OUR SUN: THE NEAREST STAR

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Contents

Summary

This article describes the structure of the Sun and the physical processes that occur within it. The text is without mathematics and is written for a general audience. Extensive references are given to allow the reader to pursue certain issues in more depth.

In the first ten sections, the different layers are described, starting from the core and advancing to the outer atmosphere, the solar wind and the heliosphere.

In the next five sections, some special topics are considered, such as the internal rotation of the Sun; the physical origin of the solar cycle; solar activity; and the heating of the outer atmosphere and acceleration of the solar wind. In the last part, the Sun's influence on the Earth is discussed b briefly.

1. Introduction

Our Sun is a typical middle-aged star, one of billions like it in our Milky Way Galaxy.

As the source of all the energy Earth receives, the Sun is literally the most important star to humanity. Ancient cultures recognized its central importance to life and worshipped it as a god. Because it is so near, we have been able to learn a great deal about the way a typical star functions. Astrophysics as a whole has benefited in many ways from discoveries made on the Sun.

The Sun affects the Earth not only by the light it emits but also by its "wind" of electrically charged particles and by the huge masses of gas it ejects sporadically. These "coronal mass ejections" generate auroras and severe geomagnetic storms when they collide with Earth. Some evidence points to the Sun's influence on our climate as well.

According to current ideas, the Sun formed in the collapse of a large interstellar cloud of hydrogen and helium molecules, about 4.7 billion years ago. As it contracted by self-gravitation it heated and spun faster. If we can extrapolate from observations of other stars that are forming, the Sun blew away a fraction of its initial mass and most of its angular momentum in a fast solar wind. Thermonuclear reactions were ignited in the solar core and after a few million years the Sun settled into its present stable state. Calculations of the evolution of the Sun suggest that its energy output has increased by about 25 percent during its lifetime. Such models predict that in approximately five billion years the Sun will exhaust the hydrogen fuel in its core and will then pass through a series of transformations into a white dwarf.

Table 1 summarizes some of the Sun's basic properties. Its surface chemical composition (Table 2) was determined by comparing the spectrum with those of laboratory samples. All the terrestrial elements are found in the Sun and helium was discovered there first.

Mean distance from Earth	**149.60 x 10^6 km**
Age	4.6 x 10^9 years
Equatorial radius	695500 km
Mass	1.989 x 10^{30} kg
Composition (by mass) (1)	
Hydrogen	0.739
Helium	0.248
Heavy elements	0.0126
Rotation period	
equatorial, synodic	27.2753 days
equatorial, sidereal	25.38 days
Solar constant (Total irradiance)(2)	1364- 1368 Watts/meter^2

(1) Basu, S. and Antia,H.M., arXiv:0711.4590v1, Physics Reports, 2008
(2) National Geophysical Data Center

Table 1. Properties of the Sun

The Sun emits light of all wavelengths; from picometer (10^{-12} m) X-rays to decameter (10 m) radio waves. In general the hottest regions emit the shortest wavelengths but non-thermal radiation (e.g. gamma rays) is emitted also. The surface of the Sun emits a smooth spectrum that peaks at about 500 nanometers (10^{-9} m), a yellow-green color to which our eyes and the chlorophyll of plants are most sensitive.

Unlike the Earth, the Sun does not have a solid core; it is gaseous everywhere. At the Sun's center, the density of the compressed gas is estimated at 150 times that of water.

Numerical models of the Sun indicate that the temperature of the Sun decreases uniformly outward from about 15 MK in the core to about 6000 K at the surface. The temperature rises steeply in the thin outer atmosphere, which is inhomogeneous and highly dynamic. Values of temperature between one and five million Kelvin are detected there.

The interior of the Sun consists of several layers as shown in Figure 1. The layers are in order: a core, in which all solar energy is generated; an overlying radiative zone, where energy is carried to the surface by diffusion of photons; a convective zone, in which heat is transported outward by circulating cells of plasma; the photosphere, a thin layer where light escapes the Sun; the chromosphere and transition zone where the temperature rises sharply; and finally the multi-million Kelvin corona Figure 2. A hot fluctuating solar wind of electrically charged particles escapes the corona at speeds up to 800 km/s and blows past all the planets.

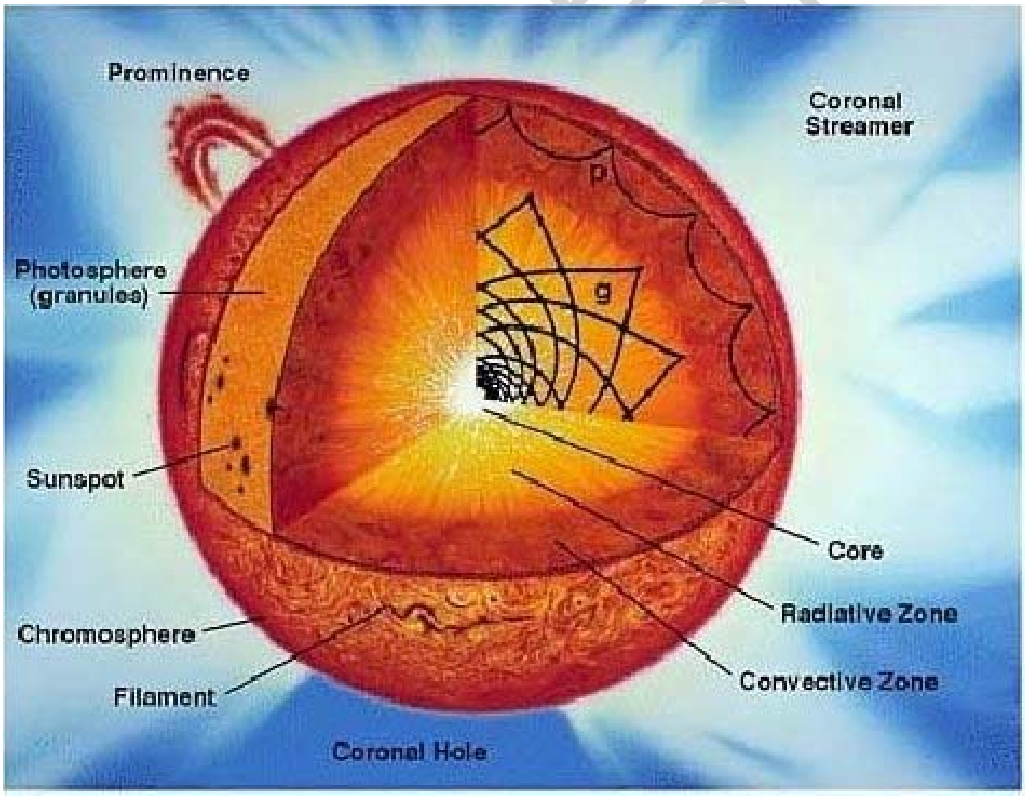

Figure 1. A cartoon of the layers of the Sun (Courtesy of SOHO)

