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.

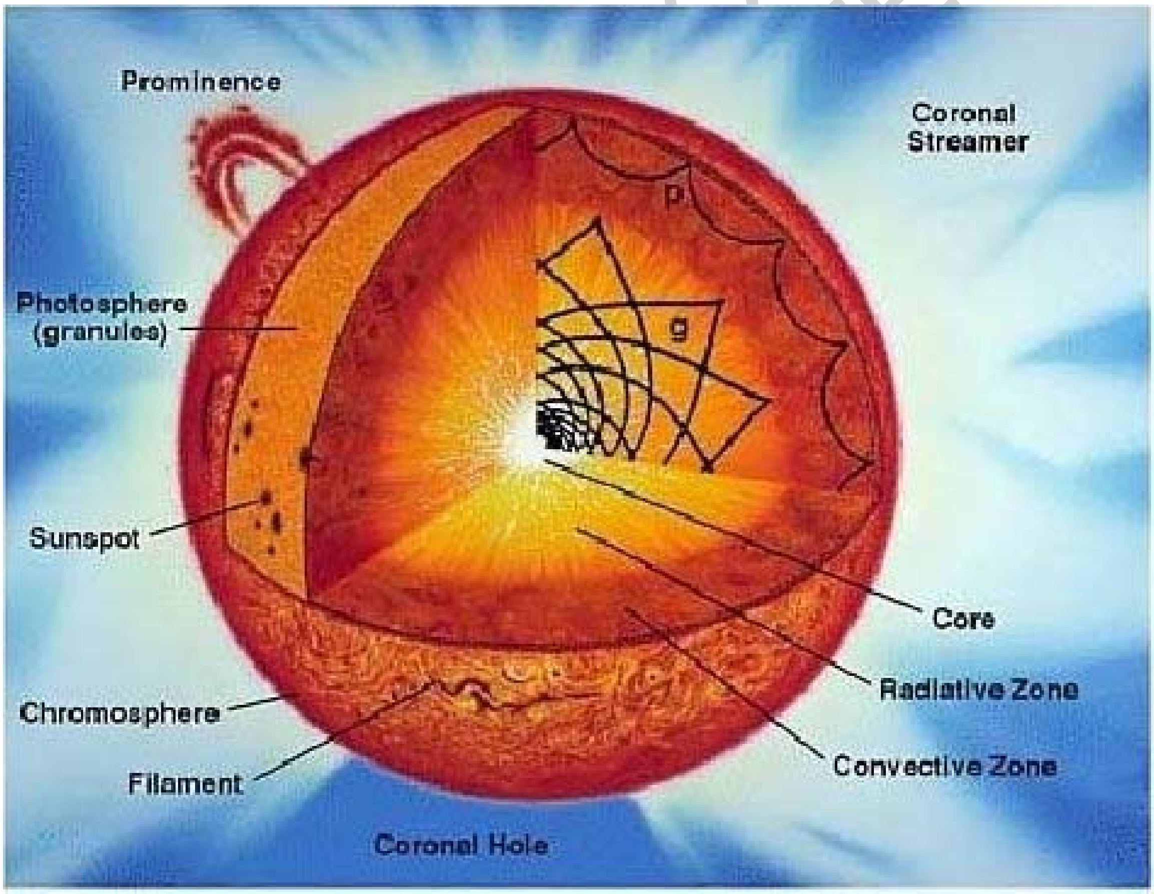

Figure 1. A cartoon of the layers of the Sun (Courtesy of SOHO)

