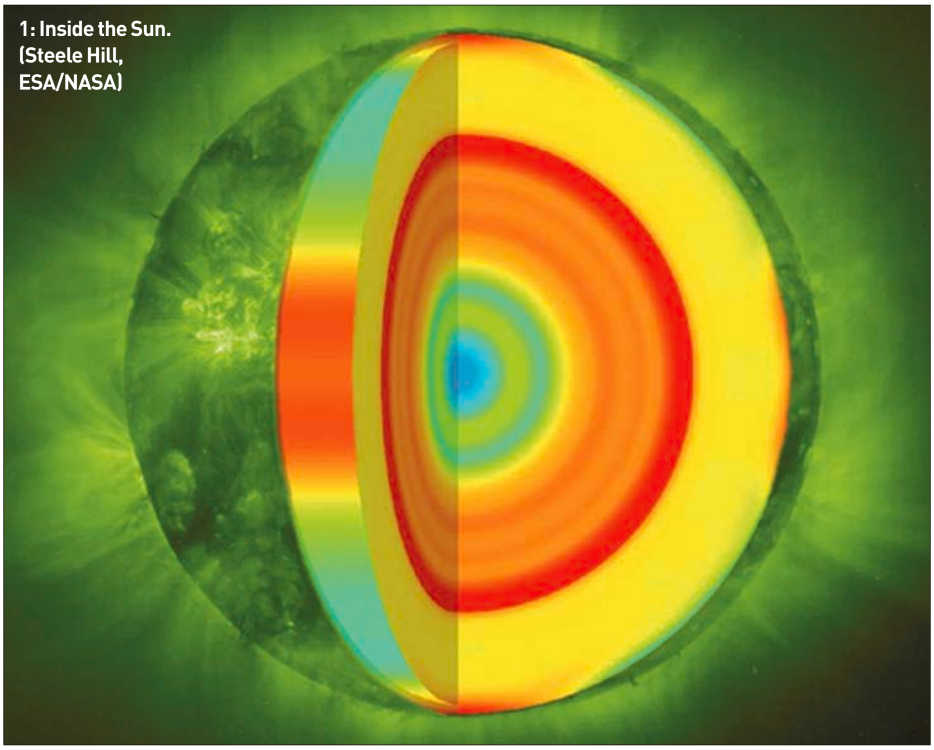
The sound of the Sun

Bill Chaplin and Istvan Ballai review developments in helioseismology – the resonant choir of the Sun – a discipline that now probes the Sun from core to corona.

Abstract

Observations of resonant phenomena on the Sun are now being made that have their origins not only in the interior, but also in structures in the tenuous solar atmosphere. The challenge for solar researchers is to reconcile the flood of observations and theory from these varied scales and locations to further improve our understanding of the Sun. Here, we look at some of the exciting challenges facing researchers delving into the seismology of the Sun.


1: Inside the Sun. (Steele Hill, ESA/NASA)

Helioseismology is the study of the Sun by observing its resonant modes of oscillation. This field has been associated, historically, with internal modes that are acoustic in nature (p modes) – including radial oscillations of the whole interior – and attempts to uncover their gravitational counterparts. However, in the past half-decade or so, observations of resonant phenomena have been extended into the Sun's tenuous outer atmosphere, where oscillations of coronal structures have been uncovered. Helioseismology should therefore now be regarded as a field that encompasses a "resonant choir" from the core all the way out to the corona.

Intriguingly, observations of flares in some very active late-type stars have raised the possibility that coronal oscillations may turn out to be a ubiquitous feature (Mullan and Johnson 1995, Mathioudakis *et al.* 2003, Mitra-Kraev *et al.* 2005); internal p modes have already been detected, with impressive precision, in over half-a-dozen late-type, Sun-like stars (e.g. see Bedding and Kjeldsen 2003). The RAS discussion meeting "Seismology of the Sun: from the inner core to corona", held earlier this year, focused on aspects of helioseismology in the interior and atmosphere (see Ballai and Chaplin 2005 for a full report). In this article we consider some of the important issues raised at the meeting that face both areas of the field.

