SYNTHESIS OF SOLAR-STELLAR SEISMOLOGY — MEETING SUMMARY

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1. Introduction

The Sun has generally been described as the Rosetta Stone of astronomy. This label is especially apt because our star is sufficiently close to Earth for a detailed scrutiny of its surface, a luxury that is not readily available for distant stars. It is our fond hope that the interior of the Sun and stars can be used as an astrophysical laboratory for testing theories of atomic and nuclear physics, high-temperature plasma physics, magnetohydrodynamics and neutrino physics.

The internal layers of the Sun are clearly not directly accessible to observations; nonetheless, it is possible to construct a reasonable picture of its interior. This can be accomplished with the help of a set of mathematical equations governing the mechanical and thermal equilibrium of the Sun, along with the boundary conditions provided by observations such as the mass, radius, luminosity and chemical composition.

The standard solar model is constructed with a number of simplifying assumptions, based on spherical symmetry without the inclusion of effects of rotational and magnetic forces on its structure. It adopts standard nuclear and neutrino physics, uniform initial chemical composition with the solar age of 4.6 billion years. A description of the convection zone is incorporated in the framework of local mixing-length theory with practically no overshoot into the adjoining stable layers. It also includes the gravitational settling of helium and heavy elements from the convection zone into the radiative interior.

The theoretical description of the Sun's interior is largely based on extensive numerical solutions of the structure equations, coupled with input physics pertaining to the opacity, equation of state and nuclear energy generation. This determines the physical conditions inside the Sun such as the profiles of the sound speed, density, temperature, chemical composition etc. The broad picture of the sun that has emerged is the following: The Sun is powered by thermonuclear reactions converting hydrogen into helium mainly by the proton-proton chain that operates in its energy-generating core which has a temperature upwards of 15 million K and a density close to 150 g cm^{-3}. The radiant energy slowly makes its way out of the central regions and in the outer third of the solar interior the energy transport is largely by turbulent convection.

F.-L. Deubner et al. (eds.), New Eyes to See Inside the Sun and Stars, 471–482.

The crucial issue is whether there is any way of checking the correctness of these numerically constructed models describing the internal constitution of our Sun!

2. Windows on the Sun's interior

There are at least two diagnostic probes available for looking inside the Sun:
a) Solar neutrinos, b) Solar seismology

Valiant attempts have been made since the nineteen sixties to measure the flux of neutrinos released in the Sun's energy-generating core (cf., Bahcall 1989). This diagnostic probe designed for the exceedingly difficult measurement of neutrinos from the thermonuclear reaction network sustaining the solar luminosity, is expected to provide a handle on the temperature and chemical composition prevailing in the central regions of the Sun. Davis's radiochemical chlorine experiment was the first effort to make this exceedingly difficult experiment of neutrino fluxes where the ^{37}Cl nuclei in a tank containing liquid perchloroethylene act as solar neutrino absorbers. The measured solar neutrino counting rate by Davis is reported to be 2.55 ± 0.25 SNU (SNU $= 10^{-36}$ captures per target atom per second) which clearly shows a puzzling deficit by about a factor of 3 over the predicted capture rate of 9.3 ± 1.2 SNU calculated by Bahcall and Pinsonneault (1995) for a standard solar model using OPAL opacities (Iglesias and Rogers 1996) and diffusion of heavy elements.

The Kamiokande experiment with its threshold of 7.5 MeV is sensitive to the ^{8}B neutrinos generated in the nuclear reaction network. The measured flux of these high energy neutrinos by Superkamiokande is reportedly $(2.44 \pm 0.25) \times 10^{6}$ cm^{-2} s^{-1}, while the expected flux according to the standard solar model is 6.62×10^{6} cm^{-2} s^{-1}. Unlike the foregoing experiments which are insensitive to the low-energy *pp* neutrinos, two current radiochemical experiments which use gallium detectors are capable of measuring the lower end of the solar neutrino spectrum. The reported measurements of the neutrino counting rate are 69.7 ± 8 SNU for GALLEX and 69 ± 13 SNU for SAGE (cf. Takata, these proceedings), while the theoretically predicted capture rate is 137 ± 7 SNU (cf., Bahcall and Pinsonneault 1995). There is, thus, a clear and persistent discrepancy between the measured and predicted neutrino fluxes, assuming the neutrinos to have standard physical properties (i.e., no mass, no flavour-mixing, no magnetic moment). This has cast doubts on the reliability of standard solar models, and has prompted solar physicists to look for some independent, complementary probe to determine physical conditions in the solar interior.

