II. THE SOLAR INTERIOR

INTERIOR STRUCTURE OF THE SUN.

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ABSTRACT. Observations of solar oscillations have provided us with detailed information about the solar interior. Here I consider three examples of results obtained in such helioseismic investigations: i) the effect of the equation of state on the comparison between observed and theoretical frequencies; ii) a determination of the depth of the solar convection zone; and iii) indications of deviations from standard models of the structure of the solar core.

1. Introduction.

Although the theory of stellar evolution is often regarded as a well-established part of astrophysics, it is important to realize that stars are extremely complex, compared with standard calculations of stellar models. Hence the possibility that important aspects of stellar structure or evolution might have been neglected in the calculations should be kept in mind. To test this, detailed relevant observations are required.

Observations of solar oscillations have given us a large amount of very precise data on the properties of the solar interior; this has opened up the possibility of testing computations of stellar evolution in great detail for a single star. Recent compilations list over 2000 observed frequencies, with estimated errors that are in some cases less than 0.01 per cent. This must be compared with the other relevant data that are available: the solar mass, radius and luminosity, which are known with comparable precision, and the neutrino flux, which, as is well known, is subject to considerable observational and theoretical uncertainties. Furthermore, the physical nature of the oscillations is in general well understood. The observed modes correspond to standing acoustic waves, or *p modes*. Given a solar model it is relatively straightforward to compute its oscillation frequencies. Thus, the frequencies provide a clean diagnostics of conditions inside the Sun.

On the basis of these data we may study the basic processes that determine the structure of the solar interior. In this way we can test the assumptions, of perhaps questionable validity, on which computations of stellar evolution are based. Also, such calculations require information, which is

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often uncertain, about the properties of matter under the conditions in stellar interiors. Since the frequencies are sensitive at a significant level to even quite subtle details of the equation of state or the opacity, it is possible to use the observations to study properties of plasmas under conditions so extreme that they cannot be reproduced in the laboratory.

2. Properties of the solar interior.

It is useful to review very briefly normal calculations of solar models, and their possible shortcomings (see also Bahcall & Ulrich 1988; Turck-Chièze *et al.* 1988; Bahcall 1989; Turck-Chièze 1990). It is assumed that the model is in hydrostatic and thermal equilibrium. Evolution is controlled by the gradual fusion of hydrogen into helium; it is assumed that there is no mixing in the solar interior, so that the composition in any given mass-shell is determined solely by the local nuclear burning. With these assumptions the structure is largely determined by the *microphysics* of the solar interior, *i.e.*

- the equation of state
- the opacity
- the nuclear energy generation rates.

In addition, the computation requires that the solar mass is known, as well as the initial chemical composition, which is assumed to be uniform. The goal is to compute a model at the age of the present Sun, which is also assumed to be known, with the observed radius and surface luminosity.

In practice, the initial helium abundance Y_0 cannot be determined independently and must be regarded as a free parameter of the calculation, as must the "mixing-length" parameter α which measures the efficiency of convective energy transport near the solar surface. Y_0 and α are adjusted until the model of the present Sun has the correct radius and luminosity. In this way one obtains what is sometimes called a "standard solar model". It is evidently dependent on the uncertainties in the assumed microphysics, but is otherwise well-defined.

The computation of standard solar models ignores, or grossly simplifies, a number of processes that might be labelled the *macrophysics* of the Sun. These include

- energy transport
- dynamics of convection
- convective overshoot
- molecular diffusion
- core mixing
- magnetic fields.

Energy transport by convection is treated in a rather crude way, with furthermore depends on the *a priori* unknown parameter α. Near the surface convection is probably sufficiently vigorous to have dynamic effects on the average hydrostatic equilibrium, yet such effects are often ignored. At the lower boundary of the convection zone motion is normally supposed to stop at the point where convective instability ceases; hence convective overshoot, which must surely be present, is neglected. Molecular diffusion might affect the composition profile in the convectively stable region, yet with a few exceptions has been ignored. Instabilities in the deep interior could lead to material mixing, affecting the composition profile and hence solar evolution. Finally, one probably cannot totally exclude the possibility of a magnetic field in the solar interior of sufficient magnitude to have an effect on the overall structure of the Sun. - It should be noted, however, that except for the composition profile in the radiative interior of the model, much of the uncertain macrophysics is concentrated very near the surface.