The Sun is an elastic, and therefore ideal, medium for wave propagation. Waves propagating in various solar regions have the unique ability to carry information about their environment, and therefore serve as a perfect tool for diagnostics. Measurement of the properties of waves and resulting resonant oscillations, combined with theoretical modelling of the wave phenomena, can lead to a determination of the mean plasma and field parameters.

Internal seismology – that could be called "esoseismology", with "eso" from the Greek meaning inside – is now well established. The first observations of the five-minute oscillations of the photosphere, the visible manifestation of standing acoustic waves in the interior, were made in 1960 (Leighton *et al.* 1962). It took a further decade before a theoretical basis for the phenomenon, internal standing waves, was proposed (offered independently by Ulrich [1970] and Leibacher and Stein [1971]); and half a decade after that before observational confirmation of the rich spectrum of overtones was forthcoming (Deubner 1975, Rhodes *et al.* 1977).

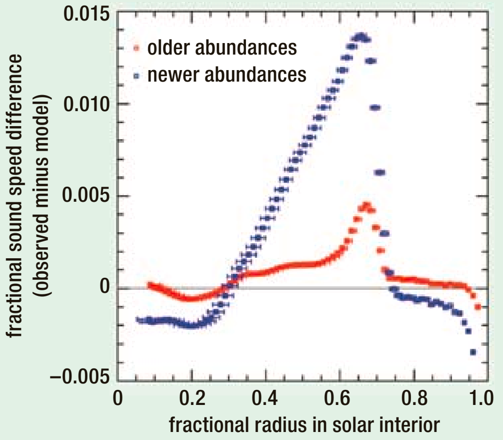
These initial observations were of modes with small horizontal wavelengths (high angular degree) that penetrated only a shallow distance into the convection zone. That the supported range of modes extended all the way to those for which either a substantial, or the entire, interior volume was engaged in pulsation became apparent only at the end of the 1970s (Claverie *et al.* 1979) thanks to observations of low-degree overtones (although the possibility had already been discussed, e.g. Wolff 1972, 1973).

The development of esoseismology, therefore, followed a path in which observations of new phenomena were made, competing theories were proposed to explain them, and improved observations allowed the theories to be tested and discriminated. In contrast the new field of coronal seismology – or, to maintain consistency in nomenclature, "coronoseismology" – and that of the solar atmosphere, saw theory come before observation.

The essential theory of coronal oscillations in magnetic structures was first published in the early 1980s (e.g. Roberts *et al.* 1984). At the time, available data were of insufficient temporal and spatial quality to reveal, observationally, modes in individual structures. Only with the advent of high-resolution, space-borne observations in the latter part of the 1990s did this breakthrough become possible. Observations have now revealed evidence for wave propagation in almost every layer of the solar atmosphere. Since the associated wavelengths and periods are larger than the ion Larmor radius and gyration period of particles, respectively, these waves can be studied within the framework of magnetohydrodynamics (MHD).

The role and importance of the magnetic field will determine a different approach inside the Sun and in its atmosphere. Below or near the photosphere the plasma β parameter (the ratio of the kinetic and magnetic pressures) is large, and the gradient of the pressure is the main restoring force. So, while magnetic fields influence the properties of the interior modes, they do so at a level where the impact can be modelled as a small perturbation on the acoustic wave speed. In the atmosphere, where the plasma β is in contrast small, the magnetic field instead dominates the nature of wave propagation, and a richer variety of waves (and oscillating modes) are possible. These waves (slow and fast magneto-acoustic waves, Alfvén waves) have differing characteristics, making the problem of atmospheric seismology very complex.

