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

PRESIDENT: R. W. Noyes  
VICE-PRESIDENT: M. Kuperus  
ORGANIZING COMMITTEE: Y. Uchida (Past President), Chen Biao, F. Deubner,  
E. Fossat, J. Harvey, V. A. Kotov, J. Leibacher,  
K. R. Sivaraman, J. O. Stenflo, P. Wilson

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 qua-  
drupole 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 func-  
tion, a spherical harmonic $Y_{lm}$(θ, φ) 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 com-  
puted 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 rela-  
tively standard model fits the data best. In particular, a convection zone depth of 0.3 $R_\odot$, 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 \( r/R_\odot = 0.6 - 0.7 \).

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 higher 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 splitings 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 \((r/R_\odot > .4)\) 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. Atmopsheric 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.

References

Dicer, R.H. 1974, Science, 184, 419.
ESA, 1983, Solar and Heliospheric Observatory Assessment Study
Fröhlich, C. and Delache, P. 1984, in Oscillations as a Probe of the Sun’s Interior, eds. G.
GONG (Global Oscillation Network Group), 1984, report No. 2, National Solar Observatory, Tucson, AZ, USA.

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 Kubica 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 — with 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, deserves 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.
Perez-Garde et al. (1981), using the $\lambda 6301.5$ line of Fe I, found a large-scale velocity pattern during a few days in September 1978 between $+48^\circ$ and $-30^\circ$ with a period of about $45^\circ$ in longitude. They also found an equatorward meridional flow with an amplitude of about 20 m/sec. This meridional motion is opposite in direction to that found previously at other observatories. This is another indication that measurements of small wavelength shifts in the solar spectrum may be plagued by errors of an unknown nature. These authors found an equatorial rotational velocity of 2.881 rad/sec.

Snider (1983), using an atomic beam resonance scattering technique for the $\lambda 7699$ line of potassium, found an equatorial rotation rate in the interval 1979 to 1982 of $13.8 - 0.2^\circ$/day sidereal. There were no significant variations in this rather low rate. These observations were made at two sites — Oberlin and Mt. Wilson.

2. Rotation from Tracers.

Considerable interest in recent years has centered on the rotation of sunspots. The extensive Greenwich data set has been much utilized in several studies of sunspot motions. These data have several important advantages: They are quite homogeneous, they cover long periods of time, and there are very few missing days. A conspicuous disadvantage of the Greenwich data set is that it contains information on sunspot groups only — that least in recent times. Group areas and positions are tabulated in the Greenwich data, but individual spot characteristics are not available, except for the case of single-spot groups, which are not typical of either groups or individual spots. Often investigators have not stressed this distinction.

Among the studies using the Greenwich data is that of Arevalo et al. (1982). In this analysis, it was found that the rotation rate of groups was higher in the interval 1874 to 1902 than in the interval 1940 to 1968. Furthermore, meridional flows as seen in spot group motions were northward in cycle 12, while in cycle 13 they were southward.

The positional correlation of Greenwich spot groups and high-speed solar wind streams has been studied by Balthasar and Schüssler (1982). In general, an anticorrelation between these quantities is observed, strongest at the post-maximum phase of the cycle. Consecutive pairs of cycles show conspicuous similarities in this respect, which led the authors to conclude that there is a tendency for activity to occur in preferred longitudes. It is known that high-speed solar wind streams tend to originate at coronal holes, so it may be that this result is to some extent a matter of definition. Coronal holes tend to avoid active regions (and therefore sunspots) so one would not expect to find a positive correlation between the two features.

Two groups (Godoli and Mazzuccconi 1983; Tuominen, Tuominen, and Kyröläinen 1983), using the Greenwich data, find the same rotational latitude shear seen in the velocity maps showing torsional oscillations. These results are barely above the noise level, and further confirmation would be desirable. This is a very important issue, because the nature of the torsional oscillation is still undefined. If these small-amplitude motions are shared by the strong photospheric magnetic fields, then this gives us more information on the depth of the oscillations.

