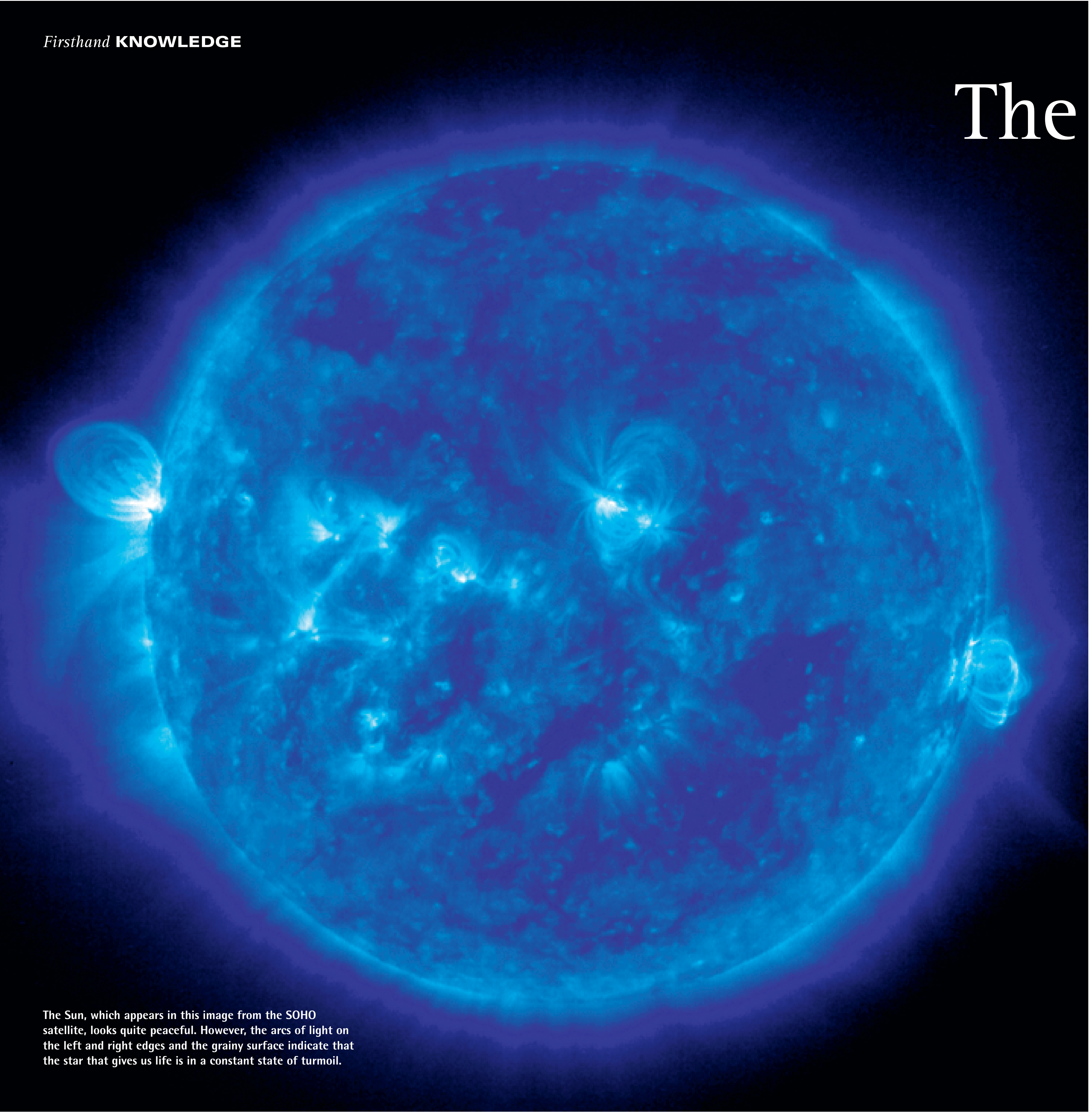
The **Pulse** of the Sun



The Sun, which appears in this image from the SOHO satellite, looks quite peaceful. However, the arcs of light on the left and right edges and the grainy surface indicate that the star that gives us life is in a constant state of turmoil.