2: Difference in sound speed between the helioseismically observed profile (from SOHO/MDI observations) and that of the solar models – with the new abundances (in blue) and the old abundances (in red). (Image kindly provided by Sarbani Basu; data from J N Bahcall, A M Serenelli and S Basu 2005 *ApJ* 621 L85)



Seismology in action

Esoseismology has provided an unprecedented probe of the opaque solar interior. As it has matured, it has also diversified, the most obvious division being into the sub-fields of "classic" global and local interior seismologies.

Modes that are coherent globally are formed by waves that live long enough to make a complete circuit of the Sun. As such, they provide a measure of internal properties averaged in solar longitude. Even though global modes allow differences in structure to be inferred at right angles to this, in latitude, it is not possible to discriminate the structure north and south of the solar equator. Only those features that have a structure that is symmetric about the equator can be uncovered. On the other hand, local techniques look at what sound waves are doing "locally" beneath small patches of the surface, rather than waiting for some average pattern of behaviour to establish globally. Some of the local methods draw strongly on techniques applied in terrestrial studies (traditional seismology or "geoseismology").

While the upper atmosphere is visible via the Sun's radiation, this far from obviates the need for, or the dramatic potential of, coronoseismology. The tenuous nature of the corona means exact magnetic field measurements (e.g. through the Zeeman or Hanle effects) are not possible; therefore it is essential to find values for this key physical quantity. Further valuable information can be inferred by means of seismic diagnostics of the plasma in the upper atmosphere, e.g. substructure, transport coefficients (essential for mechanisms occurring over short length scales such as heating), heating functions, etc.

Lifting a lid on the opaque interior

An extensive, and wide-ranging database (in the sense of types of modes covered) on the internal p modes is available to the field, from both ground and space-borne observational platforms. As the numbers and quality of data have improved, so this redundancy has begun to play an even more important role – testing, for example, the solar origin (or otherwise) of new features brought to light by observations; and the accuracy and robustness of analysis pipelines seeking to address new questions that, hitherto, had been muted by inferior precision in the data.

While the precision to which inversions for the hydrostatic and dynamic structure of the interior can now be made is impressive indeed, major challenges confront the field in this area. As higher-quality seismic data refined the inferred profile of the sound speed within the Sun, two important changes had, historically, shifted the profile of the standard solar model into better agreement with the observations – first, changes to the radiative opacities (Rogers and Iglesias 1991), then the inclusion of gravitational settling and diffusion of helium and heavy elements (e.g. Christensen-Dalsgaard *et al.* 1993). Although the differences that remained were tiny (see the red curve in figure 2), they were nevertheless significant, owing to excellent precision in the seismic frequencies.

However, the past year has seen the differences diverge as the result of a downward revision (by about 40%) of the estimated photospheric abundances of the heavy elements (Apslund *et al.* 2004). These abundances are used as input for the model calculations, and because these metals are such an important source of opacity, this has had a major effect on the sound speed profiles of the models (e.g. Turck-Chièze *et al.* 2004, Bahcall *et al.* 2005, Bahcall, Serenelli and Basu 2005). The model sound speeds are now, on average, about one half of one per cent smaller in the radiative interior compared to the old models with their old abundances (blue curve in figure 2).

