{-14}$	$4.0\ x\ 10^8$	10^6
300	$6x10^{-14}$	$6.0\ x\ 10^8$	$1.5x10^6$
275	$9x10^{-14}$	$1.0\ x\ 10^9$	$2x10^6$
250	$1x10^{-13}$	$2.0\ x\ 10^9$	$1.5x10^6$
225	$2x10^{-13}$	$3.5\ x\ 10^9$	$1x10^6$
200	$4x10^{-13}$	$7.0\ x\ 10^9$	$6x10^5$
175	$9x10^{-13}$	$1.5\ x\ 10^{10}$	$2x10^5$
150	$2x10^{-12}$	$5.0\ x\ 10^{10}$	$1x10^5$
125	$1x10^{-11}$	$3.0\ x\ 10^{11}$	$8x10^4$
100	$5x10^{-10}$	$1.0\ x\ 10^{13}$	$5\ x\ 10^4$
75	$4x10^{-8}$	$1.3\ x\ 10^{15}$	$1x10^3$
50	$1x10^{-6}$	$3.0\ x\ 10^{16}$	$1x10^2$
25	$3x10^{-5}$	$1.8\ x\ 10^{18}$	
0	$1x10^{-3}$	$2.5\ x\ 10^{19}$	

Table 3 Density of Earth's Atmosphere

The photosphere extends outward from the convection zone a distance of 500 km. Over this distance the Sun's temperature drops from 6,500 to approximately 4,400 degrees kelvin. The Sun's temperature then rises quickly through the chromosphere reaching over 1 million degrees in the corona, as shown in Figure 6. The photosphere is formally defined as the region between the top of the convection zone (the furthest that we can see into the Sun) and the location where the Sun reaches its lowest temperature (4,400 $°K$).

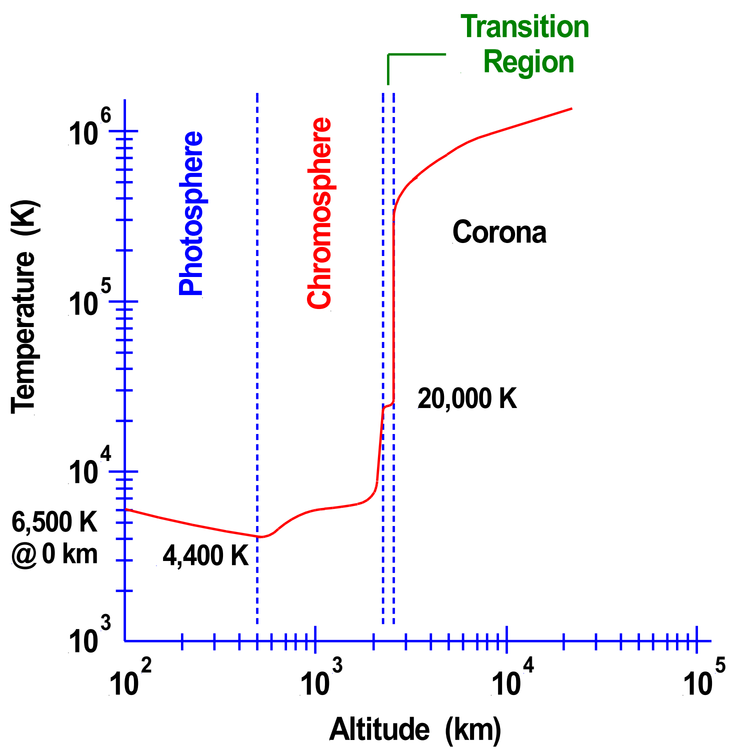

Figure 6 Temperature profile of the solar atmosphere (credit: author)

Almost all of the hydrogen and helium gas in the photosphere is in atomic form. Only about 3% of the atoms in the photosphere are ionized. Despite this low level of ionization, the electron density in the photosphere is still a million times greater than in the Earth's ionosphere ($\sim 2x10^{12}$ for the Sun and about $2x10^6$ for the densest part of the Earth's ionosphere)

The spectrum of light emitted by the photosphere is shown in Figure 7. This spectrum is determined primarily by the photosphere's 6,500 $°K$ temperature. Notice that 44% of the spectrum is visible light while only 0.001% of the spectrum is the extreme ultra-violate light responsible for Earth's ionosphere and HF radio communication.

