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

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I. INTRODUCTION

(R.W. Noyes)

The scope of Commission 12 has broadened somewhat in recent years, to include not only the structure of the solar atmosphere, but that of the solar interior as well. The scientific purview of this commission, and of the present report, are complementary to those of Commission 10 (solar activity). Rather than attempting to review all progress in solar structure studies over the past triennium, this report deals with six topics of great current interest, in which there is a great deal of current work.

Section II, on solar oscillations, emphasizes observational aspects. Reference is made here to related reviews of theoretical aspects of stellar oscillations in the reports of Commissions 35 and 27.

The President of Commission 12 wishes to take this opportunity to thank the authors of the remaining sections of this report for their conscientious and effective work in preparing these reviews. In addition, he wishes to thank the Organizing Committee of the Commission for their support during the past three years.

II. SOLAR OSCILLATIONS

(T.R. Duvall, Jr.)

The study of solar oscillations, now becoming known as helioseismology, is rapidly expanding our knowledge of the interior structure of the Sun. Questions addressed include the Sun's internal thermal structure, rotation, initial helium abundance, giant cell convection, and gravitational quadrupole moment. Recent progress has been reviewed by Deubner and Gough (1984) and Brown *et al.* (1984), and a comprehensive bibliography was published (GONG, 1984). Several conference proceedings are available (Gough, 1983; Gabriel and Noels, 1984; Belvedere and Paterno, 1984; Ulrich, 1984).

At least two restoring forces, pressure and gravity, are important for global oscillation modes. The *p*-modes have pressure as the dominant restoring force while the *g*-modes have gravity as the restoring force. The *f*-mode, or fundamental, is essentially a surface gravity wave. An oscillation mode is described by an eigenfunction of, say, vertical velocity which is a product of a radial function, a spherical harmonic $Y_{\ell m}(\theta,\phi)$ and a harmonic function of time. The radial function is, in general, an oscillatory function of radius in a restricted range of radius, exponentially decaying away from this region. This leads to the concept of a resonant cavity in radius in which the wave energy is trapped. Waves can propagate in the interior of the cavity and are reflected at the boundaries. For *p*-modes the upper boundary of the cavity is just below the visible surface and the reflection is caused by the large density gradient. The inner reflection is caused by the refraction of obliquely propagating waves away from the vertical by the increase of sound speed with depth. The inner reflection radius is mode-dependent which gives us the basic depth diagnostic capability.

1. *Thermal Structure*

One way to investigate the thermal structure of the Sun is to compare mode frequencies computed for a solar model to those observed. By trial and error, the uncertain input parameters to the model are varied to obtain a better agreement with the observed frequencies. In addition, some models can be safely excluded because of the large discrepancies between computed and observed frequencies. This procedure has been generally successful in obtaining mode frequencies accurate to better than 1% (Ulrich and Rhodes, 1983; Shibahashi *et al.*, 1983). The general result is that a relatively standard model fits the data best. In particular, a convection zone depth of 0.3 R_o, a helium abundance of $Y = 0.25$ and a heavy element abundance of $Z = 0.02$ are preferred.

Many of the observed mode frequencies have relative accuracies of 0.1% or better, but none of the models predict frequencies within the observational uncertainties. This has led to suggestions that the physics in the models is incomplete (Gough, 1984). Christensen-Dalsgaard and Gough (1984) have shown the differences between the computed (model 1 of Christensen-Dalsgaard, 1982) and observed frequencies are similar functions of frequency at constant degree. For the different degrees ($l = 1 - 200$) the positions of the bottom of the cavities range over a large fraction of the solar radius. The only area that these modes have in common is the outer few percent by radius and so it was concluded that the dominant error in the models is in this region. A second effect seen was a rather abrupt change in the frequency errors between degrees 20 and 40. This suggests another error in the model between the bottoms of the $l = 20$ and $l = 40$ cavities, or roughly $r/R_o = 0.6 - 0.7$.

