Probing the Solar Interior

Hearing the Heartbeats of the Sun

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Recent developments in solar seismology have enabled us to observe and analyse the vibrations of the sun, and help to probe its hidden interior. Understanding the sun's internal structure and dynamics promises to test and expand our knowledge of physics, cosmology, and astrophysics. Seismic sounding of the sun has begun to shed light on its hidden internal anatomy.

Introduction

Our daytime star *the sun* is often termed as the Rosetta Stone for understanding other stars. The distant stars appear only as point-like objects even with the world's largest telescope. On the other hand, the complex and varying face of the sun's outer layers can be seen at the finest scales of time and space. Most of what we know of the physics of stars relies heavily on our knowledge of the sun. This knowledge, however, is not complete because we can not observe the internal structure of the sun where a variety of fundamental processes occur.

The sun's interior (*Figure 1*) is hidden under the photosphere and is invisible to powerful telescopes in visible, X-ray or radio wavelengths. Photospheric features such as dark sunspots, their motion, solar activity cycle, the granulations etc., are some surface expressions of the vigorous processes taking place in the sun's interior.

In the absence of a 'direct' view, our knowledge of the sun's interior is based on mathematical equations describing physical processes operating within a star. A simple model star at 'zero' age is assumed as rotation-less and having zero magnetic field

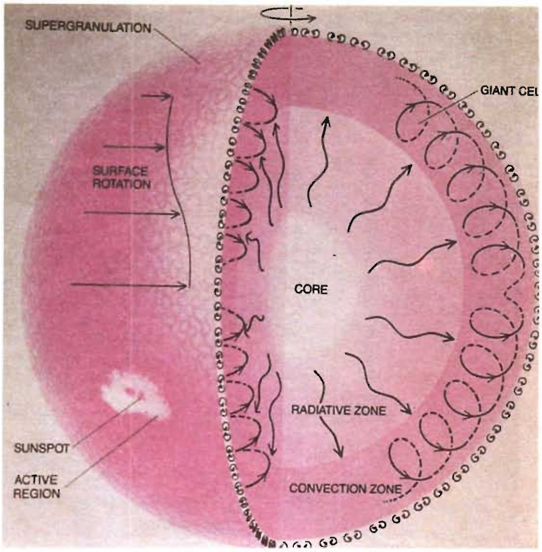

Figure 1. Sun's interior as known by theoretical models. Energy is generated by thermonuclear fusion in the core, and diffuses outward by radiation, and then by convection to the outer visible surface, the photosphere.

and a specified chemical composition. It is then mathematically evolved to the current age of the sun, 4.8 billion years, to recreate its present size, mass, and luminosity.

A test of this so called 'Standard Solar Model' is provided through the weakly-interacting neutrinos [1], created in the central powerhouse, the core, by nuclear fusion reactions. However, we encounter a problem of the shortage of neutrinos from the theoretical prediction of 7.2 ± 3.3 SNU (Solar Neutrino Units) to the observed 2.2 ± 0.3 SNU. Resolution of this shortage could lie in particle physics. Neutrinos oscillate among three types, only one of which is detectable by the neutrino experiments. The implications of such a result which requires that neutrinos have a nonzero rest mass would be profound for physics and cosmology. Another possibility is that our models of solar interior (and hence that of all stellar interiors) are incorrect in some significant way.

[1] See Joshipura, *Resonance*, Vol.2, No.8, pp.79–81, 1997.