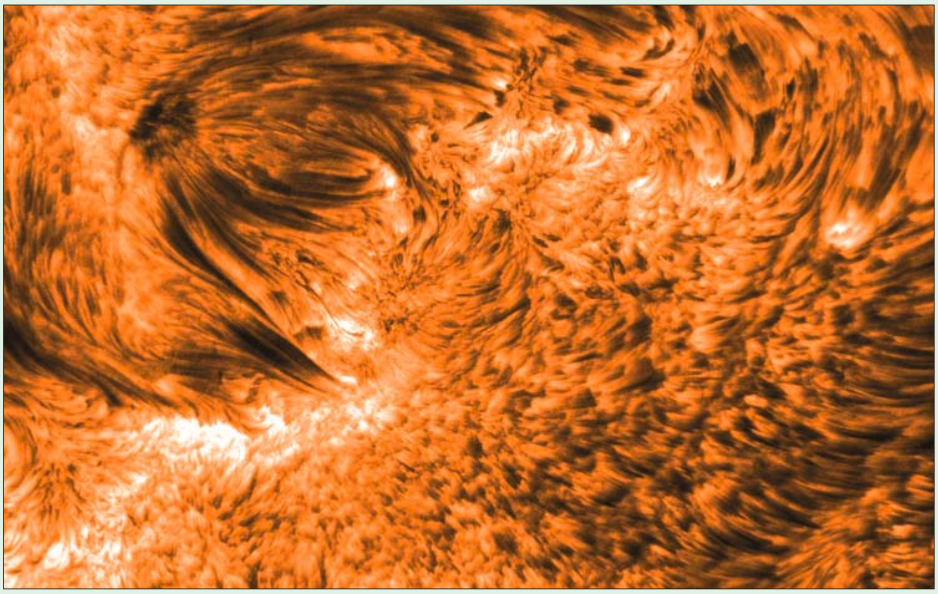
Recent work suggests updates of the calculations used to derive the opacities (e.g. Seaton and Badnell 2004) are unlikely to explain fully the new discrepancies (e.g. Antia and Basu 2005). It is possible that some form of mixing, or enhanced diffusion (Guzik *et al.* 2005) may have an important role to play. Suffice to say this is an area that is concentrating minds.

Long, high-quality datasets remain the key to providing precise and accurate inference on the deep radiative interior and core. The detection of very low-frequency core-penetrating (low-degree) modes remains a primary goal of observers. Because the observational signatures are so weak the continued collection of data – ideally by at least two programmes to allow for correlation analyses – is vital.

The low degree modes are extremely long lived – while low-degree modes near the centre of the 5-minute spectrum, at ≈3000 μHz, have a lifetime of the order of a few days those down at 1000 μHz show values of roughly 1 year. At frequencies lower still, where claimed detections are sporadic and uncertain, lifetimes of the order of decades – possibly up to centuries near the fundamental tones – are expected. Irrespective of the precise values, the long-lived nature of these modes means that once they are uncovered their frequencies and splittings can, in principle, be measured to exquisite precision and accuracy.

The detection of very low-overtone p modes offers the prospect of significant improvement for inference on the sound speed in the core. In contrast, recent studies suggest the going may be harder for studies of rotation (Chaplin *et al.* 2004). A precise determination of the rotational profile in the core may have to await the detection of interior gravity (g) modes. The coming few years should see a renewed push in this area, on both the observational and analysis fronts – i.e. better instrumentation, designed specifically for g-mode detection (e.g. GOLF-NG, Turck-Chièze *et al.* 2005, PICARD, Damé *et al.* 2001), and new ways of looking at the data.

Measurements of the properties of the internal p modes also provide important input for studies of the solar cycle. Here, both the classic global and local seismic techniques are being applied. Arguably the most important observational input for dynamo theorists and modellers has been the rotation profile uncovered in the outer parts of the solar interior by the global-mode data. This revealed the thin layer just beneath the base of the convection zone – the tachocline – across which a large shear in the radial rotational rate is maintained. This is now widely accepted as being the site at which poloidal magnetic field is "stretched" into a toroidal configuration (called the omega effect). There remain many



3: Solar spicules with super resolution observed by the Swedish Solar Telescope (La Palma). (Source: cover page of *Nature* 2004 430 courtesy R Erdélyi and B De Pontieu)

open questions regarding how fresh poloidal field is then recovered from toroidal field. Helioseismology should again have an important part to play in resolving these issues, for example by placing tighter constraints on possible magnetic field strengths through the convection zone.

