February 2020

Kenneth N. Larson KJ6RZ

Chapter 2

Structure of the Sun

www.skywave-radio.org

Revised 11/2024

2 The Sun

The Sun is the energy source that makes life on Earth possible. It is the energy source that drives terrestrial and space weather systems, that creates the ionosphere, and makes possible over the horizon HF radio communications. To understand HF radio propagations we must first have a basic understanding of the Sun, how it formed, its internal structure, its atmosphere, and its all important but very chaotic solar cycle. These are the topics of the next few chapters.

Unlike the Earth, the Sun is composed almost entirely of hydrogen and helium gas. The composition of the Sun is shown in Table 1. Helium accounts for just under 8% of all atoms in the Sun while 92% of the atoms are hydrogen. However, the mass of a helium atom, which contains two protons and two neutrons, is four times greater than that of hydrogen which has only a single proton. Because of this difference, 27% of the Sun's mass is composed of helium while hydrogen accounts for 71% of the mass.

In addition to hydrogen and helium, the Sun contains trace amounts of all elements in the chemical periodic table, the most abundant of these being Oxygen, Carbon, and Nitrogen.

	% 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

All of the hydrogen in the universe, plus very small amounts of helium and even smaller amount of lithium, were produced during the formation of the universe some 13.8 billion years ago. With the exception of hydrogen, and the small initial quantities of helium and lithium, all elements in the periodic table up through iron were produced by thermonuclear fusion within the cores of stars that existed a long time ago. Most of the helium and lithium present today was also produced in the same manner. The heavier elements were largely created during catastrophic super nova explosions of very massive stars. The remains of these dead stars made up the nebula of gas from which the Sun and the planets of the solar system were formed. The Sun evolved first around 4.603 billion years ago. The Earth formed about 60 million years later, 4.543 billion years ago. The mass of the Sun $(1.9\ x\ 10^{30}\ kg)$ accounts for over 99% of the total mass in the solar system. This amounts to about 300,000 times the mass of the Earth.

Gravity resulting from the Sun's immense size compresses the Sun's hydrogen and helium gas into a hot dense core. The core is surrounded by the radiation and convection zones, as illustrated in Figure 1. The names of these two zones are derived from the type of heat transfer that occurs in each zone, as explained later.

In this figure the radius of the core, radiation zone, and convection zone are given in terms of $R_\odot$ where $R_\odot$ is the Sun's radius (696,000 km). The internal characteristics of the Sun are summarized in Table 2.

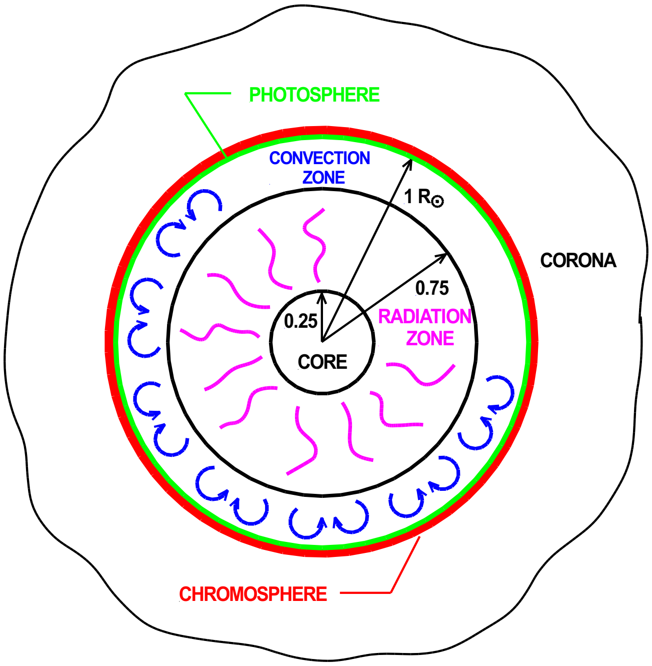

Figure 1 Structure of the Sun (credit: author)

Zone	**Radius**	**Distance**	**Depth**	**Temp °K**	**Density g/cm^3**
	Sun's center			$15.8\ x\ 10^6$	160
Core	↕		174,000 km	↕	
	$0.25\ R_\odot$	174,000 km		$7.8\ x\ 10^6$	20
Radiation	↕		348,000 km	↕	
	$0.75\ R_\odot$	522,000 km		$1.9\ x\ 10^6$	0.15
Convection	↕		174,000 km	↕	
	$1.00\ R_\odot$	696,000 km		6,500	$2.78\ x\ 10^{-7}$

Table 2 Internal characteristics of the Sun (note: 1 km = 0.621371 miles)

Above the convection zone lie the photosphere, chromosphere, and corona which we refer to as the Sun's atmosphere since we can see through them. Temperatures and density within the convection zone cause it to be opaque. The characteristics of the photosphere, chromosphere, and corona regions are summarized in Table 3.

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 3 Characteristics of the photosphere, chromosphere, and corona

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)

The chromosphere stretches outward above the photosphere to an altitude of around 2,300 km. As shown in Table 3, the altitude given here is measured from the top of the convection zone. 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 around 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 3.

Figure 3 View of chromosphere during a solar eclipse (credit: Wikipedia)

The corona begins 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 4.

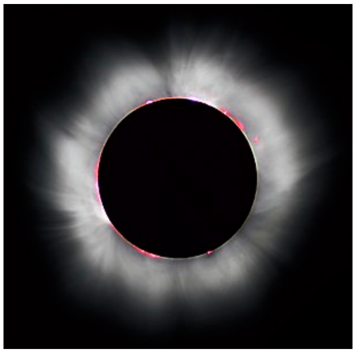

Figure 4 Solar eclipse (credit: Wikipedia)

2.1 Sun's Core

The Sun's core is 27 times larger than the entire Earth (Earth's radius = 6,371 km). The Sun itself is over 100 times larger than the Earth. The core extends from the center of the Sun out to a distance of about $0.25R_{\odot}$.