The Sun's surface undergoes a series of mechanical vibrations which manifest as Doppler shifts oscillating with a period centred predominantly around five minutes (Leighton, Noyes and Simon 1962). A theoretical explanation of these oscillations was given by Ulrich (1970) and independently, by Leibacher and Stein (1971) emphasizing the role of the interior acting as an acoustic cavity for the waves excited and trapped inside the solar body. Later, Deubner (1979) made accurate measurements of the periods and horizontal wavelengths of the five-minute oscillations to derive a power spectrum showing narrow ridges. These global oscillations are superpositions of millions of resonant normal modes which sample different layers of the Sun and carry information about the hidden solar layers, in much the same way as geoseismology reveals the structure of the earth's interior. This seismic tool, provided by a rich spectrum of velocity fields observed at the solar surface, with frequencies determined to a precision better than 1 part in 10^{5}, has indeed revealed the physical make-up of the Sun's interior with tantalizing precision.

The progress and puzzles in helioseismology were outlined by Tim Brown who emphasized the need to study the line asymmetries, shapes and their shifts, particularly for locating the source of excitation for these oscillations. The observational input for helioseismic measurements comes from ground-based networks and space-based instruments:

RESOLVED SUN	SUN AS A STAR
GONG	BISON
LOWL	IRIS
Mt WILSON	SOUTH POLE
SOHO (MDI)	SOHO (GOLF & VIRGO)

Elsworth stressed the overwhelming advantages in having continuous data sets from these varied observations and recommended a search for low degree modes, preferably of low order, in order to gain more accurate information about the central regions of the Sun. Frank Hill described the strategies for data analysis and drew particular attention to the possible pitfalls in the reduction of massive datasets, highlighting the many steps that go into the data processing such as calibration, proper mode identification, image geometry determination, mode parameters (e.g. amplitudes, frequencies, linewidths) and special care for considering spatial leaks structure, cross-talk, multi-site merging, etc.

The accurately determined helioseismic data can then be analyzed in two ways:

i) Direct model fitting (Forward method)

ii) Inversion method.

In the Forward method, a set of solar models is constructed with one or more adjustable parameters which are perturbed to obtain the linear eigenfrequencies of oscillations for comparison with the observed p-mode frequencies. The fit cannot, in practice, be perfect, but such an approach indicates the depth of the outer convection zone to be $\simeq$ 200,000 km, deeper than previous estimates and the helium abundance by mass in the envelope to be $\simeq 0.25$. An interesting outcome of such an approach is that the computed opacities near the base of the convection zone ($T \gtrsim 2 \times 10^6$ K) are found to be too low, a situation later modified with more up-to-date Livermore calculations. (Iglesias and Rogers 1996).

The inversion methods which have been effectively developed for inferring the physical conditions inside the Sun with the accurately available p-mode data, were described by Thompson. Most of these inversions are based on some kind of a linearization process and have resorted to one of the following methods: Regularized Least Squares, Optimally Localized Averaging Kernels, Asymptotic Representation, with some ad hoc trade-off parameter. A major accomplishment of the inversion technique has been a determination of the sound speed throughout much of the solar interior to a precision of better than 0.1% and the density to a somewhat lower accuracy (Gough et al. 1996). Fig. 1 shows the relative difference in the sound speed between the Sun and the standard solar model with gravitational settling of helium and heavy elements for the GONG, MDI and BBSO + BiSON datasets. The dominant features in the sound speed difference, which are shared by essentially all the data sets, occur in regions of the model with substantial composition gradients such as in the nuclear burning core and beneath the convection zone from which helium and heavy elements diffuse into the interior.

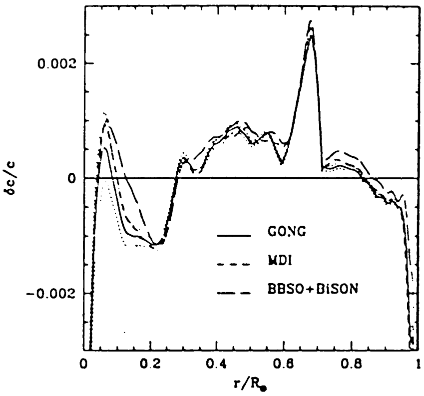

Figure 1. Relative difference in sound speed between the Sun and the standard solar model of Christensen-Dalsgaard et al. (1996) as inferred using various sets of observed frequencies.

