COMMISSION 12: RADIATION AND STRUCTURE OF THE SOLAR ATMOSPHERE (RADIATION ET STRUCTURE DE L'ATMOSPHERE SOLAIRE)

President: M. Kuperus Vice president: J. Harvey

I. INTRODUCTION

(M. Kuperus)

Solar Physics has been traditionally divided into Structure and Radiation of the Solar Atmosphere (commission 12) and Solar Activity (commission 10). There has been increasing evidence that solar activity, which is basically of magnetic origin, occurs on a great variety of scales and thus immediately touches upon the structure of the solar atmosphere as well as the structure and dynamics of the convection zone. As a consequence progress in the field of origin and evolution of solar magnetic fields from a large scale, 'the dynamo', to small scale is included in this report. In the past few years particular attention has been paid to the fact that the fluctuations in the magnetic field are much larger than the mean field and that the dynamo modes may be stochastically excited. The question whether there is a magnetic reservoir at the bottom of the convection zone still remains to be resolved. The interaction of the convection and the magnetic field resulting in an enhancement of the magnetic field in the intergranular lanes is studied by numerical modelling.

A real understanding of the magnetohydrodynamics of the subphotospheric layers requires a detailed study of the solar oscillations. The excitation of the so-called p-modes is likely to take place in the turbulent convection zone. Helioseismology will make it possible to study the thermodynamic and magnetohydrodynamic structure of the solar interior, thus preparing a foundation for stellar seismology, a field of growing interest, which will lead to a new understanding of stellar interior structure.

The outer solar atmosphere seems to consist primarily of structures that are shaken or sheared by photospheric motions. There is some evidence that the powering of the outer layers is magnetic of origin, though the actual mechanism is still a matter of debate.

It is of great importance to Astronomy and Astrophysics that the above mentioned outstanding problems of solar interior structure, solar magnetohydrodynamics and solar outer atmosphere are understood so that further progress can be made in stellar physics. For this to occur new resolution solar instrumentation is needed.

The president of commission 12 thanks the authors of this report for their contributions. He also wishes to thank the organizing committee for their support during the last three years.

II. SOLAR INTERIOR STRUCTURE

(Ken C. Libbrecht)

A great deal of progress has been made in recent years in the field of helioseismology (for a review of the field see Deubner and Gough 1984, Christensen-Dalsgaard et al. 1985, and Leibacher et al. 1985). Although it's been less than a decade since individual p-modes were first identified in solar velocity data (Grec et al. 1980), measurements have recently been made (unpublished) which isolated thousands of p-modes and determined each of their frequencies with accuracies as high as a few tenths of a microhertz, or to a part in 10^4. While in the past makers of the standard solar model were constrained to duplicate little other than the measured mass, radius, and luminosity of the sun, measured p-mode frequencies now provide thousands of additional model constraints. Solar p-mode frequencies have quickly risen to be among the most accurately determined physically significant quantities in all of astrophysics. (For contrast, pulsar period measurements have been made to accuracies of 10^{12} or greater, but this reflects simply a rotation rate of a neutron star, which returns no physical understanding of the phenomenon. Pulsar period derivatives are physically interesting, but their measurements are not nearly so precise, to a part in 10^4 with the binary pulsar 1913+16, for example.

Using the p-mode frequency measurements to determine the interior structure of the sun promises to be a very interesting but difficult task. Current standard solar models are able to reproduce most of the mode frequencies to of order one percent (unpublished) which confirms our basic understanding of the oscillations but is far from reproducing the frequencies at the level of their measurement uncertainties. Theoretical efforts are currently under way to better understand the basic properties of the solar interior, such as the equation of state and the opacity of the solar plasma, in order to produce an improved solar model which will better fit the observations.

Another approach to using the p-mode data is to invert the measured frequencies into a measurement of the speed of sound as a function of radius in the solar interior. A first result in this direction has been given by Christensen-Dalsgaard et al. (1985), where the sound speed determined from p-modes agreed quite well with that from the standard model calculation. Although the p-mode frequencies do not provide a very sensitive probe of the deep solar interior below one-half to one-third of a solar radius, they do provide a very good probe of the convection zone and the transition region between the radiative zone and the convection zone.