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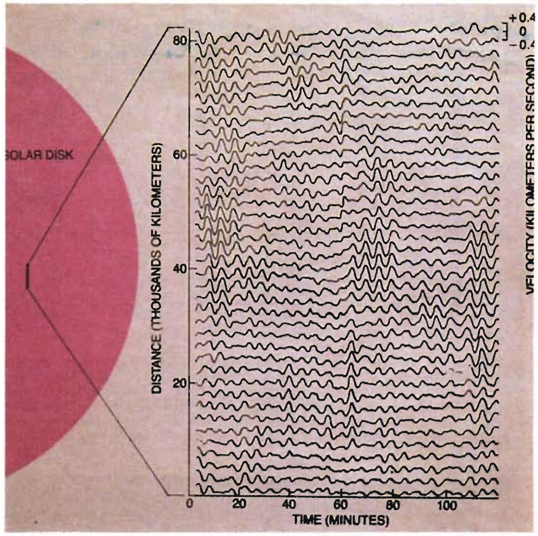
Helioseismology: The Science of the Ringing Sun

Solar physicists have noticed that our sun is continuously oscillating as a huge 'gong'. The oscillations (*Figure 2*) can not be 'heard', but there are ways by which it is possible to 'see'

Figure 2. 5-minute solar oscillations revealed by motions observed over a narrow 80,000 km long strip of the sun's surface over a 120 minutes period.



them. R B Leighton, R W Noyes, and G W Simon first observed these oscillations at the Mt. Wilson Observatory. They set out to study the velocity patterns of gases at the surface of the sun using the concept of the Doppler Effect. According to this, the wavelength of light increases when the source is moving away (redward shift), and decreases when it is moving towards (blueward shift) the observer.

It is possible to use this effect to measure the up and down-flows of solar gas by selecting a suitable spectral line of the sun's photosphere. The velocity observation made over a strip of photosphere with time showed an oscillatory or wavy motion with a period of about 5 minutes, with a maximum velocity amplitude of around 0.5 km/sec. The pattern having appeared at some point on the solar surface persists for about half an hour, then dies away, but a similar pattern would be in progress elsewhere.

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During 1970s, it was suggested that the oscillatory motions were due to a superposition of millions of individual sound wave modes excited and trapped in the solar interior. Using these modes a powerful method termed as Helioseismology or Solar Seismology has been developed which allows an extremely revealing view of the sun's anatomy all the way from its surface to the very centre. It depends on precise measurement of frequencies and amplitudes of the oscillation modes. Helioseismology is conceptually analogous to earth's seismology, which studies the earth's interior through analysis of free oscillations induced by earthquakes. In the case of the sun, the oscillations are produced not by the build-up and release of stress in a solid crust, but rather by the continuous stimulation of motions through the gaseous interior of the sun.

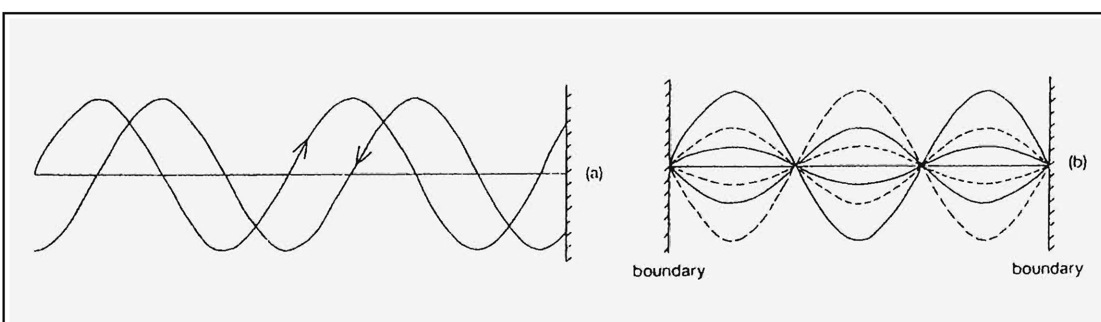
Helioseismology is conceptually analogous to earth's seismology,

The Sun as a Giant Organ Pipe

Let us examine the propagation of sound waves having been excited by some disturbance as parcels of compressed and rarefied gas. The pressure of the gas acts as restoring force which tends to bring back the gas to its undisturbed state. Just as light waves undergo reflection at a surface, sound waves are reflected from a boundary as in acoustic cavities like an organ pipe.