Other investigations using the Greenwich data in this interval include that of White (1982) on the velocity dispersions of single spots (groups). He found that the velocity dispersion does not vary with latitude, is twice as large in longitude as in latitude, and is smaller for smaller spots. Kopecky (1982) has listed the high-latitude spot groups $\geq 40$ for the interval 1874 to 1976 from the Greenwich data. Tang (1981) has studied high latitude spots in the interval 1978 to 1979 for rotation rate and finds a slightly slower rotation rate at the high latitudes than predicted from the Newton and Nunn (1951) formula. A similar result was found by Landman and Takushi (1981) using data from 1966 to 1968. They found high latitude rotation in agreement with the Newton and Nunn result from the years 1934 to 1944.

The 17th century records of Scheiner and Hevelius have been examined (Yallop, et al. 1982) for rotation information. These authors find no significant difference in rotation rate from modern times. A similar result was found by Abarbanell and Wöhl (1981).

The Mt. Wilson white light photographs from 1921 to 1982 have been measured for positions and areas of all sunspots (Howard, Gilman, and Gilman 1984). Individual sunspot positions have been matched with data from the following day to obtain returns of the same sunspots. In order to do this a computer algorithm had to be devised to match the pattern of sunspots on consecutive days. Thus, for the first time, rotation rates and latitude drifts of individual sunspots could be derived on a massive scale over a long time interval. One of the first results to come from this
study was that the largest spots rotate more slowly by several percent than the smallest spots. This may represent a different depth at which the magnetic fields of large and small spots are linked. Using the same data set, Gilman and Howard (1984) discovered a systematic variation of the rotation rate of sunspots with phase in the solar activity cycle. A slight rise in the rotation rate is detected at solar minimum, and a smaller and less well-defined increase is seen near solar maximum. In the interval 1967 to 1982, for which there are Doppler velocity data for solar rotation from the Mt. Wilson magnetograph, the Doppler-determined rotation rate of the Sun shows a similar twin-peaked behavior. An increased rotation rate at minimum was found by Rovithis (1982) using Greenwich data for the 18th cycle (1945-54), who also found a slight difference between the rotation rates of the north and south hemispheres, with the north being slightly faster. Arevalo et al. (1982), from an examination of Greenwich spot group data over several early sunspot cycles, show a plot with a twin-peaked cyclic variation of spot rotation similar to that found in the Mt. Wilson data.

Another long set of non-Greenwich data is that of Kanzelhöhe. Lustig (1982, 1983) used data from 1947 to 1979 to study the rotation rates of individual sunspots. He found that group types H and J, which are larger than group types C and D, also have slower rotation rates. Using individual spot data, Lustig determined that the differential rotation gradient declined slightly during the interval. Also, he found that the equatorial rotation rate is slightly faster during minimum than during the maximum years.

Another study of individual spots is that of Koch, Wöhl, and Schröter (1981). They determined that the rotation rate of any one spot was remarkably constant in time but that different spots differed in their rotation rates significantly.

Ternullo, Zappala, and Zuccarello (1981), using spot groups observed at Catania, found that young spots rotate faster than old spots. It is possible that this is the same effect as the size-rotation correlation discussed above. The older spots tend to be larger and rotate slower than the smaller spots, which don’t live as long. It is not easy to determine which is the important factor in this case. Judging from the results of Koch et al. (1981) described above, it seems most likely that individual spots do not change their rates as they age. Whether or not they change rotation rate as they change size is an open question.

**Magnetic Field Rotation**

A special type of tracer is the weak magnetic field pattern seen in solar magnetogram observations. Snodgrass (1983) has examined the Mt. Wilson daily magnetic data covering 1967-1982 and used a cross-correlation technique in narrow latitude zones to determine day-to-day differences in longitude corresponding to the rotation rate of the patterns. The result is a rate remarkably constant with time and agreeing well with the Newton and Nunn (1951) value near the equator. At higher latitudes, where sunspots are scarce, the magnetic pattern results agreed well with the Mt. Wilson Doppler results. The errors in these determinations varied from 0.1% at low latitudes to 1.1% at very high latitudes. The cycle-related variations seen in the spot and Doppler results are not seen in the magnetic field data.