It is in principle possible to separate out changes to the mode frequencies that have their origins either in the near-surface layers or deeper-lying regions. The total change is dominated by the former, near-surface contribution: from the global-mode analyses it is starting to become possible to make inference, subject to certain assumptions, on the changes to fields that would be needed to give rise to the frequency changes in these layers (Dziembowski and Goode 2005) – in essence, "magnetohelioseismology" (Thompson 2005).

Changes to the mode excitation and damping parameters (e.g. observed powers and frequency-domain line widths) provide further pieces of the jigsaw, with information on how the acoustic waves interact with the convection. Advances in theoretical modelling of mode power and damping are not only important for making inference on convective properties, but are crucial for accurate predictions of mode detectibility. This has a bearing on the solar low-frequency detection problem, i.e. if we find a mode candidate, is the implied power associated with it plausible? Then there are the obvious implications for other Sun-like stars – for example, target selection, i.e. which stars are worth devoting precious observing time to?

Local methods are particularly suited to solar cycle studies, in that regions beneath individual active features can be probed. Local seismologies are allowing a first look at the wave speed and material flow beneath active regions and individual sunspots (see Thompson 2004 for an overview) and progress is being made on understanding the acoustics of magnetic layers (e.g. Lindsey and Braun 2005a, b, Cally 2005). Both higher-quality data, and developments to the analysis methods, offer the prospect of discriminating details of the underlying structure, e.g. are spots single large, or multiple fibril-like, structures beneath the surface?

The ability to probe the architecture of magnetic fields in the convection zone would, as mentioned above, be of great interest in the context of the dynamo. Flux trapped in the upper parts of the zone would presumably play some role in flux-transport-like dynamos. Deeper down twists in the magnetic field, and the way flux might then be "shredded", is important to how the so-called alpha effect works in interface dynamos.

Linking interior to atmosphere

Magnetic field generated in the solar interior penetrates the surface and "holds" the solar atmosphere together. It is therefore natural to search for interior–atmospheric links that have their origin in the influence of magnetic structures.

Direct links to the upper atmosphere have been sought in studies of correlations between active events, such as flares, and large excitations of the internal p modes. There is some evidence to suggest flares may contribute, on occasion, to enhanced levels of acoustic emission (Kosovichev and Zharkova 1999, Donea, Braun and Lindsey 1999, Ambastha, Basu and Antia 2003), but more work is needed in this area. These studies bear on the influence the atmosphere has on acoustic waves in the interior – but what about those mechanisms that might act in the reverse direction?

It is well known that the upper atmospheric structures act as a filter for waves from below; only those with a frequency below the acoustic cut-off are able to reach higher altitudes. Recent work (De Pontieu *et al.* 2004, 2005) has suggested a possible mechanism by which the interior acoustic waves might be channelled to the upper regions of the solar atmosphere along emerging, tilted magnetic structures. It is proposed that the upper-atmosphere transients (e.g. spicules; see figure 3) are generated, and sustained, by the 5-minute photospheric oscillations and that furthermore the "moss" (in the transition region) and coronal oscillations might have the same origin. This idea is supported by observations that show waves and oscillations with periods predominantly around 5 minutes. Since waves of similar period can be found almost anywhere in the solar atmosphere it seems this temporal range is a preferred "golden" period for the solar plasma.

Recent high-resolution observations have also revealed that transient events, such as prominences, may support wave propagation either as a whole or in substructure fibrils, with periods ranging from a few seconds up to 2 hours (Lin *et al.* 2003). Theoretical attempts are being made to describe these waves and to use them to obtain valuable data on the structure and properties of solar prominences (Oliver and Ballester 2002). In particular, oscillations of a single fibril have been studied (Díaz *et al.* 2001, 2002) that may be an important ingredient for global oscillations (Díaz *et al.* 2005). It is likely the consideration of equilibrium steady flows (in accordance with observations) and realistic geometries will have an important role to play in further understanding these solar features.