In the late 1800s absorption spectrum lines were discovered in the photosphere that did not correspond to any chemical elements known on Earth. In 1868 Norman Lockyer theorized that these spectral lines were produced by a new element. He named the new element helium after the Greek Sun God Helios. Helium was discovered on Earth 25 years later.

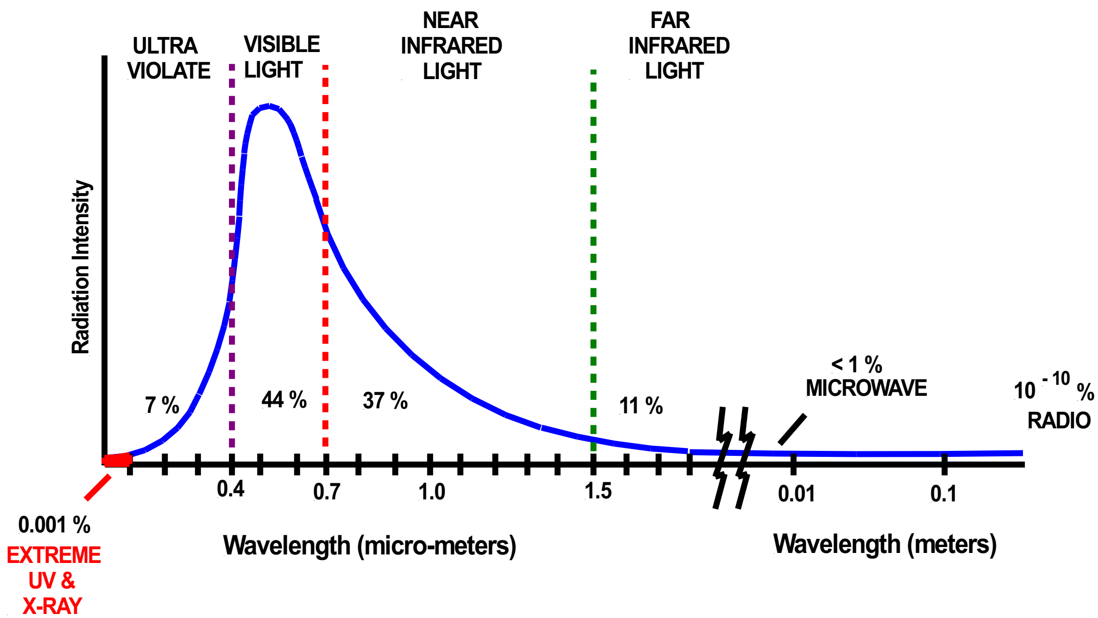

Figure 7 Solar spectrum (credit: author)

The most interesting phenomena occurring in the photosphere are granulation, sunspots and Faculae.

3.1.1 Granulation

The granular appearance of the photosphere shown in Figure 8 is caused by the convection zone protruding into the base of the photosphere. The bright granules are bubbles of hot plasma originating from deep within the convection zone. Heat from the granules radiates into the photosphere heating the base of the photosphere to around 6,500 degrees kelvin. The radiated heat cools the plasma as it flows outward from the center of a granule. As it cools the plasma density increases causing it to sink back into the convection zone around the outer edge of the granule. The cool sinking plasma forms a dark channel around each granule.

Typically, granules range in diameter from about 300 to 2,000 kilometers and lasts from 5 to 20 minutes before disappearing. New granules quickly appear in roughly the same location, giving the photosphere a boiling appearance. The center to center spacing between adjacent granules is around 1,400 km but varies widely. The Sun is typically covered by about 4 million granules at any given time.

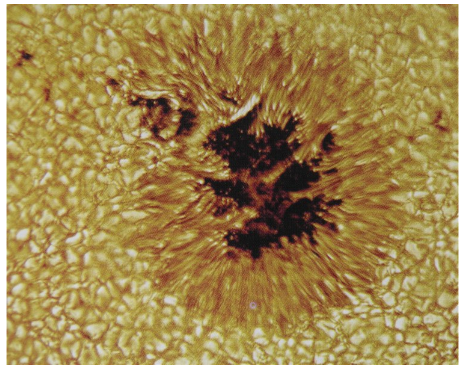

Figure 8 Granulation (credit: spaceweatherlive.com)

A closer view of granulation is shown in Figure 9 with an image of North America superimposed for reference.

