GENESIS
SEARCH FOR ORIGINS
Education

The Sun and Solar Wind: A Search for the Beginning

The Structured Sun

APPENDIX C

Much remains unknown about the structure of the sun, particularly in its interior. It is traditional for purposes of discussion to organize the anatomy of the sun around the core and shells surrounding the core. These shells are referred to as the radiative layer (or zone), the convection layer, and the photosphere, which is the surface “layer” that we are able to observe. Actually the gaseous photosphere layer is somewhat vaguely defined, as it probably is several hundred kilometers thick. It separates the opaque solar mass from the atmospheric regions, which are the chromosphere and, ultimately, the corona.

The Core

At the extremely dense core, which holds about 50% of the sun’s total mass but only about 1.5% of the total volume, the conditions are extreme, to say the least. The temperature is thought to be around 15 million degrees Kelvin and these conditions are so extreme that all atomic materials present are stripped of their electrons to leave a hot brew of protons, neutrons, nuclei, and free electrons. The pressure at the core is perhaps 250 billion times larger than the pressure of the Earth’s atmosphere. The sun does not suffer gravitational collapse only because of this enormous outward pressure, which is generated by the heat produced in the core. Nor does it explode like a hydrogen bomb, because the stupendous mass of the gases above the core contains its explosiveness. As noted above, the core density is extremely high. A bucket full of core material would be so heavy that you would be unable to lift it. At the core, we find the nuclear inferno that produces the energy that ultimately is spewed forth into space. The sun’s energy is manifested in the form of short wavelength gamma rays, which can be regarded as tiny packets of energy called photons, the particle component of electromagnetic radiation. If we could see into the core, it would appear black, since none of the energy produced there lies in the visible part of the spectrum (see Student Text, “Electromagnetic Radiation”). Through collisional losses, the gamma ray photons are soon reduced to longer wavelength and less energetic x-ray photons, which remain outside of the visible part of the electromagnetic spectrum.

The Radiative Zone

The x-ray photons produced in the core follow a long and torturous route as they work their way to the surface of the sun, following a path of reduced temperature, pressure, and density. Once the photons escape from the core, they travel outward in the radiative zone, where some of the electrons in the radiative zone are captured by helium nuclei (He^{2+}) to form ionized helium atoms (He^{+}). The radiative zone is packed with ionized hydrogen and helium atoms, and extends from the core of the sun about 70% of the distance to the surface. This mixture of ionized hot gases and electrons is called **plasma** and is sometimes regarded as a fourth state of matter. While moving through the radiative zone, the photons encounter less and less dense materials. Two-thirds of the way through, the density is about the same as that of air at the Earth's surface, and at the edge of the zone, the density is thought to be around 0.1 g/cm^3.

Deep in the radiative zone, the photons collide with particles and change direction in random ways. Each photon may travel only a few millimeters before it suffers another collision and is set off in a different direction. Nevertheless, the photons continue to work their way toward the surface by meandering in zig-zag fashion toward regions of lower temperature and pressure. The time that it takes for them to complete their journey to the surface is measured in millions of years, which is an incredible fact given that photons travel at the speed of light! To put it in more personal terms, the sunlight that gave you your summer tan resulted from a nuclear reaction that took place perhaps 1,000,000 years ago deep within the core of the sun.

The Convection Layer

The collisions suffered by the photons rob them of part of their energy. Consequently, their wavelengths gradually become longer and longer as they move toward the convection zone. Ultimately, wavelengths corresponding to visible light are reached. Finally, the photons arrive at the convection layer, 150,000 km below the surface, where temperatures have moderated to about 1 million degrees Kelvin or less—a pleasant day, by solar standards. Here, nuclei are able to hold on to electrons, and neutral atoms are found. And by this time, the photon energies have been degraded to the point that the gaseous atoms in the convection zone absorb the energy of the photons and hold on to it rather than having it bounced off or absorbed and re-radiated. These atoms effectively block the outward flow of radiative energy, and the energy absorbed by the atoms makes them enormously hot. At that point the convection currents, like those we have observed in warming liquids and air, take over and carry the sun's energy to the photosphere on seething rivers of hot gases.

As the temperature of the gas that absorbs the radiative energy at the bottom of the convection zone increases, it expands, becoming less than the other gas in its surroundings. These bundles of hot gas, being less dense, move up to the surface, where they radiate away their excess energy to space. In the process, they become cooler and more dense and sink down again. So you have a huge number of "conveyor belts" with hot gas moving up and cooler gas moving down.

At the surface (photosphere) the gas is very turbulent, rising up in the center of structures called convection cells (supergranules), flowing to the cell boundaries and then sinking. The processes going on at these cell boundaries, where plasmas with oppositely oriented magnetic fields collide and magnetic energy is converted into kinetic energy, are probably responsible for the heating of the corona and the acceleration of the solar wind. So the convection zone is the key to the solar wind.

Interestingly, although it may have taken the photons millions of years to reach the convection zone, the energy they deliver rises through the entire convection zone in about three months. It is important to realize that all of the energy emitted at the surface of the sun is transported there by convection.