When a sound wave travels repeatedly between two reflecting boundaries (*Figure 3*), an acoustic or resonant cavity is formed within which the wave is trapped. The result is a wave motion that progressively builds up and fades away as a whole, with 'nodal' points where the displacement and velocity are always zero. This motion is called a standing wave or 'mode'. The condition for a mode is that its wavelength must be twice the

Figure 3. Wave motion illustrating the formation of solar oscillations: (a) wave reflected from a single boundary, (b) a standing wave formed by wave reflected at two boundaries located at the nodes.

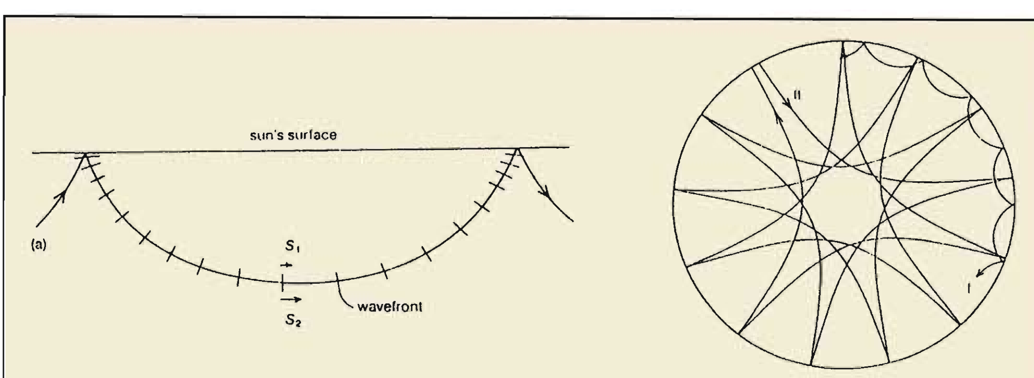


p modes give a sensitive indication of conditions prevailing in the solar interior.

distance between the boundaries (the fundamental mode), or equal to submultiples of the fundamental wavelength (overtones or harmonics).

Although there are no physical boundaries inside the sun, acoustic cavities exist in the solar interior due to density and temperature gradients that can reflect or refract sound waves. Let us consider a wavefront propagating into the solar interior from the surface (*Figure 4*). As it travels to deeper and hotter layers, the sound speed 'c' increases as it is proportional to the square-root of the temperature *T*. Thus, the deepest part of the wavefront travels faster than the shallower part, and its path is successively bent, such that it is refracted back to the sun's surface. At the surface, the wavefront is reflected inwards, because it encounters a steep drop in the density and it can not propagate outwards any further.

These trapped sound modes are called *p* modes, where *p* stands for the restoring force, pressure. Their speed and direction depend on temperature, composition and motions within the sun, hence, they give a sensitive indication of conditions prevailing in the solar interior. The modes penetrate deep inside the sun, but their effects at the solar surface are evident in the form of surface brightness or velocity fluctuations. Since the wavelength and brightness variations are very small, it requires great precision to detect them. Yet, a rich spectrum of solar global waves has been detected.



gure 4. (a) Wave being flected at two points in e solar surface, (b) wave odes having different avelengths penetrating to fferent depths in the sun.

Properties of Solar Global Oscillations

Because the resonant cavities of the waves lie within the spherical sun, a mathematical description of their spatial structure must include functions that depend on latitude, longitude and radius. The global oscillation can be best given by using spherical harmonic functions for an observable parameter such as velocity or intensity fluctuation as follows:

$$\tilde{\sigma}(r,\theta,\varphi,t) = \sum_{nlm} \sigma_n(r) Y_l^m(\theta,\varphi) \exp(i\omega t)$$

where $Y_l^m(\theta,\varphi) = P_l^m(\cos\theta)\exp(i\,m\,\varphi)$ are spherical harmonic functions of colatitude θ, and longitude φ, and r denotes the depth. A given mode with frequency ω is characterised by three integers l, m, n, where the surface structure of the mode is given by the degree l (the total number of nodal planes slicing the solar surface, or the number of complete circles on which the vertical component of the velocity is always zero), and the azimuthal order m, (the total number of planes cutting the equator perpendicularly and takes $2l+1$ values, $-l, \ldots, l$) (*Figure 5*). The depth structure of the mode is determined by its radial order n, or the overtone number $\sigma(r)$.

