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An overview of the conference

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Abstract. An eminent solar physicist has been quoted as saying that "despite exquisite images we have of the Sun's surface, we know almost nothing about its interior" (Browne 1995). The conference offered an excellent opportunity to test this statement. It left at least the present author with an impression that our current knowledge about the solar interior is not quite as limited as indicated, although it did raise, without properly answering, the question of the true meaning of "knowledge" in this context. Also, many, perhaps most, of the questions raised in the introductory review by Roxburgh cannot yet be said to be fully answered. Thus there is certainly much more to learn.

Key words: Sun: structure — Sun: oscillations — helioseismology

1. Introduction

The conference covered aspects of solar structure and dynamics from the chromosphere to the core, with illuminating connections to oscillations and other phenomena in other stars. In this overview, I shall generally proceed from the outside of the Sun towards the interior, although a clean division into different regions is neither meaning- nor useful. Needless to say, a brief description of three intense days of scientific presentation cannot do justice to the full range of topics. Rather, these notes should be regarded as my own personal impressions of some of the highlights of what was an extremely exciting and successful conference.

Although it was not emphasized during the conference, it should be noted that the conference was part of the celebration of the Golden Jubilee of the Tata Institute of Fundamental Research. It is certainly an honour to contribute to such an important occasion for one of the premier scientific institutions, in the field of this conference as well as in an impressively broad range of other fields. I have no doubt that all participants would join me in wishing the Tata Institute continuing success in its scientific endeavours.

2. The solar atmosphere

Deubner presented measurements of phase relations between intensity and velocity, and between oscillations at different levels of the atmosphere. The results apparently indicated the presence of standing waves in the chromosphere while the oscillations appeared evanescent in the deeper parts of the atmosphere. The observations were evidently of very high quality, and of potentially major significance for the investigation of the properties of the atmospheric oscillations. However, currently even a rudimentary theoretical understanding of them seems to be missing. In particular, the presence of standing waves indicates reflection in the upper parts of the atmosphere, yet atmospheric models do not naturally provide such reflection with adequate efficiency. Also, there can be little doubt that the highly inhomogeneous nature of the upper atmosphere has to be taken into account in the modelling of these effects. Nevertheless, it is evident that observations of this nature provide information both about the properties of the modes and potentially about aspects of the structure of the atmosphere which cannot easily be probed with traditional (radiation-)spectroscopic techniques. Insofar as the modes are concerned, information may be expected on the processes that damp and excite the modes including, with data close to the photosphere, the effects of convection. With better understanding of the physics of the oscillations in the atmosphere the phase observations can perhaps lead to helioatmospheroseimic investigations of atmospheric structure.

It should also be noted that these studies of the solar oscillations are closely related to work on amplitude and phase relations for rapidly oscillating Ap Stars, discussed by Kurtz. It appears that the observed variations cannot be explained simply in terms of limb darkening corresponding to a reasonable relation between temperature and optical depth. Again, it is evident that a better understanding of the atmospheric properties of the oscillations is required. Given such understanding, measurements of this nature may provide information also about the degrees of the oscillations, of crucial importance to the interpretation of data on stellar oscillations.

3. The influence of the magnetic field

Pallé showed fascinating results on the frequency variation during the solar cycle. Although similar results for intermediate- and high-degree modes strongly indicate that the source of the variation is very close to the solar surface and directly correlated with the surface magnetic fields (Woodard *et al.* 1991; Bachmann & Brown 1993), Pallé had evidence for a significant difference between the behaviour of modes of degree 0, 1 and 2; furthermore, there were signs of hysteresis in the variation. These results suggest that the physical mechanisms underlying the variation may be more complex than previously suspected, although independent observational verification would obviously be welcome. Roberts presented a possible mechanism in terms of variations in a chromospheric canopy field and in chromospheric temperature which could largely account for the observed frequency dependence of the solar-cycle change. One remaining question with this type of model, however, is whether it would remain valid for a more realistic representation of the complex structure of the upper solar atmosphere.