Measurements of the rotatonal splitting of p-mode frequencies have also been proceeding apace, with recent contributions by Duvall et al. (1986) and Brown and Morrow (1987). Efforts to invert the measurements to infer the solar rotation rate as a function of depth and latitude are still in progress, but it is likely that helioseismology will provide a quite accurate determination of the rotation rate throughout the convection zone. Such a measurement will be invaluable for comparison with computer models of the solar convection zone (Glatzmaier 1985), and is important input for understanding the solar dynamo. Recent measurements of the surface rotation rate determined by the 60-year Mt. Wilson white-lightplate collection (Gilman and Howard 1984) showed a one percent increase in the surface rotation rate during solar minimum. If true it should be possible to measure this increase using p-modes as well.

While the p-mode frequencies provide input for understanding the solar interior structure, their measured amplitudes reflect the dynamics of the mode excitation and damping mechanisms. Calculations of overstability mechanisms, such as the κ-mechanism, are still unable to confidently determine if the p-modes are stable or overstable, owing to our poor understanding of turbulent viscosity in the convection zone. However it is beginning to appear that the modes must be stable, since if they were unstable it is likely that a few modes would grow to very large amplitudes, as is seen in other oscillating stars such as the Cepheids, in contrast to the millions of low-amplitude p-modes observed in the sun.

A more likely mechanism for exciting the p-modes is via turbulent convection, originally proposed by Goldreich and Keeley (1977). The acoustic noise generated in the convection zone is trapped inside the solar acoustic cavity, and results in the excitation of the sun's normal modes. Recent work by Goldreich and Kumar (1986) predicts the energy E of a solar p-mode is given by the familiar-looking formula $E = mc^2$, where m is the mass of a resonant turbulent eddy, and c is the sound speed inside the eddy. For 5-minute oscillations, a resonant eddy is simply a solar granule, and the predicted energy is of order 10^{28} ergs, which is in fairly good agreement with observation (Libbrecht et al. 1986).

The theoretical work by Goldreich and Kumar represents a fundamental improvement in our understanding of the interaction of turbulence with sound waves, and is good example of how "basic" research in astrophysics can have broad implications. This work, which describes the emission and absorption of sound waves by turbulence, is an extension of the seminal work by Lighthill (1952) which described the emission of sound by turbulence, with the most common application being none other than airport noise.

Other helioseismology results include the report by Woodard and Noyes (1985) of the detection of solar cycle shifts of p-mode frequencies of 0.1 μHz per year between 1980 and 1984. This result has yet to be confirmed, however, and other workers (unpublished) have placed upper limits of approximately 0.1 μHz/yr on p-mode frequency shifts. While it appeared in the past that g-modes had also been detected on the sun (see Solar Phys. vol. 82 1983, Delache and Scherrer 1983), more recent measurements have turned up negative, and the general agreement of the solar community is that g-mode detections have not been confirmed.

The solar neutrino problem remains a problem, but recently the MSW theory of neutrino oscillations (Mikheyev and Smirnov 1986, Wolfenstein 1979) has been accepted as an attractive solution to the dilemma. Although the oscillation of electron neutrinos into other neutrino states (the μ and τ neutrinos) was suggested some time ago as a possible explanation of the solar neutrino measurements, the MSW authors showed that the theory of the weak interaction indicated resonance interactions in the presence of matter that greatly enhance the neutrino oscillation phenomenon. The theory also suggests a number of other measurements to constrain the neutrino mass and mixing angle (Dar and Mann 1987), including measuring the difference in the daytime and nighttime solar neutrino flux owing to oscillation inside the earth. Where in the past it was thought that neutrinos would pass effortlessly through light-years of lead shielding, now it is not even clear that they can pass through even the earth unscathed. However the MSW theory is not the only explanation of the neutrino measurements; it has been shown by Gilliland et al. (1986) that a sufficient number of weakly interacting massive particles (WIMPs) inside the sun could also reduce the flux of solar neutrinos.