The core occupies approximately 1.6% of the Sun's total volume. The volume of the Sun is $V_s = \frac{4}{3}\pi\left(R_{\odot}\right)^3$ and that of the core is $V_c = \frac{4}{3}\pi\left(0.25R_{\odot}\right)^3$. While the core is relatively small compared to the rest of the Sun, it contains almost two-thirds of the Sun's total mass. The density at the center of the core is around $160\ g/cm^3$ approximately 160 times the density of liquid water (the density of water is defined as $1\ g/cm^3$) . Density drops rapidly to about $10\ g/cm^3$ at the outer edge of the core (at $0.25R_{\odot}$).

The core's tremendous temperature (15.8 million degrees kelvin) and pressure $(2.50\ x\ 10^{17}\ dynes/\ cm^2)$ causes a sustained thermonuclear reaction to spontaneously occur in the core fusing hydrogen into helium and releasing an enormous amount of energy in the process. This thermonuclear reaction is the source of the Sun's energy.

The outward gas pressure created by the high temperatures and thermonuclear reaction in the Sun's core just balances the inward force of the Sun's gravity. Because of this balance, the size of the Sun has remained essentially the same for the last four and a half billion years and will retain its current size several more billion years. After that the size and energy output from the Sun will change radically as the Sun nears the end of its life.

Interestingly, the thermonuclear fusion of hydrogen into helium in the Sun's core is a self regulating negative feedback system.

1. Higher Fusion Rate: A slight increase in fusion rate will cause the core to heat up and expand. Expansion reduces the hydrogen density within the core which in turn reduces the rate of fusion. The core cools back down and shrinks to its stable size, density, temperature, and fusion rate.

2. Lower Fusion Rate: A slight decrease in the fusion rate will cause the core to cool and compress in size under the Sun's tremendous gravitational force. Compression increases the hydrogen density within the core increasing the fusion rate. The core heats back up and expands to its stable size, density, temperature, and fusion rate.

The Sun's gravitational force causes helium, which is heavier than hydrogen, to sink to the center of the core pushing the lighter hydrogen toward the core's outer regions. Because of this distribution, peak energy generation within the core occurs at about $0.1R_{\odot}$ instead of at the center of the core as one would expect. To date about half of the Sun's core hydrogen has been "burned" into helium.

The 15.8 million degree temperature in the core is so hot that all atoms in the core (hydrogen, helium, and other elements) are fully ionized. That is, they are stripped of all of their electrons leaving a plasma of positively charged nuclei in a sea of negatively charged electrons. Temperature is a measure of thermal motion so 15.8 million degrees means that nuclei within the core are moving at extremely high speeds.

2.2 The Sun's Thermonuclear Reactions

A number of thermonuclear fusion reactions occur in the Sun's core. However, the dominant reaction, known as the Proton-Proton Chain, is believed to produces about 85% of the Sun's energy.

The standard chemical nomenclature is used in describing this chain of reactions. Specifically $_aX^b$ where X is an atom, "a" is the atomic number of the atom (the number of protons in its nucleus), and "b" is its mass number (the number of protons plus neutrons in its nucleus).

The Proton-Proton Chain (p-p chain) consists of three steps.

The first step occurs during the hyper-speed collision of two hydrogen nuclei (two protons). The collision is so violent that a positron β^+ and a neutrino υ are ejected from one of the protons changing it into a neutron. (A positron is particle with the same mass as an electron, but with a positive charge.) As the collision continues, the tremendous impact rams the neutron into the remaining proton with such force that they bond into a deuterium nuclei. The resulting deuterium nuclei consists of one proton and one neutron $({}_1H^2)$ and is known as heavy hydrogen. In equation form this reaction is

$${}_1H^1 + {}_1H^1 = {}_1H^2 + \beta^+ + \upsilon$$

This reaction is incredibly rare. Many trillions of collisions occur between hydrogen nuclei before one occurs with such horrific energy to create deuterium. The low probably of this reaction occurring slows down the rate of fusion within the core allowing the Sun, and other similar stars, to exist for billions of years instead of burning out in just a few million years.

The positron " β^+ " in the above equation is quickly annihilated by one of the vast number of negatively charged electrons "e" available within the core producing two gamma rays "γ" in the process.

$$\beta^+ + e^- = 2\gamma$$

Step 1 is shown in Figure 5.