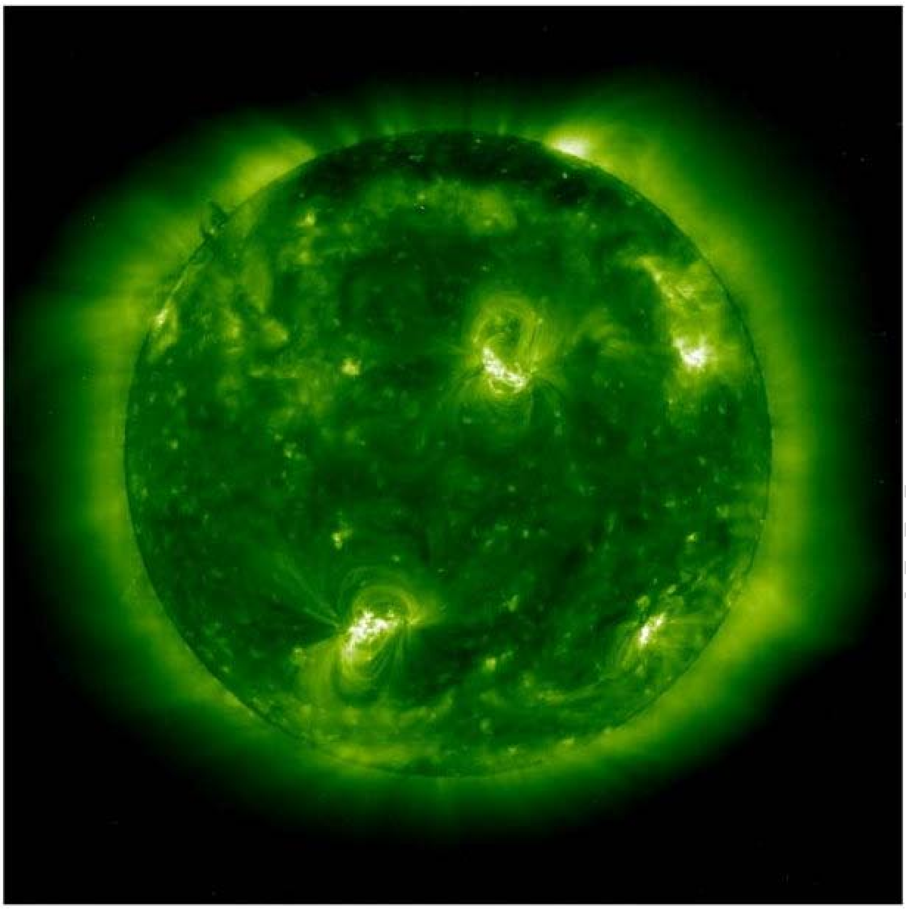

Figure 2. The solar corona imaged at a wavelength of 19.5 nm, which corresponds to a temperature between one and two million Kelvin. Notice the bright active regions, loops and the cold dark poles. (Courtesy of SOHO/EIT)

Magnetic fields control the shapes and behavior of all the features in the Sun's atmosphere. Magnetism is also responsible for the many varieties of solar activity, including sunspots, solar flares and ejections of coronal mass. All forms of solar activity vary in an 11-year cycle whose amplitude also varies with periods of 88 years and longer.

The Sun does not rotate as a solid body would. At the photosphere, its equator completes a rotation from east to west in 27.3 days, as seen from the orbiting Earth. At higher latitudes, the surface rotates more slowly. At latitude 70 degrees, for example the synodic period of rotation is 32 days. This variation in latitude is known as differential rotation. Figure 3 (Snodgrass and Ulrich, 1990) illustrates this variation at the photosphere.

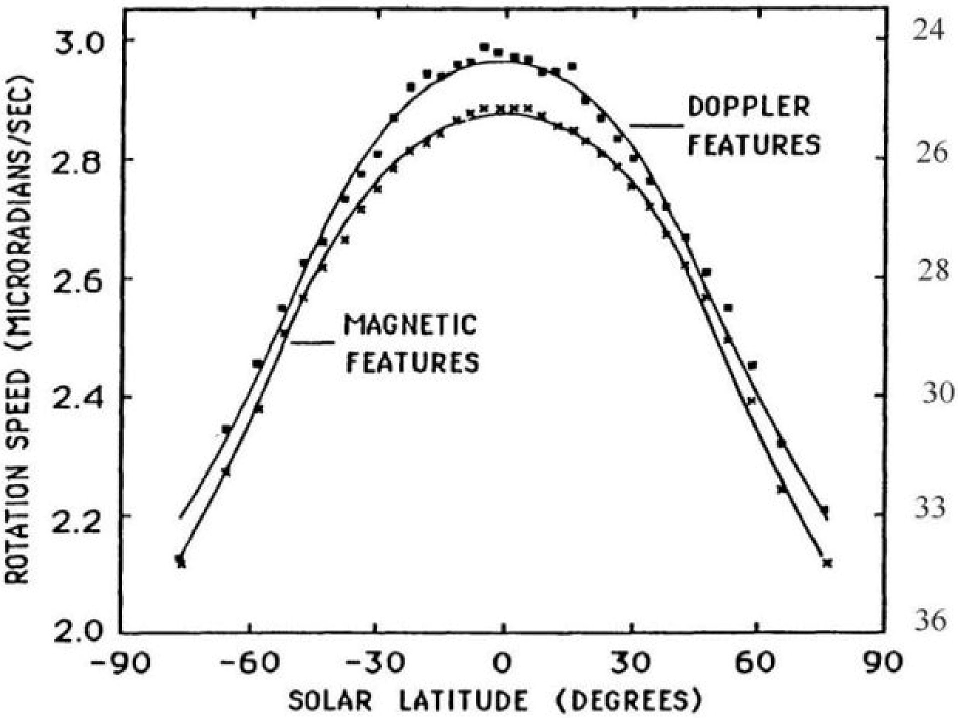

Figure 3. A plot of differential rotation in the photosphere as a function of solar latitude. "Doppler features" refer to the network that is defined by the borders of supergranules. "Magnetic features" refer to large-area averages of the magnetic flux (Courtesy of H. Snodgrass and R. Ulrich, Ap.J 351, 409, 1990)

Sound waves generated in the turbulent convection zone combine to form a complicated pattern of standing waves all through the Sun. From observations of the pattern near the surface, scientists can derive several important properties of the interior, including the temperature profile and the variation of rotation with depth and latitude. This field of research is called helioseismology, in analogy to seismology of the Earth. (See Section 12 on helioseismology)

This article is organized in two parts. A survey of the principle properties of the different layers of the Sun is presented in the first part. Several important topics are discussed in more depth in the second part, including theory and modeling. Cross-references between the parts are given to assist the reader in finding information.

1.1 The Core

For over two hundred years, the source of the Sun's energy was one of the great problems in astrophysics. The solution was found only after nuclear energy had been discovered, after the predominance of hydrogen was accepted and after Einstein had predicted the equivalence of mass and energy. Even then, constructing a logical chain of nuclear reactions defeated many of best physicists of the twentieth century. In 1938, Hans Bethe (Cornell University) and Charles Critchfield (George Washington University) independently discovered the critical reactions that fuse four protons fuse into a nucleus of helium, with a release of 26.73 Mev of energy.

Table 3 summarizes the nuclear reactions in the proton-proton chain that is the primary process in the core. The net result is to convert four protons into a helium nucleus, with the release of a fast positron, a neutrino and a gamma ray photon. For every gram of hydrogen transformed into helium, 185000 kilowatt-hours of energy are released. Notice the production of so-called electron neutrinos.

1.Proton + Proton	Deuterium + Positron + neutrino
2.Deuterium + Proton	Helium 3+ gamma photon
3.Helium 3 + Helium 3	Helium 4 + Proton + Proton
Side branches	
PPII branch (probability of 0.31)	
2aHelium 3+ Helium 4	Beryllium 7+ gamma photon
3aBeryllium 7+ electron	Lithium7+neutrino
4aLithium7 + Proton	Helium 4 + Helium 4
PPIII branch (probability of0.003)	
3bBeryllium 7 +Proton	Boron 8 + gamma photon
4b Boron 8	Beryllium 8 + Positron + neutrino
5b Beryllium 8	Helium 4 + Helium 4

Table 3. Proton - Proton Chain Reaction

Many theorists have constructed numerical models of the Sun, which predict the radial variations of temperature, density, and isotopic composition, all as functions of time. They are guided by a few general principles and constrained by a minimum of three observed constants. These are the radius, mass and age of the Sun.

Despite the solar activity cycle, the Sun as a whole is neither expanding nor contracting, except on a timescale of millions of years. Therefore the weight of each layer must be supported by the gradient of gas pressure across it. This is the principle of *hydrostatic equilibrium*. Secondly, energy does not accumulate for any significant time in the Sun. Therefore each layer must pass on as much heat as it receives, on average. This is the principle of *thermal equilibrium*. Finally, all atomic states are statistically constant; none disappears catastrophically. Therefore certain general laws of thermodynamic equilibrium (formulated by J.C. Maxwell and L. Boltzmann) must hold.

With these principles, an initial composition and the reaction rates of thermonuclear reactions, a model of the temperature and density distribution along a solar radius can be constructed.

Until the 1960s the only empirical constraints on such a “standard” solar model were the known radius, age and luminosity of the Sun. In 1968 Raymond Davis (Brookhaven National Laboratory) reported for the first time a measurement of the flux of solar neutrinos that are released in the proton-proton chain and travel unimpeded though the Sun to the Earth. John Bahcall compared Davis’s measured flux with predictions from a standard solar model. The predicted flux was too large by at least a factor of two and the discrepancy persisted as measurements continued over the next 15 years. Was the standard model of the Sun in error? Or were the measurements biased in some way? A thorough review was made of all the factors entering the comparison, but no resolution to the problem could be found.