4. Rotating Distortions

Dicke (1982) has suggested that earlier observations of the figure of the solar limb, which showed a cyclic variation with a period of close to 12 days, result from the rotation of the solar core distorted by a strong magnetic field. Dicke calculates that such a field would experience a torsional oscillation within a period of years. Libbrecht (1984) has made more recent observations of the shape of the solar limb with an improved version of the instrument first used by Dicke and his collaborators. Libbrecht's observations were made at a much better site than the original set, and they show no more than the distortion expected by a reasonable extrapolation of the surface rotation; moreover they show no significant rotating distortion. Solar oscillation data (reviewed in Sec. II above) presently give conflicting results about whether there is rapid rotation in the deep solar interior.

5. Torsional Oscillations

Some further work was carried out in this interval on torsional oscillations of the Sun. Labonte and Howard (1982) used the latitude zone Doppler velocity data to search for the torsional oscillations. This method does not depend on the latitude series solution for the rotation, so it is not subject to possible influence from the choice of terms in the latitude expansion. Using the latitude-strip data only, the torsional oscillations may be seen, although against a rather noisy...
background. Another feature that shows up in this plot (Figure 8 of the LaBonte and Howard paper) is a one-cycle-per-hemisphere torsional wave which is characterized by a faster rotation at high latitudes near solar minimum and a faster rotation at low latitudes near solar maximum. The amplitude is roughly that of the traveling torsional wave, i.e. \( \sim 5 \text{ m s}^{-1} \). The high latitude portion of this pattern was found earlier by Livingston and Duvall (1979).

There is evidence for a 1/2 cycle-per-hemisphere oscillation in a comparison of equatorial rotation rates determined from north and south data separately (Howard et al. 1983). The amplitude is comparable to those of the two modes mentioned above.

The cyclic variation of the rotation rate of the Sun determined from sunspot and Doppler data discussed above is essentially another mode of torsional oscillation. In this case, the amplitude is about 200 ms\(^{-1}\), which is much larger than the other modes.

References

IV. SOLAR GRANULATION
(R. Muller)

During the period 1981-1984, major developments have been made in the analysis of the shape and shifts of photospheric lines used as a diagnostic of the convection in the outer layers of the Sun. The first three-dimensional numerical simulation of the solar granulation has been developed, and it is able to reproduce with some success most of the observed morphological and spectroscopic properties of granulation. It is becoming clear that the properties of the solar granulation are variable over the solar cycle. Many questions remain to be solved; further progress will rely heavily on expected improvements of the spatial resolution of the observations and the availability of larger computers.
1. Morphological structure of the solar granulation.

Wittmann (1981), analysing high resolution Spektro-Stratoskop photographs (Mehlretter, 1978), confirms several accepted values like the fractional area of granules (47.1%), the corrected contrast (22%), and the asymmetry of intensity histograms. However, he finds a somewhat larger granular size than usually accepted, and a shorter lifetime (5.8 min).

It appears that granules are more evenly spaced than random points (Lawrence, 1983) and form bright chains, with contrast exceeding the mean contrast of granulation by several percent and of longer lifetime (Perfilenkov, 1981). Confirming and extending the last result, Oda (1984) finds that the bright and exploding granules tend to form chains, defining a cellular pattern comparable in size to that of the mesogranulation. Isophotal contour maps of a single granule are presented by Bray and Loughhead (1984).

Recent measurements of the granulation contrast are in reasonable agreement around 5500A, but are very uncertain in the blue and the red, so that they do not allow comparison with models (Bray, 1982).