PHOTO: SOHO/ESA/NASA

The Sun appears to us as a calmly blazing ball of gas in the sky. In reality, it is seething inside and the entire mass vibrates like a bell. Much as geophysicists use waves caused by earthquakes to explore the structure of our planet, solar researchers use the vibrations of our star to gain insights into its interior. This is how **LAURENT GIZON** *from the* **MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH** *in Katlenburg-Lindau studies the Sun's magnetic field. And he wants to apply this method to distant stars, as well.*

In the interior of the Sun, parcels of hot gas rise to the surface, cool off and descend again. Physicists call this rise and fall of matter convection, which occurs very similarly in a saucepan. This results in the formation of a granular pattern that can be seen on the Sun. This convection also produces sound waves that propagate through the Sun and cause it to vibrate, like a clapper hits a bell. Researchers working with Robert Leighton at the California Institute of Technology first discovered this phenomenon some 40 years ago. They registered a five-minute oscillation on the solar surface.

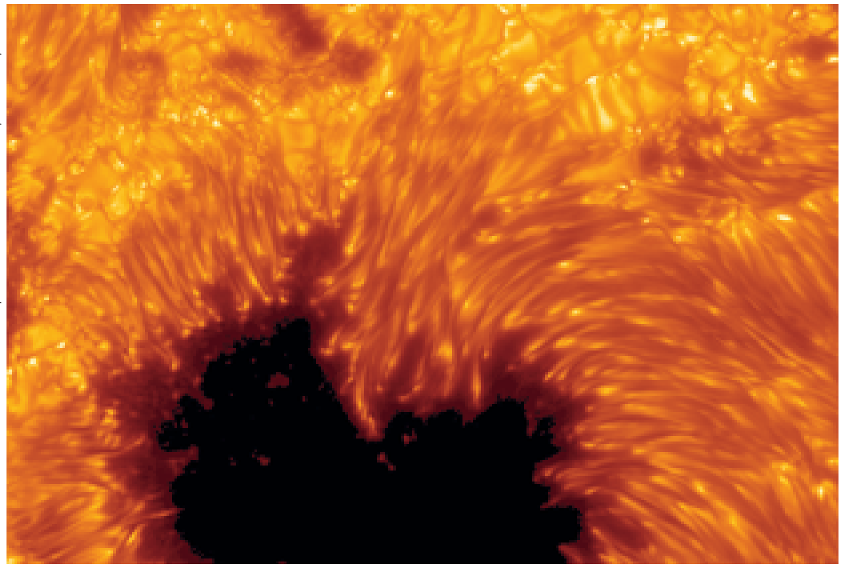
Shortly after this observation, it was speculated that these vibrations might be caused by acoustic waves. German solar physicist Franz-Ludwig Deubner confirmed this interpretation with improved observations carried out in 1975, and a new discipline was born: helioseismology.

The study of solar oscillations requires long, nearly continuous observations of the solar surface. This is possible today thanks to a worldwide network of ground-based telescopes, and above all to the joint European-American space observatory SOHO, which has been recording one image per minute of the Sun's surface velocity field almost without interruption since 1996.

A RICH SPECTRUM OF OSCILLATIONS

Today we know that the five-minute oscillation Leighton discovered is a superposition of millions of modes of oscillation of various frequencies. The manner in which the frequencies and wavelengths are coupled provides information about what kind of waves they are, and also about the interior structure of the Sun. Solar physicists study these relationships in a power spectrum. There, the lowermost branch at the lowest frequencies corresponds to surface waves that propagate horizontally, similar to those on the surface of a deep

PHOTO: G.B. SCHARMER ET AL., INSTITUTE FOR SOLAR PHYSICS OF THE ROYAL SWEDISH ACADEMY OF SCIENCES, ALBA NOVA UNIVERSITY CENTER, STOCKHOLM, SWEDEN



Things are particularly complex in the vicinity of sunspots. They are exciting objects of study for helioseismologists.