New constraints on the interior structure of the Sun began to appear in the 1980s. Observations of the vibration patterns of the Sun (a topic called helioseismology, see Section 12) yielded an *empirical* determination of the Sun’s internal temperature distribution. In 1988, John Bahcall and Roger Ulrich used these helioseismic results to construct a new model (see Figure 4). This improved model still predicted a neutrino surplus of about a factor of three. In 2006, Bahcall and associates computed ten thousand solar models, varying 21 input parameters randomly, in order to determine the best match with the neutrino counts and the helioseismic data (Bahcall et al, 2006). The best model matched the empirical temperature profile to within 0.1 percent but still predicted too many neutrinos. So the solution to the neutrino problem evidently demanded new physics, not simply a change in the internal structure of the Sun. The solution turned out to lie in the properties of elementary particles.

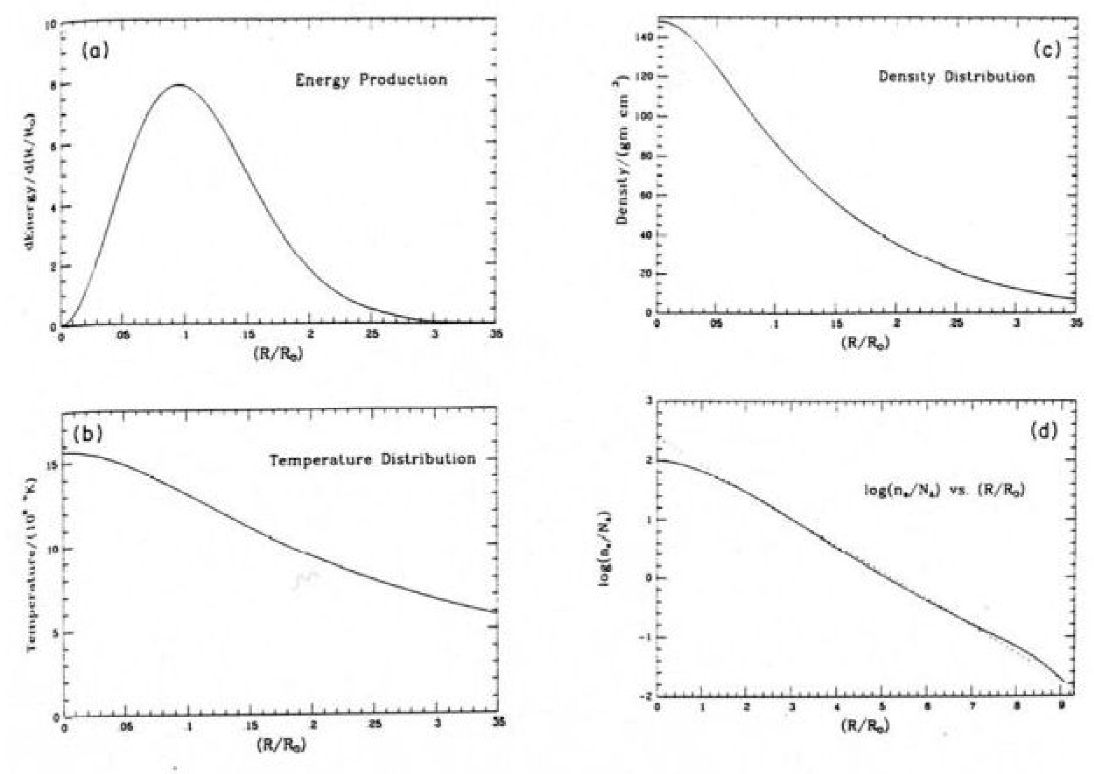

Figure 4. Graphs of physical quantities in the solar core as a function of radius. This “standard model”, based in part on results from helioseismology, predicted a flux of neutrinos three times the flux determined by Davis. (Courtesy of J. Bacall and R. Ulrich, Rev Modern Physics, 60,297,1988.).

Neutrinos were known to have three “flavors”: electron, muon, and tauon, which are named after their partner leptons in the Standard Model of elementary particles. The proton-proton chain in the Sun produces only electron neutrinos and Davis’s experiment was designed to detect only those.

One year after Davis published his first results, Vladimir Gribov and Bruno Pontecorvo proposed that neutrinos might oscillate in flavor after leaving the core of the Sun. Then in 1985, S. Mikheyev, A.Smirnov and L.Wolfenstein predicted that this oscillation would be greatly enhanced as it passed through the dense interior of the Sun. In the following fifteen years, new neutrino detectors were built in Canada, Europe, Japan and Russia. Their combined data were sufficient to prove in 2001 that two-thirds of all solar neutrinos are indeed converted from electron neutrinos to muon or tauon neutrinos, which Davis's experiment could not detect.

To summarize, the latest solar models of temperature and density are correct in predicting about three times as many electron neutrinos as are observed, and the MSW effect accounts for the reduction. However, a new problem with solar models has arisen recently. The temperature gradient one calculates along a radius depends on the opacity of the solar material. The opacity, in turn depends on the concentration (or "abundance") of carbon, nitrogen and oxygen atoms among others). Martin Asplund (Australian National University) and associates have recently derived abundances for these heavy atoms in the photosphere that are about a factor of two lower than previous estimates. Assuming that these new abundances prevail throughout the Sun, the theoretical solar models no longer predict solar oscillation frequencies in accord with helioseismic results. Several proposals to resolve this problem have been advanced, but as of late 2008, no solution seems satisfactory. We shall have to await further developments.

Theorists have debated whether the core is well mixed, and if so, how. Mixing is important because it could profoundly influence the stability and evolution of the Sun. One proposed mixing mechanism is the Helium 3 instability. Helium 3 is an isotope with two protons and one neutron; it is about 2000 times rarer in the Sun than helium 4, which has two neutrons. Helium 3 is produced in a key step of the proton-proton chain (See Table 3). It is consumed in the hottest part of the core but could accumulate in a cooler outer shell of the core, leading to a steep gradient of chemical composition and possibly the generation of gravity waves in the plasma. Mixing might also occur because of diffusion, turbulent convection or a slow meridional circulation induced by a jump in the speed of rotation at the core-radiative boundary. At present there is no consensus on whether mixing occurs within the core.

2. The Radiative Zone

Four modes of energy transfer operate in the Sun: convection, conduction, radiative transport, and hydromagnetic waves. In the core and radiative zone, energy transport by the diffusion of radiation is more efficient than convection and predominates. Their roles reverse in the convection zone, above the radiative zone. Conduction and hydromagnetic waves are important only in the atmosphere of the Sun.

The solar gases are almost fully ionized at the high temperature (several million Kelvin) in the radiative zone. The Saha equation, with modifications (Longair, 1984) determines the abundance of each type of ion. At the prevailing temperatures in the radiative zone, protons, helium nuclei and electrons are the most abundant particles, with minor traces of all the other ions. Electrical charge neutrality prevails over sufficiently large volumes. Such a state of matter is called “plasma”.

The temperature gradient in the radiative zone is determined by the transport of energy by emission and absorption of photons. Energy leaves the core in the form of X- rays, which are easily absorbed, and as the kinetic energy of fast electrons and nuclei (i.e., “heat”). Throughout the zone, particles and photons exchange energy. A photon that is absorbed by a particle raises the particle’s internal or kinetic energy. Conversely, a particle that emits a photon loses a part of its energy.

Calculations of the opacity of the plasma have been carried out in exhaustive detail, with the use of the known chemical composition and cross-sections for photon capture. The opacity in the zone is sufficiently high to guarantee that a photon will be absorbed in a distance in which the temperature hardly changes. As a result, the spectrum of photon energy in the zone is that of a black body at the local temperature. (Longair,1984). Similarly collisions among the particles are frequent enough to redistribute the absorbed photon energy and to maintain a Maxwellian distribution of particle velocities at the local temperature (Longair, 1984). Finally all atomic states are populated according to Boltzmann statistics. In a word, each small volume of gas in the radiative zone behaves as though it is (nearly) in thermodynamic equilibrium at the local temperature.

However the leakage of radiation from the solar surface enforces a slow negative gradient of temperature throughout the zone. Photons must diffuse through the plasma, in a process similar to the diffusion of heat through a solid or a dye in water. The opacity of the plasma acts as a kind of diffusion coefficient for the diffusion of photons toward the surface. An individual photon has a slight chance of advancing toward the surface because slightly fewer absorbing particles lie in the outward direction. After an ion absorbs a single high-energy photon it may emit two or more photons of lower energies. In this way, the energy spectrum of photons gradually shifts to the red, or equivalently the temperature of the plasma decreases outward. It is estimated that if the same photon were emitted and absorbed repeatedly in a simple scattering process, it would require about a million years to reach the surface.