The horizontal wave-number of a mode is given by $k_h^2 = (l(l+1)/r)^2$ at a radius r from the solar centre. The complexity of the velocity structure associated with a given mode increases with increasing l or m. The effects of redward and blueward

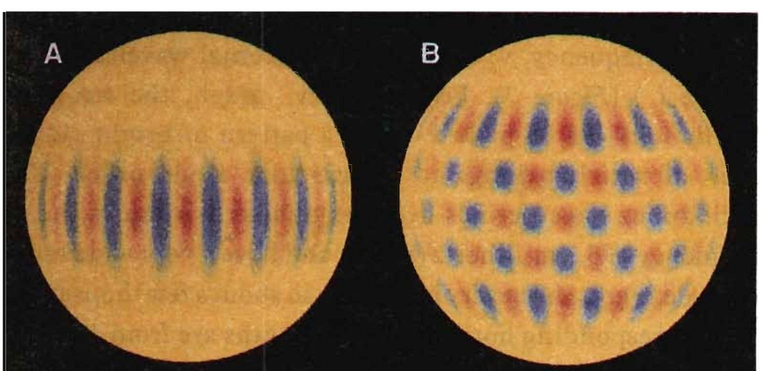
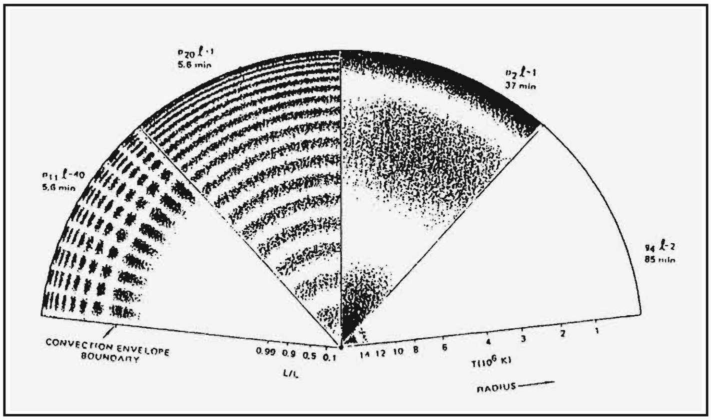


Figure 5. Surface fluctuations associated with solar p-modes of degree l=20, and (A) m=20, (B) m=14. Blue and red denote up and down-ward Doppler motions.

Figure 6. Radial propagation of p modes with periods of 5.6 and 37 minutes, and g mode with a 85 minutes period .



velocities are cancelled for large l, m modes in integrated sunlight observations. This is the reason that the modes with low degree whose horizontal wavelengths are comparable to the size of the sun have attracted much attention.

Other types of oscillation modes are expected to propagate in the solar interior in which buoyancy rather than pressure is the restoring force. These are the g or gravity modes (*Figure 6*). They are expected to have very low frequencies (long periods of hours) and amplitudes and can propagate in a medium where no convection currents exist, i.e., in the deep radiation zone of the sun and are hence difficult to observe. These elusive g modes, if detected can be valuable to decipher the innermost structures of the sun.

g modes are expected to have very low frequencies and amplitudes.

The p and g modes can be illustrated by a two-dimensional power spectrum: a l–ν graph of observed wave-period (or its inverse, frequency, ν) against the horizontal wavelength (or degree l) (*Figure 7*). From the l–ν graph, the strongest oscillations can be picked out as a pattern of bright ridges, each of which belongs to a particular mode order. The oscillations have periods averaging about 5 minutes, i.e., a frequency of 3.3 millihertz (mHz), and have a very wide range of mode degree (from very low values to about a few thousands). The corresponding horizontal wavelengths are from 4000 km to hundreds of thousands of kms.