New observations from the Taiwanese TON network of wave absorption by active regions were presented by Chou; due to the high spatial resolution this set of instruments appears very well suited for such observations. Variation in the apparent absorption with the size of the annulus in which the analysis was carried out was interpreted in terms of the finite lifetime of the waves. The details of the absorption mechanisms are as yet not known with any certainty. Spruit presented an analysis of various mechanisms, in particular the "leaky-waveguide model", whereby a fluxtube might cause an energy leak from the cavity where the acoustic modes are trapped. Similar mechanisms may also be relevant to the interaction between oscillations and magnetic field in rapidly oscillating Ap stars. On the related question of the apparent (or real) suppression of oscillation amplitude in active regions several models were considered, included the model proposed by T. M. Brown which invoke a change in the eigenfunction in the superficial layers of the Sun.

The origin and emergence of the solar magnetic field were discussed by Choudhuri who pointed out that magnetic buoyance would cause difficulty for dynamo action in the bulk of the convection zone; this indicated a probable need to confine the dynamo to the layers just below the convection zone, as subsequently supported by the helioseismic inferences on the solar internal rotation. Magnetic buoyancy can account for the overall properties of the emergent active regions, including Joy's law of the inclination of pairs of sunspots, provided the field strength is of order 10^5 Gauss.

4. Treatment of convection, and the region of "muck"

The region of vigorous convection just beneath the surface is a very important source of uncertainty in the modelling of solar structure and oscillations. Indeed, as shown by Christensen-Dalsgaard this region appears to dominate the discrepancy between the observed frequencies and frequencies of normal solar models. Thus, the helioseismic data may provide an important diagnostic of stellar convection, provided other uncertainties in this region can be controlled.

Convection affects the properties of the oscillations in several different ways, possibly not clearly separated. At the most basic level, the equilibrium structure of the near-surface region depends strongly on the treatment of convection, through the dependence of the convective flux and the turbulent pressure on the stratification. Such effects may in fact dominate, accounting for much of the discrepancy between the observed frequencies and frequencies of simple mixing-length models. The perturbation in the convective flux and turbulent pressure appears, based on non-local mixing-length models (Balmforth 1992) to play an important rôle for the energetics of the oscillations. Computed damping rates may be compared with the observed line widths of the modes, indicating that mixing-length calculations are in at least rough agreement with the behaviour of the solar modes. Also, the oscillations are believed to be excited stochastically by non-linear driving by convection. Models of these processes may be tested against the observed average value and fluctuations of the modal power.

Two conceptually very different approaches to the modelling of convection were presented. Canuto discussed descriptions based on turbulence theory, either through closure techniques or with the so-called Wyld-Dyson formulation. A substantial strength of these approaches is that they can be applied to other examples of turbulent flows, including tests against laboratory data. In this way it may also be possible to constrain the parameters that enter into the formulations. On the other hand, the application has so far been limited to relatively simple physical situations, considering the flow to be incompressible and neglecting the details of radiative transport and thermodynamics of a realistic stellar plasma. In contrast, the large-scale numerical simulations discussed by Nordlund are based on a detailed description of the physics of the plasma, such as the equation of state and radiative effects. Also, they encompass the complete large-scale dynamics of the system, including possible oscillations, and hence offer a possibility for direct investigations of the interaction between convection and oscillations. Such simulations, however, are limited to relatively small parts of the Sun and the "solar time" covered is severely constrained by computational expense. Furthermore, the numerical resolution is clearly inadequate to cover the entire range of turbulent scales, and thus some approximation to the sub-grid-scale behaviour is required. Whether or not these approximations compromise the solution on the dominant scale was subject to some discussion, which did perhaps not reach a definite conclusion. However, it seems obvious that there is considerable scope for combining the turbulence-theoretical description with the numerical simulations, as a way of handling the smaller-scale effects and to gain a better understanding of the numerical results.

The results presented by Nordlund were in impressive qualitative agreement with the observed surface behaviour of granulation. Also, it appeared that some insight is now being gained into the properties of convection at the lower boundary of the convection zone, including penetration and mixing into the stable region, although simulations of this region suffer from the large ratio between the dynamical and thermal timescale, requiring severe rescaling of the parameters. Simulations of convective penetration were also presented by Singh *et al.*. Insight on these processes is of great potential importance in connection with the mounting helioseismic evidence for mixing immediately below the convection zone (see Section 6 below).

Toomre discussed simulations of large-scale convection, emphasizing also effects of rotation. A very important aspect is the possibility of "inverse cascade", creating large-scale structures from the turbulence; this was considered also by Krishan. Indeed, dynamo action might be considered as one example of such large-scale organization, while other examples can be found in oceanography or laboratory turbulence experiments. One type of such organization could be motion in the form of jets in the solar convection zone, analogous to the jet streams in the Earth's atmosphere or possibly in the atmospheres of the giant planets. If such structures have a sufficient lifetime they may be detectable through helioseismic analysis.