3. Properties of solar oscillations.

The observed solar oscillations[1] have cyclic frequencies ν between about 1500 and 5000 μHz; their behaviour on the solar surface ranges from spherically symmetric oscillations to oscillations whose wavelengths are at the limit of observational resolution. Recent reviews of the theory and observations of solar oscillations have been given by Libbrecht (1988a), Vorontsov & Zharkov (1989) and Christensen-Dalsgaard & Berthomieu (1990).

The oscillations correspond to standing waves, or *normal modes*, of the Sun. A mode of oscillation is characterized by three wave numbers: the *radial order* n which, roughly, gives the number of zeros in the eigenfunction in the radial direction; the *degree* ℓ; and the *azimuthal order* m, ranging between $-\ell$ and ℓ, which measures the number of zeros in longitude. The degree is related to the horizontal wavenumber k_h and wavelength λ of the mode at radius r by

$$k_h = \frac{2\pi}{\lambda} = \frac{L}{r}, \qquad (1)$$

where $L = \sqrt{\ell(\ell+1)}$.

Apart from damping or excitation, the time dependence of a single mode is harmonic, as $\cos(\omega t)$. The *angular frequency* ω is related to the cyclic frequency ν through $\omega = 2\pi\nu$. In general $\omega = \omega_{n\ell m}$ depends on all three wave numbers. However if rotation or other departures from spherical symmetry are ignored, $\omega_{n\ell m}$ does not depend on m. I shall adopt this approximation here.

In calculations of solar oscillation frequencies it is common to ignore a number of complicating features that are so far badly understood, such as·

- nonadiabaticity
- excitation, more generally
- dynamical effects of convection
- detailed atmospheric behaviour
- magnetic fields.

More detailed calculations show that these approximations may change the frequencies by several μHz. Thus they have a substantial effect on comparisons between observed and computed frequencies. On the other hand, the complications are essentially all located near the solar surface. Thus they add to the uncertainty of the surface region already found in the calculation

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[1]with the exception of oscillations at long periods whose identity is still in doubt

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of the model but do not directly affect the properties of the oscillations in the deeper solar interior.

With this simplification the computation of the oscillation frequencies is a straightforward numerical problem. However, to understand the results it is useful to consider the asymptotic theory of the oscillations. The observed p modes can be approximated locally by plane sound waves, with the dispersion relation $k^2 \equiv k_r^2 + k_h^2 = \omega^2/c^2$. Here k_r and k_h are the radial and horizontal components of the wave vector, and c is the adiabatic sound speed. Using equation (1), we obtain $k_r^2 = \omega^2/c^2 - L^2/r^2$. This shows that there is a *turning point* where $k_r = 0$ and the wave propagates horizontally, the location $r = r_t$ of which is determined by

$$\frac{c(r_t)}{r_t} = \frac{\omega}{L}. \tag{2}$$

It corresponds to a point of total internal reflection; for $r < r_t$, $k_r^2 < 0$, and the mode decays exponentially. At the surface the wave is reflected by the steep density gradient. A mode of oscillation is a standing wave, formed as an interference pattern between waves travelling between the internal and the surface reflection. It is trapped between the surface and r_t, and hence its frequency depends largely on conditions in this region.

Since c decreases with increasing radius, the turning point radius increases with increasing ℓ. Modes at highest observed values of ℓ are confined to the outermost fraction of a percent of the solar radius, whereas the lowest-degree modes penetrate essentially to the centre. Hence, by considering different modes of oscillation one is effectively sampling different parts of the Sun. In fact, it has been possible to invert the frequencies, to infer the sound speed as a function of position in most of the Sun (*e.g.* Christensen-Dalsgaard *et al.* 1985; Brodsky & Vorontsov 1987).

In analyzing frequency differences between observations and theory, one must correct for the fact that with increasing r_t the modes extend over a smaller fraction of the solar mass, and hence their frequencies are easier to perturb. This effect may be eliminated by considering scaled frequency differences $Q_{n\ell}\delta\omega_{n\ell}$, where $Q_{n\ell}$ is a measure of the inertia in the mode, relative to the inertia of an $\ell = 0$ mode of the same frequency (*e.g.* Christensen-Dalsgaard 1988a; Christensen-Dalsgaard & Berthomieu 1990). For modifications to the model which are confined close to the surface, the resulting $Q_{n\ell}\delta\omega_{n\ell}$ is mainly a function of frequency. The condition for this to be true is that the extent of the region over which the modification is significant is much smaller than the depth of penetration of the modes considered. It follows that if $Q_{n\ell}\delta\omega_{n\ell}$ *does* depend on ℓ for a set of modes, the change in the model extends at least to the lower turning point of those modes. Also it may be shown that low-frequency modes are insensitive to modifications that are confined to the superficial layers of the model (Libbrecht 1988b; Christensen-Dalsgaard 1988b).