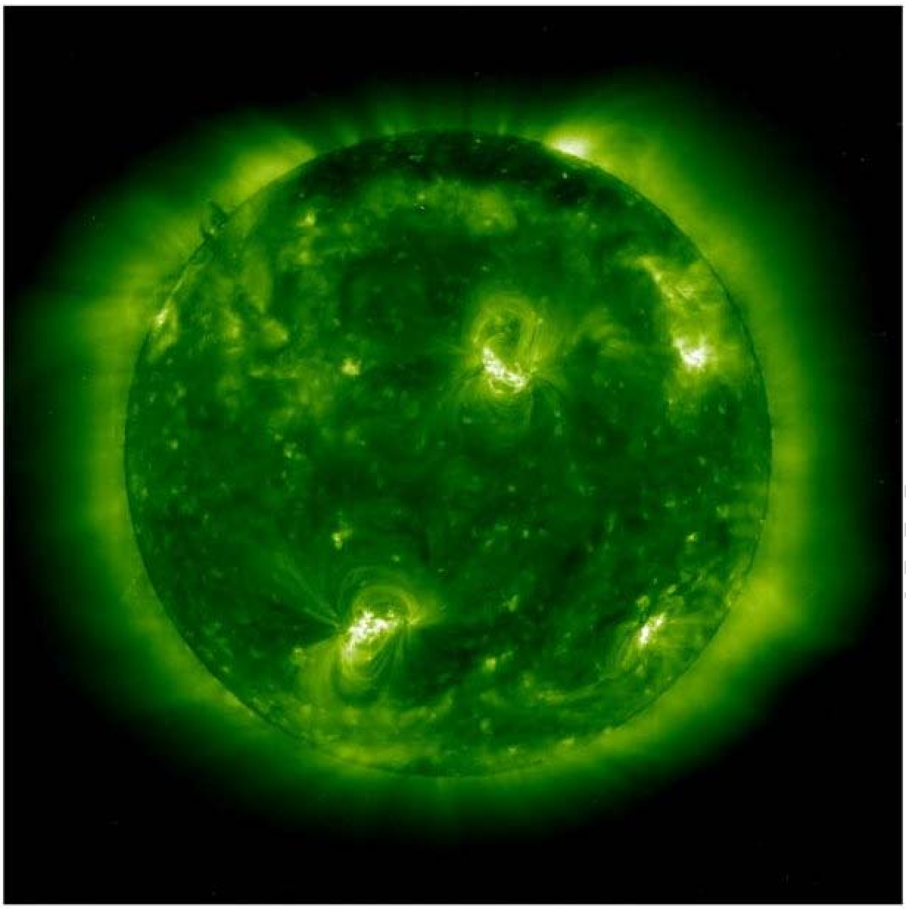

Figure 2. The solar corona imaged at a wavelength of 19.5 nm, which corresponds to a temperature between one and two million Kelvin. Notice the bright active regions, loops and the cold dark poles. (Courtesy of SOHO/EIT)

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.

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.