3. The Convection Zone

As the temperature decreases along an outward radius, ions are able to capture and bind more valence electrons. That is, the average degree of ionization declines. For example, at a temperature of ten million Kelvin iron atoms have lost, on average, 20 electrons; at one million Kelvin they have lost only nine electrons. (Arnaud, M., and Raymond, J.,1992).

With more bound electrons, ions present greater opacity to incident photons; the absorption of photons is more efficient and photon diffusion slows correspondingly. The negative temperature gradient must steepen, therefore to maintain a constant total flux of energy through each spherical shell in the interior.

At a radius of 0.713 R, the gradient reaches a critical value at which convection sets in and becomes a more efficient mechanism for energy transport than radiation. This is the boundary between the radiative and convection zones.

In laboratory experiments, convection begins in a layer of fluid when the temperature gradient is raised to the point where the Rayleigh number (the ratio of buoyant forces and drag forces) exceeds a critical value of about 1100. By comparison the Rayleigh number at the base of the solar convection zone is estimated at about a billion. With such an extreme value, convection in the Sun is predicted to be very vigorous.

As a consequence, solar convection is also expected to be highly turbulent. The dimensionless Reynolds number, which determines the transition from smooth laminar flow to turbulent flow, is about 10^{19} at the base of the convection zone, well beyond the critical value of about 2100.

One might expect therefore, that the motions of plasma within the convection zone would be totally chaotic. Nevertheless two (or possibly three) discrete sizes of convection cells have been observed in or just below the photosphere. They are in order of size, granules (smaller than about 2000 km); mesogranules (about 7000 km) and supergranules (30000 km on average). Whether mesogranules are distinct convective cells is still being debated. (For a recent review of the dynamics of the convection zone, see Miesch, 2005).

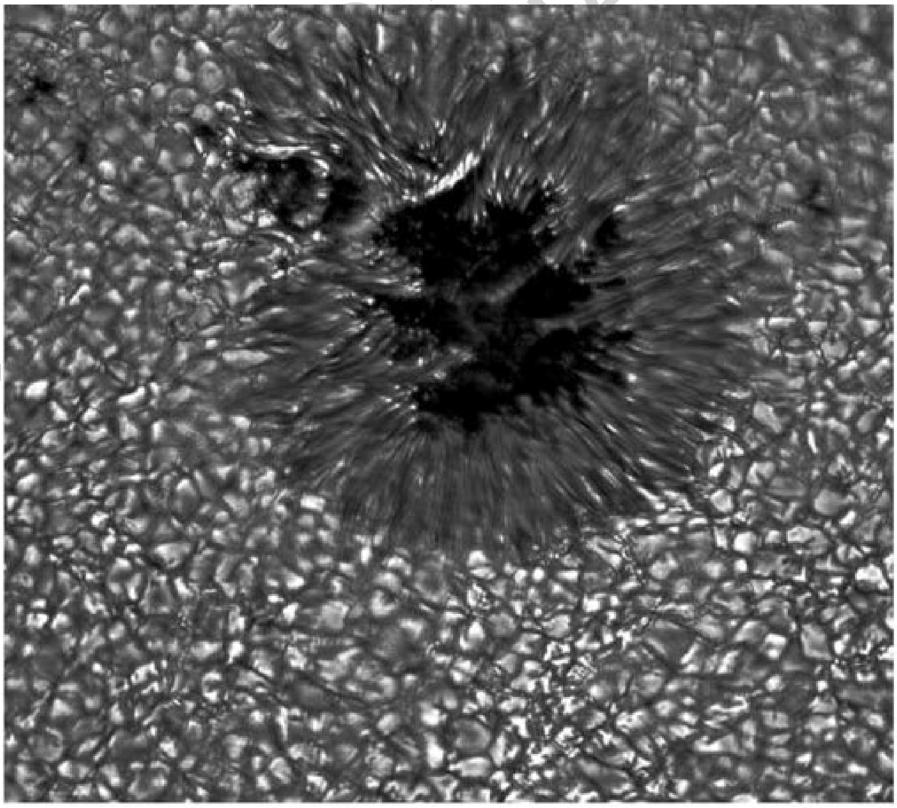

Figure 5. A sunspot and the surrounding granulation. A typical granule size is about 1400 km in size. (Courtesy of NSO)

Granules cover the surface of the Sun in visible light (Figure 5). They are bright at their centers and bounded by darker lanes less than one hundred kilometers wide. Although they appear simple in the picture, granules are surprisingly difficult to characterize except statistically. (Title et al, 1989; Nesis, A. et al, 2003) A typical granule rises at about a kilometer per second at its center, expands horizontally at about 300 m/s, then cools and sinks or breaks apart, all within about ten minutes. Some granules disintegrate ("explode") rapidly, but most simply fade and are replaced.

High- resolution movies and spectra of granules show down-flows as high as 2 km/s in the lanes. The down-flows in the lanes are associated with magnetic fields as strong as several hundred gauss. Granules are smaller, slower and longer-lived in the regions of strong magnetic field that surround sunspots.

Robert Stein and Äke Nordlund (1998) calculated numerical simulations of granules in the top 2000 km of the convection zone. They found an important asymmetry in the plasma flows. Hot plasma rises slowly as a broad cell, spreads horizontally, turns over and cools as it radiates its heat to space. The cool plasma sinks into the narrow borders of the cell. Below the surface layer, the downflows merge into narrow vortices. Their simulations reproduced many of the observed characteristics of the granulation with enough realism to suggest that they understand the basic physics quite well. Helioseismic observations of the top 15000 km of the photosphere (Kosevichev, 2000) have confirmed these predictions in broad outline, although the data are still fairly coarse.

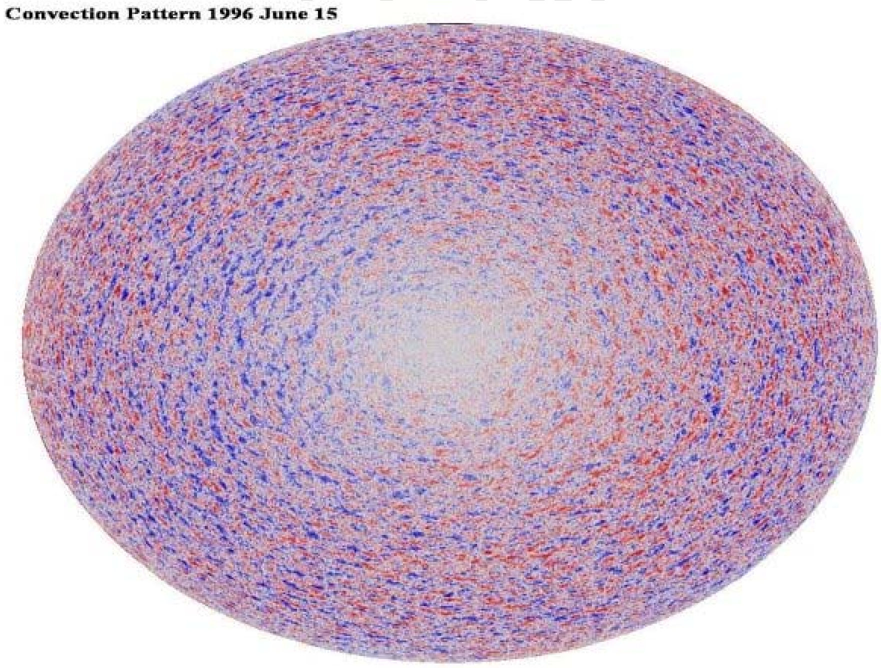

Figure 6. Super granules are most easily detected as a pattern of velocity in the line of sight. Blue and red colors indicate advancing and receding borders of cells, respectively (Courtesy of NASA/SOHO/MDI)

In 1962 Robert Leighton and his students at the California Institute of Technology discovered a second size of convective cells, the supergranulation. These cells are detected most easily in maps of Doppler velocity of the upper photosphere (Figure 6) Recent observations from the SOHO satellite (Panaveni, 2004) show that they range in size from 17 to 43 mega meters, with a mean of 27 Mm, and have lifetimes of 16 to 32 hours, with a mean of 27 hours. Plasma flows horizontally from a cell's center towards its boundary at about 0.5 km/s. Down flows in the boundary reach a few kilometers per second. The boundaries of the cells also contain enhanced magnetic fields, which form a coarse network covering the Sun.