3. Helioseismic constraints on solar structure

Vauclair summarized the principal constraints on the internal structure of the Sun inferred from helioseismic inversions.

1. The base of the convection zone: $r = (0.713 \pm 0.001)R_\odot$,
2. Extent of the overshoot beneath the convection zone: $d \lesssim 0.05H_p$,
3. Helium abundance in the solar envelope, $Y = 0.24 - 0.25$. Evidence for gravitational settling of helium and heavy elements out of the envelope and resultant chemical segregation,
4. Revision of input microphysics: opacities and equation of state (OPAL), nuclear reaction rates and Canuto-Mazzitelli prescription for convection,
5. Detection of boundaries of convection zones and seismic signatures of the HeII ionization zone.

Chaboyer discussed the role of lithium as a tracer of mixing in stars, particularly in the context of the Sun where the surface abundance of lithium is lower by about a factor of 140 compared to the meteoritic value. This can be attributed to the lithium depletion due to a combined action of rotationally induced mixing and diffusion at the base of the convection zone. Such a mixing would result in a flattening of the composition gradient beneath the convection zone and this should lead to a reduction in the pronounced bump in $\delta c/c$ around $r = 0.67R_\odot$ in Fig. 1.

The acoustic structure, namely, $c(r)$ and $\rho(r)$ obtained from the primary inversion of the accurate helioseismic data, can be profitably used to infer the thermal and composition profiles in the solar interior. For this purpose, of course, we need to employ the equations of thermal balance and energy transport, together with the auxiliary input provided by the opacity, nuclear energy generation rate and thermodynamic state of matter. Three approaches have been adopted in the literature for constructing seismic models (cf., Antia and Chitre 1995; Kosovichev 1996; Shibahashi and Takata 1996; Roxburgh 1996), and once the run of temperature, density and chemical composition is determined, it becomes possible to calculate the expected neutrino fluxes for these models. Remarkably, with the allowance of arbitrary variations in the input opacities and even relaxation of the thermal equilibrium condition, it turns out to be difficult to produce a seismic model that is simultaneously consistent with any two of the

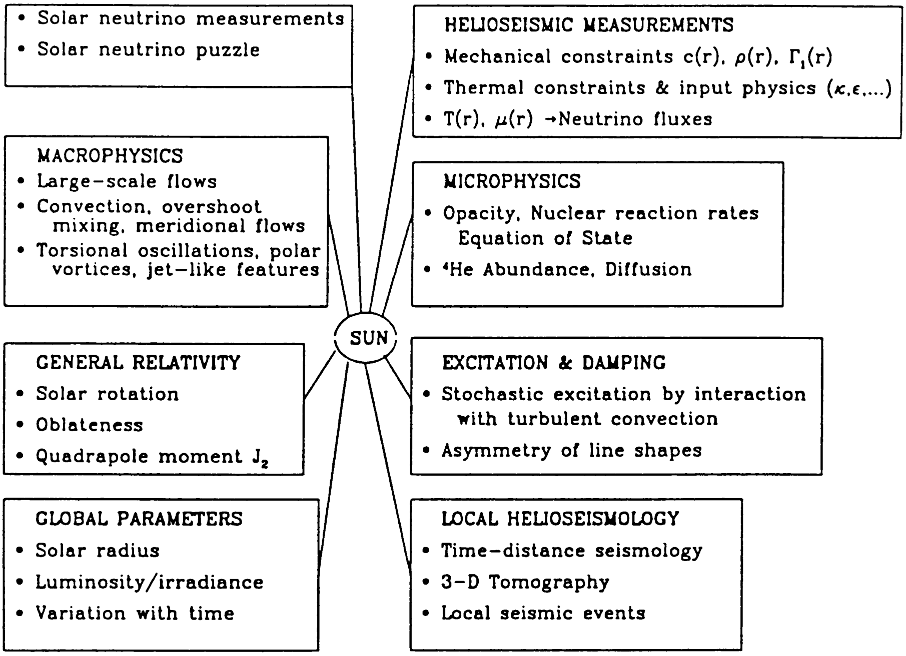

Figure 2.

existing solar neutrino experiments (Antia and Chitre 1997). A possible resolution of the solar neutrino puzzle should, therefore, be sought not in the astrophysical domain, but in the framework of non-standard neutrino physics, cf. the MSW effect (Bahcall and Bethe 1990). The various windows to look into the solar interior are schematically illustrated in Fig. 2.