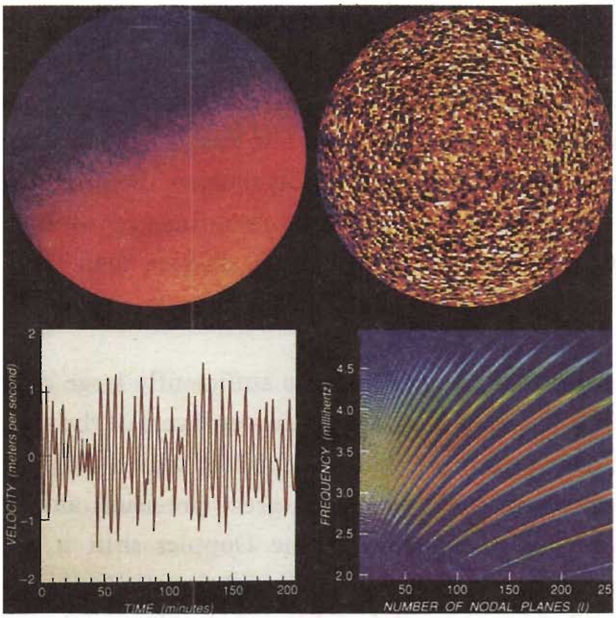


Figure 7. Solar Doppler image shows the dominant solar rotation: blue part is approaching and red receding from the observer (upper left). The surface velocity undulations are revealed when solar rotation is removed (upper right). Velocity pattern obtained at an individual location with time (lower left), and l-ν diagram (lower right).

Modes having intermediate degree, $l \sim 50$ to 150, penetrate only the upper tenth of sun's radius, while low l modes (i.e., large wavelength) penetrate deeper. Extreme cases of very low degree modes are those with $l=0$, for which the whole sun pulsates in and out of phase, or $l=1$, in which one hemisphere expands in phase while the other contracts in phase. The lower the degree, the greater is the fraction of the entire sun that moves in phase.

The resultant velocity field associated with the superposition of millions of such modes is very complex, and individual modes are unrecognisable from the spatial patterns of velocity alone. Only through the measurement of their individual frequencies can they be unravelled. The challenge is to detect velocities of the order of a few metres per second from a distance of 150 million kilometres!

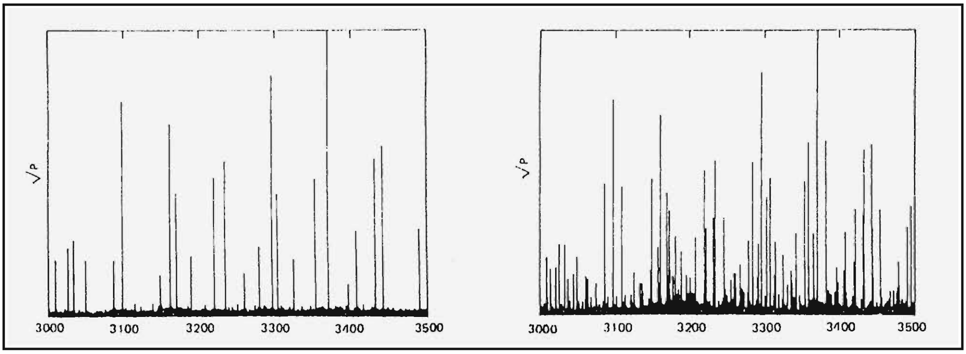
Observational Requirements to Detect Solar Oscillations

For observing low degree modes, one simply records the Doppler shift of integrated point-like sun or sun as a star, in which the light from entire solar disk is mixed together. In such observations, the Doppler shifts corresponding to the high degree modes, which have small structures are essentially cancelled out while modes with low l (= 0, 1, 2, or 3) produce radial motion that is in phase across much of the solar disk. This yields a detectable spectral shift in unimaged sunlight. The resulting power spectrum is much simpler than that which emerges from observation on high l.