In general, many different effects contribute to the uncertainties in the frequency calculations arising from the "muck" in the near-surface region. These include errors in the mean structure of the model and the thermodynamics of solar matter, as well as effects of dynamics and, for example, magnetic fields. Thus it is difficult or impossible to study the individual effects in isolation; the best one may hope is probably to obtain independent constraints on some of the effects, and in this way be able to use the observed properties of the oscillations to study others. One very important exception are the f modes: their frequencies are largely insensitive to errors in the average equilibrium structure and thermodynamics; thus differences between the observed and computed frequencies provide information about departures from the average structure, such as convectively induced fluctuations, flows and effects of magnetic fields. Ghosh *et al.*

considered one example of such effects, *viz.* a simplified representation of the sub-surface flow velocity, and showed that this could be adjusted to fit at least some of the properties of the observed f-mode frequencies. With the greatly improving data expected from ongoing experiments, particularly the SOI/MDI investigation on SOHO, such analyses are likely to be important diagnostics of the "muck" region.

Observational information on the excitation processes is becoming available. Elsworth showed that the distribution of low-degree mode amplitudes was approximately exponential, in accordance with predictions for stochastic excitation, although with a possible excess amongst the largest-amplitude modes. The local behaviour of the excitation processes was discussed by Goode, who showed that so-called "acoustic events" are correlated with regions of strong cooling and hence downdraft. This is not inconsistent with the behaviour obtained in hydrodynamical simulations of near-surface convection.

5. Three-dimensional windows on the Sun's interior

Most helioseismic investigations have so far been concerned with averaged properties of the Sun: the spherically symmetric structure or the azimuthally averaged velocity field expressed as an angular velocity. However, it is of evident interest to investigate departures from these properties, particularly in the convection zone where one may expect more complex, and very likely time-dependent, structures. To detect these requires techniques for analyzing the oscillations beyond the customary normal-mode analysis.

Kosovichev presented a method for determining the three-dimensional structure and flow though tomographic inversion. The technique is based on time-distance diagrams, obtained by correlating the oscillation signal at different locations on the solar surface and at different times, and in many ways equivalent to the travel-time analysis commonly used in geoseismology (Duvall *et al.* 1993, 1996; D'Silva 1996). By making a least-squares fit to the time-distance data, Kosovichev was able to determine the fluctuations in sound speed around the mean structure, and the three-dimensional sub-surface velocity field. It is probably fair to say that the detailed properties of this technique, in terms of error propagation and resolution, are currently somewhat ill-defined. Nevertheless, it represents a novel and very promising way of obtaining information about the dynamics of the convection zone. Other local techniques, such as the use of ring diagrams (Hill 1989; Patrón *et al.* 1995) and Hilbert transforms (Julien, Gough & Toomre 1995), are also being developed; when such techniques are applied to the high-resolution data to be obtained with the SOI/MDI instrument we may hope for a much improved understanding of the large-scale properties of convection.

6. The structure of the Sun's interior

The helioseismic investigation of solar internal structure is usually carried out by comparing the observed frequencies with frequencies of solar models. In this way the physics of stellar modelling, and the simplifying assumptions involved in the calculations, may be tested. It is evidently desirable to carry out the calculations with the best available physics, and including as many effects as are feasible. In particular, recent helioseimic investigations have provided strong evidence for the importance of settling and diffusion in the solar interior, previously often neglected. On the other hand, it must be stressed that "standard" solar modelling does not involve parameters which may be "tweaked" to match the observed data.

As discussed by Christensen-Dalsgaard, the near-surface effects can largely be eliminated from differences between observed frequencies and frequencies of solar models. Having done so, the residuals can be inverted to infer the difference in structure between the Sun and the model. Dziembowski showed that, even with the current data restricted to acoustic modes, it is possible to obtain localized averages of solar structure down to a fractional radius of $r/R \simeq 0.05$. Interestingly, modes of degree $5 - 13$ contribute to the determination of the core structure, even though simple asymptotic theory would suggest that they do not penetrate sufficiently deeply: this is a result of the non-local nature of the information on solar structure and is unlike the corresponding inverse problem for solar internal rotation.