These properties of the oscillations are particularly important in the light of the errors near the surface of the model. These errors may be expected to lead to scaled frequency errors that are essentially independent of ℓ and small at low frequency. Frequency errors that do not have these properties therefore indicate errors in the bulk of the model.

4. Results.

Here I can only give a brief summary of some of the results on solar internal structure that have been obtained recently from helioseismic investigations. In addition to the references given, it might be noted that some of these issues were discussed in more detail by Christensen-Dalsgaard (1988a) and Christensen-Dalsgaard (1989).

4.1 Effects of the equation of state.

It is of obvious interest to compare observed frequencies of solar oscillations with frequencies of representative models. To illustrate also the effect of using different formulations of the equation of state, I consider two such models. One model uses the simple EFF (Eggleton, Faulkner & Flannery 1973) equation of state, the other the far more elaborate MHD equation of state (Hummer & Mihalas 1988; Mihalas, Däppen & Hummer 1988; Däppen *et al.* 1988). In both cases opacities from the Los Alamos Opacity Library (Huebner *et al.* 1977) were used. The computational procedures, and the detailed effects of the equation of state on the model and frequencies, were discussed by Christensen-Dalsgaard, Däppen & Lebreton (1988).

Figure 1 shows differences, scaled to remove the ℓ-dependence of the mode inertia, between selected observed frequencies from Duvall *et al.* (1988) and Libbrecht & Kaufman (1988), and computed frequencies for these two models. The most obvious feature is the reduction in the ℓ-dependence of the differences when going from the EFF to the MHD equation of state, particularly for $\ell \geq 50$. This strongly indicates that the error in the interior of the model, particularly in the convection zone where modes of degree higher than about 50 are trapped, has been reduced by using the MHD equation of state (Christensen-Dalsgaard, Däppen & Lebreton 1988). For modes with $\ell < 40$, which penetrate beneath the convection zone, there remains a substantial ℓ-dependence, indicating that there are significant errors in the radiative interior of the model. In fact, as discussed in the following section, the convection zone appears to be too shallow in this model.

Apart from this difficulty, there is a striking agreement between the observed frequencies and those of the MHD model. For this model the errors for modes of degree exceeding 100 are comparable with the estimated observational errors. Some care is required, however, when interpreting this result, given the known inadequacies in the model and frequency computations. It is likely that the agreement in Figure 1b is fortuitous, resulting from a partial cancellation of several sources of error. However, such errors would mainly affect the frequency-dependence of the frequency differences. Given the relatively small variation of the differences with degree it is likely that there are no gross errors in the bulk of the model. Indications of problems in the core are discussed in section 4.3 below.

4.2 The depth of the solar convection zone.

The transition from adiabatic stratification of the temperature in the convection zone to subadiabatic stratification in the radiative region below takes place quite rapidly. There is a similar transition in the gradient of sound

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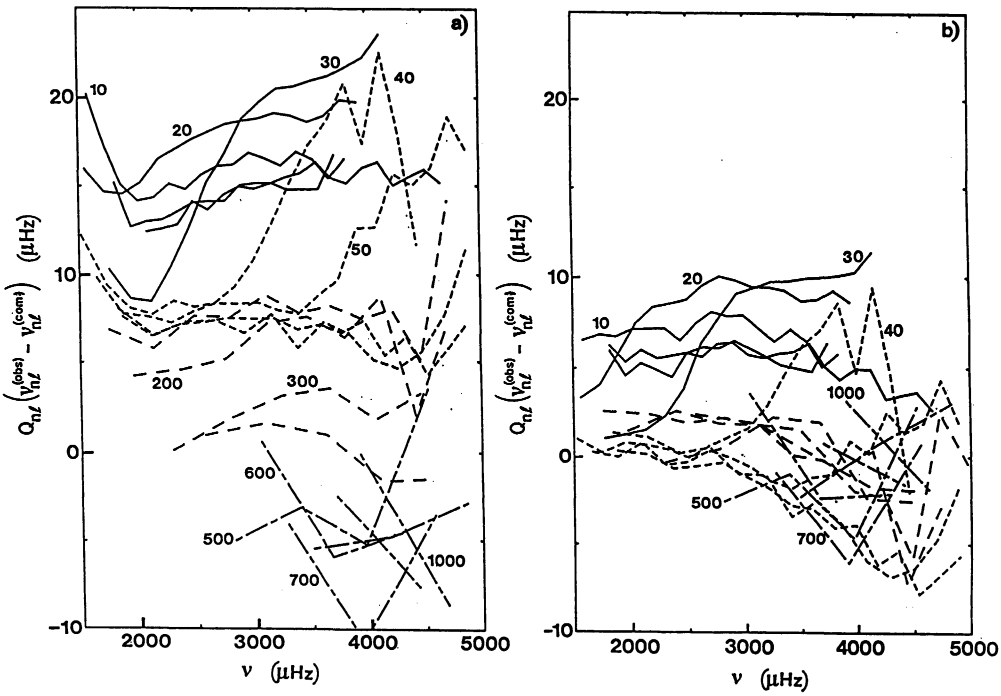