By analysing the frequencies of a sufficiently large number of oscillation modes, progressively deeper layers of the sun can be probed. However, the velocity associated with a single mode is extremely small and it requires great precision and a stable spectrometer for detection of the Doppler shift it produces. There is another difficulty: the first observations of low-degree solar oscillations showed that the periods (T) and therefore the frequencies ($1/T$) of these modes are very closely spaced. In order to distinguish them it is required to observe the sun for long enough duration to allow modes with frequencies that are only slightly different to go out of phase with each other. Unfortunately, it is not possible to observe continuously for longer duration from one single groundbased location, due to day-night cycle.

Figure 8. Power spectrum of synthetic solar oscillations showing the contaminating effect of data gaps.

It is found that a 12-hour continuous observation is not sufficient, and the night gaps in observation introduce spurious frequencies around (*Figure 8*) genuine solar modes, separated by $\Delta\nu \sim 1/d$ in the solar power spectrum, where d is the time interval between



the gaps. These spurious features make it nearly impossible to unambiguously identify the real solar modes; therefore, it is essential to reduce gaps in solar coverage. Fortunately, there are ways available for achieving this goal:

(i) *Observations from the south pole*: Several days of continuous solar coverage can be made during austral summer from the south pole. However, in most cases, observational runs longer than 5-7 days have been found to be difficult to obtain due to the harsh weather conditions.

(ii) *Network of Ground-based Observatories*: A network of ground-based observatories with identical instruments can be formed at longitudes located around the world where the sun never sets. The data from these locations can be combined to give a near continuous 24-hour solar coverage over several months. The Global Oscillation Network Group (GONG) project, coordinated by the National Solar Observatory, USA, is one such important international effort involving a large solar community (*Figure* 9).

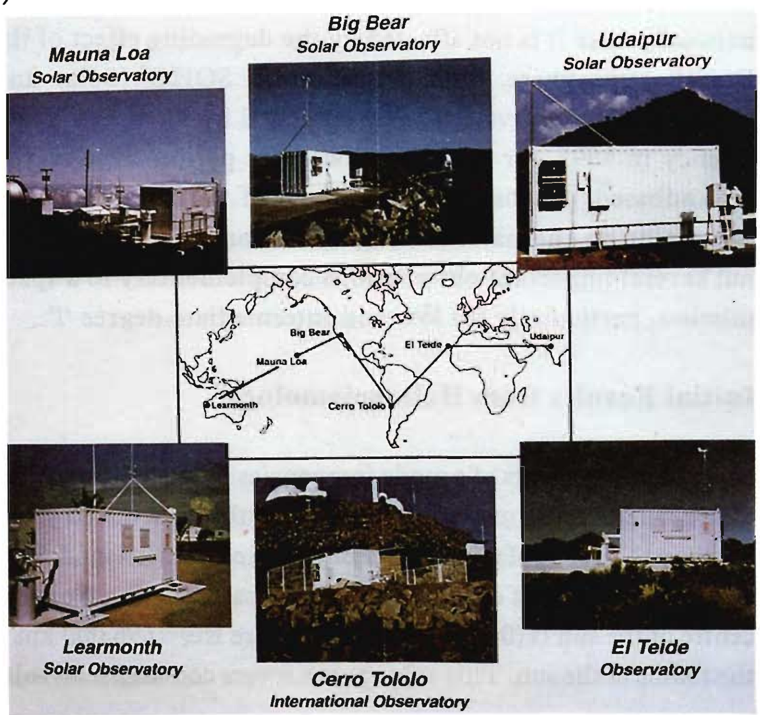


Figure 9. The GONG network of groundbased observatories for 24-hour continuous solar observations.

Each site of the GONG network takes digital velocity images of full disk sun every minute.