Results on helioseismic inversion were presented by Basu *et al.*. The inferred difference in squared sound speed between the Sun and the "standard solar model" most closely in accordance with other constraints on the Sun is strikingly small, less about 0.5 per cent. It is dominated by a sharp peak just below the convection zone, the solar sound speed being higher than the sound speed in the model, while at the edge of the core the sound speed in the Sun is *lower* than in the model. Both effects might be the result of weak mixing in the Sun: below the convection zone this would reduce the sharp gradient in the hydrogen abundance caused by settling of helium and would therefore increase the sound speed, while mixing in the core would increase the central hydrogen abundance while reducing it at the edge of the core where therefore also the sound speed would be reduced. Indeed, models by the Yale group which incorporate rotational mixing does suppress the difference just beneath the convection zone. Mixing beneath the convection zone is also required to explain the reduction of the present surface lithium, relative to the solar-system value.

It was emphasized by Roxburgh and by Dziembowski that helioseismic information on solar structure provides no direct constraint on the solar internal temperature and hence on the neutrino production rate. The oscillation frequencies are essentially determined by the "mechanical" properties of the solar interior, *i.e.*, the variation of pressure, density and sound speed. To relate these to temperature, further information on the physics and properties of the solar interior is required, such as the equation of state, opacity and composition. Indeed, Roxburgh showed that if the internal composition profile is not constrained by the usually assumed history of nuclear burning, and if substantial variations in opacity, relative to the normally assumed tables, are allowed, it is possible to obtain a temperature profile which is consistent with the helioseismically inferred structure, while predicting low fluxes of solar neutrinos. However, it may perhaps be questioned whether the required modifications in the physics are realistic. Also, it would be a curious coincidence if the "standard solar model", which of course has a high neutrino flux, just happened to agree very closely with solar sound speed and density, while departing substantially in temperature and composition profile.

7. The physics of the Sun's interior

In themselves, the details of the structure of the solar interior are comparatively uninteresting. A much more fundamental goal is to investigate the physical properties of matter in the Sun which lead to the inferred structure. A very important example is the equation of state: in the almost adiabatic part of the convection zone the structure and the properties of the oscillations are determined largely by the thermodynamics of the gas, together with the constant composition and specific entropy, while, for example, the opacity has no direct effect. Thus this region, which contains the second helium ionization zone and ionization zones of heavier elements, is very well suited for investigating the details of the thermodynamic properties of the gas.

Däppen reviewed the properties of the equation of state and the way in which they can be constrained by helioseismic data. Two very detailed, but conceptually completely different, descriptions have been developed: the MHD formulation which is based on the so-called chemical picture and the Livermore (or OPAL) formulation which uses the physical picture. Interestingly, the leading-order effects are the same in the two formulations: in both cases the dominant deviation from the simple uncoupled ionizing gas arises from Coulomb effects. Beyond this level, however, they differ significantly. One difference was that the version of MHD considered by Däppen included the so-called τ factor, aimed at reducing the high-density effects of the Debye-Hückl treatment of the Coulomb effects. This specific form of the τ factor is now considered to be somewhat questionable, although its effect under solar conditions is modest. Helioseismic inversion has shown that models using the OPAL equation of state are substantially closer to the solar sound speed than are models computed with MHD. Although other, so far neglected, effects might change this conclusion the results do indicate the sensitivity of the solar oscillation frequencies to the subtleties of the equation of state.

The validity of such tests depends on the other assumptions made about the relevant region. In particular, even quite modest departures from the assumed nearly adiabatic stratification might have an effect of comparable magnitude to the subtle thermodynamical properties which are being sought. There is some evidence that the hydrodynamical simulations predict a slightly larger superadiabatic gradient in the relevant region. Furthermore, one cannot exclude that convective fluctuations, even if likely to be small in the second helium ionization zone, might introduce systematic effects on the frequencies. These issues need urgent attention. They also indicate the intimate interplay between the various aspects of testing the physics of the solar interior, at the level of precision which is now being reached.

Guzik also emphasized the importance of the equation of state and confirmed that the OPAL formulation appears to produce frequencies in somewhat better agreement with the observations than those obtained with MHD. She furthermore stressed the possible effects of the uncertainties in the atmospheric opacities and effects of the nonadiabaticity of the oscillations; these effects will obviously have a form similar to those of other near-surface problems in the model, and they must be constrained before the data can be used to probe, for example, the properties of the top of the convection zone.