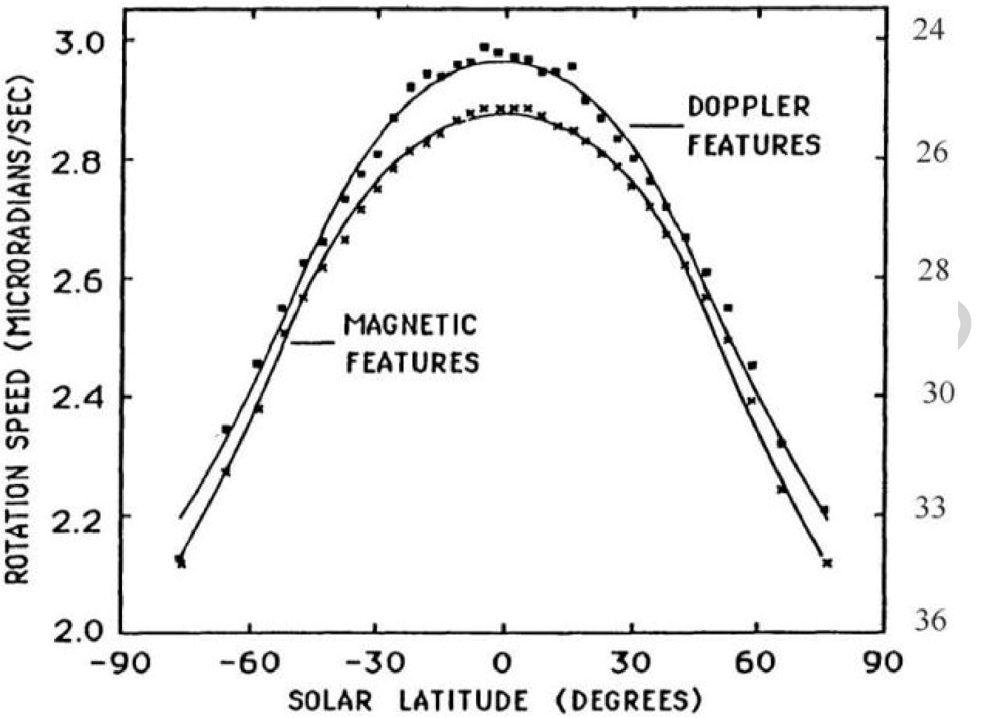

Figure 3. A plot of differential rotation in the photosphere as a function of solar latitude. “Doppler features” refer to the network that is defined by the borders of supergranules. “Magnetic features” refer to large-area averages of the magnetic flux (Courtesy of H. Snodgrass and R. Ulrich, Ap.J 351,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

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.

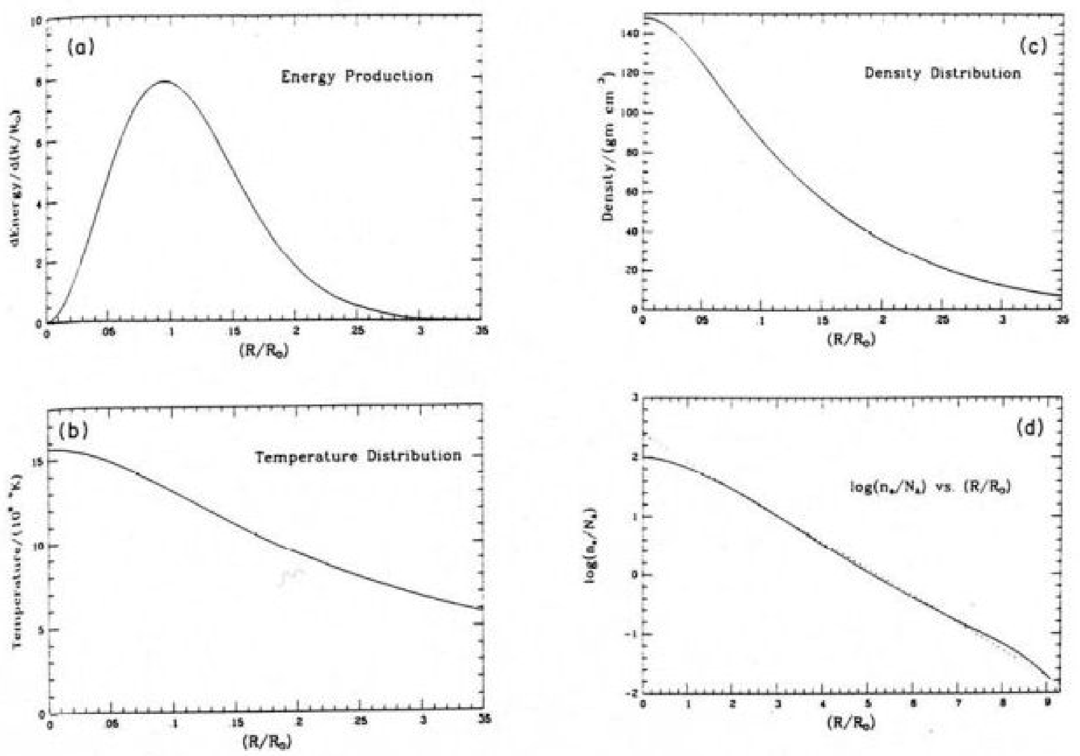

Figure 4. Graphs of physical quantities in the solar core as a function of radius. This "standard model", based in part on results from helioseismology, predicted a flux of neutrinos three times the flux determined by Davis. (Courtesy of J. Bacall and R. Ulrich, Rev Modern Physics, 60,297,1988.).

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.

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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.