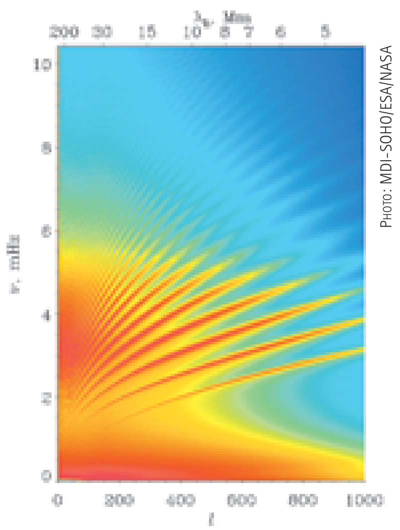


PHOTO: MDI-SOHO/ESA/NASA

Solar waves are seen in the oscillation power spectrum. Each branch in this diagram provides us with a relationship between frequencies and wavelengths of solar oscillations.

ocean. All other branches correspond to various overtones of the acoustic modes of oscillation. At the longest wavelengths, the oscillations reach the deepest layers of the sun.

In global helioseismology, the measurements of the frequencies of the millions of modes of oscillation are used to create a solar model. A number of physical parameters are inferred, such as temperature, density, pressure and gas flow velocity as a function of depth and heliographic latitude.

Global helioseismology can already look back on numerous successes. The standard theory of stellar structure plays a central role in modern astrophysics. Stellar models not only describe the structure of the stars, but also predict how they evolve. These models also enable astrophysicists to narrow down the age and chemical composition of galaxies and the universe as a whole. The Sun serves as an important test case for stellar models because it is our closest star and allows for very precise observations.

Transport of Solar Energy

A key issue in stellar modeling is how the energy in the core – where it is released by nuclear fusion reactions – reaches the surface. Light particles (photons) transport the energy out of the solar core. While traveling through the solar plasma, photons release a portion of their energy in countless absorption and re-emission events involving atoms. In the upper layers, however, which become gradually thinner and cooler, the behavior changes. This is where convection occurs, with gas bubbles transporting the energy.

One of the first triumphs of helioseismology was the finding that this outer convective envelope extends to a depth of 0.71 solar radii, making it possible to identify the correct model of the convection zone out of many widely differing predictions. Furthermore, the previous values for opacities, which describe how much light can pass through matter, had to be revised to reconcile the temperature profile in the models with the helioseismological data. It would not have been possible to measure opacities in laboratories on Earth, because the extreme conditions in the solar interior cannot be reproduced here.

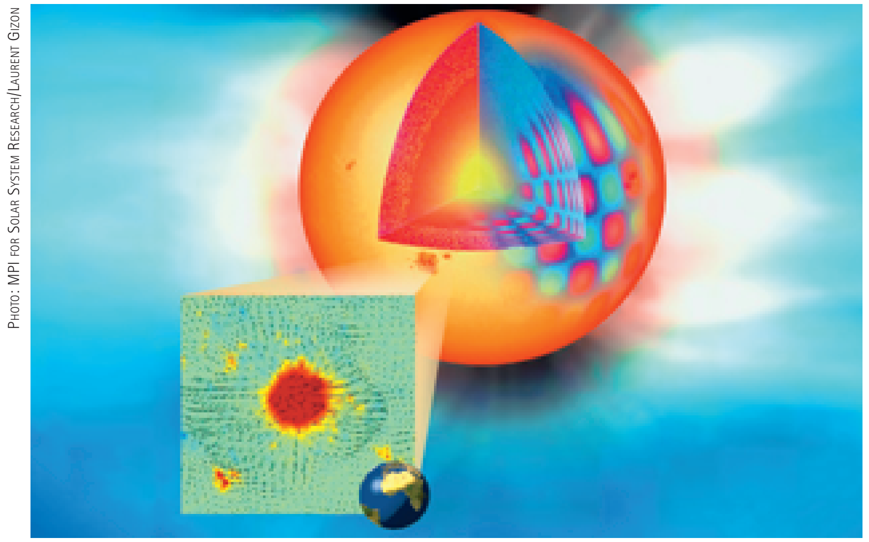
Another great contribution of helioseismology concerns the solar neutrino problem. Neutrinos are elementary particles that are created in great numbers by nuclear reactions in the Sun's core. They pass through the Sun nearly unimpeded and escape into space. The standard solar model predicts quite accurately how many of these solar neutrinos should reach the Earth. Researchers were thus surprised when their instruments registered about 30 percent fewer neutrinos than expected.