The physics of nuclear reactions was discussed by Turck-Chièze. Here, also, major progress has been made recently, not least in the treatment of electron screening. These improvements have significant effects on the predictions of neutrino fluxes, while the effects on the oscillations are generally small. (On the other hand Dziembowski did note that some changes in reaction rates of sufficient magnitude to reduce the neutrino fluxes to the observed value would have a definite helioseismic signature.) She also noted, based on a preprint by Tsytovich *et al.* (1996), that there may be remaining uncertainties in the opacities of the solar core as a result of collective plasma effects. The reality of the claims made by Tsytovich *et al.* is still subject to debate, however.

8. Solar internal rotation

Helioseismic inferences of the solar internal rotation were the subject of considerable debate. Tomczyk discussed results obtained from 1 year of observations with the High Altitude Observatory's LOWL instrument. For degrees higher than a few, the rotational splittings can be determined relatively precisely, allowing inversion for the dependence of rotation on latitude and depth outside a fractional radius $r/R \simeq 0.3$. The results confirm and substantially tighten up inferences based on earlier datasets: in much of the convection zone rotation is found to vary with latitude approximately as on the surface; at the base of the convection zone there is a transition which is probably unresolved, to rotation essentially independent of depth and latitude in the radiative interior.

To obtain information about rotation of the core, splittings of modes of degree $l = 1$ and 2 are required. These splittings are of the same order of magnitude as the natural line widths of the modes, except at quite low frequency; furthermore, the analysis of the LOWL data is complicated by the daily sidelobes. As stressed by Tomczyk, these effects may introduce systematic errors in the splittings; thus, although the splitting for $l = 1$ appeared to be low, compared with the surface rotation rate, and hence might naively be taken to imply slow rotation of the core, he attached little weight to this result. Furthermore, he noted that analysis of a 6-month time string of LOWL data had indicated a rather more rapidly rotating core.

Two other sets of splittings for low-degree modes, obtained with the IRIS and BiSON networks for velocity measurements in integrated light, were presented. Fossat showed results on the IRIS network, which is now operating six stations. To reduce the problems of the marginal resolution of the rotationally split frequencies, the data have been analyzed in terms of correlation techniques, resulting in relatively well-determined average splittings for each degree; for $l = 1, 2$ and 3 the results were 456 ± 12 nHz, 430 ± 17 nHz and 461 ± 17 nHz, respectively. This may be compared with the surface equatorial rotation rate of around 452 nHz. Thus the results indicate a core rotating at, or slight faster than, the rate of the bulk of the solar interior. Elsworth discussed results from a 16-month sequence of observations with the 6-station BiSON network. These were largely based on low-frequency modes where the the natural line width is so small that rotationally split components could be clearly separated. Although the individual determinations showed considerable scatter, the average, around 416 ± 9 nHz was substantially below both the IRIS result and the surface equatorial rate. Indeed, as shown by Elsworth *et al.* (1995), the splittings strongly indicate that the core is rotating substantially more slowly than mean rate of the solar interior. Such a result would pose grave problems for our understanding of the evolution of solar internal rotation.

The discrepancy between the independent determinations of the low-degree splittings clearly represents a serious problem. It is possible that the different analysis techniques introduce systematic errors in the results; thus, for example, it probably cannot be excluded that the correlation techniques used for the IRIS data might overestimate the splittings. To resolve these problems, further work on the existing data is clearly required. One attractive possibility might be exchange of raw data, as a test of the sensitivity of the results to the details of the analyses. Another promising approach is analysis of artificial data, using simulations which as realistically as possible reproduce the expected statistical properties of the data. In the somewhat longer term, results from the helioseismic instruments on the SOHO satellite, and a continuation of the ground-based network observations, will undoubtedly help to clarify the situation and settle the questions on the solar core rotation.

The rotation of the solar surface can be determined by following the motion of surface features. Gupta *et al.* presented a careful analysis of a very extensive series of white-light images obtained at the Kodaikanal Observatory. This allowed determination of the surface rotation velocities with errors as low as 3 $\mathrm{m\,s^{-1}}$. Also, differences between rotation rates inferred from different types of features, assumed to be anchored at different depths, are in approximate agreement with the helioseismically variation of the angular velocity in the upper parts of the convection zone. It is planned to combine the Kodaikanal data with similar data obtained at the Mt Wilson observatory. This would represent an excellent example of a retroactive network to observe solar rotation, over many decades.