2. Statistical analysis of brightness fluctuations.

New evaluations of rms brightness fluctuations ($\Delta I_{\text{rms}}$), corrected for instrumental and atmospheric blurring fall near the lower limit of the range 10–20% from previous evaluations (Schmidt et al., 1981, solar eclipse observation at Irazu; Durrant et al., 1983, Spektro-Stratoskop pictures). As these new values are not safer than the previous ones, the true $\Delta I_{\text{rms}}$ of the solar granulation remains dubious. It is confirmed that the change of rms fluctuation from the centre of the disk to $\mu = 0.3$ is small. Fitting the observed spread function of Deubner and Mattig (1975) by the sum of two Lorentzians, rather than by two Gaussians, Nordlund (1984a) re-evaluated the $\Delta I_{\text{rms}}$ of the solar granulation which is thus increased from 12.7% (Deubner and Mattig, 1975) to about 20% at 6070 Angstrom. This value is in good agreement with the $\Delta I$ rms of the Nordlund’s tri-dimensional numerical model (Nordlund, 1982) of 20 – 25% at 6000 Angstrom.

Bi-dimensional power spectra obtained by Schmidt et al. (1981) and Durrant et al. (1983) are in good agreement with previously published single peak power spectra, while the bi-dimensional power spectrum, derived from one dimensional scans by Wittmann (1981), exhibits a multi-component peak; similar peak splitting was already reported in the past by a few authors but its existence as a property of the solar granulation remains doubtful.

The correct formulation of statistical analysis in the general case of a tilted image is derived by Wiesmeier and Durrant (1981) both for uni- and bii-dimensional observations; restoration by the point spread function is included in the formulation. V. der Lühe (1981) demonstrated that Optical Fourier Transformation, if carefully handled, may be a reliable alternative to the usual numerical procedures for deriving the power spectrum of the solar granulation. Ricott et al. (1982) performed estimations of Fried’s parameter $r_0$, simultaneously using the same telescope, from the observed solar granulation contrast and from the variance of angle-of-arrival fluctuations; $r_0$ obtained by both methods are well correlated.

Fluctuations of the limb position, due to brightness fluctuations of the granular pattern, do not exceed a few thousandths of a second of arc (Lites, 1982).

3. Empirical models of temperature and velocity.

Temperature models. Durrant et al. (1981) have shown that if the “geometrical smoothing” toward the limb is taken into account, recent empirical temperature models of the solar granulation, in which the temperature fluctuation is rapidly vanishing in the lower photosphere, are able to reproduce the centre-to-limb variation of the continuum intensity, as well as the intensity fluctuations in spectral lines, observed with the Spektro-Stratoskop. Karpinsky (1981) reports on measurements of the horizontal gradient of brightness of granules of 1.5 to 2.0 K/km, the peak values reaching 2.7 K/km; the values can be as high as 5.0 to 10.0 K/km when corrected for distortions.

Velocity models. The steepness of the decrease with height in the photosphere of the rms vertical velocity field associated with the solar granulation is a much debated question (see, for example, the flat gradient model of Durrant et al., 1979 and the steep gradient model of Keil, 1980). It seems that the discrepancy is a result of the different procedures used to separate the convective and oscillatory components. The results of Bässgen and Deubner (1982) who analyse a high resolution time series of spectra obtained at Sacramento Peak Observatory, and use the resulting $k - \omega$ diagram to separate convective and oscillating powers, favor the flat gradient model. The coherence of the vertical convective velocities is maintained at least up to 300 km in the photosphere (Durrant...
and Nesis, 1982; Pravdijuk, 1982), confirming previous results. The penetration of convective cells to such high levels also favors a flat gradient model. It is found by Durrant and Nesis that the velocity coherence of the structures of sizes in the range 2–6 arcsec is maintained high up into the photosphere while it is lost more rapidly for smaller structures.

It is confirmed that the coherence between continuum intensities and vertical velocities is restricted to the lower photosphere (Durrant and Nesis, 1982; Nesis et al., 1983). The horizontal velocity patterns are not coherent with the vertical velocity, or with the brightness pattern, indicating lack of horizontal heat transport. It is not possible to conclude how the horizontal velocity and its variation with the height in the atmosphere is related to the structure of granules (Nesis et al., 1983).