The Photosphere

At the very top of the convection zone is the photosphere, the visible bright surface of the sun. Here, where the temperatures are even more moderate and the gas densities are quite small (estimated to be one-millionth the density of water or less), the gaseous atoms no longer block radiative flow. As the hot atoms cool, they release their excess energy once again as photons that stream unimpeded into space and ultimately provide support for life on Earth.

The pebbly, granular surface of the sun, the photosphere, is where early astronomers focused most of their attention. It is here that we find the easily observed blotches that are now called sunspots. Sunspots come and go in a regular rhythm about 11 years long, but there is uncertainty about the driving force behind their appearance and disappearance. They vary in size and often occur in groups that sprawl over hundreds of millions of square kilometers on the sun's surface. They look dark because they are cooler than the surrounding surface of the sun. Sunspots are thought to arise from the temporary inhibition of convection currents by strong localized magnetic fields. In other words, if a convection current is prevented from carrying its load of thermal energy to the surface, the surface served by that current will cool and a sunspot will appear. Intervals of high sunspot activity usually coincide with a wide range of other dramatic solar events such as coronal mass ejections (CMEs) and flares, which often manifest themselves by disrupting communications, and arguably, even weather patterns on Earth.

The Chromosphere

The lower atmosphere of the sun—the chromosphere—escaped scrutiny by early astronomers because it is invisible when compared to the bright photosphere below it. The relatively miniscule amount of light emitted by the chromosphere is only momentarily visible to the unaided eye during a total solar eclipse when the moon blocks light from the photosphere. The chromosphere appears transiently under these conditions as a thin, bright red ribbon that encircles the silhouette of the moon. Modern astronomers have been able to study the chromosphere at their convenience, owing to the wide variety of instruments that are available to them.

The chromosphere has indeed proved to be an exciting and unique feature of the solar landscape. It is here that solar astronomers have found a host of transient exotic structures, including spicules, prominences, and plages. The spicules are abundant but short-lived, evanescent streams of hot gases that vault high into the chromosphere. More impressive and photogenic are the prominences, some of which are spectacular bright loops of hot gas that arch high above the top of the chromosphere and often extend into the corona. Some of them have widths the size of Earth while others may approach half the diameter of the sun itself.

Prominences often are associated with sunspots and some of them—the quiescent prominences—may hold their shape for months before collapsing. Others—called eruptive prominences—erupt from the chromosphere as gaseous streamers. Finally there are the plages, which are bright, cloud-like structures that are found in the vicinity of sunspots.

Closely related to prominences are monstrously energetic coronal mass ejections (CMEs) and flares, which typically begin as a loop that explodes within a few hours and spews all sorts of solar garbage into space, including a strong blast of x-rays and ultraviolet rays. These radiations arrive at Earth eight minutes later and can cause severe disruptions of the ionization in the Earth's upper atmosphere. This in turn can cause major problems with communications and power systems everywhere on Earth. After about twenty-four minutes, the next wave hits. This consists of very high-energy protons that could be extremely harmful to any astronauts who happen to be in the way. Finally, after one or two days, the Earth is slammed with a magnetic shock wave travelling at more than 600 miles per second. In 1989, one of the strongest flares ever observed erupted, causing a power failure all across the province of Quebec and creating an aurora borealis that was seen as far south as Key West, Florida.

The power of coronal mass ejections (CMEs) and flares cannot be overestimated. Flare temperatures may reach 50 million degrees Kelvin, which is several times hotter than the core of the sun. If the power of a CME or flare could be harnessed, it would be sufficient to provide the energy needs of the inhabitants of Earth for millions of years.

The chromosphere seems to derive its spectacular behavior from the dominant force in the solar atmosphere, which is magnetism. In contrast to the dense plasmas in the sun's lower regions, the plasmas of the atmosphere are dilute and are unable to contain the immense magnetic field of the sun. Rather, the magnetic fields dictate the behavior of the plasma in the sun's atmosphere, giving rise to the bizarre features that characterize this region. Loop prominences, for example, are observed when plasma is captured by magnetic fields and bent back into the chromosphere.

The Corona

The outermost layer of the solar atmosphere is the corona, which in some ways is the most mysterious layer of all. It is mysterious because, contrary to expectations and seemingly to the laws of thermodynamics, the temperature rises steadily from a minimum of around 4000 degrees Kelvin in the chromosphere to more than a million degrees Kelvin in the corona. This makes the corona the hottest part of the solar region outside of the sun's core! How is it possible for heat to be transported from a cooler body (the chromosphere) to a hotter body (the corona)? Even today, there is uncertainty about the mechanism of energy transfer to the corona, but it is thought by many astrophysicists to be the result of magnetic waves transported along magnetic field lines emerging from the sun.

The incredibly dilute, superheated gases of the corona reach millions of miles into space. Those who have witnessed a total eclipse have seen the corona as a luminous white halo surrounding the solar disk, which is an effect that results from photospheric light bouncing off free electrons in the coronal plasma. The corona is synchronized with the solar activity cycle, changing shape from a jagged ring around the sun during the peak of the cycle to wispy plumes and streamers that reach millions of miles into space at the end of the cycle. The plasma-like or streamer features in the corona are pictures of the solar wind leaving the sun. The streamers are the origin of the dense, lower-speed component of the solar wind.