9. Seismology of other stars

The richness of the solar data should not blind us to the importance of extending the seismic investigations to other stars. After all, the Sun is just one example of the wide range of stellar types, caught in the middle of a rather quiescent period of evolution. By considering it alone, we would miss a broad range of phenomena of great importance to general stellar evolution. Examples are properties of convective cores, element separation from gravitational settling to a much larger degree than for the Sun, and effects of rapid rotation.

Shibahashi gave an overview of the difficulties and possibilities in observing oscillations of stars like and unlike the Sun. Much of the problem is observational: very extended sequences of almost continuous observations are often needed to resolve the complex spectra, and in the case of solar-like oscillations, at least, the expected amplitudes are so small that detection requires pushing the observational procedures to their limits. Indeed, no unambiguous detection has been made so far of solar-like oscillations in another star; perhaps the most plausible case is the sub-giant η Boo where oscillations were inferred in measurements of spectral-line intensities (Kjeldsen *et al.* 1995). However, even here independent confirmation is required.

A major goal of observing other stars is to extend from the solar case the parameter range over which the physics and properties of stellar interiors can be tested. In addition, information will be obtained on the excitation processes. In the solar-like case, stochastic excitation by convection appears by far the most plausible hypothesis. Thus determination of amplitudes of other stars, as a function of frequency and stellar parameters, will provide crucial information about the excitation processes and ultimately, one might hope, about the subsurface properties of convection.

Shibahashi also addressed pulsating stars unlike the Sun, concentrating on β Cephei stars and other pulsating B stars. These stars are very attractive targets for seismological investigations: unlike the Sun they have extensive convective cores, and hence they offer the possibility of studying overshoot from such cores and other mixing processes, which could have important effects on the evolution of comparatively massive stars. Recent substantial revisions of opacities have led to an understanding of the pulsations of these stars as resulting from the κ mechanism. In the case of β Cephei itself, Shibahashi presented evidence for effects of rotation and a magnetic field, possibly organized as an oblique rotator. This may greatly complicate the spectrum of oscillations.

Effects of rotation and magnetic fields appear to dominate in the rapidly oscillation Ap stars, discussed by Kurtz and by Martinez. Very extensive observations of these stars show them to exhibit a range of phenomena, many of which are only partly or barely understood. A very interesting feature are variations in frequencies, now observed in several cases; these variations are superficially similar to those seen for the Sun, although it appears unlikely that the detailed underlying physical mechanisms can be the same as in the solar case.

Apart from the Sun, the most extensive sets of observed frequencies have been determined for the pulsating white dwarfs. Marar *et al.* presented results obtained from the so-called Whole Earth Telescope, involving coordinated observations from a network involving a substantial number of telescopes. Results from the analysis of the frequencies include very precise determinations of white-dwarf masses, measurements of rotation rates with some evidence for variation with depth, and possible evidence for magnetic fields.

10. Problems and prospects

The summary of the conference given above, incomplete as it is, indicates the great range of activities within the fields of helio- and asteroseismology, and the degree of detail to which the Sun has already been investigated. This does provide an indication that the pessimism expressed in the quote given by Browne (1995), with regards to our present knowledge about the solar interior, is perhaps misplaced.

However, from a different perspective these investigations are just beginning. The results so far have confirmed our overall view of solar structure and evolution but also revealed the limitations of this view. We have evidence for mixing processes so far not taken into account, but little idea about the origin or details of these processes. We have demonstrated the ability of the helioseismic data to distinguish between different formulations of the equation of state, beyond the simplest level, but we do not yet have a definite indication of how the properties of the plasma should be modelled. We have inferred the gross properties of rotation in much of the Sun, but the details remain unexplored, particularly with regard to the transition at the base of the convection zone; and the crucial question of the rotation of the solar core still awaits a definite answer. We have had initial glimpses of the power of oscillation observations to probe the three-dimensional structure and dynamics in the upper parts of the convection zone, and to investigate the properties of active regions; but the details of these phenomena, or indeed the precise meaning of the measurements, are still unclear. Finally, the extension of seismic investigations to other solar-like stars is still in its infancy, in a state similar to that of global helioseismology 15 – 20 years ago.