4. Hydrodynamical flows and internal rotation

Convection is the primary mode of energy transport in the regions just below the solar surface which extends to a depth of $0.287R_\odot$. Ulrich stressed the role of rotation in modifying the large-scale convective flow and redistributing the kinetic energy, and of the magnetic fields in redirecting the energy flow with the resultant changes in the output of solar radiation. Basically, the convection zone may be regarded as a reservoir for the energy storage through changes in the solar radius. From the MDI and the Mt Wilson supersynoptic chart data, Ulrich furnished evidence for long-duration convective patterns highlighting the striking east-west velocity flows that drift towards the equator. The suggestive existence of long-lifetime convective flows (duragranulation), intermediate in scale between supergranulation and giant cells, and their possible interaction with the rotation field was discussed by Ulrich for chanelling energy into east-west flows. Schou also reported a signature for such torsional oscillation patterns from the inversion of f-mode eigenfrequency splittings, and pointed out that magnetic fields do not seem to play much role in driving these flows.

Ayukov pointed out the importance of including the effects due to non-adiabaticity

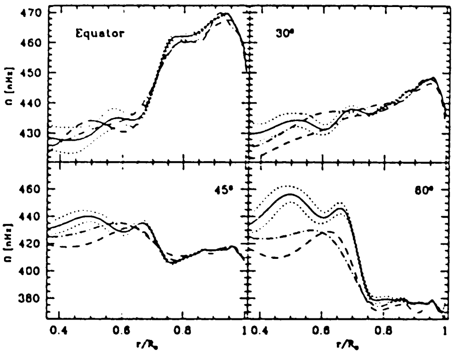

Figure 3. Rotation rate inside the Sun at different latitudes as inferred using various sets of observed frequencies. The continuous line represents the results using MDI data, the dashed line those using the GONG data while the dot-dashed line is for BBSO+BiSON combined data. The dotted lines represent the 1σ error limits on MDI results.

and contributions from the turbulent pressure for better agreement between theoretical treatment of the structure of the outer convection zone and observed oscillation frequencies. With the imposition of the helioseismic constraints (sound speed and state of matter) Shibahashi obtained the mechanical and thermal properties of the solar convective envelope for deducing the depth of the convection zone and the helium abundance. Roxburgh emphasized the importance of convective overshooting and mixing in the context of solar and stellar evolution, especially since penetration from convective cores into adjoining stable regions can have a non-negligible influence on the structure as well as the evolutionary properties.

It is now widely accepted that the observed solar p-mode oscillations are stochastically excited by turbulent convection in the sub-surface layers of the Sun. Goldreich discussed the approximate equipartition between the energies of acoustic modes and resonant turbulent eddies with lifetimes comparable to the mode periods. He also drew attention to the role of this convective driving mechanism operating in pulsating white dwarfs (ZZ Ceti stars). In his discussion of the excitation and damping of p-modes, Nordlund reported the results of his numerical experiments to highlight the role of entropy fluctuations associated with convective downdrafts in driving the oscillations by overcoming the damping due to Reynolds stresses (i.e., turbulent pressure compared to which viscous and radiative damping are small). The study of line asymmetries and widths in the power spectrum of oscillations was stressed by Nigam for diagnosing the physics of excitation and damping of solar p-modes.

Helioseismology has made it possible to probe the variation with depth and latitude of angular velocity in the sun's interior. The inversions applied to the MDI splitting data yield a rotation profile which is in broad agreement with the general picture of solar internal rotation earlier inferred from the GONG, BBSO/BiSON splitting data, as can be seen from Fig. 3. The detailed inference about the internal rotation and large-scale flows from the MDI data was summarized by Schou: The observed latitudinal differential rotation persists through the convection zone with the angular velocity practically constant on surfaces of constant latitude, while the radiative interior, rotates almost uniformly at a value close to 0.93 of the equatorial angular velocity. There is a radial shear layer (tachocline) at the transition between

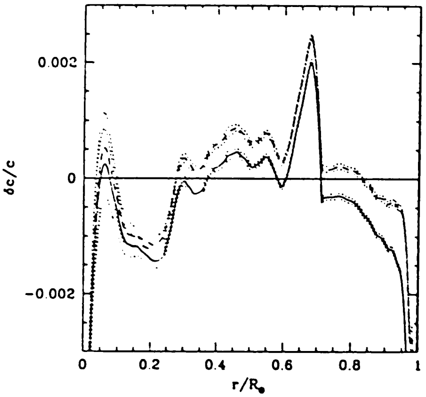

Figure 4. Relative difference in sound speed between the Sun and the standard solar model of Christensen-Dalsgaard et al. (1996) as inferred using different values for solar radius. The continuous line represents the results using $R_\odot = 695.78$ Mm, while the dashed line represents those using $R_\odot = 695.99$ Mm. The dotted lines show the 1σ error limits.