Realistic simulations of supergranulation still lie in the future. There is no agreement at present on the depth of the cells. Theorists are even debating whether supergranules are a distinct scale of convection. Marc Rast (2003) for example has proposed that the scale of supergranulation arises from the interaction of downdrafts between granules. Rieutord et al (2000) suggest it is a large-scale nonlinear instability caused by exploding granules. After analyzing a continuous 60-day sequence of Doppler velocity images from SOHO, L. Gizon and T. Duvall (2003) concluded that supergranulation supports a convective traveling wave.

In 2002, however, Marc DeRosa and Juri Toomre (University of Colorado) and Peter Gilman (High Altitude Observatory) published the results of a simulation of convection that is coupled with solar rotation in a thin surface shell. They found cells with diameter as large as 200,000 km that are bounded by downflows. Within these huge cells, upflows appear with diameters as small as 20,000 km. Here may be the first signs of supergranules.

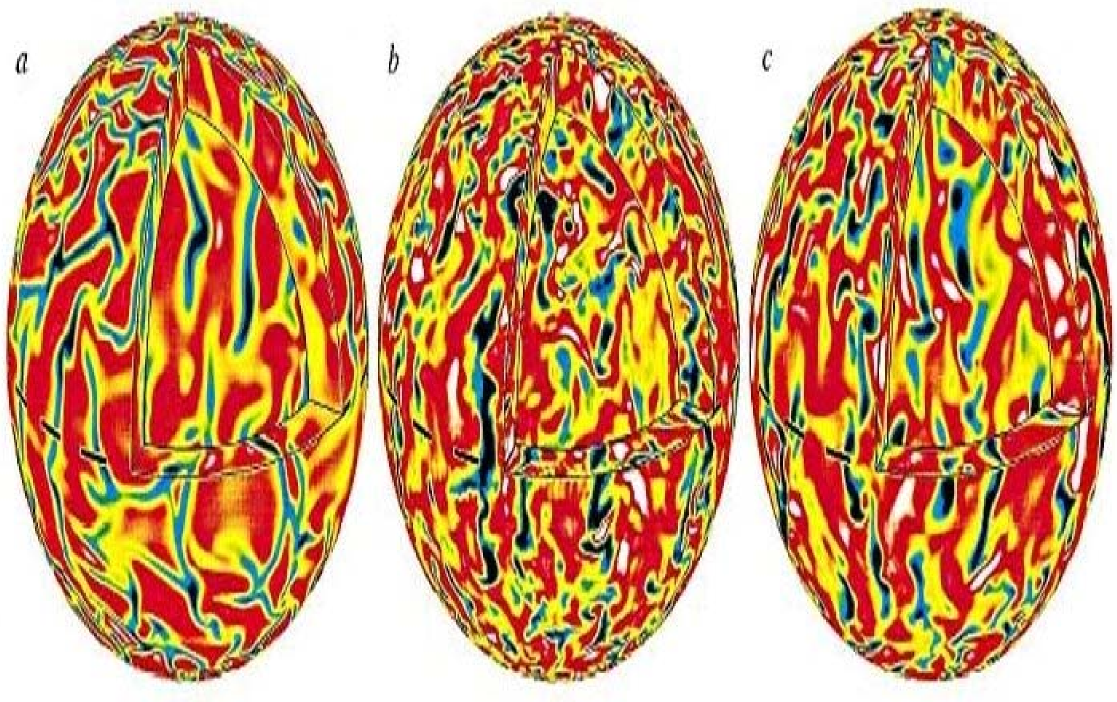

Figure 7. Snapshots of radial velocity at the top of the convection zone, for different parameters, from numerical simulations. Blue/black indicates downflows; red/white indicates upflows. (Courtesy of Elliott, J. et al, Ap J 533, 546, 2000)

Considerable progress has been made in the past decade in simulating the dynamics of the deep convection zone (Miesch, 2005). The convection cells there are predicted to range in size up to the full depth of the zone (200,000 km), which presents many computational difficulties. The density of the plasma varies by a factor of a hundred from top to bottom for example. Convective motions are also highly turbulent.

The general picture emerging from recent simulations is again, one of broad slowly rising flows that are bordered by narrow fast vortical downdrafts. Brummel et al (1998) have discovered that solar rotation causes the vortices to align with the local direction of rotation.

As a rising cell expands horizontally, the Coriolis force causes it to rotate cyclonically, like the storms in the Earth’s atmosphere. As a result, convection and rotation combine to produce a complicated and time-dependent flow pattern in the convection zone. Figure 7 shows the evolution of convection cells at the top of the zone (Elliott, J. et al, 2000). Helioeseismic observations are beginning to test such predictions.

As mentioned earlier, solar convection is predicted to be extremely turbulent. So although there is some large-scale order in the flows, there is also a tremendous amount of fine structure. At present even the most powerful computers cannot follow the tangled flows in full detail, nor is it necessary to understand at least the elements of the Sun’s behavior. Figure 8 shows a snapshot of a numerical simulation of convection in a box, which has unprecedented spatial resolution.

Figure 8. A high-resolution snapshot of simulated convection in a box, showing contours of density. Here we are looking into the side of a rectangular computational

box of convecting fluid. In this instant of the simulation, we see how the fluid is twisted into sheets and filaments (Courtesy of Lawrence Livermore National Laboratory)

4. The Photosphere

The photosphere, the effective surface of the Sun, is a thin layer from which most of the Sun's radiation escapes. Its temperature profile is determined by the transport of energy by the emission and absorption of radiation and secondarily by convection.

The photospheric spectrum (Figure 9) has approximately the shape of a black body spectrum at a temperature of about 6000 K. It extends from the near ultraviolet (300 nm) to the near infrared (2 microns). The spectrum is marked by thousands of atomic and molecular absorption lines, whose wavelengths were first measured by Joseph von Fraunhofer in 1813.

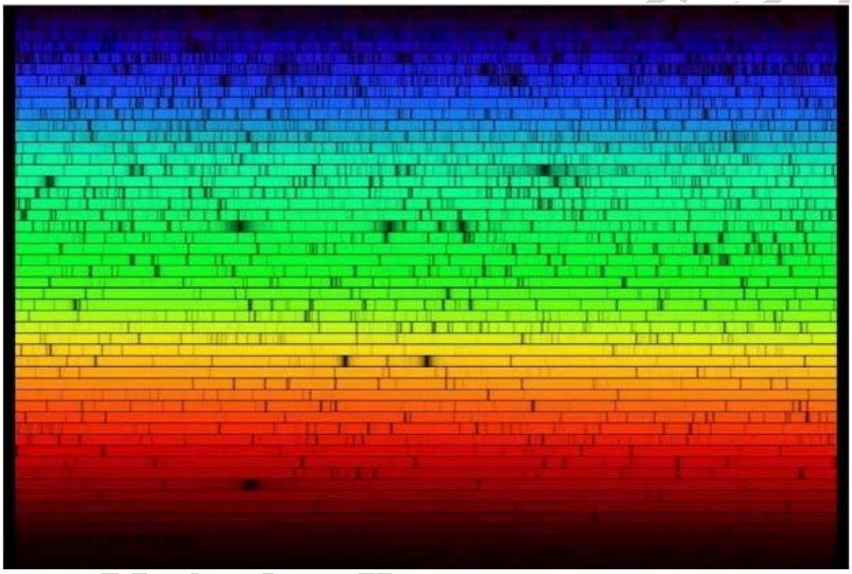

Figure 9. The spectrum of the photosphere consists of a smooth gradation of color from violet to red, overlaid with a pattern of thousands of spectral lines that reveal the many chemical elements in the Sun. In this image the spectrum was folded into strips with an "echelle" spectrograph, to make it more compact. (Courtesy of Nigel Sharp, NS0)

Each stage of ionization of each element in the Sun produces a different characteristic spectrum. For example, neutral calcium atoms absorb light strongly at 610.3 nm. Singly ionized calcium atoms, which have lost a single electron, do not absorb light at 610.3 but produce the two most prominent lines in the visible spectrum at 393.4 and 396.8 nm. The infrared bands of molecules, such as CO, CN and CH, are also strong.

Each line in the spectrum is not perfectly sharp, but has a small spread in wavelength that depends on the motion of the absorbing atoms, among other things. An atom at rest with respect to the average photosphere absorbs very strongly, so when we look into the Sun at the central wavelength we can only see as far as an upper layer of the photosphere. Atoms that are moving absorb less effectively at line center and we can see down to a deeper layer. Because the black body temperature increases with depth in the photosphere, the spectral line is darker at its central wavelength than at neighboring wavelengths. (This is a very crude explanation for the formation of absorption lines; for more details see Mihalas, 1970).