References

Brown, T.M. and Morrow, C.A.: 1987, Ap. J. **314**, L21
Christensen-Dalsgaard, J., Gough, D., and Toomre, J.: 1985, Science **229**, 923
Christensen-Dalsgaard, J., Duvall, T.L., Gough, D.O., Harvey, J.W. and Rhodes, E.J.: 1985, Nature **315**, 378
Dar, A. and Mann, A.: 1987, Nature **325**, 790
Delache, P., and Scherrer, P.H.: 1983, Nature **306**, 651
Deubner, F.-L. and Gough, D.: 1984, Ann. Rev. Astron. Astrophys. **22**, 593
Duvall, T.L., Harvey, J.W. and Pomerantz, M.A.: 1986, Nature **321**, 500
Gilliland, R.L., Faulkner, J., Press, W.H., Spergel, D.N.: 1986, ap. J. **306**, 703
Gilman, P.A. and Howard, R.: 1984, Ap. J. **283**, 385
Glatzmaier, G.A.: 1985, Ap. J. **291**, 300
Goldreich, P. and Keeley, D.: 1977, Ap. J. **212**, 243
Goldreich, P. and Kumar, P.: 1986, IAU Symposium no. 123, Aarhus, Denmark
Grec, G., Fossat, E., and Pomerantz, M.: 1980 Nature **288**, 541
Leibacher, J.W., Noyes, R.W., Toomre, J., and Ulrich, R.K., Sept. 1985, Scientific American
Libbrecht, K.G., Popp, B.D., Kaufman, J.M. and Penn, M.J.: 1986, Nature **323**, 235
Lighthill, M.J.: 1952, Proc. Roy. Soc. London **A211**, 564
Mikheyev, S.P. and Smirnov, A.Y.: 1986, Nuovo cim. **9C**, 17

Woodard, M.F. and Noyes, R.W.: 1985, Nature **318**, 449
Wolfenstein, L.: 1979, Phys. Rev. **D20**, 2634

III. THE SOLAR DYNAMO

(M. Stix)

Traditionally the theory of the solar dynamo has been divided into two parts. The first, more difficult part, is the derivation of equations governing the mean magnetic field; the second, easier, is the solution of this equation, and the interpretation of the result in terms of observed solar magnetism. This report follows the traditional division.

1. Mean Field Equations

Mean field equations contain the effects of turbulence in form of transport coefficients, notably the turbulent diffusivity β, and the regeneration coefficient, α, for the mean poloidal field. These coefficients have often been calculated in the "approximation of second order correlations" (= "first order smoothing"). A formally complete solution has been given by Hoyng (1985). For the case of isotropic turbulence Nicklaus (1987), using an ensemble of polarized waves (Drummond et al., 1984) and the formalism of ordered cumulants, calculated corrections arising from fourth order correlations. These are proportional to $S^2 = (u\tau/l)^2$, which unfortunately is of order 1 in the solar convection zone. Moreover, not only the α-coefficient, but also the correction to the β-coefficient depends on the helicity of the turbulent flow.

In a different approach, Drummond and Horgan (1986) used the same set of polarized waves and calculated the exact Lagrangian solution of the induction equation. For the purpose of averaging they computed the paths of a large number ($\simeq 10^5$) of fluid particles. In the examples treated they obtained α and β coefficients which were surprisingly close to the results of the second order correlation approximation. The Lagrangian approach was also employed by Molchanov et al. (1984) and by Vainshtein and Kichatinov (1986) in more general investigations of a magnetic field in a turbulent medium of high conductivity.

A different derivation of an α-coefficient was given by Schmitt (1984, 1985) on the basis of dynamically unstable magnetostrophic waves (propagating in a magnetic layer at the base of the convection zone, see below).

The role of magnetic field fluctuations (on the Sun, these are large compared to the mean field!) in dynamo theory was emphasized by Hoyng (1987a,b). He derives a new equation for the tensor $\langle \mathbf{BB} \rangle$ and shows that, in addition to α and β, a third important transport coefficient, related to the mean vorticity, occurs.

2. Solar Dynamo Models

Solutions of the mean field equation in a spherical geometry have been systematically studied by Rädler (1986a), Bräuer and Rädler (1987), and Yoshimura (1984a,b,c). These studies bear on the question of mode selection, e.g. whether a mean field of odd or of even parity will be excited first, or whether the field is oscillatory or steady. Hoyng (1987b) suggests that a number of dynamo modes could be simultaneously present at any one time due to stochastic excitation, and that these modes should be compared to the modes analysed by Stenflo and Vogel (1986). The dominant mode found by these authors is a combination of odd zonal harmonics, all with the same period of 22 years, and corresponds to the leading mode predicted by most $\alpha\omega$-dynamos. Non-axisymmetric modes are strongly opposed in $\alpha\omega$-dynamos by the differential rotation (Rädler, 1986b).