Figure 1. Scaled differences between observed and computed frequencies for selected values of ℓ. Panels a) and b) are based on models computed with the EFF and the MHD equations of state, respectively. Points corresponding to a given value of ℓ have been connected, according to the following convention: ℓ = 0, 5, 10, 20, 30 (————); ℓ = 40, 50, 70, 100 (- - - - - - - - -); ℓ = 150, 200, 300, 400 (— — — — — —); and ℓ = 500, 600, 700, 800, 900, 1000 (—-—-—-).

speed, which can be located in the sound speed determined from inversion of the oscillation frequencies. It was noted by Gough (1984, 1986) that this transition is particularly evident in the quantity

$$W_0 \equiv \frac{r^2}{GM}\frac{dc^2}{dr}, \tag{3}$$

where G is the gravitational constant and M is the mass of the Sun. In the adiabatically stratified part of the convection zone, outside ionization zones of abundant elements, $W_0 \approx -2/3$, and W_0 increases rapidly beneath the convection zone. This behaviour is clearly visible in W_0 as inferred from the inversion. Christensen-Dalsgaard, Gough & Thompson (1990) made careful tests, based on artificial data, of this method for determining the depth d_b of the convection zone and applied to the observed solar frequencies. The result was that in the Sun $d_b = 0.287 \pm 0.003\ R$, where R is the radius of the Sun. The inversion also provided a measure of the sound speed at the bottom of the convection zone. From this, the temperature T_b at this point can be determined, provided that the chemical composition is known. If, as suggested by calibration of solar models, the hydrogen abundance X is in the range 0.7 - 0.74, T_b = 2.13 - 2.28×10^6 K.

The depth of the convection zone in the MHD model considered in the previous section was 0.267 R, *i.e.* significantly lower than the solar value. This is consistent with the pattern of frequency differences shown in Figure 1b. An explanation could be that the opacities are too low in the region around the base of the convection zone; if instead the Cox & Tabor (1976) tables are used, d_b is 0.285 R, very close to the inferred value for the Sun. It should be noted, however, that what is measured is the extent of the adiabatically stratified region. This probably includes most of the region of convective overshoot beneath the convectively unstable layer. In fact, the increase in d_b required to bring the model illustrated in Figure 1b into agreement with the solar d_b is not inconsistent with the, admittedly uncertain, estimates of the extent of the convective overshoot (*e.g.* Schmitt, Rosner & Bohn 1984; Roxburgh 1985).

4.3 Conditions in the solar core.

Only those p modes that have the lowest degree penetrate to the energy-generating core of the Sun. Hence this region, which is of course of special interest for understanding solar evolution and finding a solution to the neutrino problem, is particularly difficult to probe with five-minute oscillation data. Nevertheless some information has recently emerged, although the consequences for our understanding of the deep solar interior are still unclear.

Figure 2 shows results obtained by Gough & Kosovichev (1988) from inversions for the sound speed c and the density ρ in the solar core, in terms of relative deviations from a standard solar model. Rather similar results for the sound speed have been obtained with different inversion methods (Christensen-Dalsgaard, Gough & Thompson 1988; Vorontsov 1988; Dziembowski, Pamyatnykh & Sienkiewicz 1990). In these inversions there is a tendency for a subtantial positive sound speed difference very near the centre; this, however, could well be an artifact of the analysis. Thompson (1990) carried out a similar analysis for the density difference, with very similar results. He pointed out that considerable care is required when interpreting the results: the inferred $\delta\rho/\rho$ is in fact an average with fairly complex weight functions, extending over a substantial range in r. Thus, for example, it is likely that the actual density difference at the centre is greater, perhaps by a factor of two, than the 10 per cent difference shown in Figure 2b.