By analyzing the strength of the Fraunhofer lines, one can determine the number of atoms of a particular species and excitation in the line of sight. From such data scientists perform a chemical analysis of the Sun's surface layers (Table 2). The same composition is thought to prevail everywhere in the Sun with the possible exceptions of the core and the corona. The solar composition is similar to that of comets.

Element	**Log (number)**
Hydrogen	12.00
Helium	10.99 ± 0.035
Carbon	8.55 ± 0.05
Nitrogen	7.97 ± 0.07
Oxygen	8.87 ± 0.07
Neon	8.08 ±0.06
Sodium	6.33 ± 0.03
Magnesium	7.58 ± 0.05
Calcium	6.36 ± 0.02
Iron	7.50 ± 0.04

Grevesse, N.; Noels, A.; Sauvel, A.J.
Cosmical Abundances, ASP Conference Series 99, 117, 1996
S. Holt, Sonneborn, G. (eds)

Table 2. The most abundant elements in the solar photosphere

5. The Chromosphere

The temperature of the photosphere falls to a minimum of about 4700 K and begins to increase with increasing height thereafter. At temperatures higher than about 6000 K, the solar atmosphere is neither homogeneous nor static; this is the region called the chromosphere. It takes its name from the flash of red color that was seen at the limb of the Sun, just as the Moon covered the visible disk during total eclipses.

The chromosphere can be observed over the disk of the Sun in many strong spectral lines, such as the two calcium lines at 393.3 nm and 396.8 nm, the Balmer alpha line of hydrogen at 656.3 nm, and the Lyman alpha line of hydrogen at 121.6 nm. At the central wavelength each line is in emission (relative to neighboring "continuum" wavelengths) and outlines the magnetized borders of the supergranulation as a coarse network (Figure 10). The network is also bright in a broad band of continuum radiation around 850 microns.(Lindsey et al 1990).

Much of the mass of the chromosphere resides in "spicules" that are located over the coarse network. Spicules are jets of ionized gas that rise at speeds of 10-20 km/s to heights of 10 to 15,000 km above the photosphere and fade or fall back. Their temperatures are around 10 – 15,000 K. Many models have been proposed to explain their origin and dynamics. They could be some form of acoustic shock or a magnetic wave propagating along magnetic field lines, but no consensus exists despite four decades of research. (Sterling, 2000)

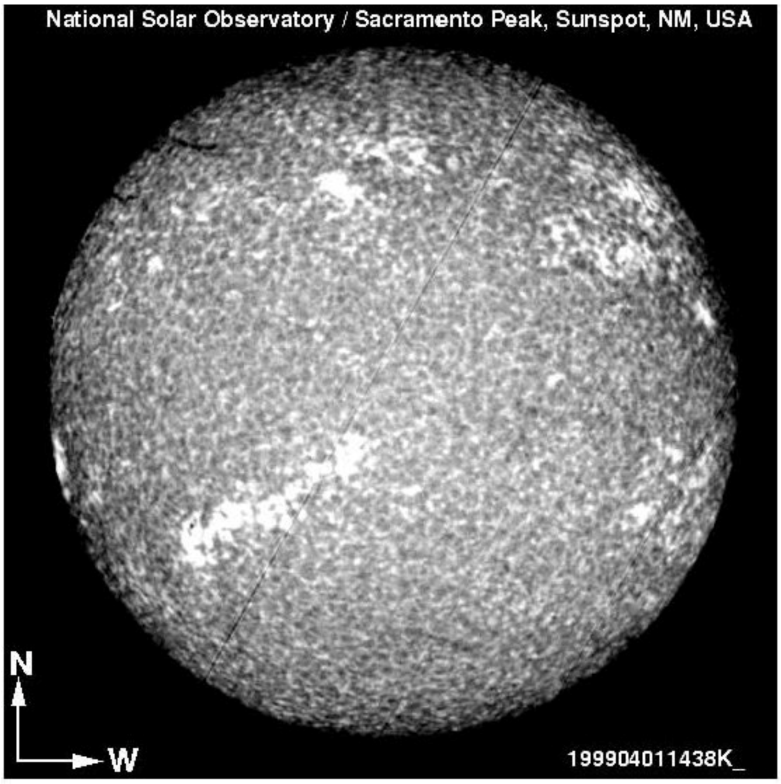

Figure 10. The chromospheric network in the light of singly-ionized calcium 393.3 nm. The network outlines the borders of supergranule cells. (Courtesy of National Solar Observatory).

The general increase of temperature with increasing height in the solar atmosphere is one of the major outstanding problems in solar physics. We'll return to this topic later in this article.

Above the photosphere, the solar atmosphere is neither smooth nor static. It is shaped, heated and propelled by the magnetic fields that thread through it. To understand the structure and behavior of the corona we need first to introduce solar magnetism. We'll return to the corona and its extensions into space in later sections.

6. The Magnetic Sun

In 1907 George Ellery Hale opened an entirely new branch of solar physics when he discovered that sunspots are the sites of powerful magnetic fields. A mature sunspot (Figure 5) has a dark central "umbra", where the field strength can exceed 2500 gauss, or about ten thousand times the strength of the Earth's polar field. The field lines emerge nearly vertically in the umbra and incline further from the vertical in the filamentary "penumbra" that surrounds the umbra.

Hale observed that sunspots emerge in pairs of opposite polarity and that they grow and decay within a week or so. He also discovered how the polarities of sunspots vary in space and time during an 11-year sunspot cycle. (We'll discuss this discovery in connection with the solar cycle, Section 11)

In the century following Hale's discovery of magnetic fields in sunspots, a comprehensive picture of the Sun's magnetic behavior has emerged. In this section we describe the size distribution of magnetic flux elements and their interaction with surface plasma motions.

The Sun generates magnetic fields at the base of its convection zone that emerge at the photosphere as hairpin loops that extend into the low corona (Figures 11 and 17). If a loop contains a large amount of magnetic flux, a pair of sunspots will appear at its footpoints in the photosphere. The sunspots have opposite magnetic polarity because the direction of the field is uniform along the length of the loop. A sunspot may not have a visible companion however if one foot of the loop spreads out over a considerable distance.

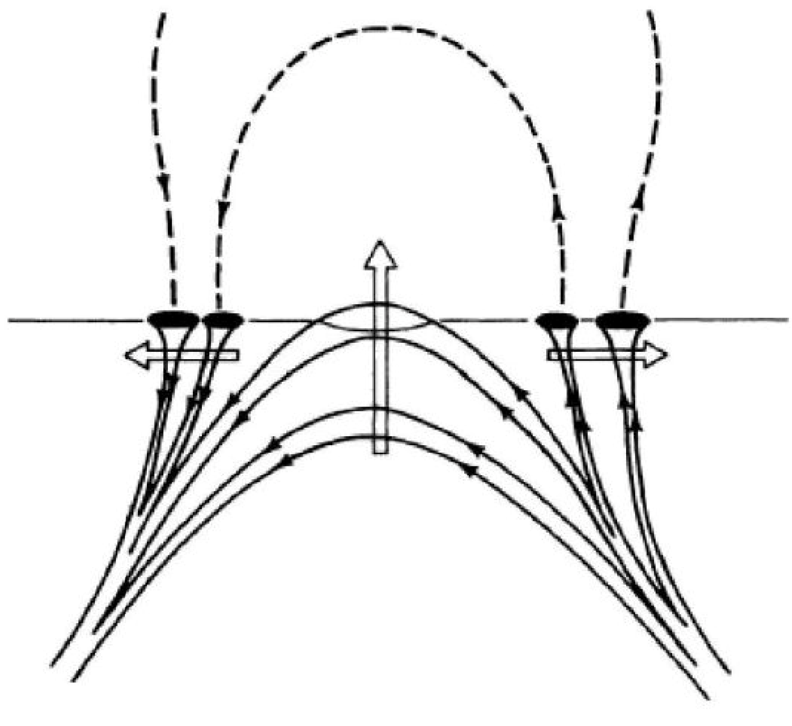

Figure 11. A cartoon of the rise of a magnetic flux tube from the convection zone. The footpoints of the loops mark the positions in the photosphere where pores and sunspots will form. (Courtesy of C. Zwaan, 1987)

Magnetic loops emerge with varying amounts of flux and may emerge as frayed or shredded ropes. As a result sunspots appear in a range of sizes, from a few thousand kilometers to giants as large as 60000 km. In the center of a large sunspot the field strength may reach 3000 gauss.