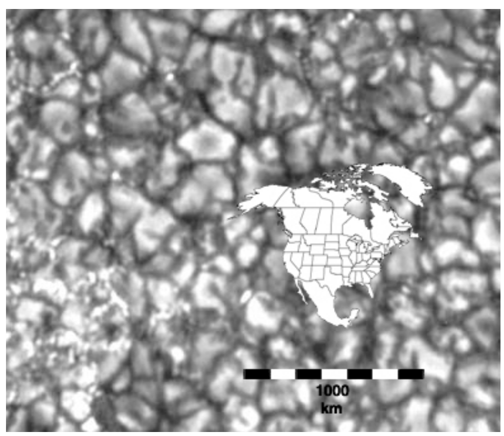

Figure 9 Thermal cells (granules) reaching the photosphere and sinking back into the convection zone. North America superimposed as a reference (credit: Wikipedia)

3.1.2 Sunspots

Sunspots are black irregularly shaped blemishes on the Sun's surface. The picture on the right in Figure 10 shows large numbers of sunspots covering the Sun. Sunspots appear, increase in number, and then gradually disappear over roughly a 11 year solar cycle. A solar cycle is arbitrarily defined to begin at sunspot minimum when few if any sunspots are visible. Increasing numbers of sunspots appear at a fairly rapid rate as the cycle progresses. 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 again at the end of the cycle. The picture on the left side of Figure 10 shows the Sun at solar minimum (few if any sunspots).

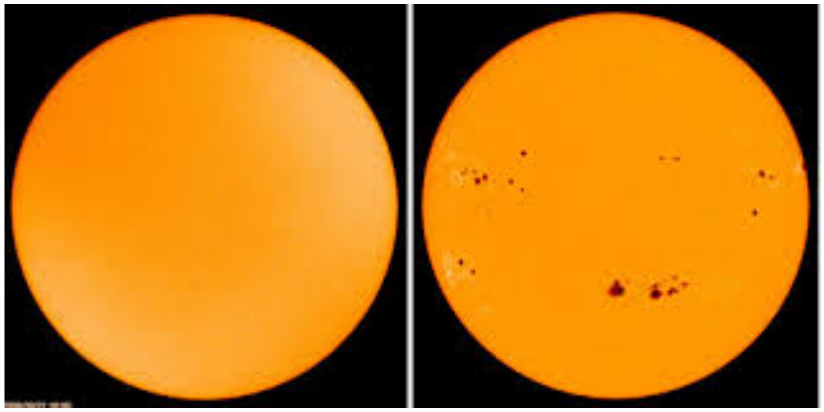

Figure 10 Sun at Solar minimum and maximum (credit: springer.com)

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 11. A second sunspot occurs were 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.

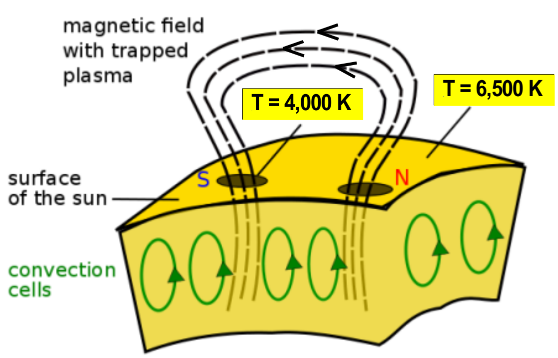

Figure 11 Formation of sunspots (credit: Sky Maps with Pierre Auger Data)

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 around 2,500 degrees cooler than the surrounding photosphere. The sunspot's lower temperature is why it appears black in color.

The center of a sunspot is the umbra while the outer lighter colored region is the penumbra shown in Figure 12. 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 and lighter in color. 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.

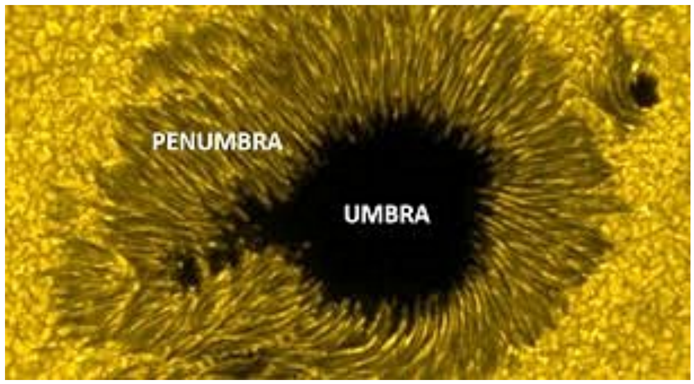

Figure 12 A closer look at sunspots (credit: spaceweatherlive.com)

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.