It is so far not clear how this deviation from the standard model has come about. Gough & Kosovichev (1988) determined the difference in hydrogen abundance X by imposing the equations of stellar structure, assuming the opacity and energy generation rate to be given. The resulting δX, which was similar in shape to $\delta c/c$ as shown in Figure 2a, corresponds approximately to what would result from a small amount of partial mixing of the

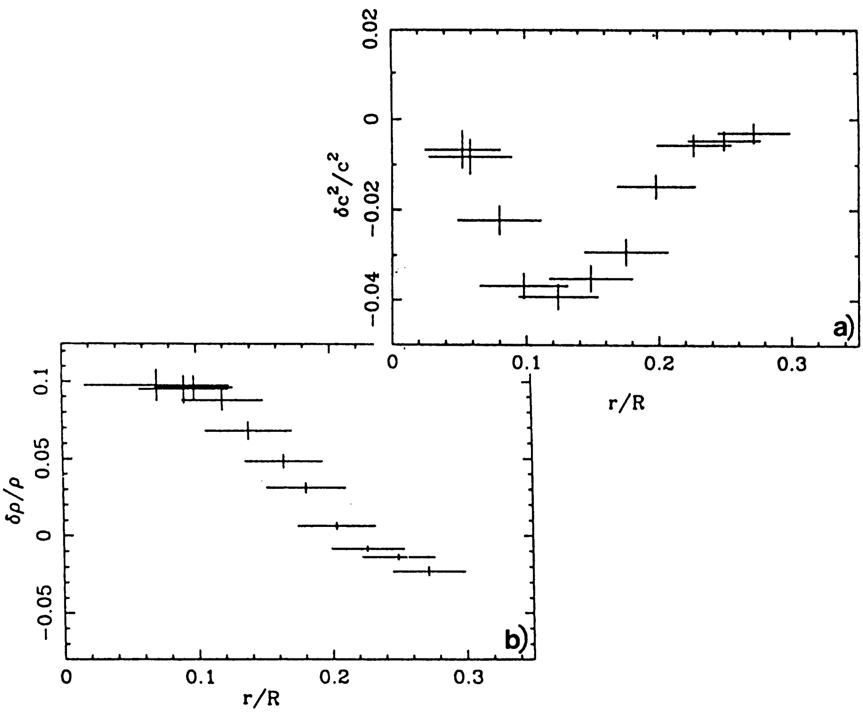

Figure 2. Relative difference in sound speed c (panel a) and density ρ (panel b) between the Sun and a standard solar model (Model 1 of Christensen-Dalsgaard 1982), obtained from inversion of frequencies of low-degree solar p modes. These results are averages over the actual differences, the horizontal size of the crosses giving a measure of the extent of the average; the vertical size gives estimates of the standard errors of the results. (From Gough & Kosovichev 1988).

solar core. From this Gough & Kosovichev (1990) inferred the temperature difference between the Sun and the model and hence were able to estimate the expected neutrino flux; the result was somewhat lower than for a standard model, although still in excess of the observed value. A possible difficulty with the interpretation in terms of partial mixing is that this, at least in some cases, leads to a *decrease* in the central density (*e.g.* Christensen-Dalsgaard 1986), in contrast to the results shown in Figure 2b.

Dziembowski, Pamyatnykh & Sienkiewicz (1990) used a slightly different inversion for the sound speed, with a positive sound-speed difference at the centre, to determine the variation of pressure $p(r)$ and $\rho(r)$. Given $p(r)$ and $\rho(r)$, using a parameterized expression for the hydrogen abundance $X(r)$, and imposing the constraint that the total luminosity should have the observed value, they determined the structure of the core such that the neutrino flux was minimized. They found that for realistic parameters this minimum flux was considerably *higher* than for the standard model. The reasons for the

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discrepancy with Gough & Kosovichev are so far unclear, but it is not unlikely that the differences in the assumed $c(r)$ near the centre play a substantial role.