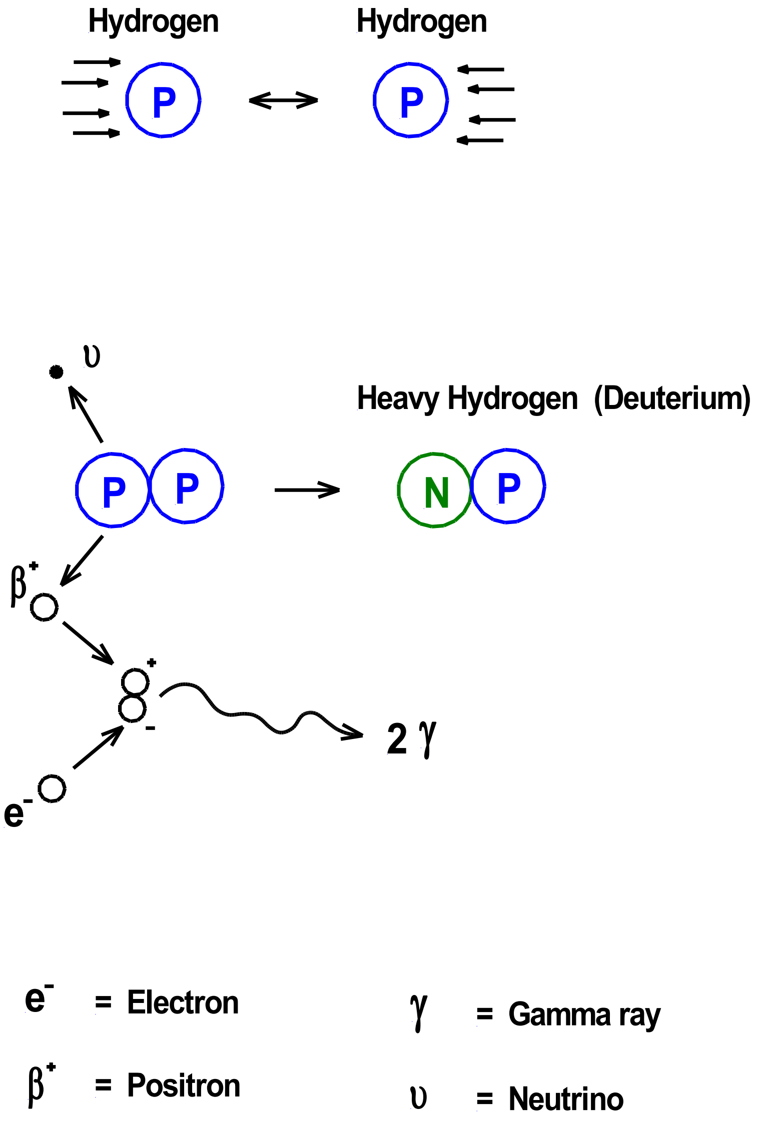

Figure 5 P-P Chain Step-1 (credit: author)

The second step of the p-p chain consists of a deuterium nuclei combining with a hydrogen nuclei to produce an isotope of helium ${}_2He^3$ (light helium) and a gamma ray, as shown in Figure 6.

$${}_1H^2 + {}_1H^1 = {}_2He^3 + \gamma$$

This step occurs quickly since there are a vast number of hydrogen nuclei available to combine with the deuterium nuclei.

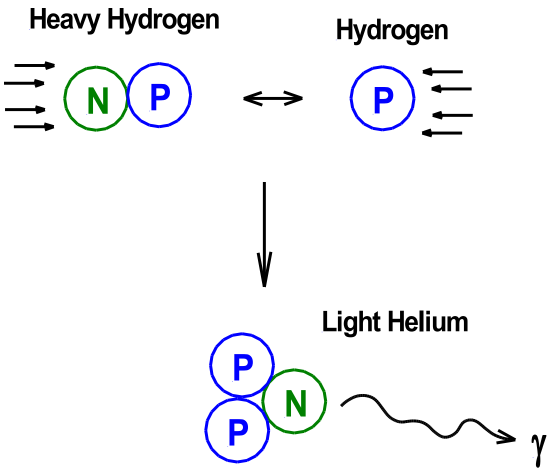

Figure 6 P-P Chain Step-2 (credit: author)

The final step of the p-p chain, shown in Figure 7, consists of two ${}_2He^3$ light helium isotopes combining to form one normal ${}_2He^4$ helium nuclei and two hydrogen nuclei

$${}_2He^3 + {}_2He^3 = {}_2He^4 + 2({}_1H^1)$$

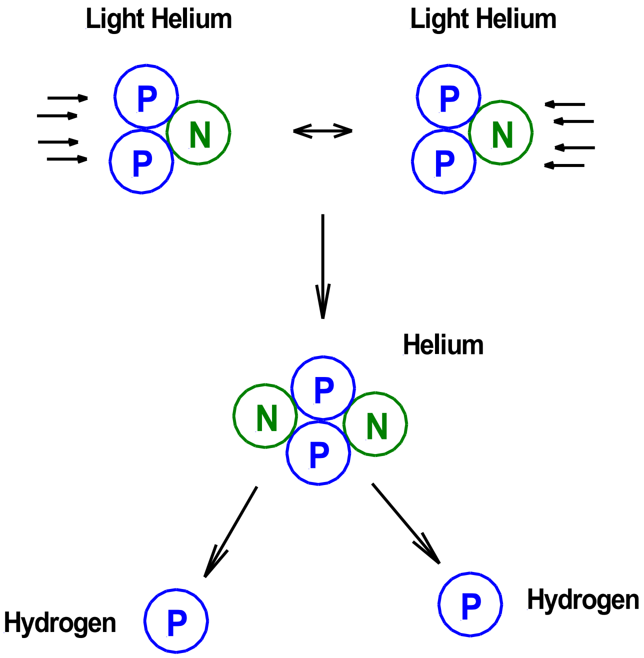

Figure 7 P-P Chain Step-3 (credit: author)

The gamma ray radiation released by the p-p chain, and other less prominent fusion reactions, produce the Sun's energy.

One of the products of the above reactions is a neutrino. A neutrino is an extremely small particle without any electrical charge. The mass of a neutrino is a million times smaller than an electron (a billion times smaller than a hydrogen nuclei). It interacts so weakly with other particles that it can pass through thousands of miles of steel without hitting anything. About 2% of the energy produced by the p-p chain is carried off by neutrinos and lost to outer space without contributing anything to the Sun's energy and luminosity.

The extreme rarity of the first step in the p-p chain has a profound affect on the possibility of life throughout the universe. The simplest form of life (blue-green algae) took nearly a billion years to form on Earth. Another 3 billion years passed before more complex forms of life began appearing. If stars burned themselves out in only a few million years, life as we know it would not have time to start. This in fact was the initial problem with Darwin's theory of evolution. The leading scientists at the time rejected Darwin's theory because it was believed the Earth was less than 50 million years old. It was not until atoms and radio activity were discovered in the early 1900s that the age of the Earth was found to be over 4 billion years old, old enough for Darwin's theory to be correct. The extreme rarity of the first step in the p-p chain makes life possible .

The chemical composition of the Sun, in terms of mass, is fairly uniform consisting of 71% hydrogen, 27% helium, and 2% other elements, about the same composition found throughout the universe. While the Sun as a whole has largely retained its original chemical composition, the core has not. Thermonuclear fusion has altered the composition within the core to approximately 34% hydrogen and 64% helium by mass. Because the energy transfer out of the core is radiation rather than convection, the products of the thermonuclear reaction (helium and trace elements) remain locked inside the core. More importantly, temperature gradients prevent the vast supply of hydrogen available throughout the rest of the Sun from reaching the core. Consequently, the supply of hydrogen in the core will eventually run out and the Sun will die.