Sunspots are part of the Sun's photosphere and thus rotate with the Sun. In Figure 13 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.

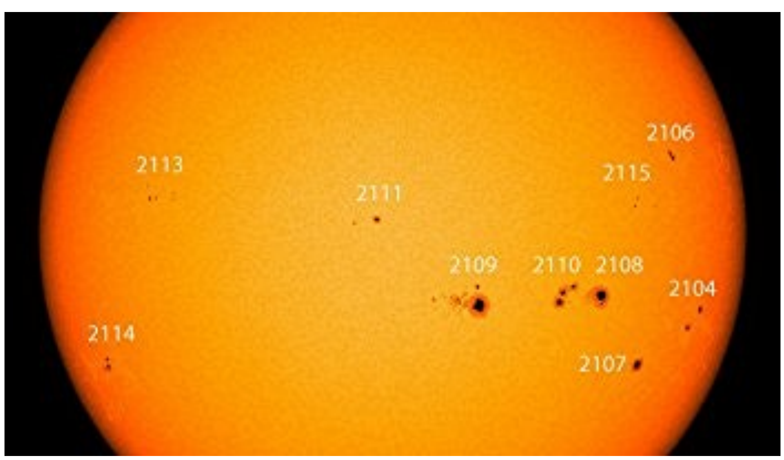

Figure 13 Sunspots on the face of the Sun (credit: NOAA Space Weather Prediction Center)

3.1.3 Faculae

Faculae are bright hot depressions in the photosphere at locations where strong vertical magnetic fields emerge from the Sun's surface. However, a faculae magnetic field is not nearly as strong as that found in the umbra of a sunspot. Faculae are hotter than the surrounding photosphere which is why they appear bright. Within a faculae heat radiates from the walls of the faculae depression as well as from the bottom of the depression accounting in part for the faculae being hotter and brighter than the surrounding photosphere.

About 90% of faculae are associated with sunspots. Faculae typically appear several days before the appearance of sunspots and survive considerably longer. In terms of HF radio propagation, faculae are important because they are overlaid by hot Extreme Ultra-Violet (EUV) emitting plages in the chromosphere. It is the Sun's EUV radiation that creates the Earth's ionosphere.

3.2 Chromosphere

The chromosphere stretches outward from the top of the photosphere to an altitude of around 2,300 km. Normally the chromosphere is not visible because the photosphere is so bright. In fact, the photosphere is 10,000 times brighter than the chromosphere. However, the chromosphere can be seen as a rosy red ring along the outer edge of the Sun during a full solar eclipse. During a full eclipse the Earth's moon blocks out the bright photosphere allowing the chromosphere to be seen. A full eclipse is shown in Figure 14

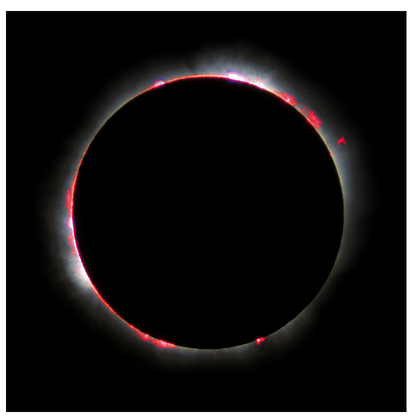

Figure 14 View of chromosphere during a solar eclipse (credit: Wikipedia)

The name chromosphere means sphere of color. The chromosphere's reddish appearance, shown in Figure 15, is the result of hydrogen atom electrons dropping from their $n = 3$ to $n = 2$ energy levels, emitting photons in the process. The wavelength of these photons is 656.3 nm which is in the red part of the spectrum. The chromosphere can be observed in great detail by viewing the Sun with a telescope equipped with a hydrogen-alpha (H_α) filter.