To move beyond the present state, efforts in many different areas of research are required. However, perhaps the most crucial aspect is the need for more accurate and extensive data, to allow resolution of the subtleties in solar interior structure and dynamics at a substantially deeper level than is now possible. Fortunately, we are in the middle of a revolution of the observational status of helioseismology, thanks to several large international projects. Central to these efforts is the GONG project, summarized by Leibacher, of establishing a network of six observing stations. Full operation of the network commenced just before the present conference, with the opening of the station at the Udaipur Solar Observatory; at the time of writing the initial results are being analyzed, in preparation for publication in a special issue of Science scheduled to appear on May 31. In addition, the SOHO satellite carrying three helioseismic experiments was launched successfully on December 2 1995, and has now started full operation at the L_1 point between the Sun and the Earth. Together with the continuing operation of the BiSON, IRIS and TON networks, the GONG and SOHO projects will provide data of exceptionally high quality, extending from low-degree, low-frequency modes probing the core to modes of very high degree providing detailed information about the upper parts of the convection zone. Furthermore, a major improvement in the observations of oscillations of other stars is expected from the EVRIS experiment to be launched on a Russian Mars probe in November; an even more dramatic advance would result if the European Space Agency selects the STARS project to observe solar-like stellar oscillations in a large number of stars, in the current round of selection for the so-called M_3 mission.

Despite these excellent prospects one serious problem remains, namely the insufficient manpower. This was quite evident from the presentation of the observational projects, perhaps most strikingly in the case of the TON project. However, in all cases the analysis of the data was severely restricted or delayed by lack of people. This is the case even for the GONG project, where the subtleties of data merging and the determination of mode parameters are only now being fully realized. There is a similar shortfall in the theoretical interpretation of the data and required modelling. Part of this problem is related to funding: there is a tendency that funds for instrument development are more easily obtained than support for the utilization of the resulting data. However, there is also a perhaps surprising reluctance on the part of students to enter the field, world-wide. This may in part be explained by the fact that field is so young that public awareness of it is still limited. In addition, there is perhaps a perception that the physics of stellar interiors is fully understood and hence boring, in contrast to more exotic areas of astrophysics. It behoves us, as active participants, to counteract this tendency and work towards involving a broader community in the marvellous adventure of investigating the deepest secrets of a star.

11. Acknowledgements

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References

Bachmann, K. T. & Brown, T. M., 1993. *Astrophys. J.*, **411**, L45 – L48.

Balmforth, N. J., 1992. *Mon. Not. R. astr. Soc.*, **255**, 603 – 631.

Browne, M. W., 1995. The New York Times, Tuesday, October 24. p. B5

D'Silva, S., 1996. *Astrophys. J.*, **469**, in the press.

Duvall, T. L. Jr, D'Silva, S., Jefferies, S. M., Harvey, J. W. & Schou, J., 1996. *Nature*, **379**, 235.

Duvall, T. L., Jefferies, S. M., Harvey, J. W. & Pomerantz, M. A., 1993. *Nature*, **362**, 430 – 432.

Elsworth, Y., Howe, R., Isaak, G. R., McLeod, C. P., Miller, B. A., New, R., Wheeler, S. J. & Gough, D. O., 1995. *Nature*, **376**, 669 – 672.

Hill, F., 1989. *Astrophys. J.*, **343**, L69 - L71.

Julien, K. A., Gough, D. O. & Toomre, J., 1995. In: *Proc. Fourth SOHO Workshop: Helioseismology*, eds Hoeksema, J. T., Domingo, V., Fleck, B & Battrick, B., ESA SP-376, ESTEC, Noordwijk, p. 155 – 160.

Kjeldsen, H., Bedding, T. R., Viskum, M. & Frandsen, S., 1995. *Astron. J.*, **109**, 1313 – 1319.

Patrón, J., Hill, F., Rhodes Jr, E. J., Korzennik, S. G. & Cacciani, A., 1995. *Astrophys. J.*, **455**, 746 – 757.

Tsytovich, V. N., Bingham, R., de Angelis, U., Forlani, A. & Occorsio, M. R., 1996. *Astroparticle Phys.*, in the press.

Woodard, M. F., Kuhn, J. R., Murray, N. & Libbrecht, K. G., 1991. *Astrophys. J.*, **373**, L81 – L84.