Another approach to the investigation of the thermal structure is to attempt to obtain the internal structure directly from the observed frequencies. This procedure, known as inverse theory, has been successfully employed in terrestrial seismology and should be applicable to the solar problem. The initial attempts to invert the observed frequencies utilize asymptotic relations for the frequencies (Gough, 1984; Christensen-Dalsgaard *et al.*, 1984) that are not as accurate as the full eigenmode calculations. The initial conclusions are that the dominant errors in the models are very near the surface.

2. *Rotation*

The rotation of the solar interior has intrigued investigators for nearly two decades since the suggestion of Dicke (1974) that a rapidly rotating solar interior would influence the relativistic interpretation of the precession of planetary orbits through an enhanced solar gravitational quadrupole moment. In addition, differential rotation is thought to drive the eleven-year activity cycle and so radial and latitudinal profiles of rotation are needed to understand this phenomenon. The oscillation modes are sensitive to the interior rotation in a well-defined way. For *p*-modes a mode frequency is shifted by an amount proportional to the product of the azimuthal order, m, and the integral of a kernel function multiplied by the rotation frequency, over the interior of the star. Since different modes sample different parts of the star, we can in principle obtain the interior rotation from the measurements of a sufficient number of frequency shifts.

The initial attempts to measure subsurface rotation utilized sectoral modes ($|m| = l$) of high degree l (Deubner *et al.*, 1979). These are the natural modes to start with, as the frequency shifts are large (and thus easily measurable) due to the large value of $|m|$. The sectoral modes of high l are confined to the equatorial zone and so information is obtained on the depth dependence of the equatorial rotation. Modes of high degree are confined to a rather shallow layer near the surface and so the depth range covered is small. The original depth variation seen by Deubner *et al.* (1979) was not confirmed by subsequent observations (Rhodes *et al.*, 1983) although Hill *et al.* (1983) have argued that giant cell convection may cause time variations in the observed rotational splitting.

At low degrees, the observational problems are magnified although the information content in the modes is much higher. An $l = 1$ *p*-mode with a period near 5 minutes is confined in a cavity that ranges over 95% of the Sun's radius. An $l = 1$ *g*-mode is confined mostly to the deep interior and is actually a much better probe of that region. The frequency shifts of the low-degree modes are, however, much smaller because of the reduced value of $|m|$. In addition, most of the effort at low degrees have been on observations with little or no spatial resolution and hence the prograde and retrograde modes are not clearly separated as they are in the high-degree case. The initial rotational splitting observations for low-degree *p*-modes in the five-minute band (Claverie *et al.*, 1981) have not been confirmed by the later observations of Woodard (1984). And, in fact, Woodard has made a powerful argument that the $l = 1$ and 2 *p*-mode splitting cannot be resolved without spatial resolution because of the finite lifetime of the modes with periods near five minutes.

The advantage of spatial resolution has been demonstrated by the sectoral mode splittings of low to intermediate degree ($l = 1 - 100$) observed by Duvall and Harvey (1984). These data have been used to derive a radial rotation profile by Duvall *et al.* (1984). The results show that over most of the radius ($r/R_o > .4$) the rotation rate is close to the surface rate with a slight decline with radius. The gravitational quadrupole moment, J_2, calculated from this rotation profile makes a negligible contribution to the precession of planetary orbits.

3. *g-modes*

Measurements of g-modes would be an important step in helioseismology. The g-mode frequencies are determined mainly by conditions in the deep interior (where internal gravity waves can propagate) in contrast to the p-modes, whose frequencies are very sensitive to the structure near the surface. Several observational problems are associated with the detection of g-modes. Theoretical calculations tell us that the evanescent region in the convection zone will reduce the eigenfunctions of high-degree g-modes to an unobservable level at the surface and so we would probably only be able to observe the lowest few values of spherical harmonic degree l.

The frequencies of g-modes are low ($\nu < 0.3$ mHz) and for moderate resolution $\Delta\nu \approx 0.1$ mHz the temporal power spectrum of these low $- l$ modes should be crowded. The solar background (active regions, supergranulation, granulation) may contribute significant power at the frequencies in question. In contrast, the lifetimes of the g-modes could be considerably longer than any of the data strings currently being analyzed and so progress could be made with longer data sequences. Several groups claim to have detected g-modes (Delache and Scherrer, 1983; van der Raay *et al.*, 1984; Fröhlich and Delache, 1984; Kotov *et al.*, 1984; Hill *et al.*, 1982). The different observations are not in agreement (where there is overlap) on the frequencies of modes present and the mode identifications. For a given spherical harmonic degree, the g-modes are asymptotically (high n) equally spaced in period as a function of radial order n (Berthomieu *et al.*, 1978). There is also not general agreement on the fundamental period spacing.