2.3 Heat Transport

The energy produced in the core is in the form of heat, as apposed to mechanical energy, chemical energy, etc. Heat is the transfer of energy from a hot object to a cooler one measured in joules (the unit for energy). In the case of the Sun, the energy transfer is from the extremely hot core out to progressively cooler regions of the Sun, the coolest region being the photosphere (the visible surface of the Sun).

Heat can be transferred in three different ways, by

- Conduction,
- Convection, or by
- Radiation

2.3.1 Conduction

Conduction is the transfer of heat **in the absence of fluid motion**, for example by physical contact between a hot object and a cooler one. Figure 8 shows heat being conducted along a rod that is heated at one end. The heated end of the rod is very hot meaning that the molecules at this end are in a high state of agitation. These energetic molecules collide with cooler molecules to the right, further away from the rod's heated end. The collisions transfer energy to the cooler molecules causing them to become hotter, but not quiet as hot as the molecules at the rod's heated end. The newly heated molecules in tern collide with molecules still further to the right along the rod causing them to also become hotter, but again not as hot as the molecules to the left. This process continues along the length of the rod with the amount of heat energy being transferred toward the right slowly decreasing.

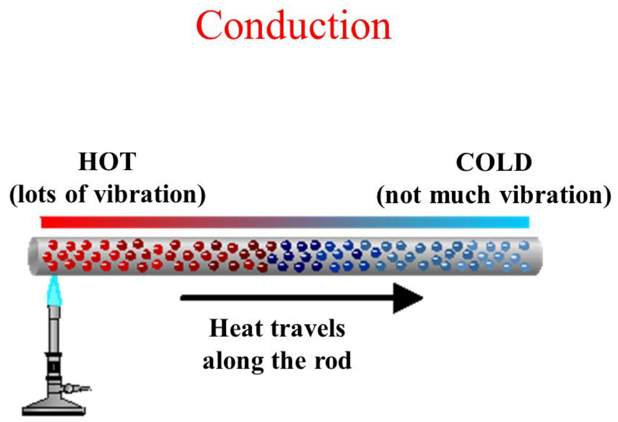

Figure 8 Conduction (credit: Prof. R. Shanthini – slideplayer.com)

The rate at which heat conduction occurs depends on the thermal conductivity of the material being heated. Metals have a high thermal conductivity and thus conduct heat quickly. The conductivity of ceramics is less than that of metals. Thus, the length of a metal rod gets much hotter than a ceramic one. Gasses, including those on the Sun, have low thermal conductivity and thus conduct heat slowly.

2.3.2 Convection

Convection is the transfer of heat **by fluid motion**. Convection is a common phenomenon. Examples of convection include boiling water in a pan and the rising of warm air from the Earth's surface into the atmosphere.

In the case of Earth's atmosphere, air temperature decreases with elevation. For example, the air temperature at 7,000 feet in Yosemite National Park is much cooler than in the city of Fresno in the valley below. If r is the distance above Earth's surface (altitude) and $T(r)$ is the temperature at that distance, then the change in temperature $dT(r)$ for a small change in distance dr is defined as the temperature gradient. That is,

$$Temperature\ Gradient\ \equiv \frac{-d\,T(r)}{dr}$$

The temperature gradient is negative since temperature decreases with increasing distance r from the Earth's surface.

Earth's surface is heated unevenly by the Sun. For example, a grassy knoll will quite likely be warmer than a near by area of trees and other foliage. A parcel of air in contact with a hot spot, like a grassy knoll, is heated and becomes warmer. As it is heated it expands, its density drops relative to the surrounding air, and it becomes buoyant. The parcel of air starts floating upward. The temperature within the parcel decreases as the parcel expands. However, we assume that the parcel does not exchange any energy with its surroundings in the short time that it takes to float a small distance upward. The temperature and density within the parcel do change, but its internal energy remains the same. The parcel of air is an example of an adiabatic process. The temperature change within the parcel over a short distance is defined as the adiabatic temperature gradient. So

$$Adiabatic\ Temperature\ Gradient\ \equiv \left[\frac{-d\,T(r)}{dr}\right]_{ad} = \frac{[-d\,T(r)]_{ad}}{dr}$$

Again, the negative signs are required since the adiabatic temperature also decrease with increasing distance r from the Earth's surface.

If the parcel cools slower than the surrounding air, it will remain warmer than its surroundings, continue to expand, and float upward forming a gentle updraft. As the rising air cools to its saturation point, moisture carried aloft by the air will condense forming a cumulus cloud.

Evaporation cools the air around the outer edges of the cloud causing the air to become heavy and sink toward the ground. As it sinks it is warmed by compression as it descends into the denser warmer air below. If the sinking air heats slower than the surrounding air, it will continue to be cooler than its surroundings and continue to fall forming a down draft.

Warm rising air in combination with cool air that is descending forms a convective air flow, as shown in Figure 9. A "popcorn" sky of small cumulus clouds, like that shown in Figure 10, surrounded by open areas of blue sky often form during warm summer days. Each tinny cloud marks the location of a rising column of air while the clear areas between the clouds are regions where the air is sinking. Convection stirs up the atmosphere mixing warm moist air near the ground with cool dry air above.

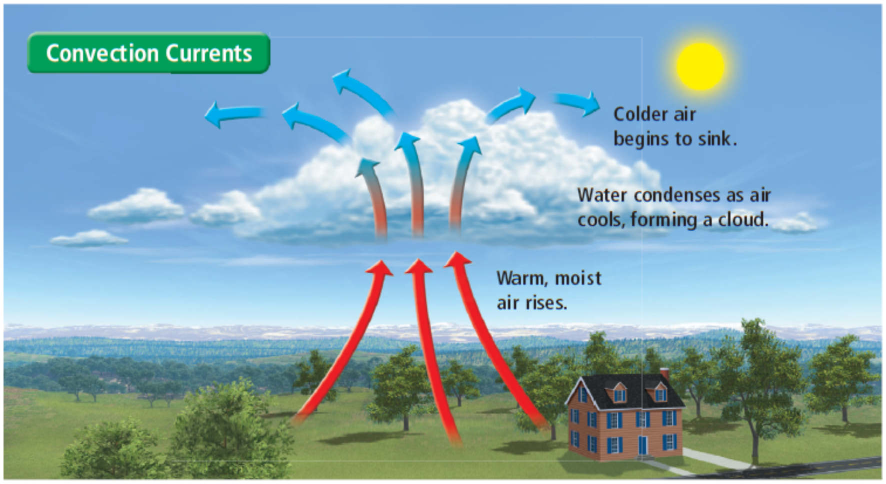

Figure 9 Convection Currents (Credit: Google)