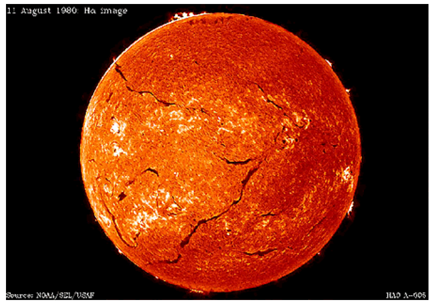

Figure 15 Chromosphere seen in H-alpha light (credit: universitytoday.com)

The density of the chromosphere is ten thousand times less than the photosphere dropping rapidly from $6.22\ x\ 10^{-9}\ \text{g/cm}^3$ at 500 km to $7\ x\ 10^{-13}\ \text{g/cm}^3$ at 2,300 km. This is roughly the same density as the F Layer of Earth's ionosphere 175 km above Earth's surface. The density of hydrogen atoms at 500 km is about $2.65\ x\ 10^{15}\ atoms\ per\ cm^3$. This number drops to around $1.38\ x\ 10^{10}\ atoms\ per\ cm^3$ at 2,300 km as illustrated in Figure 16.

The chromosphere's temperature profile is also shown in Figure 16 . The chromosphere temperature rises from 4,400 $°K$ at 500 km to around 20,000 $°K$ at an altitude of 2,300 km. A temperature plateau occurs from 1,000 to 2,000 km. Over this distance the chromosphere's temperature slowly rises from 6,000 to 7,000 $°K$. The plateau is caused by the ionization of hydrogen which occurs at temperatures > 5,000 $°K$. The chromosphere temperature rises quickly after the hydrogen becomes fully ionized. This occurs at an altitude of about 2,100 km and temperature of 8,000 $°K$. A second plateau occurs at approximately 2,300 km. This plateau is defined as the transition zone between the upper chromosphere and the bottom of the corona. The transition zone is about 300 km wide extending from an altitude of 2,300 to 2,600 km.

The interesting phenomena occurring in the chromosphere include spicules and plages.

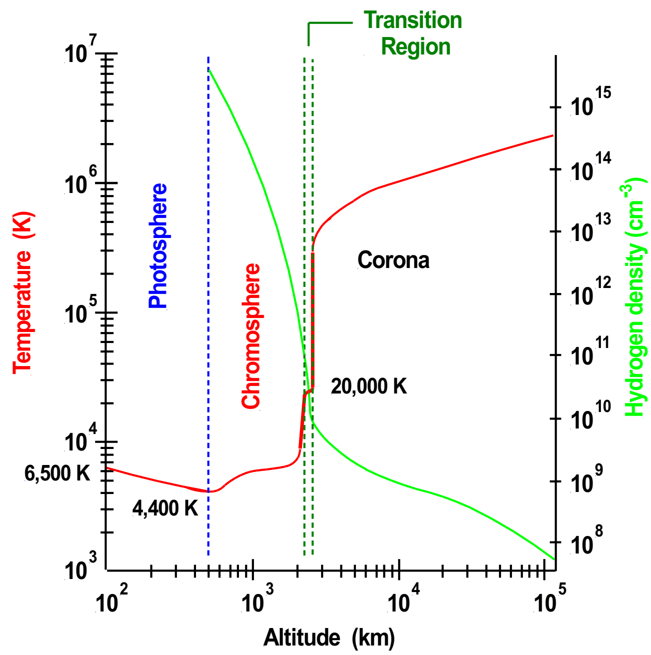

Figure 16 Chromosphere temperature - density profile (credit: adapted from A. Gabriel 1976)

3.2.1 Spicules

In quiet regions of the Sun, magnetic fields extend radially outward from the photosphere, through the chromosphere, and well into the corona before looping back to the photosphere at a distant location. Reddish colored jets of gas called spicules, shown in Figure 17, are seen on the limb of the chromosphere following these radial magnetic fields outward. Spicules protrude far into the corona reaching heights well over 10,000 km. Figure 18 is a closer view of spicules.

An individual spicule typically last from 5 to 15 minutes traveling outward at speeds up to 25 km/sec. Generally a spicule is about 500 km in diameter and ranges in temperature from 9,000 °K at an altitude of 2,000 km to over 16,000 °K at 8 – 10 km. It is estimated that over 30,000 spicules exist at any given moment.