The GONG network consists of six observing stations keeping a continuous watch on the sun. These sites are Udaipur Solar Observatory (Physical Research Laboratory), India; Canary island, Spain; Cerro-Tololo Inter-American Observatory, Chile; Big Bear Solar Observatory, USA; Mauna Loa, Hawaii; and Learmonth, Australia. This network became fully operational in October 1995, after a six-year site evaluation of 20 potential sites. Each site takes digital velocity images of full disk sun every minute, collecting around 200 megabytes of data per day from a single site, which works out to more than 1 gigabyte per day for the GONG network. The GONG project takes imaged solar data as against previous networks such as UK sponsored BiSON and French sponsored IRIS projects which use integrated-light from sun, i.e., sun as a star. The integrated light measurements are sensitive only to modes with $0 \leq l \leq 4$, while GONG project with 256×256 pixel imaging covers $l \leq 250$.

(iii) *Observation from a spaceborne platform*: In principle, observation from a space platform, placed into a sunlit orbit between the sun and earth, is better than the groundbased network, since it is not affected by the degrading effect of the Earth's atmosphere. Such a spacecraft, SOHO[2] (Solar and Heliospheric Observatory), was launched by European Space Agency in 1995, for a nominal two year period. However, a groundbased network has advantage of better access, less constraint on the payload weight, economy, and can carry out several important observations complementary to a space mission, particularly for low and intermediate degree 'l'.

[2] see Dwivedi. *Resonance*. Vol.2. No.9, pp.75-76,1997,

Initial Results from Helioseismology

Initial measurements of p mode frequencies have shown that the discrepancies with model predictions could be reduced if we increase the depth of the convection zone in standard models by about 50%. The best current value of the base location from the centre of the sun is (0.71 ± 0.003) R$\odot$, where R$\odot$ = 696,000 km is the radius of the sun. This value puts a severe constraint on solar

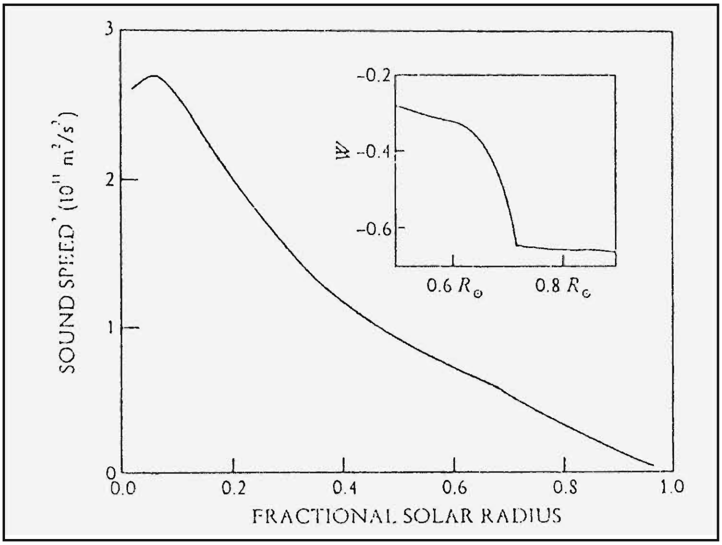


Figure 10. Sound speed inside the sun.

solar models. Also, models with low helium abundance in the core, constructed to solve the solar neutrino deficiency, were found inconsistent with the observed low-degree modes. Current determinations of the Helium mass abundance in the convection zone are between 23% to 26%, while standard solar models and Big-Bang cosmology requires a larger value of around 28%. Unfortunately, the current data is not accurate enough to extend these inferences all the way to the core.

The sound speed depends on the density and temperature of the solar material (*Figure 10*), and it affects the frequency of p modes. Early results showed that the sound speed was higher in the real sun than in models. This result suggests that several model parameters need adjustments in order to improve the solar models.

Oscillation frequencies are altered by the solar rotation – the shift in the frequency of p modes due to solar rotation is proportional to the azimuthal order m. The surface rotation of the sun is known to decrease with increasing latitude. The models constructed to explain this differential solar rotation have produced constant internal rotational profiles (*Figure 11*) on cylindrical surfaces, parallel to the rotation axis of the sun.