the convection zone and the radiative interior the structure of which is yet to be resolved. A quite striking feature of the rotation profile is the presence of bumps and wiggles suggestive of zonal bands of fast and slow rotation reminiscent of torsional oscillations migrating from high to low latitude during a solar cycle. A noteworthy observation reported by Schou was a hint of a jet-like feature at 75-degrees latitude located at a radial distance of $0.95R_\odot$ and also a very slowly rotating structure near the polar regions, a polar vortex extending to a significant depth inside.

5. Global properties of the Sun

The fundamental mode (f-mode) provides a valuable diagnostic probe of the flows, rotation rate and magnetic fields present in the surface regions of the Sun. Interestingly, the accurately measured f-mode frequencies from the GONG/MDI datasets can also provide a handle to infer a reasonably accurate measure of solar radius (Antia 1997, Schou et al. 1997). The f-mode frequencies are largely independent of the stratification in the solar surface layers and asymptotically satisfy the dispersion relation (Gough 1977): $\omega^2 = gk(1+\epsilon)$, where ($g = GM/R^2$ and $k = \sqrt{\ell(\ell+1)}/R$) to give $\delta R/R \sim -2/3\ \delta\omega/\omega$. It turns out that the observed f-mode frequencies are approximately 0.05% higher than those predicted by the standard solar model with $R_\odot = 695.99$ Mm. This implies a decrease in (seismic) solar radius in the range of $200 - 300$ km. Similar conclusions are reached by Brown and Christensen-Dalsgaard (1997) from measurements of the solar diameter. The possible errors resulting from uncertainty in the value of the solar radius will naturally be reflected in helioseismic inversions. Fig. 4 shows the relative difference in sound speed between the Sun and the current standard solar model of Christensen-Dalsgaard et al. (1996) with two values of the solar radius, 695.780 Mm and 695.99 Mm. It is clear that the difference in the sound speed due to a decrease in the solar radius by 210 km is more than the estimated inversion errors through the bulk of the solar interior.

With the availability of better data through the present solar activity we hope f-mode frequencies and their temporal variation can furnish us with independent estimates of not only the seismic radius of the Sun, but also its oblateness and their solar cycle related variations. An important outcome of the inferred differential rotation profile of the Sun is that the quadrupole moment, J_2 of the solar gravitational potential caused by the centrifugal force is about $1.7 \times 10^{-7}\, GM/R^3$, consistent with the prediction of General Relativity and also the radar ranging measurements.

Fröhlich presented a composite account of the total solar irradiance measurements, during the past 17 years from NIMBUS, ACRIM and VIRGO showing variations over all time scales ranging from days to years. Over the solar activity cycle, the total irradiance variability is seen to be about 0.1%, with the enhancement at the level of ~ 0.2%, contributed by faculae, bright networks etc., while the decrease of 0.1 % is on account of the overall darkening effects of sunspots. The total irradiance changes appear to be well correlated with the *p*-mode frequency variation with the solar cycle. Theoretical explanations of the observed solar irradiance were discussed by Spruit. He advanced plausible arguments about the role of the convective envelope acting as a reservoir for thermal energy and the irradiance being modulated largely by the surface effects arising from sunspots and small-scale magnetic fields.

6. Small-scale structures in the Sun: local helioseismology

It can be readily appreciated that global helioseismology has furnished a considerable amount of information about the solar interior. Clearly, it is important to enquire if we can attempt a scaled-down version of the inversion techniques for probing the small-scaled localized structures.

The time-distance helioseismology is a newly developed technique to construct three-dimensional tomographic inversion of the solar internal layers. The remarkable results obtained with this powerful method were described by Duvall and Kosovichev in (i) tracking subsurface meridional flows, (ii) revealing flow-fields on supergranular scales, iii) mapping of converging and diverging flows round sunspots, (iv) providing an effective measure of the antisymmetric component of solar differential rotation (asymmetry in rotation profiles in the two hemispheres not revealed by traditional technique based on inversion of frequency splittings).

This is a very powerful method for probing the localized structures in the sun and has clearly a great potential, although the validity of the ray approximation and aspects relating to changes in path lengths and wave speeds need to be investigated further.