4. *Conclusions*

Much has been learned in the study of global solar oscillations and much remains to be done. Interesting physical problems, such as how the latitudinal differential rotation varies with depth, have not yet begun to be attacked. Observationally there are several impediments to further progress, including the day-night cycle, the need for two-dimensional imaging and atmospheric seeing. Atmospheric seeing is a problem only for the high-degree modes which require high spatial resolution to observe. The day-night cycle introduces spurious peaks into the spectra from a single mid-latitude observing site. This difficulty can be adequately overcome with a network of mid-latitude sites judiciously placed around the globe. The Birmingham group has been operating a two-station network with considerable success during the last several summers. The Birmingham and Nice groups are proposing to build extensive networks of stations for the study of oscillations in unimaged sunlight. A network of imaging stations that would observe the low and intermediate degree modes is being proposed by the Global Oscillation Network Group (GONG). The problem of seeing as well could be solved by going to space, and both the European (ESA, 1983) and US (Noyes and Rhodes, 1984) space agencies are studying the possibilities. Major advances in helioseismology should come from the implementation of any or all of the network or space proposals.

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III. SOLAR ROTATION

(Robert F. Howard)

1. *Spectroscopic Studies*

The study of solar rotation using the Doppler effect in solar spectrum lines continues to be an active and fruitful area of research. Duvall (1982) has confirmed a slower rotation rate for the photosphere than for sunspots, which bears on an earlier controversy regarding this point between the Stanford Solar Observatory and some other observatories. The issue is not settled, however.

The analysis of Doppler data has been discussed by Kubicela and Karabin (1983), who have proposed a new vector formulation for the reduction of solar disk data, including the effects of the Earth's orbit on the velocity signal. Snodgrass *et al.* (1983) have discovered an error in the calibration of the Mt. Wilson velocity signal which resulted from an error in the published wavelengths of the solar spectrum lines that have been used in calibrating the observations. This error, which was present in the Stanford Solar Observatory data as well, resulted in an over-estimate of the rotation velocity in all earlier published results from these observatories of 0.55%.

A comprehensive summary of the Mt. Wilson Doppler rotation results starting in 1967 was published by Howard *et al.* (1983). This work gives the rotation rate and latitude dependence over the time interval in one-rotation averages. Other characteristics of the large-scale velocity fields are also listed in this paper.

Balthasar (1983) has analyzed the depth dependence of the solar rotation rate using 63 Fraunhofer lines observed with the Fourier transform spectrometer at the National Solar Observatory in the visible region of the spectrum. He finds, in agreement with other observers in earlier years, that the rotation rate is slightly higher at higher elevations in the solar atmosphere. This result still remains a puzzle, with no theoretical explanation.

The rotation rate of a faintly discernible pattern of polar velocity field — large-scale cellular pattern centered on the pole — ith a rotation period of 30 days was found in Doppler observations by Cram, Durney, and Guenther (1983). This is the first evidence of any such pattern. This interesting result, which would have profound implications in the study of interior structure and dynamics, deserve verification and further study.

Variations with time of the Doppler velocity signal were the topic of a study by Kuveler and Wöhl (1983). These authors detected a decrease of nearly 2% in the equatorial rotation rate of the Sun between 1981 and 1982, in agreement with unpublished results from other observatories. The variations seen on a daily basis and the absolute value of the rotation are not in such good agreement between the various sites. Evidently instrumental effects affect the daily determinations of rotation rate significantly at most or all observatories. To what extent long-term averages of rotation rate are affected by instrumental effects is not yet known. The measurement of the rotation rate of the Sun by spectroscopic techniques is still a very uncertain process, and systematic errors are evidently not yet totally negligible.