At first, some scientists suspected that temperature and pressure in the Sun's core were lower than the standard model predicted. This would result in the creation of fewer neutrinos. This hypothesis, however, proved to be untenable, as helioseismology ultimately confirmed the standard solar model. Thus, the solution to the solar neutrino problem had to be found elsewhere. It is clear today that it was the standard model of particle physics that was incorrect: contrary to what was previously assumed, neutrinos are not massless. They can change "identity" on their way from the Sun to the Earth, and escape detection. For the neutrino detectors on Earth, a fraction of the neutrinos is invisible.

Since these initial successes, helioseismology has made great progress. Today, it is used to measure, for example, the gas motions in the solar interior or the effect of the magnetic field on waves. The search for the origin and variability of the solar magnetic field is of central importance.

This magnetic field controls solar activity, which varies with a period of about 11 years. At times of strong activity, massive flares occur on the surface, and gigantic plasma clouds are ejected from the outer solar atmosphere, the corona, and tear through the planetary system at great speed.

PHOTO: MPI FOR SOLAR SYSTEM RESEARCH/LAURENT GIZON



Cross-section of the Sun showing a mode of oscillation. The enlarged blow-out shows the gas flows beneath a sunspot, as identified with local helioseismology. The Earth is depicted in the bottom right corner for size comparison.

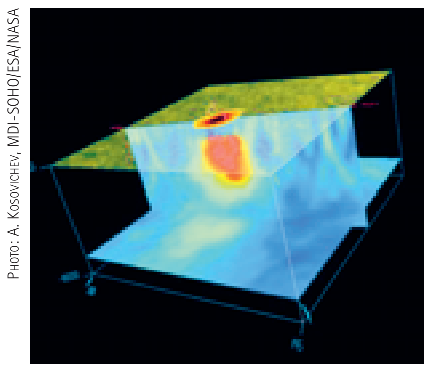
Flares Paralyze Electrical Networks

Increased solar activity impacts our planet in widely different ways. One or two days after a flare, a plasma cloud might collide with the Earth's magnetic field. Under certain circumstances, some particles can penetrate the magnetic cage. Then they shoot into the atmosphere and, upon colliding with atoms and molecules, produce impressive northern lights. The high-energy particles can also pose a threat to astronauts, they can damage or even completely incapacitate satellites orbiting the Earth, and they can interfere with radio and mobile communications. In extreme cases, they may cause an entire power grid to collapse.

There is currently a heated debate about whether fluctuations in solar activity will impact the climate in the long term. In Europe for instance, the period between 1640 and 1710, for which it has been determined that sunspot activity was unusually low, coincided with a period of cold weather – the height of what is now known as the Little Ice Age. Thus, the analysis of solar magnetic activity could have a very direct impact on our day-to-day lives.

It is not yet understood why these eruptions occur. Physical models are required, however, to predict "space weather," which is a subject of growing worldwide interest, both in research and in some industry sectors. It is believed that eruptions occur when magnetic loops above sunspots snap into a new, less energetic configuration, releasing energy. Solar storms occur preferentially at the height of the 11-year solar cycle, when sunspots and magnetic regions are larger and more numerous. At the same time, during the course of the cycle, sunspots preferably occur at different heliographic latitudes: when activity decreases, the spots appear ever closer to the solar equator. Furthermore, it is observed that sunspots usually occur in pairs of opposite magnetic polarities. Within sunspot groups, magnetic polarities reverse every 11 years, resulting in the 22-year Hale magnetic cycle. These phenomena are somehow linked to the Sun's global magnetic field. According to current theories, the magnetic field originates in the outer layers of the Sun, where convection takes place. There, matter not only rises and falls, but also rotates around the Sun at high speeds in a well defined way. Magnetic field lines are coupled to the solar plasma and get stretched and twisted by the flows. The internal rotation of the solar plasma varies both perpendicularly to the surface

PHOTO: A. KOSOVICHEV, MDI-SOHO/ESA/NASA



There are significant variations in the speed at which waves propagate below a sunspot. High wave speeds are shown in red.