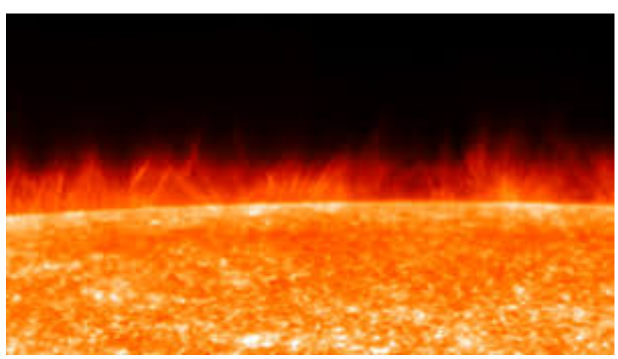

Figure 17 Spicules shown on the limb of the chromosphere (credit: jaxa / NASA)

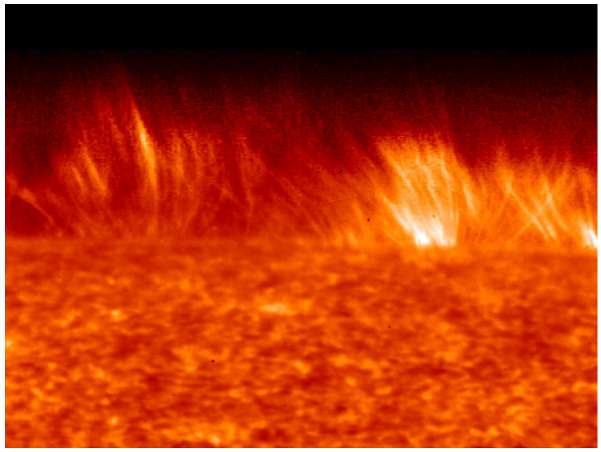

Figure 18 Closer view of spicules (credit: www.nasa.gov/sites/default/files/images)

3.2.2 Plages

Plages are hot bright irregularly shaped areas easily visible in the image of the chromosphere shown in Figure 19. Plages are formed in the chromosphere by intense magnetic fields radiating out from faculae in the underlying photosphere. Like the faculae below them, 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 extreme ultra violate (EUV) light responsible for ionizing Earth's upper atmosphere.

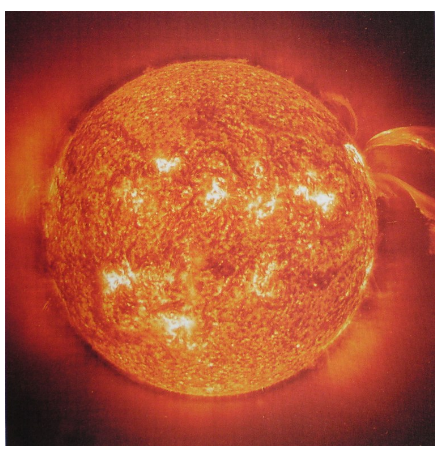

Figure 19 Sun's chromosphere shown in H alpha (H_α) light (credit: universitytoday.com)

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 plages. The problem is that plages can not be seen in normal sunlight because the photosphere is too bright. But sunspots 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.

3.3 Corona

The corona begins at the top of the transition zone, just above the chromosphere. It extends outward for more than 2 million km. There is no actual upper boundary for the corona. It continuously thins as it stretches outward from the Sun and eventually disappears into interplanetary space.

Like the chromosphere, the corona is normally not visible because the photosphere is so bright. In perspective, the photosphere is 10,000 times brighter than the chromosphere and a million times brighter than the corona. During a full eclipse the white coronal light is visible surrounding the Sun as shown in Figure 20.

The density of the corona drops from $5\ x\ 10^{-13}\ \mathrm{g/cm^3}$ just above the transition zone to less than $1\ x\ 10^{-16}\ \mathrm{g/cm^3}$ two million km out from the Sun. The density of hydrogen atoms at 2,300 km is about $1.38\ x\ 10^{10}\ atoms\ per\ cm^3$. This number drops to around $1\ x\ 10^{5}\ atoms\ per\ cm^3$ at two million km as illustrated in Figure 16. This range of densities is similar to that of Earth's atmosphere 300 – 500 km above Earth's surface. Note that the International Space Station orbits in this region at an altitude of 350 – 420 km.

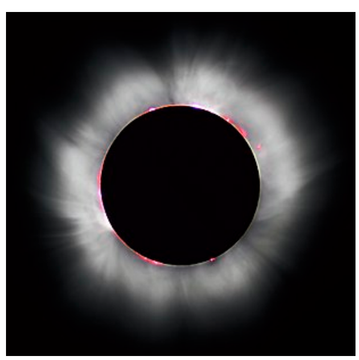

Figure 20 Solar eclipse (credit: Wikipedia)

The corona is extremely hot ranging from around 1 million degrees just above the transition zone to well over 2 million degrees in the outer part of the corona.

The corona's white light, at altitudes out to $1.5\ x\ 10^6$ km, is produced by highly energetic free electrons scattering light radiated by the photosphere. Further out grains of interplanetary dust are responsible for the scattering.