Into the corona

The solar corona is the outermost layer of the solar atmosphere where the gas is almost completely ionized and temperatures are higher than one million degrees Kelvin. The behaviour and dynamics of the plasma are controlled by the magnetic field, which does not spread uniformly, but tends to accumulate in entities called magnetic flux tubes or loops. These loops are the "building blocks" of the active solar corona.

Table 1: Comparison of esoseismology and coronoseismology

	Seismology of the interior (esoseismology)	Seismology of the corona (coronoseismology)
Visibility	Interior opaque to radiation	Corona visible by radiation
Wave types	Acoustic-gravitational waves	Slow and fast magneto-acoustic waves and Alfvén waves
Magnetic field effects	Modelled as small perturbation on wave speed	Dominant in determining nature of wave propagation
Studies	Classic seismology of globally coherent modes (including whole-Sun, radial oscillations); and local analysis beneath surface patches	Dominated by seismology of individual coronal structures (e.g. loops); global (fast magneto-acoustic) modes have possibly been observed
Observations	Most prominent observed modes (in both global and local analyses) have periods of 3 to 10 minutes and are high overtones	Observed periods for individual structures again on the order of minutes; interpreted as fundamental and low-overtone modes of structures
Lifetimes of observed modes	Vary typically from hours to years	On the order of seconds to minutes
Data types	Multiple datasets; near-continuous observations over many years	Multiple datasets; "event"-driven data
Data duration	Stretches of data lasting anywhere from hours (some local applications) to years (some global applications)	Stretches of data lasting the order of one hour

The birth of coronoseismology as an observational field was marked by the identification of kink oscillations of coronal loops in EUV TRACE data (Aschwanden *et al.* 1999, Nakariakov *et al.* 1999). Kink oscillations, the quasi-harmonic displacements of entire loops, can be seen with an imaging telescope if the plane of the oscillation is perpendicular to the line of sight. The Bastille Day flare on 14 July 1998 generated several oscillating loops around the flare epicentre. They oscillated with different periods, of the order of several minutes, with all segments vibrating in phase. It was concluded that the oscillations were produced by a standing wave, of wavelength twice the length of the loop. Since both the wavelength and period can be measured observationally, it is possible to estimate the phase speed, which is connected to the Alfvén speed inside and outside the loop. In turn, this allows for an estimate of the strength of the magnetic field – a vital parameter of coronal physics.

Rapid decay

Observations also show that waves decay very rapidly (on the order of minutes, corresponding to one to a few periods). Possible candidates for this damping include non-ideal effects (shear viscosity, thermal conduction), or effects related to the inhomogeneous character of the plasma (resonant absorption, phase-mixing, or stratification). While damping due to non-ideal effects would give us values for transport coefficients, it is clear that the derived values do not agree with the predicted values in the literature.

The damping of quasi-mode kink oscillations in cylindrical flux tubes, by means of resonant absorption, supports the idea that this process may be a significant component operating in the observed rapid decay of transverse coronal loop oscillations (Ruderman and Roberts 2003).

Recently, our theoretical understanding of the resonant damping process in coronal loops has been significantly improved by relaxing previous simplifying assumptions, such as the consideration of thin boundaries that connect the constant internal and external (coronal) densities, and the use of 2-D equilibrium models with a variation of density in both the radial and axial directions of the tube. The use of resonant absorption for coronal plasma diagnostics allows for the determination of the density ratio in coronal loops, as well as the characteristic length scale of inhomogeneities (Andries *et al.* 2005).

The encouraging start for MHD coronoseismology took place at the same time as the identification of other MHD modes (propagating slow and fast modes, fast trains, global sausage modes, solar global waves or EIT waves, etc), which together are stimulating further development of the method. Future new space instruments such as Solar-B, STEREO, the Solar Dynamical Observatory and the Solar Orbiter, with improved resolution, from different viewpoints, will improve markedly the quality of coronal MHD wave observations. ●

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