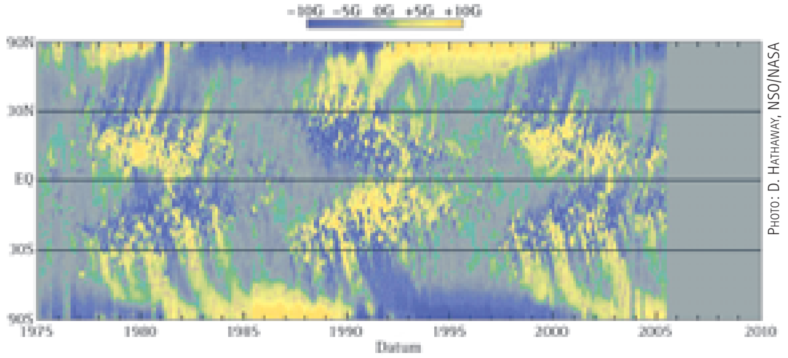


Photo: D. Hathaway, NSO/NASA

Sunspots usually occur in pairs with opposite magnetic polarities. In the course of the 11-year activity cycle, sunspot pairs not only appear at varying heliographic latitudes, but also change polarities (shown in yellow and blue).

and with heliographic latitude. This plays a key role in solar dynamo theory. The non-uniform rotation of the Sun shears the magnetic field lines and pumps energy into the magnetic field. The magnetic field lines store this energy just like a rubber band that is stretched and twirled.

Motions in the north-south direction are also considered to be one of the causes of the polarity reversal of the global magnetic field every 11 years, but a lot of things remain in the dark in this regard. One of the main goals of helioseismology today is to map these internal mass motions and their temporal variation to help solve the puzzle of the solar cycle.

Significant progress has already been made. For example, helioseismology revealed that, throughout the convection zone, rotation is mostly constant along radial lines: in the equatorial regions, the solar matter rotates about its axis once every 25 days, while at high latitudes it takes 35 days. This is in agreement with visual observations of the solar surface. The entire radiative zone, on the other hand, appears to rotate like a rigid body, with a period of about 27 days. This means that there is a strong shear in the rotation of the solar matter at the transition between the radiative and the convective zones. It is assumed that the solar dynamo originates from this transition layer – also known as the tachocline.

Recently, through helioseismological analysis, researchers even succeeded in establishing a connection between internal mass movements and the characteristics of the solar cycle. They discovered that the rotation varies not only with heliographic latitude, but also with time: latitudinal bands of faster and slower rotation migrate toward the equator. This time-varying rotation pattern exhibits a periodicity of 11 years and occurs throughout the upper half of the convection zone. This could indicate a "migrating wave," which some dynamo theories predict.

In addition, mysterious, quasi-periodic changes in the rotational velocity, with a period of 1.3 years, were discovered near the tachocline. This discovery has not yet been explained, and makes clear that we are still far from a full understanding of the internal dynamics of the Sun.

Search for Origin of Solar Activity

Traditional helioseismology views the Sun as a body that is completely symmetric around its axis of rotation. Most recently, we have begun to analyze the amplitudes and the phases of the solar oscillations to study the Sun in three-dimensions. This leads to "local" helioseismology. This method is similar, in a way, to ultrasonic tomography used in medicine. This method measures the time it takes for solar waves to propagate through the interior between any two locations on the surface. The propagation times provide information about buried inhomogeneities

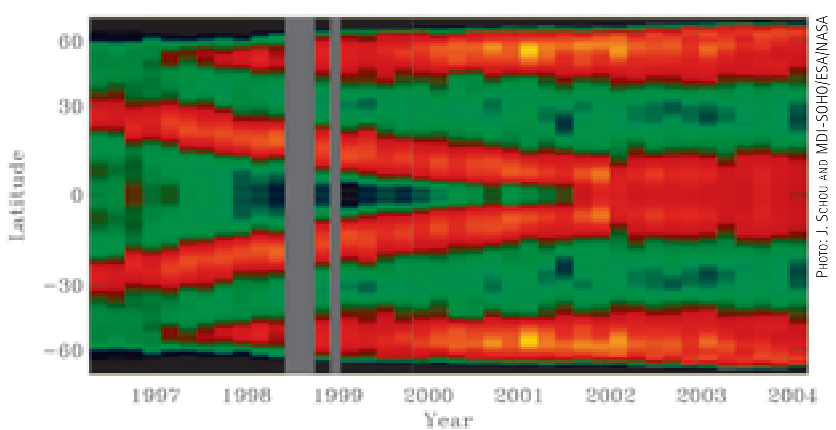


Photo: J. Schou and MDI-SOHO/ESA/NASA

The rotation of the solar interior varies during the 11-year cycle. Red shades indicate higher rotation velocities than average, while blue shades indicate slower rotation.

and flows along the internal propagation paths of the waves. This method pinpointed the existence of an internal flow between the equator and the poles that could serve as a mechanism for the latitudinal transport of the magnetic flux and determine the period of the solar cycle.