Figure 10 Popcorn Sky (credit: weather.ou.edu)

For convection to occur (warm air rising and cool air sinking) the adiabatic temperature gradient within an air parcel must be less than the temperature gradient of the surrounding air. That is

$$\left[\frac{d\,T(r)}{dr}\right]_{ad} < \frac{d\,T(r)}{dr} \qquad for\ convection\ to\ occur$$

Nothing happens if the reverse is true. If

$$\left[\frac{d\,T(r)}{dr}\right]_{ad} > \frac{d\,T(r)}{dr} \qquad no\ convection$$

In this case the atmosphere near the Earth's surface is stable (stagnate) with no ascending or descending air flow.

2.3.3 Radiation

Radiation is the transfer of heat via electromagnetic waves. Electromagnetic energy spans the entire spectrum from very low frequency radio waves at one end of the spectrum to gamma rays "γ" at the opposite end. Gamma rays are the most energetic highest frequency form of electromagnetic energy. Somewhere toward the upper end of the spectrum is visible light (violate through red) that we are capable of seeing. Infrared radiation is just below the visible light spectrum. X-rays and extreme ultra-violate light occupy the spectral region between gamma rays and visible light, as illustrated in the Figure 11.

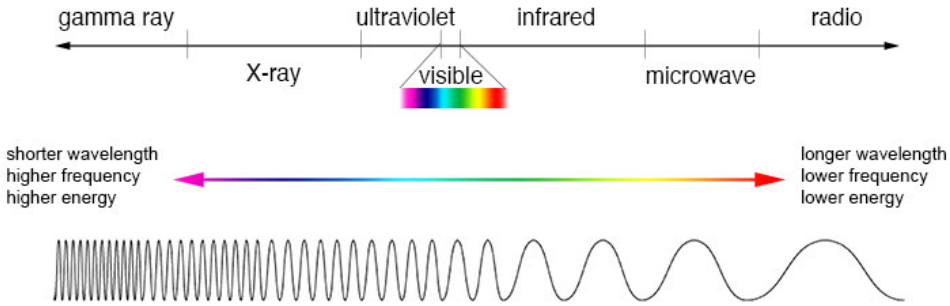

Figure 11 Electromagnetic spectrum (credit: NASA – www.ces.fau.edu)

Electromagnetic radiation has a wave-particle duality. When propagating from one place to another it does so as a wave exhibiting a wave amplitude, phase, and frequency. When interacting with matter (nuclei, atoms, molecules, etc.) it does so as a particle, a photon with zero mass but traveling at the speed of light. The energy E carried by a photon is $E = hf$ where h is Planck's constant $(6.6261\ x\ 10^{-34}\ joules\ per\ second)$ and f is the frequency of the photon's electromagnetic wave. Gamma ray γ photons are the highest energy photons since they posses the highest frequency electromagnetic waves.

2.4 Transport of Thermonuclear Heat

Transport of thermo-nuclear heat away from the Sun's core takes place mainly by radiation and convection.

2.4.1 Temperature Gradient

The temperature gradient $\left[\frac{dT}{dr}\right]$ is the rate at which temperature is changing at a distance r from the center of the Sun. The temperature gradient at any point within the Sun is

$$-\left[\frac{dT}{dr}\right] = \frac{-\,3\,\overline{\kappa_R}\,\rho}{16\,\sigma\,T^3}\,F_{rad}$$

where

$\left[\frac{dT}{dr}\right]$ = the temperature gradient

F_{rad} = radiant flux of energy (photons) emanating from the thermo-nuclear reactions within the Sun's core

T = kelvin temperature at the point of interest in the Sun's interior

ρ = the density of the solar material (hydrogen and helium gas) at that point

σ = the Stefan – Boltzmann constant

$\overline{\kappa_R}$ = Rosseland mean opacity

The Rosseland mean opacity requires some additional explanation. The change in the intensity of light dI_λ as it travels through a gas is proportional to its initial intensity, I_λ , the distance traveled, dr, and the density of the gas, ρ , where λ is the light's wavelength. That is

$$dI_\lambda = -\,\kappa_\lambda\,\rho\,I_\lambda\,dr$$

The term r is the distance from the center of the Sun. dr is the change in that distance. The minus sign in the above equation indicates that intensity decreases with distance r as photons, traveling outward through the Sun's hydrogen and helium gas, are gradually absorbed.

The quantity κ_λ is called the absorption coefficient or **opacity**. Opacity depends not only on the wavelength of the light being absorbed but also on the composition, density, and temperature of the gas through which the light is traveling.

It is often convenient to use an opacity term which is the average, or mean, of all the opacities over the range of wavelengths of interest. This is known as the Rosseland mean opacity. The Rosseland opacity, which is independent of wavelength, depends only on the gas composition, density, and temperature in the region of interest.

2.4.2 Adiabatic Temperature Gradient

The adiabatic temperature gradient is the rate at which the temperature within a small parcel of gas would change if it moved a short distance, dr, without exchanging any heat energy with its surroundings. The temperature, volume, and density of the parcel all change as it moves a distance dr, but its internal energy does not change.

The adiabatic temperature gradient at any point within the Sun is

$$-\left[\frac{dT}{dr}\right]_{ad} = -\left[1 - \frac{c_v}{c_p}\right]\frac{T}{P}\frac{dP}{dr}$$

where

$\left[\frac{dT}{dr}\right]_{ad}$ = the adiabatic temperature gradient

c_v = the specific heat of the region's gas measured at constant volume (the quantity of heat that must be added to 1 unit of mass of a gas to raise its temperature of by 1 $°K$ if its volume is held constant)

c_p = the specific heat of the gas at constant pressure (the quantity of heat that must be added to 1 unit of mass of a gas to raise its temperature of by 1 $°K$ if its pressure is held constant)

T = the region's temperature

P = the region's pressure

2.4.3 Radiative vs Convective Heat Transfer

Radiative heat transfer is the dominate form of heat flow everywhere in the Sun where the temperature gradient is less than the adiabatic gradient, that is whenever

$$-\left[\frac{dT}{dr}\right] < \left[\frac{-dT}{dr}\right]_{ad}$$

or equivalently whenever

$$\frac{d(\log T)}{d(\log P)} < 0.4$$

as shown in Figure 12.