Figure 21 shows the corona symmetrically elongated about the equator during solar minimum. During solar minimum active regions of the Sun are found at low latitudes causing the symmetrical elongation. In Figure 22 long streamers radiate out from the corona during solar maximum. These streamers are driven by active regions located at higher latitudes on the Sun.

Figure 21 Corona during solar minimum (credit: NOAA)

Figure 22 Corona during solar maximum (credit: skyandtelescope.org)

3.4 The Sun in Old Age

The lifespan of the Sun is expected to be about 10 billion years. The Sun is now 4.6 billion years old, what could be termed middle age. There is an ample supply of hydrogen in the Sun allowing it to last 100 billion years. However, there are no mechanisms within the Sun to deliver this enormous supply of hydrogen to the core where it is needed to sustain nuclear fusion. Instead, the radiation zone acts like a hot dense insulating blanket 348,000 km deep surrounding the core. There are no down drafts in the radiation zone to transport hydrogen into the core. The hydrogen in the radiation zone is essentially “locked in place”. Mixing of hydrogen and helium gas occurs only in the convection zone at the outer edge of the Sun. Consequently, over the next 5 billion years the Sun will steadily deplete the hydrogen in its core as the hydrogen is fused into helium. Depleted of hydrogen fuel, the nuclear fusion process will slow down causing the core to shrink under the weight of the overlying layers. As it shrinks it will heat up eventually reaching the point at which nuclear fusion re-ignites fusing helium into carbon, nitrogen, and oxygen. Heat generated by the accelerating fusion of helium will cause the Sun to balloon into a red giant engulfing the orbits of Mercury and Venus as shown in Figure 23.

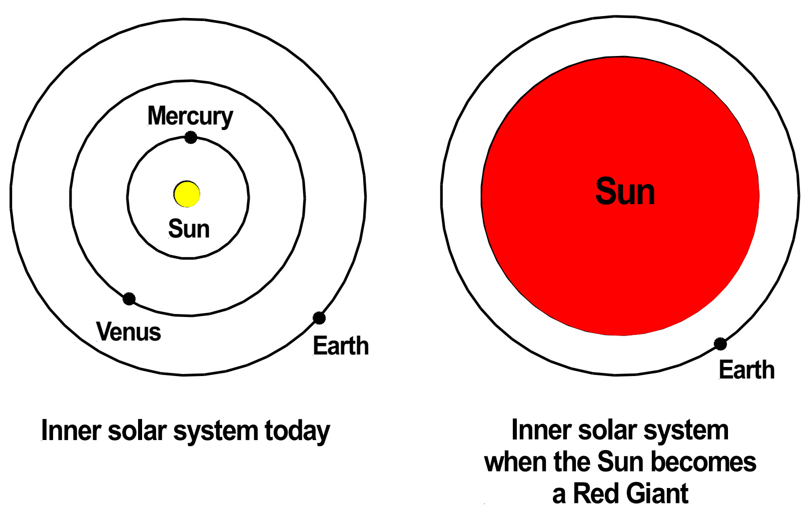

Figure 23 The Sun in old age (credit: author)

Compared to hydrogen, the supply of helium will run out quickly. With no nuclear fuel remaining, the heat needed to keep the Sun in balance with its inward gravitational force will no longer be generated. The Sun, then a red giant, will collapse in 1 to 2 million years. As it collapses it will again heat up igniting nuclear fusion of hydrogen remaining in its outer fringes triggering a massive explosion. The explosion will blow off the outer portion of the Sun into an expanding shell of gas known as a planetary nebula. The remaining core of the Sun will shrink and become hotter forming a brilliant blue-white dwarf star at the center of the planetary nebula shown in Figure 24.

The radiant pressure from the blue-white dwarf will cause the nebula to expand out into space, thin, and eventually disappear. After about 100,000 years all that will be left of the Sun is its highly compressed core. The Sun will have become a white dwarf slightly larger than the Earth with a density of $1\ x\ 10^9\ kg/m^3$ (200,000 times the density of Earth). So dense in fact that a single "sugar cube" of its material will weigh hundreds of tons. A white dwarf is one of the densest objects in the universe surpassed only by neutron stars. Over billions of years the white dwarf will cool until it becomes a dark black cinder lost in the emptiness of space.