As I was studying local processes in the near-surface layers, I found complex horizontal flows – also referred to as solar subsurface weather. The plasma flows appear to be highly organized near large, magnetically active regions. Away from the active regions, there are meanders, jets and vortices that may be related to deep large-scale convection.

I also analyzed relatively small-scale phenomena. An example of this is supergranulation, which corresponds to convection cells with a diameter of around 30,000 kilometers. These convective motions play an important role in the redistribution of the magnetic flux on the solar surface. We were surprised to discover that the pattern of supergranulation propagates in the direction of the Sun's rotation faster than the local plasma flow, like a traveling wave. However, we are still a long way from understanding supergranulation, and we need further observations and refined theoretical models.

The oldest known phenomenon on the Sun, the dark spots mentioned above, are now also one of the objects of helioseismology research. Sunspots are regions in which the energy supply from the interior is impeded, and their temperature is about 1,500 degrees less than that of the quiet surface (photosphere) – which is why they appear black in contrast. Researchers have managed to measure the three-dimensional structure of wave-speed perturbations below sunspots. These perturbations are caused by a combination of magnetic and temperature anomalies that we have not yet been able to disentangle. However, the discovery of organized flows beneath sunspots could help explain why the sunspots persist as stable structures for many weeks.

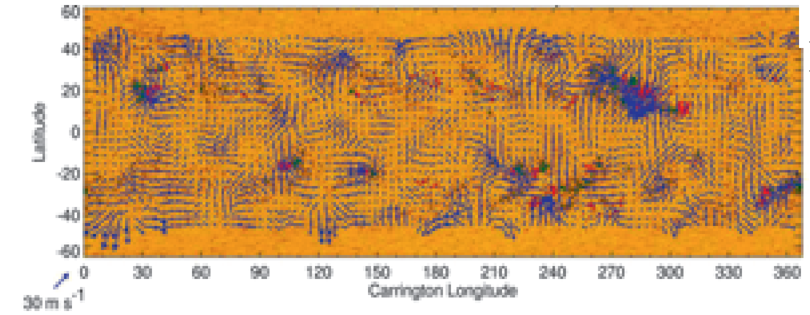


Photo: L. Gizon, MDI-SOHO/ESA/NASA

Flows at a depth of 1,000 kilometers (blue arrows) converge toward magnetically active regions on the surface (red and green patches).

Local helioseismology is still developing, but it promises many more discoveries. One of its numerous ambitious goals is to directly image the magnetic field in the solar interior. This will require measuring local anisotropies in wave propagation, as wave speeds differ along and across magnetic field lines.

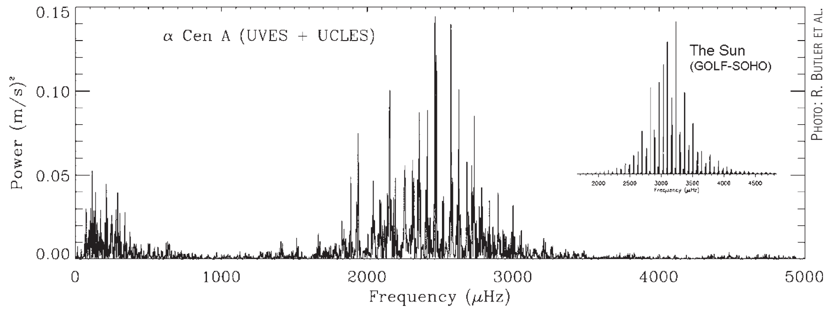
Quakes on Distant Stars

The successes of helioseismology have encouraged astronomers to also apply this method to stars. Unlike the Sun, stars, due to their enormous distance, appear as point-like objects. Thus, the oscillation modes that can be observed are averaged across the entire surface. The challenge for astronomers in this young field of asteroseismology has been to measure oscillations with sufficient accuracy in order to provide useful constraints on internal stellar structure. This only became possible in recent years for sun-like stars with the aid of large, ground-based telescopes.