5. Discussion.

The comparison of observed and theoretical frequencies shows that it is possible, amongst standard solar models, to match the observations to within less than about 0.3 per cent. Thus it appears that there are no gross errors in normal calculations of solar evolution. This is no ground for complacency, however. The remaining errors in the computed frequencies are systematic, and are furthermore considerably higher than estimated intrinsic errors in either the observations or the computations. Thus there remain significant problems in the model. The accuracy of the observations is such that even fairly subtle changes in the equation of state can have significant effects on the frequencies. Similarly the computed frequencies are sensitive to the assumed opacities. Thus it is possible to test descriptions of the properties of plasmas on the basis of the observations. Also, it is of some interest that it has been possible to determine the extent of the convection zone, which is of importance for studies of convection zone dynamics, on the basis of the observations.

The solar core poses particular difficulties. There seems to be substantial evidence that the central density is somewhat higher than in standard models, and that there is a region of lower sound speed in the outer parts of the core. However the interpretation of these results, in terms of their origin and their effect on the neutrino flux, is currently rather unclear. It is likely that improved observations of low-degree p modes will help; but we also need a better understanding of the relations between various changes in the core of the Sun.

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DISCUSSION

ALURKAR: What's the status of the global oscillation of period 2h 40min ? How effective are they for studies of the solar interior?

CHRISTENSEN-DALSGAARD: Long-period oscillations of the Sun are standing gravity waves, with large amplitudes in the solar core. Thus they are potentially very effective as probes of the core, and definite observation of these modes is highly desirable. Unfortunately, the observational situation is unclear. There have been reports of several oscillations with long periods, in addition to the initially discovered 2h 40min oscillation. However, the identification, or even solar nature, of these oscillations is still questionable. It is likely that only the forthcoming observations from networks or from space will settle the issue - we all hope that the modes are there!

VAN BALLEGOOIJEN: You find agreement between theory and observation regarding the structure near the base of the convection zone. Can you put an upper limit on the extent of convective overshooting?

CHRISTENSEN-DALSGAARD: The inferred depth includes the adiabatic part of the overshoot region. Hence the extent of this region cannot be estimated without reference to solar models, and it is strongly dependent on the opacity, which determines the depth where the transition to convective stability takes place. Estimates of the extent of the transitions to purely radiative stratification probably depends strongly on the details of the transition. I would guess that substantial deviations from the behaviour in normal solar models over more than $0.01R_{\odot}$ would have been detectable. To test this requires careful calculations of frequencies, and subsequent inversion of them, for models with various forms of overshooting.

CHOUDHURI: Is it possible to conclude anything about the strength of overshooting from the sharpness of the kink in the curve for W_0 (equation 3)?

CHRISTENSEN-DALSGAARD: With the present observations, the shape of the kink is consistent with that of a normal solar model, without overshooting. To study details of the overshooting better observations will be required.

VARMA: If one could identify and monitor magnetoacoustic oscillations in the Sun, would it be possible to draw information about the structure of magnetic fields inside the Sun?

CHRISTENSEN-DALSGAARD: There is no evidence for global magnetoacoustic oscillations of the Sun, as a separate class of modes. However, the observed p-modes would be perturbed by the presence of a large-scale magnetic field, and from observations of such frequence shifts information about the field might be obtained.*

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*Editor: A detailed description of these effects has been given by Roberts and Campbell (Nature 323,603,1986), Campbell and Roberts (Ap J 338,538,1989), Gough and Thompson (MNRAS, in press) and by several other authors at IAU Symp. 123 (Ed. JC-CHRISTENSEN-DALSGAARD and S Frandsen).

MOGILEVSKIJ: What is your opinion about the structure of the plasma and magnetic field in the zone between the core and the base of the convection zone?

CHRISTENSEN-DALSGAARD: A large-scale magnetic field would contribute to the splitting of frequencies according to azimuthal order m, giving rise to an even component in the expansion of splitting as a function of m. There is some observational evidence for such an even component. From this Dziembowski & Goode have inferred the evidence of a strong localized magnetic field at the base of the convection zone, at perhaps 1MG. However, the observations are probably still not decisive.

Fine-structure vertical magnetic flux tubes near the solar surface would scatter the modes and hence contribute to the damping; it might also cause a frequency shift, as shown by Bogdan & Zweibel (1985). This, however, must be considered as a part of the uncertainty introduced by the solar surface region.

ORAEVSKY: In 1991 USSR is launching a satellite called "Coronas" for global observations of the Sun. This includes measurements of global Sun oscillations. The Institute of Terrestial Magnetism, Ionosphere and Radio Wave Propagation of USSR Academy of Sciences welcomes all research Institutes and groups to take part in this mission.

CHRISTENSEN-DALSGAARD: We look forward very much to the results of these observations.