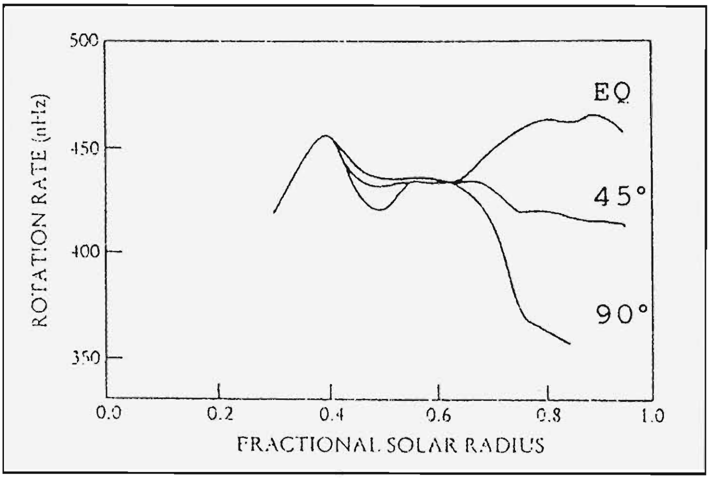


Figure 11. Profiles of internal solar rotation.

However, helioseismology indicates that the rotation rate in the vicinity of the equator unexpectedly increases with depth.

Other major results (*Figure 11*) are: (i) the rotation throughout the convection zone is similar to that at the surface (ii) the outer part of the radiative zone rotates at a constant, intermediate rate. The resulting shear between the radiative and convection zones may hold the key to the origin of 11-year solar activity cycle but there is no theoretical explanation for this kind of rotation.

Models suggest that much of the angular momentum of the contracting solar gas cloud was shed out by transfer to the solar wind, while the central core should have retained most of its original angular momentum. The fast rotating core can have enormous astrophysical implications. The initial results from helioseismology do not allow a very rapidly spinning core. In fact, it surprisingly suggests that the core may be the slowest rotating part of the sun! If this is true, how and where was its angular momentum shed? It is expected that answer to this puzzle will be provided by helioseismology.

Helioseismology suggests that the core may be the slowest rotating part of the sun.

It is found that p mode frequencies change by about 1 part per thousand during the solar activity cycle (*Figure 12*). This unexpected result is perhaps related to the changes in the surface temperature and magnetic field strengths. Interactions of p

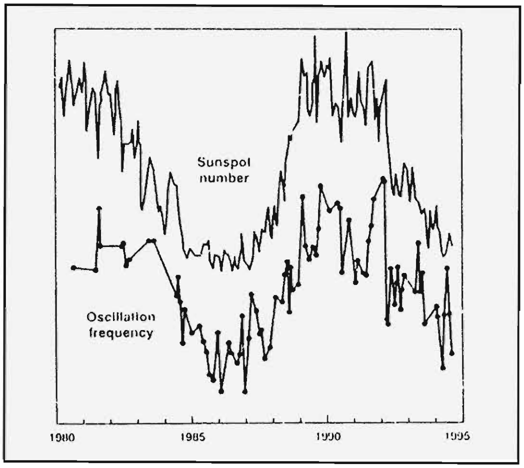


Figure 12. p mode frequency variation with solar cycle.

modes with sunspots and active regions observed on the outer layers of sun are also contributing to the knowledge of their birth and evolution.

The Future Prospects

The solar seismology and its findings, are putting us on the threshold of a golden era of our understanding of how stars work. It is expected that as the projects dedicated to helioseismology make further progress, our knowledge of the global properties of the sun and their changes with solar activity cycle will be much better defined. The technique of helioseismology is being further extended to other stars – asteroseismology. Such an advance would allow additional tests of the theory of stellar structure and evolution. With more precise and accurate measurements, it should become possible to detect the *g* (gravity) modes, which would provide a finer tool to study the solar core. Exciting times are ahead for solar physics in particular and physics, astrophysics, in general.

Suggested Reading

- Kenneth J H Phillips. *Guide to the Sun.* Cambridge University Press, 1992.
- John Harvey. Helioseismology. *Physics Today*. October 1995.
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