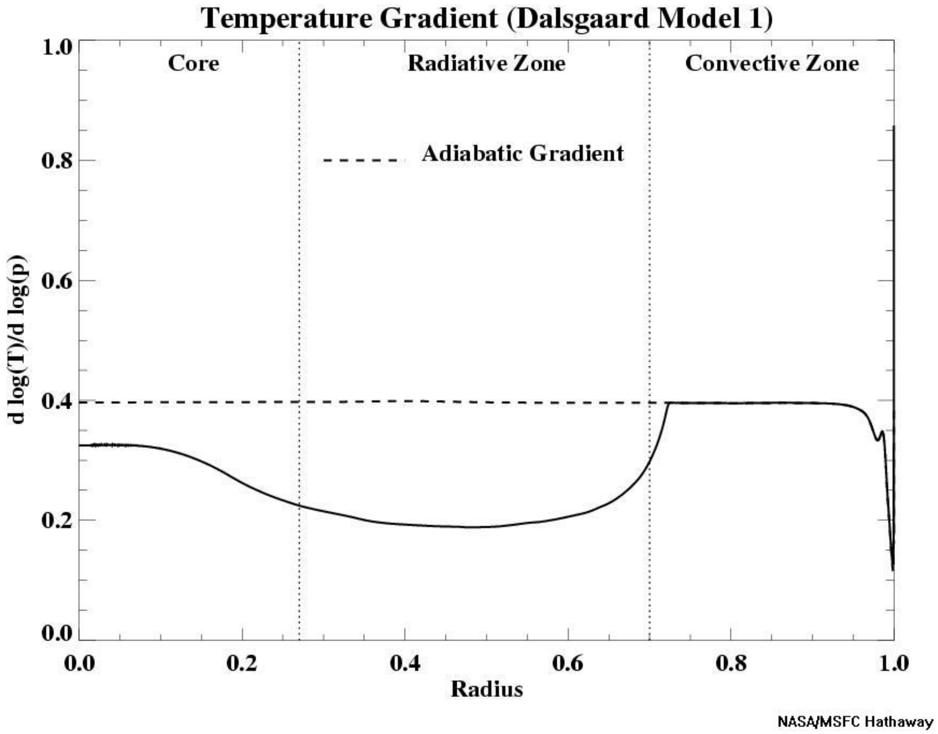

Figure 12 Temperature Gradient (credit: solarscience.msfc.nasa.gov)

Conversely, convection is the dominant heat transfer mechanism whenever the adiabatic temperature gradient is less, even slightly less, than the surrounding temperature gradient. That is, convection will occur whenever

$$-\left[\frac{dT}{dr}\right] \geq \left[\frac{-dT}{dr}\right]_{ad}$$

meaning that

$$\frac{-3\,\overline{\kappa_R}\,\rho}{16\,\sigma\,T^3}\,F_{rad} \geq -\left[1-\frac{c_v}{c_p}\right]\frac{T}{P}\frac{dP}{dr}$$

and

$$\frac{d(\log T)}{d(\log P)} = 0.4$$

In general terms, convection will occur

1. When the stellar opacity $\overline{\kappa_R}$ is large. Opacity is a deterrent to radiation.
2. In regions where ionization of hydrogen and helium is in the process of actively occurring. Ionization causes large specific heats and low adiabatic temperature gradient. This condition does not apply in regions where hydrogen and helium are already fully ionized.
3. When the local gravitational acceleration is low, as would be the case in very distended stars, resulting in a low adiabatic temperature gradient.
4. When the rate of thermo-nuclear energy generation is high leading to large radiant energy fluxes (F_{rad}) and corresponding large radiant temperature gradients.

2.5 Radiation Zone

From Figure 13 it is clear that temperatures in the radiation zone are very high and change slowly throughout the region. These conditions lead to a small temperature gradient $\left[\frac{dT}{dr}\right]$ in which

$$-\left[\frac{dT}{dr}\right] < \left[\frac{-dT}{dr}\right]_{ad}$$

and

$$\frac{d(\log T)}{d(\log P)} < 0.4$$

everywhere within the radiation zone, preventing convection from occurring. Consequently, radiation is the only form of heat transfer possible throughout the radiation zone.

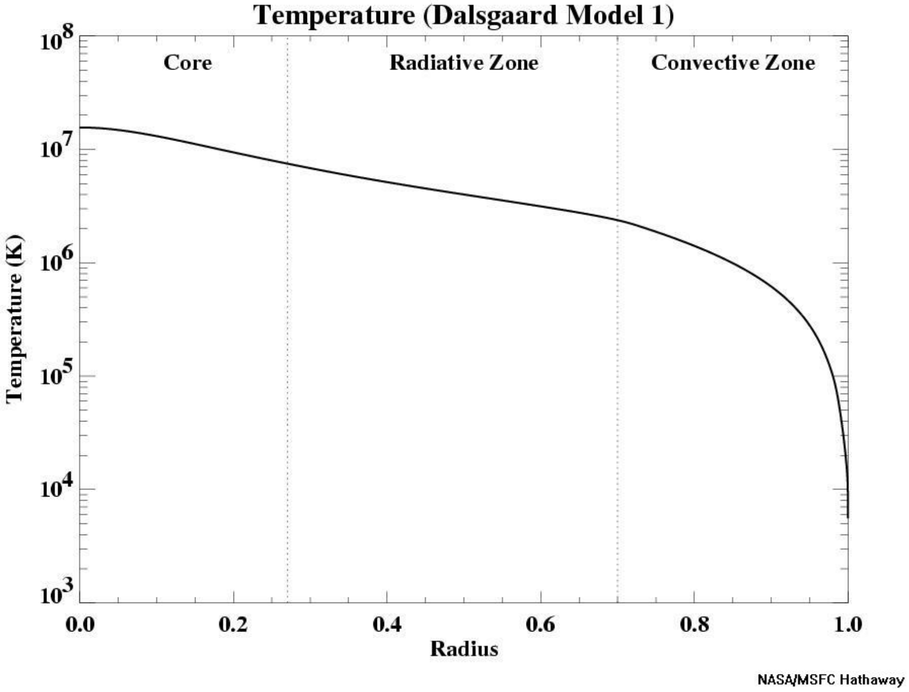

Figure 13 Temperature (credit: solarscience.msfc.nasa.gov)