Goode described the application of local helioseismology to solar flares and supersonic seismic events occurring in dark intergranular lanes that pump energy into *p*-modes. The measurements of seismic response of such localized events will clearly provide valuable information about the underlying flare mechanism and also about the subphotospheric structure of active regions.

Deubner presented a great body of information on measurements of amplitudes and phases of intensity fluctuation and Doppler shift due to wave motions as a function of frequency and wave number. This information is evidently important for studying properties of solar atmospheric oscillations and for examining the chromospheric structure. An important diagnostic of the solar chromospheric thermal stratification was provided by Ayres who argued, from observations of the strong CO lines, for the inhomogeneous structure of the chromosphere with its lower layers made up of cool gas and pervaded by network of small-scale magnetic fields . The recently reported SOHO observations of the "Sun's magnetic carpet" in the form of a sprinkling of more than tens of thousands of magnetic field concentrations spread over the sun's surface, will almost certainly have a significant influence on the chromospheric structure. The calculations reported by Banerjee on the influence of magnetic fields on the nature of oscillations in a stratified atmosphere assume importance for studying the effect of magneto-atmospheric waves on spectral line profiles.

7. Asteroseismology

The objective of asteroseismology is to construct seismic stellar models to test theories of internal structure, evolution and dynamics of stars. Asteroseismology is still in its infancy with only a limited number of modes, highly reminiscent of the situation for the Sun in the 1980s when only a very few modes were available from whole-disk measurements, in contrast to the luxury of accessing millions of modes which the current helioseismic database is endowed with. But stellar astronomy has revealed the g-mode oscillations which have been elusive in the Sun, and has supplied p-modes with a range of quantum numbers (n, l, m), which characterize the modes, for a wide class of stars. In order to understand the physical processes inside stars measurements of oscillation frequencies of a variety of stars with different masses and ages are desirable. The new developments in asteroseismology summarized by Kurtz and the theoretical aspects outlined by Christensen-Dalsgaard provided a very admirable overview of this rapidly growing field. Table 1 summarizes some of the principal features of stellar pulsators discussed at the meeting.

There is a clear need for sets of oscillation frequencies for a wide range of stars in the H-R diagram with different masses, spectral types and at different stages of stellar evolution. The information about the frequencies, amplitudes and line shapes, and their associated temporal information evidently hold the key to the internal structure and dynamics of stars. A real asset of asteroseismology is the g-modes which have large amplitudes in deep interiors and are evidently better suited than p-modes to probe the stellar cores. Equally, the frequencies of g-modes are sensitive to the mean molecular weight gradient of the layers and, as stressed by Roxburgh, these modes have the potential of diagnosing the chemically inhomogeneous central regions of stars. Furthermore, the measurements of oscillation frequencies will enhance our knowledge about how the convective efficiency (the mixing length parameter) varies with the spectral type. The width of the main sequence, for example, is extended by overshooting from the convective cores, as also the ages are extended by overshooting. The resonant modes of stellar oscillations will have a broad range of characteristic spatial scales; only the relatively low-degree modes which penetrate into the stellar cores can be observed. Presently, it may not be possible to infer the internal constitution of stars, in anywhere near as much precision as has been possible for the Sun. Nonetheless, the measurements of oscillation frequencies will provide reasonable constraints on the sound speed profiles, especially in the deep interiors of stars and in some rapid rotators even the internal rotation profiles from the splitting data. The locations of convective boundaries and the helium ionization zone can indeed be established seismically from the characteristic oscillatory signals in the frequencies resulting from discontinuities in the sound speed and its derivatives (cf. Monteiro, Christensen-Dalsgaard and Thompson, these proceedings).

The asteroseismic measurements should provide information about the surface and internal differential rotation of stars. For example, the large-amplitude δ Scuti pulsators would enable us to determine the radial as well as the latitudinal variation of the angular velocity. The asteroseismological studies should be complemented by