Pores are small unipolar sunspots that lack a penumbra. Their magnetic fields generally exceed 1500 gauss. They appear in young growing active centers and may merge to form more mature sunspots. Sunspots also grow by merging with neighbors of the same polarity.

Active regions are composed of magnetic loops of different sizes and field strength. Away from sunspots the vertical field strength at the photosphere can exceed several hundred gauss. An active region may remain coherent for weeks or months but decays slowly as supergranules transport magnetic flux outward from the region. This outward horizontal diffusion of flux at a few km/s combines with differential rotation in latitude to create long Bipolar Magnetic Regions (BMR) in the quiet Sun (Figure 12). The magnetic loops that are rooted in the positive and negative parts of a BMR expand upward to form a helmet streamer. A quiescent filament may form at the base of the streamer (See Section 8).

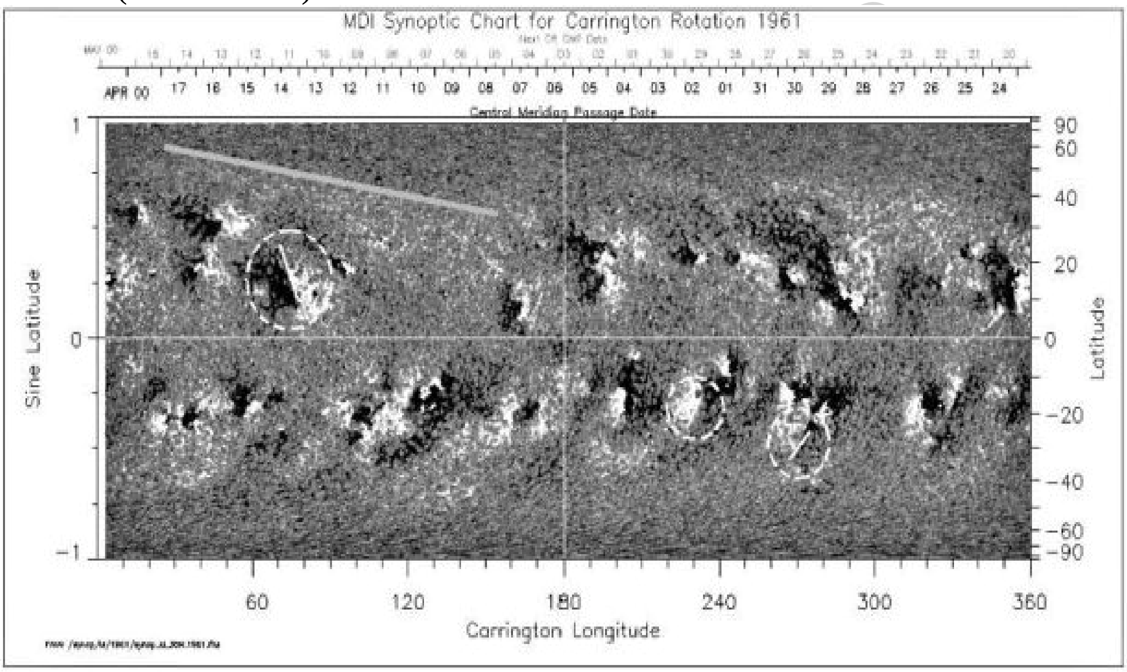

Figure 12. A snapshot of magnetic fields over the whole photosphere. White and black mark positive and negative polarities, respectively. Solar latitude is plotted vertically, longitude horizontally. Notice the gray line in the upper left quadrant that divides positive and negative polarities in a classical bi-polar magnetic region (BMR). A filament is likely to form along such a “neutral line”. (Courtesy of SOHO/MDI)

Active regions are not the only places where magnetic fields are present however. Small loops pop up all over the Sun at all phases of the solar cycle. Their footpoints in the photosphere appear as small bipoles called ephemeral active regions. A typical separation of the poles would be about 30000 km. In total, they may contain as much magnetic flux as the active regions. They are ephemeral in the sense that they have lifetimes of only one or two days and disappear by merging, canceling or possibly by submersion (Harvey and Martin, 1973; Martin, 1988).

Property	**Sunspot**	**Pore**	**Ephemeral Bipole**	**Granule tube**
Mag flux (1)	10^{22} - 10^{18}	10^{20}	< 10^{20}	10^{17}
R (Mm)	28 – 4	---	---	

R umbra (Mm)	12 –2	1		0.1
B (Gauss)	3000	2400		1000

Table 4 summarizes some of the properties of this hierarchy of solar magnetic flux elements (adapted from C.Zwann, 1987).

Over large areas of the quiet Sun, the horizontal motions of supergranules and granules shuffle magnetic flux over the surface in a sort of random walk. The downflows at the borders of supergranules concentrate the magnetic flux and form the so-called coarse network (Figure 10). Small elements of opposite magnetic polarity may cancel or reconnect in these borders, which leads to changes in field line topology (Schrijver, 1997). As a result, a dominant polarity is established around the border of a supergranule. Similarly, a small-scale network of intense magnetic field forms in the dark lanes between granules. The magnetic flux is concentrated there into thin tubes, as small as 100 km in diameter, with field strength up to a kilogauss.

7. The Transition Zone

The transition zone is defined by a range of plasma temperature that is intermediate between chromospheric and coronal temperatures, or approximately 20000 K to 600000 K. A magnetic loop may be composed solely of plasma at such temperatures. A loop with a maximum temperature of several million Kelvin may nevertheless contain a narrow transition zone near a footpoint.

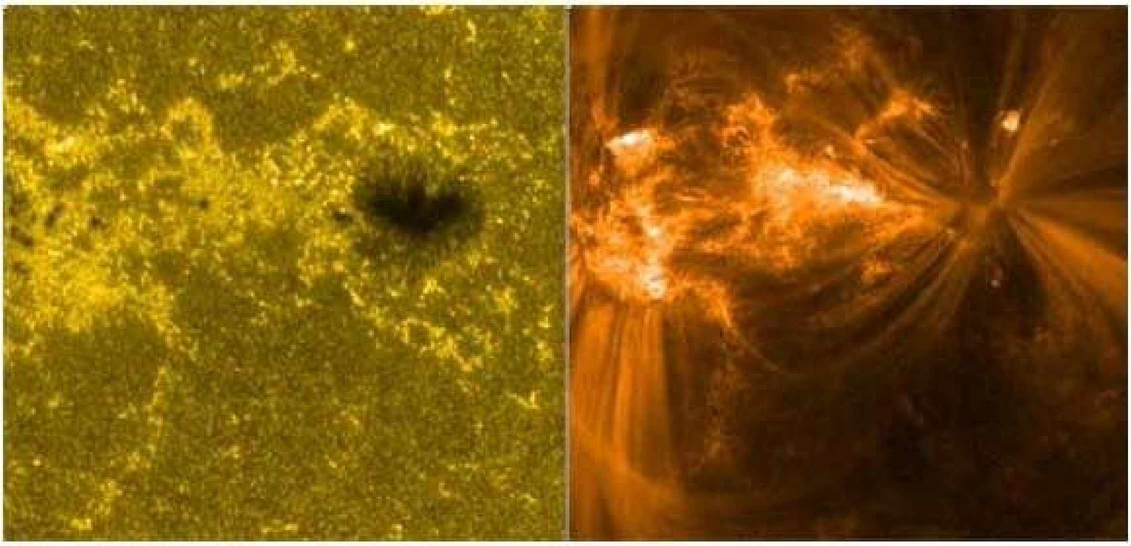

Figure 13. The left panel shows the bright transition zone structures at a temperature of about 100,000 K, with a background of granules at 6000 K. The right panel shows the overlying corona at a temperature of about 1,000,000 K (Courtesy of SOHO/EIT)

Transition zone plasma radiates a spectrum that lies mainly in the extreme ultraviolet, at wavelengths between 15 and 150 nm. It consists of bright emission lines of multiply ionized medium-weight atoms, such as carbon IV (i.e. three-times ionized carbon); nitrogen V, and oxygen VI.

Modern research on the transition zone is carried out from satellites, such as the Solar and Heliospheric Observatory (SOHO) and the Transition Zone and Coronal Explorer (TRACE). Instruments such as the Extreme ultraviolet Imaging Telescope (EIT) have yielded high -resolution images. Figures 13a and b show the transition zone at the bottoms of coronal loops in a small active region.