Gamma ray photons emanating from the Sun's core are in constant never ending collisions with hydrogen and helium nuclei throughout the radiation zone. The collisions scatter the photons in every possible direction. In addition, each collision transfers small amounts of energy from the energetic photons to the hydrogen and helium nuclei heating the radiation zone to its very high temperature.

Because of its zigzag chaotic path, a photon typically takes around 170,000 years to traverse the radiation zone. It then passes quickly through the convection layer and takes only 8 minutes to complete its journey from the Sun's photosphere to Earth. The sunlight that we enjoy today began its journey in the Sun's core shortly after modern man (homo sapien) first appeared on earth 200,000 years ago. It has been in route to us through all of human history finally arriving today.

Since the energy of a photon is $E = hf$, the frequency of a photon's electromagnetic wave must drop as it loses energy through constant collisions with hydrogen and helium nuclei. Photons which begin as gamma rays in the Sun's core are reduced to X-rays and extreme ultra-violate light by the time they emerge from the radiation zone a distance of $0.75R_\odot$ from the Sun's center.

The temperature at the center of the Sun's core is 15.8 million degrees kelvin. This temperature drops to around 7.8 million degrees kelvin at the boundary between the core and the radiation zone (at $0.25R_\odot$). The plasma density at this point is in the neighborhood of $20\ g/cm^3$. At the outer edge of the radiation zone (at $0.75R_\odot$) the temperature drops to around 1.9 million degrees kelvin and the density drops by a factor of 100 to roughly $0.15\ g/cm^3$, as shown in Figure 14.

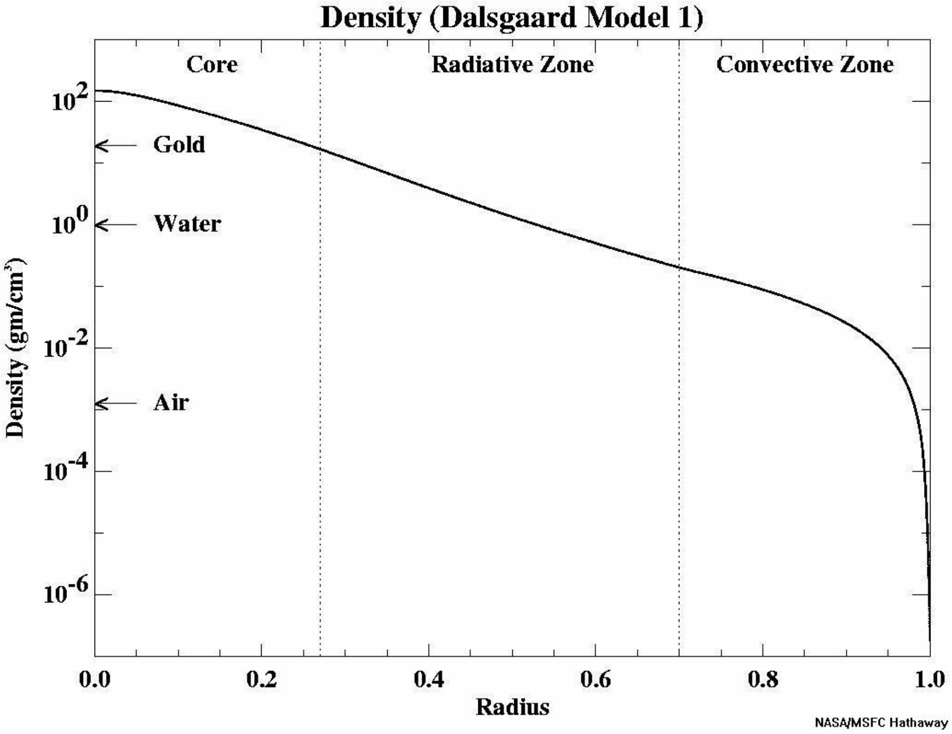

Figure 14 Density (credit: solarscience.msfc.nasa.gov)

Convection currents could deliver the vast store of hydrogen from throughout the Sun's interior to the core where it is needed to maintain the Sun's thermonuclear reaction. But the temperature gradients are such that convection can not occur in the radiation zone. Radiation is the only possible heat flow in this region of the Sun. Consequently, the radiation zone acts as a thick barrier preventing hydrogen from reaching the core where it is desperately needed to maintain the Sun's thermonuclear reaction. The life span of the Sun is therefore determined entirely by the amount of hydrogen originally in the Sun's core and the rate at which that hydrogen is "burned" into helium.

2.6 Convection Zone

Within the Sun the convection zone begins at of about $0.75R_{\odot}$. At this distance from the Sun's center the temperature is 1.9 million degrees kelvin. This is cool enough for heavier ions (such as carbon, nitrogen, oxygen, calcium, and iron) to retain some of their electrons, causing the convection zone plasma to become opaque, resisting the flow of radiation. Figure 13 above shows that temperatures drop quickly in the convection zone. The increasing opaqueness ($\overline{\kappa_R}$) and rapidly falling temperatures (T) lead to a steep temperature gradient $\left[\frac{dT}{dr}\right]$ where

$$-\left[\frac{dT}{dr}\right] = \frac{-\,3\,\overline{\kappa_R}\,\rho}{16\,\sigma\,T^3}\,F_{rad}$$

resulting in

$$-\left[\frac{dT}{dr}\right] \geq \left[\frac{-dT}{dr}\right]_{ad}$$

and

$$\frac{d(\log T)}{d(\log P)} = 0.4$$

Convection spontaneously occurs dominating heat flow within the convection zone shown in Figure 15. The convective motion carries heat quickly to the surface heating the photosphere. The convection zone plasma expands and cools as it rises. At the base of the photosphere the temperature is 6,500 K and the density is only $2.78\ x\ 10^{-7}$gm/cm³ (about 1/10,000th the density of air on Earth at sea level).