Figure 24 Planetary Nebula (credit: NASA)

References

Foukal, Peter; “Solar Astrophysics third edition”; Whiley-VCH Publishing Company, 2013

Carroll, Bradley W. and Ostlie, Dale A.; “An Introduction to Modern Astrophysics”; Addison-Wesley Publishing Company Inc., 1996

Khazanov, George; “Space Weather Fundamentals”; CRC Press, 2016

Cander, Ljiljana R.; “Ionospheric Space Weather”; Springer Geophysics, 2019

Golub, Leon and Pasachoff, Jay M.; “Nearest Star The Surprising Science of Our Sun second edition”; Cambridge University Press, 2014

Moldwin, Mark; “An Introduction to Space Weather”; Cambridge University Press, 2008

White, Stephen M.; “Solar Radio Bursts and Space Weather”; Dept. of Astronomy, University of Maryland, College Park, MD 20742 USA

Friedman, Herbert; “The Astronomer’s Universe Stars, Galaxies, and Cosmos”; W. W. Norton & Company, 1990

Davies, Kenneth; “Ionospheric Radio”; Peter Peregrinus Ltd.,1990

Levis, Curt A. ; Johnson, Joel T.; and Teixeira, Fernando L.; “Radiowave Propagation Physics and Applications”; John Wiley & Sons, Inc., 2010

McNamara, Leo F.; “The Ionosphere: Communications, Surveillance, and Direction Finding”; Krieger Publishing Company, 1991

DeSoto, Clinton B., “200 Meters & Down”; The American Radio Relay League, Inc., 1936

Yeang, Chen-Pang; “Probing The Sky With Radio Waves”; The University of Chicago Press, 2013

Piccioni, Robert L.; Everyone’s guide to Atoms Einstein and the Universe second edition”; Real Science Publishing, 2010

Hogan, Craig J.; “The Little Book of the Big Bang A Cosmic Primer”; Springer-Verlag New York, Inc., 1998

Zirin, Harold and Lang, Kenneth; “Sun - Astronomy”; Encyclopedia Britannica

Kawaler, Steven D., and Dahlstrom, Michael; “White Dwarf Stars”; American Scientist, 2000 [pdf]

“White Dwarf Stars” National Aeronautics and Space Administration, Goddard Space Flight Center, 2010

"Solar experts predict the Sun's activity in Solar Cycle 25 to be below average, similar to Solar Cycle 24"; 2019 NOAA Space Weather Workshop in Boulder, Colo.

Dobler, Sacha; "The next Grand Solar Minimum has (very likely) begun: NASA predicts lowest solar cycle in 200 years"; 14 June 2019

Kuznetsov, V. D.; "From the geophysical to heliophysical year: The results of the CORONAS-F project"; Russian Journal of Earth Sciences, Vol. 9, ES3004, doi: 10.2205/2007ES000276, 2007

Hathaway, David H., Wilson, Robert M., Reichmann, Edwin J.; "Group Sunspot Numbers: Sunspot Cycle Characteristics"; NASA/Marshall Space Flight Center, Huntsville, AL., 2002

Minzner, R. A.; "The 1976 Standard Atmosphere Above 86 km Altitude" NASA Goddard Space Flight Center, 1976

Masi, Marco; "Quantum Physics: an overview of a weird world"; Marco Masi 2018

Zettili, Nouredine; "Quantum Mechanics Concepts and Applications second edition"; John Wiley & Sons, 2009

Ahrens, C. Donald; "Essentials of Meteorology"; Wadsworth Publishing Company, 1998

"Aviation Weather"; Department of Transportation FAA and Department of Commerce NOAA, 1975

Williams, Matt; "What is heat conduction?"; Universe Today, 12/9/2014

Halliday, David and Resnick, Robert; "Physics For Students of Science and Engineering Part II second edition"; John Wiley & Sons, Inc., 1962

Zumdahl, Steven S. "Chemistry second edition"; D. C. Heath and Company, 1989

Devoldere, John; "Low-Band DXing" fourth edition; ARRL, 2005

"The ARRL Antenna Book For Radio Communications"; ARRL

Whitfield, Philip; "From So Simple A Beginning"; Marshall Editions Developments Limited, 1993

Roberts, Alice; "Evolution The Human Story"; DK, 2011

Potts, Richard and Sloan, Christopher; "What Does It Mean To Be Human?"; National Geographic,

Dr. David Hathaway, Dr. Lisa Upton "Solar Cycle Science Discover the Sun!" http://solarcyclescience.com/

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