The transition zone in a loop is highly unstable and can display rapid variations of brightness, plasma density and velocity. (Innes, 2004) Transient speeds as high as 100 km/s have been observed. So-called explosive events, or micro-flares erupt in seconds and display ejection speeds of several hundred km/s. (Dere et al 1991). The connection of these fine structures to magnetic fields in the chromosphere (the "magnetic carpet") is an active field of research (Title et al 1998; Close. et al 2003).

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Bibliography

Andrews, M. 2003, Solar Physics 218, 261.

Antiochos, S. et al 1999, Astrophysical J. 510,485.

Arnaud, M. and Raymond, J. 1992, Astrophysical J. 398, 394.

Aschwanden, M. 2001, Astrophysical J. 560, 1035.

Bacall, J. and Ulrich R. 1988, Rev Modern Physics, 60, 297.

Bahcall, J. et al 2006, Astrophysical J. Supp 365, 400.

Benz, A.O. http://solarphysics.livingreviews.org/Articles/lrsp-2008-1/).

Biermann, L. 1951, Zeitschrift fur Astrophysik 19, 274.

Brandenburg et al 1990, Astron. and Astrophysics 232, 277.

Browning, M. K. et al 2006, Astrophysical J 648, 157.

Brummel, N.H. et al 1998, Astrophysical J.493, 955.

Chaplin W. et al 1999, Monthly. Notices RAS 308,405.

Charbonneau, P. 2005, http://solarphysics.livingreviews.org/Articles/lrsp-2005-2/,

Christensen-Dalsgaard, J. 2003, Rev Mod Phys 74 1073.

Close, R.M. et al 2003, Solar Physics 212,251.

Cranmer, S. van Ballegooijen, A. 2005, Astrophysical J. Supp. 156,265.

Cranmer, S., van Ballegooijen, A. 2003, Astrophysical J. 594,573.

D.E. Innes, A. Lagg and S. K. Solanki, European Space Admin. SP-596.

Dalla, S. 2005 and Browning P, 2005, Astron. Astrophysics 436,1103.

Demoulin, P. et al, Astron. and Astrophysics 382, 650.

Dennis, B. 1985, Solar Physics 100, 465,1985.

Dere, K.et al 1991, J. Geophys. Res. 96, 9399.

DeRosa, M., Toomre,J. and Gilman, P. 2002, Astrophysical J, 581,1356.

Eddy, J. 1976, Science 192, 1189.

Elliott, J. et al 2000, Astrophysical J 533, 546.

Fan, Y. 2008, Astrophysical J. 676, 680.

Forbes, T. et al, 2006, Space Science Reviews, 123, 251.

Foukal, P. and Lean, J.1991, Science 247, 556.

Gizon, L. and Duvall, T. 2003, ESA Public. Div., ISBN 92-9092-827-1, 43.

Gosling, J. 1991, Eos 74, 611

Haber, D. et al 2002, Astrophysical J. 570, 855.

Haigh, J. 2007, *http://solarphysics.livingreviews.org/Articles/lrsp-2007-2/*

Handy, B.N. et al 1999, Solar Physics 187,229.

Harvey, K. and Martin, S. 1973, Solar Physics 32, 389.

Hirzberger, F., and Kneer, F. 2001, Astron. and Astrophysics 378,1078.

Hollweg, J. 2002, J. Geophysical Res. 107, 1147.

Howe, R. et al 2000a Astrophysical J 533, L163.

Howe, R. et al 2000b, Science 287, 2456.

http://solarphysics.livingreviews.org/Articles/lrsp-2006-2/)

Hundhausen, A. J. 1977, in *Coronal Holes and High Speed Wind Streams*, University of Colorado Press, p.225.

Innes, A. Lagg and S. K. Solanki, European Space Admin. SP-596.

Innes, D.E. 2004, European Space Admin PS 547, 215I.

Kahler, S. 1992, Ann Rev. Astron. Astrophysics 30, 113.

Kosevichev, A. 2000, Solar Physics 192,159.

Krieger, A. et al 1973, Solar Physics 29, 505.

Kueker, M. et al 1993, Astron. and Astrophysics 279, L1.

Labitzke, K.H., Van Loon, H. 1988, J.Atmos.Terrestrial Physics 50,197.

Leighton, R., Noyes, R. and Simon, G.W. 1962, Astrophysical J.135, 474.

Lemen, J.R. et al 1984, Astron. and Astrophysics 135, 313

Leroy, J-L. et al 1984, Astron. and Astrophysics 131,33.

Lindsey, C., and Braun, D.C. 2000, Sol Physics 192, 261.

Lindsey, C.A. et al 1990, Astrophysical J. 353, L53.

Liu,H., Hamilton, R.J., Astrophysical J. 199, 380, L89.

Longair, M. S. 1984 "*Theoretical Concepts in Physics*", Cambridge Univ. Press

Martin, S. 1988, Solar Physics 117, 243.

Martin, S. et al 1994, in *Solar Surface Magnetism*, NATO Advanced Research

McIntosh, SW., Charbonneau, P. 2001, Astrophysical J.563, 165.

McKay, D. and A. Van Ballegooijen 2006, Astrophysical J. 641,577.

Miesch, M..2005, http://www.livingreviews.org/lrsp-2005-1

Mihalas, D. 1970, *Stellar Atmospheres*, Freeman and Co.

Miller, J. et al, 1997, J. Geophysical R es. 102, A7, 14631.

Nesis, A. et al, 2003, Astron Nachrichten.324, 55.

Panaveni et al 2004, MN 347, 1249.

Parker, E.N. 1955, Astrophysical J. 122, 293.

Parker, E.N. 1958, Astrophysical J. 128, 664.

Petchek, H. in AAS-NASA *Symposium on the Physics of Solar Flares* (ed. Ness, W.) p 425-439 (NASA, Washington DC, 1964)

Pneumann, G. and Kopp, R. 1971, Solar Physics 18, 258.

Priest, E.R. and Forbes, T. Ann Rev. Astron. Astrophysics 10,313,2002.

Rast, M. P. 2003, Astrophysical J. 597, 1200.

Rieutord, M. et al 2002, Astron. Astrophysics, 357, 1063.

Rimmele, T.R. 1995, Astron. Astrophysics 298, 260.

Schou, J. et al 1998 Astrophysical J 505, 290.

Schrijver, C. et al 1997, Astrophysical J. 487,424.

Schwenn, R., Living Reviews in Solar Physics, vol. 3, no. 2, 2006.

Snodgrass, H, Howard,R.F. 1985, Science 228, 945.

Snodgrass, H. and Ulrich, R. 1990, Astrophysical J. 351, 409.

Solar Tachocline, 2007, D.W Hughes, R. Rosner, N. Weiss eds, Cambridge UP.

Spadaro et al, D. 2007, Astron. and Astrophysics 475, 707

Stein, R.F. and Nordlund, Ake 1998, Astrophysical J. 499, 914.

Sterling, A.C. 2000, Solar Physics 196, 79.

Sturrock, P. 1989, Solar Physics 121,387.

Thompson, M.J. et al 2003, Ann Rev. Astron. Astrophysics, 41,599.

Title, A. et al, 1989, Astrophysical J. 336, 475.

Wang, Y-M, Sheeley N.R., and A.G. Nash 1991, Astrophysical J 383,481.

White, S.M. 2005, in *Chromospheric and Coronal Magnetic Fields*, eds.

Wiegelmann, T. et al 2005, Solar Physics 228,67.

Workshop, held in Soesterberg, the Netherlands, November 1-5, 1993, Edited by R. J. Rutten and C. J. Schrijver. Dordrecht: Kluwer Academic Publishers, p.303

Yeates, A.R. 2007, Solar Physics 245, 87.

Zhang, H. 2002, Monthly. Notices RAS 332,500

Zhang, H. et al 2007, J. Geophysical Res. A10, A101020.

Zhang, M, B.C. Low , 2005, Ann Rev. Astron. Astrophysics 43, 103 2005.

Zurbruchen, T.H. 2007, Ann. Rev. of Astron. and Astrophysics 45, 297.

Biographical Sketch

Jack B. Zirker attended the City College of New York, New York University and Harvard University. He obtained a Ph.D in astronomy from Harvard in 1956. From 1956 to 1964 he was a staff scientist at the Sacramento Peak Observatory. In 1964 he accepted a professorship at the University of Hawaii at Manoa, where he served until 1976. In that year he returned to Sacramento Peak as the director, and remained there until retirement in 1994. He has served on a number of advisory panels for the National Science Foundation and the National Aeronautics and Space Administration. His published work includes numerous research papers on various aspects of solar physics and five astronomy books for a general audience.