TABLE 1. Stellar Pulsators

STAR (type)	PERIOD RANGE	MODE(s)	
Sun(G)	2–6 min	p	Stochastically driven in the outer convection zone (Goldreich)
Solar-type stars (Procyon, η Boo, Arcturus, α Cen)(G)	$\gtrsim$ 10 min	p ($n \gg 1$)	No confirmed detection of sun-like oscillations. Spectrum of regularly spaced modes in outer layers (Bedding)
White dwarfs (ZZ Ceti) (DO, DA, DB)	2–15 min	g ($n \gg 1$)	Overstable g-modes driven by stochastic excitation in the shallow convection zone. Seismic determination of white dwarf masses and confirmation of gravitational diffusion of heavy elements. Radial velocity variation in WD(G29–38) observed to have time-scale nearly same as intensity pulsation period (Clemens, Kawaler)
Rapidly oscillating Ap stars (F, A)	5–15 min	p ($n \gg 1$)	Driving due to kappa-mechanism or overstable magnetic convection! Atmospheric $T(\tau)$ relation influenced by magnetic fields. Complementary information for seismic studies from Hipparcos (Mathews)
Delta Scuti stars (F5–A2)	0.5–7 hrs	p, g	Bridge between Sun and higher mass evolved stars. Multiperiodic with dozens of acoustic & gravity modes driven by opacity mechanism operating in H, He ionization zones. Seismic potential for probing core overshoot and internal differential rotation and age determination (Breger, Guzik)
Beta Cephei stars (B1 - B2)	2–6 hrs	p, g	Metal-opacity driven multi-mode pulsators. Potentially useful for inferring metallicity and ages of young star clusters, and also for probing internal rotation and convective penetration. (Eyers)
Slowly pulsating B stars (B3 - B9)	1–4 days	$g(n \gg 1)$	Metal-opacity driven pulsators. Over 100 new periodic B stars reported by Hipparcos. (Dziembowski, Eyers, Aerts)
γ Doradus-type stars (Early F)	1–2 days	$g(n \gg 1)$	Over 2 dozen early F-types with non-radial g-mode pulsations of low degree, probably stochastically driven. Relevant to the radial variation of solar-type stars for for unambiguous signature in planetary searches (Krisciunas)
Hot B subdwarfs (B)	120–500 sec	p, f	Newly discovered multiperiodic pulsators driven by metal opacity mechanism. Peculiar chemical abundance, diffusion (Stobie, Fontaine)

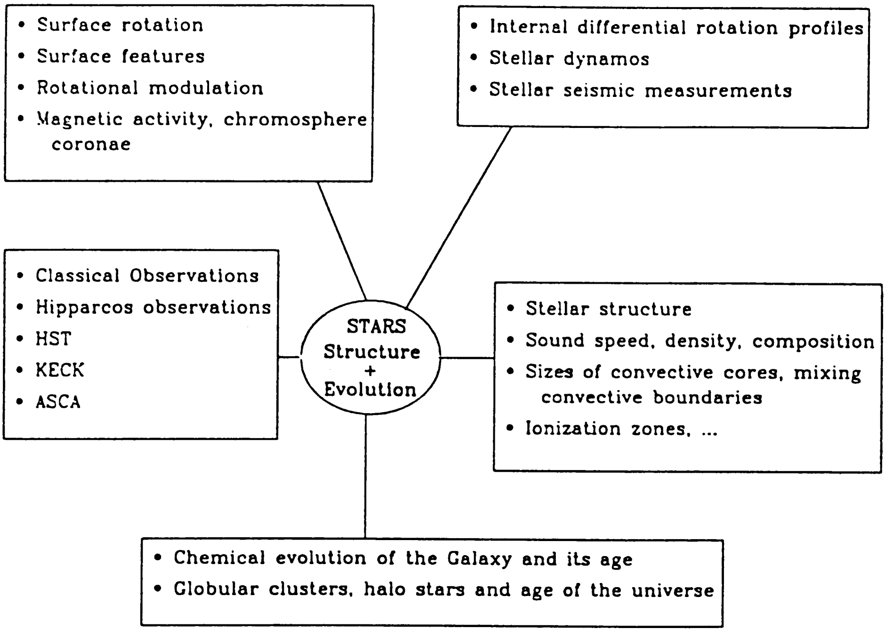

Figure 5.

monitoring activity in the sun-like and late-type stars. The rotational modulation observed in the far UV is a fairly sensitive measure of stellar rotation periods, as UV indicators are useful for tracking magnetic activity on stars. The rotation rate, and hence the activity, is found to decrease with age because of the loss of angular momentum via the magnetic wind, giving an indirect handle on the stellar age. Clearly, measurements of gross radial rotational shear are crucial for locating the seat of the magnetic dynamo operating in sun-like stars.