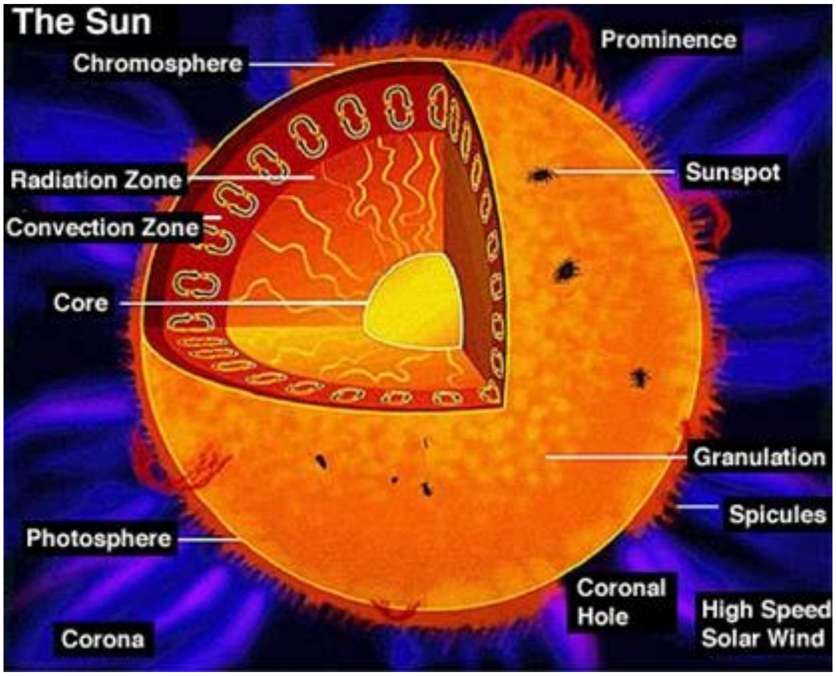

Figure 15 The Sun (credit: NASA's Cosmos – ase.tufts.edu)

The size of a star's convection zone depends on its mass. Low mass stars have large convection zones while high mass stars may not have a convection zone at all.

Very small Class M stars, shown in Figure 16, have steep temperature gradients, large $-\left[\frac{dT}{dr}\right]$, between their core and photosphere so that

$$-\left[\frac{dT}{dr}\right] \geq \left[\frac{-dT}{dr}\right]_{ad}$$

throughout the star. This means that convection is the only possible form of heat flow within the interiors of these very small stars. These stars do not have radiation zones. Instead, their convection zones occupy all of the star's interior. This provides the star with a considerable advantage. The convection zone of a tiny star delivers hydrogen from throughout the star's interior to its core continuously fueling the star's thermonuclear reaction. Consequently, small stars have a very long-life span in excess of 100 billion years.

Radiation zones develop as stars become more massive. Development of a radiation zone means that a star's convection zone must shrink in size. The convection zone in the Sun, a Class G star, occupies less than 30% of the Sun's interior. The existence of a radiation zone blocks the flow of hydrogen into the core considerably shorting the star's life. Without an inflow of hydrogen, the star's life is completely determined by the amount of hydrogen initially in the star's core. Once that hydrogen is gone (fused into helium) the life of the star is at an end. The life span of stars such as the Sun is around 10 billion years.

The convection zone shrinks to a very thin layer enveloping the outer part of stars much more massive than the Sun. In the largest stars the convection zone disappears completely. However, for these massive stars steep temperature gradients can develop within the core itself creating a convective core. The tremendous temperatures and pressures within the cores of these massive stars cause them to burn their available supply of hydrogen very quickly. Consequently, the life span of massive stars is very short. The most massive stars can burn out and explode in supernovas after only a few million years.

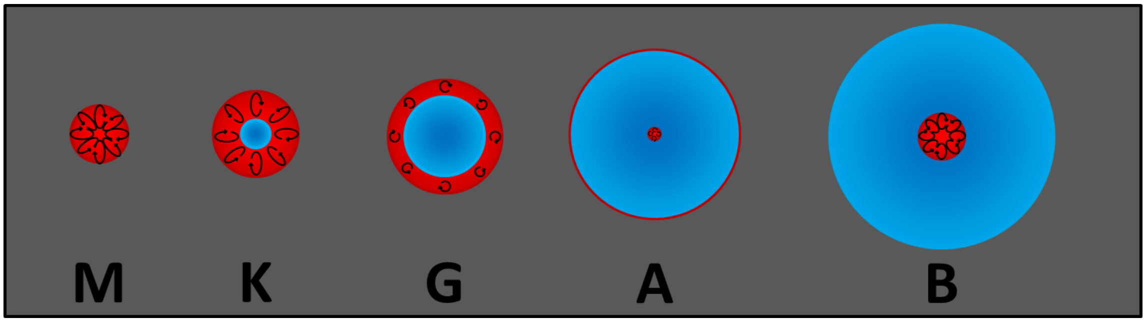

Figure 16 Convection zone in various star classes (credit: Hathaway - solarcyclescience.com)

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

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

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

Hunsucker, R. D. and Hargreaves, J.K.; “The High-Latitude Ionosphere and its Effects on Radio Propagation”; Cambridge University Press, 2003

Conselice, Christopher J.; “The Beginning to the End of the Universe: The emergence of Matter”; Astronomy January 2021

Goodman, John M.; “Space Weather & Telecommunications”; Springer Science+Business Media, Inc. 2005

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

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/

Solar Physics Group at NASA's Marshall Space Flight Center
https://solarscience.msfc.nasa.gov