Since, as already mentioned, the surface of a star cannot be observed as a disk, we can detect only the simplest modes of stellar oscillations – radial, dipole and quadrupole oscillations. Nevertheless, it is possible to extract two basic parameters from the frequencies of these modes. The first is the time it takes for sound to travel across the star's diameter. This is a global characteristic that is closely linked to the average mass density, and thus the star's mass. The second is related to the helium content in the core of the star. This offers a unique opportunity to accurately determine a star's age because the helium content in its core increases with time as nuclear fusion reactions convert hydrogen into helium.

The frequencies of stellar oscillations include even more information. They could lead to the detection of key features of stellar interiors, such as the boundaries of convection zones. This would allow us to refine the theory of energy transport by convection, which currently remains very approximate. In order to understand stellar structure and evolution, however, it is important to measure oscillations on stars with differing masses and ages. In principle, asteroseismology can also be used to estimate internal rotation, as is done for the Sun. Such information could help understand stellar activity cycles and dynamo theory.

Based on numerical simulations, I recently showed that it is even possible to determine the inclination of the rotation axis of a star, which is particularly interesting in the case of



The Very Large Telescope was able to measure a number of modes of oscillation on Alpha Centauri, providing information about the interior of this star. The inset shows the solar spectrum of oscillations for comparison.

binary stars and central stars of planetary systems.

Helioseismologists require high-quality oscillation spectra, and asteroseismologists also hope to obtain measurement data for as many stars as possible. We are looking into a promising future. NASA is taking the lead on the next major technological step for helioseismology with the Solar Dynamics Observatory (SDO), which is set to launch in 2008. On board will be the first instrument that was specifically developed for local helioseismology. One of the most important scientific goals is to study the fine structure and the temporal evolution of magnetic regions and subsurface flows. My team at the Max Planck Institute for Solar System Research will be helping to analyze the SDO data.

Around 2013, the European Space Agency (ESA) will send Solar Orbiter on a mission. This probe will leave the plane of the solar system, the ecliptic, to examine the Sun's polar regions. Also, the Solar Orbiter data will be combined with that of other telescopes that look at the Sun from a different angle. This will permit stereoscopic analyses to probe very deep regions of the Sun. In particular, it will be possible to identify, in greater detail, variations at the base of the convection zone, where the solar dynamo is presumed to be at work. Our team is involved in the development of Solar Orbiter.

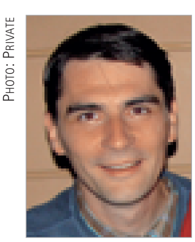
Asteroseismology, too, is entering an exciting phase, as it benefits from the search for planets orbiting distant stars. This is because this search requires the measurement of minute periodic fluctuations of the star around the common center of the extrasolar system. In a spectrum, they have a similar signature as global pulsations. The motion of the star as a whole, however, is much slower than the pulsations – so it is easy to distinguish the two.

Seismologists Rely on New Instruments

The best measurements are currently being made at the European Southern Observatory in the Chilean Andes, using the HARPS spectrograph on a 3.6-meter telescope in La Silla and the UVES spectrograph on the Very Large Telescope. In the coming years, even more precise spectrographs will be installed on several large ground-based telescopes, making it possible to measure star velocities with greater precision than ever before.

However, observation time on the large telescopes is limited, which is why dedicated space telescopes are an attractive solution for obtaining nearly uninterrupted long-term observation of many types of pulsating stars. The WIRE and MOST satellites have already detected stellar oscillations based on fluctuations in light intensity. ESA's COROT satellite, which is expected to be launched in 2006, will be even more powerful. And additional, similar missions are currently being planned.

We thus hope that asteroseismology will make great progress in the coming decades. One day, it may even be possible to use optical interferometry to spatially resolve hundreds of oscillation modes on a single star, as has been done for the Sun. New discoveries depend, however, not only on new observations, but also on improved theoretical models.



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