The information gained from the oscillation frequencies is, of course, complementary to the classical data about stars such as magnitude and colour-index. The H-R diagram for stellar oscillation frequencies introduced by Christensen-Dalsgaard (1988) shows the seismic parameters which are sensitive to different aspects of stellar structure. Thus, the large separation, Δ, is sensitive to the outer layers of stars, while the small separation, δ carries information about the core-structure. The data on Δ and δ can be profitably employed for improving our knowledge of convective core overshoot, especially the variation of the extent of penetration with stellar mass.

From values of the seismic parameters it should be possible to determine the mass and age of a star provided there is information available about the chemical composition and the convective efficiency. Recall, the low-degree data for massive stars contain information from the small separation, δ, about the discontinuity in the mean molecular weight and the density at the core boundary, a signal which is reflected in a discontinuity in the sound speed. Roxburgh emphasized the penetrative power of the seismic parameter, δ and noted how its oscillatory behaviour carries a signature of the convective core and its variation with frequency tracks the density profile in the central regions. Thus, stellar seismology would serve as a powerful diagnostic of the chemically inhomogeneous interior of stars which is a crucial input for stellar evolution.

Stars in a cluster or in a binary system are particularly valuable targets for seismology. The oscillation data along with the classical observations can be gainfully utilized for calibrating cluster parameters for improving estimates of mass and age of stars in clusters and for a better understanding of cluster distances. The hope is to have a better handle on the distance scale in the Galaxy and eventually the cosmological distances through designing more precise period-luminosity relations. The chemistry of the Galaxy and its chemical evolution would become amenable from the study of stars in various populations such as the disk, bulge and halo, through the seismic constraints imposed on helium abundance, heavy element diffusion, core sizes. Note that our current understanding of the chronology of the Universe is directed by stellar models with an uncertainty of a factor of 2 in the production rate of heavy elements. Consequently, at present asteroseismology, which seems to be the only tool available to look inside the stars, can assist in providing a better constraint on the age of the Galaxy, and hence on the value of the Hubble constant. Fig. 5 shows the central role of stellar structure and evolution in the context of astrophysical setting. The effectiveness of combining asteroseismic data with the classical observations with HST, KECK coupled with Hipparcos measurements for advancing the frontiers of astronomy is self-evident. What we need to develop are reliable methods for mode identification, and this can be accomplished with coordinated multicolour photometry and spectroscopy from networks distributed round the globe (cf WET, δ Scuti campaigns). For this purpose, the community must appeal for more multisite campaigns of long duration and for high precision photometric observations with satellite-borne instruments such as SOHO, COROT through this solar cycle and beyond. So be it!

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References

Antia, H. M. 1997, A&A (in press) astro-ph/9707226
Antia, H. M. and Chitre, S. M.: 1995, ApJ 442, 434
Antia, H. M. and Chitre, S. M.: 1997, MNRAS 289, L1
Bahcall, J. N.: 1989, Neutrino Astrophysics, Cambridge University Press, Cambridge
Bahcall, J. N. and Bethe, H. A.: 1990, Phys. Rev. Lett. 65, 2233
Bahcall, J. N. and Pinsonneault, M. H.: 1995, Rev. Mod. Phys. 67, 781
Brown, T. and Christensen-Dalsgaard, J.: 1997,
Deubner, F.-L.: 1979. A&A 44, 371.
Christensen-Dalsgaard, J.: 1988, in Advances in Helio- and Asteroseismology, eds. J. Christensen-Dalsgaard and S. Frandsen, Reidel, pp 295-298
Christensen-Dalsgaard, J., Däppen, W. et al. 1996, Science 272, 1286.
Gough, D. O., Kosovichev, A. G. et al: 1996, Science 272, 1296
Gough, D. O.: 1977, in The Energy Balance and Hydrodynamics of the Solar Chromosphere and Corona, Eds. R.-M. Bonnete and P. Delache, G. de Bussac, pp 3-36
Iglesias, C. A. and Rogers, F. J. 1996, ApJ 464, 943
Kosovichev, A. G.: 1996, Bull. Astron. Soc. India 24, 355
Leibacher, J. W. and Stein, R. F. 1971, Ap Lett 7, 191
Leighton, R. B., Noyes, R. W. and Simon, G. W.: 1962, ApJ 135, 474
Roxburgh, I. W.: 1996, Bull. Astron. Soc. India 24, 89
Schou J., Kosovichev A. G., Goode P. R., Dziembowski W. A., 1997, ApJ 489, L197
Shibahashi, H. and Takata, M.: 1996, PASJ 48, 377
Ulrich, R. K.: 1970, ApJ 162, 993