An analysis of the Doppler shift fluctuations in the profile of the strong Na I D1 line, instead of the more usual analysis of fluctuations in the core of lines of different strengths, failed to provide new information about the structure of the velocity field in the photosphere (Edmonds and Jin-Chung Hsu, 1983).

4. Shift and asymmetry of photospheric line profiles.

Spatially unresolved photospheric line profiles are asymmetric (C-shape of the line bisector) and blueshifted; these properties are signatures of the presence of convection and are used to get information about the vertical and horizontal structure of the photosphere; but this is not a trivial problem.

**Line shift and asymmetry as tests for convection models.** Kaisig and Durrant (1982) investigate in detail the information content of the shifts of mean line profiles with the aid of a perturbation analysis and a two-stream model. They demonstrate that the characteristic C-shape of mean solar line profiles is due not to the larger velocity amplitude of the downflow as proposed by Dravins et al. (1981), but to a complex opacity effect. The analysis of shifts of photospheric lines does not allow separation of the depth dependence of velocity, δv(h), and temperature, δT(h), fluctuations, but it is useful as tests of convective models (Kaisig and Durrant, 1982, Kaisig and Schröter, 1983; Kostick, 1983).

Methods based on the analysis of the third central moment M3 of the line profiles (Marmolino and Severino, 1981) and on a linear analysis of the bisector (Buonaura and Caccin, 1982) have been developed to retrieve δv(h). The main limitation of both methods is that they are applicable only to data with infinite resolution. Pierce (1984) shows that an observed Fraunhofer line to a fitted gaussian yields more information on shape and asymmetry of the solar line than the simple bisector method.

**Line asymmetry and blue-shift-parameters dependence.** Balthasar (1984) finds that lines with cores formed in higher layers show larger asymmetries. Analysis of lines of ionized elements (Fe II) confirms the weak increase of the blue-shift with increasing excitation potential found for neutral elements (Dravins and Larsson, 1983). These authors also report that lines formed in shorter wavelength regions are more blue-shifted than lines in the red. In their investigation, Dravins and Larsson used the Kitt Peak Wavelength Table by Pierce and Breckinridge (1973), while Balthasar used observations obtained with the Fourier-Transform-Spectrometer (FTS) at the Mac Math Telescope of the Kitt Peak National Observatory (KPNO).

Some authors find that line asymmetry changes with time (Roca-Cortes et al., 1983, but the line KI 7699 investigated is found high in the photosphere and is more sensitive to oscillations than to convection), while others do not (Cavallini et al., 1982).

Accurate measurements of the shape of Fe I 6301.5, performed with a Fabry-Perot spectrometer, agree with previous measurements (Cavallini et al., 1982). The shape of the KI 7699 line profile is also confirmed by new measurements (Roca-Cortes et al., 1983).

**Limb effect.** The blue-shift progressively decreases as one moves away from the disk centre and may even become a supergravitational redshift at the extreme limb; this is known as the limb effect. Balthasar (1984) confirms the existence of supergravitational red-shifts at the limb for many photospheric lines; in addition he finds that the red-shifts for lines from ionized elements are larger than those from neutral elements. Brandt and Schröter (1982), analysing spectra with iodine reference lines obtained at Locarno Observatory, confirm earlier findings that the limb effect is a combination of shifts of the line centre and the centre-to-limb variation of the shape; at the limb the asymmetry disappears. The relative blue-shift of many lines at cos Θ = 0.8 compared to the disk center is confirmed by Brandt and Schröter (1982) and by Balthasar (1984).
Latitude variation. It appears that there is a significant difference between the limb-effect curves along the polar and equatorial diameters for $\cos \Theta \leq 0.4$ and a rather strong indication of a latitude dependence of the line bisector C-shape (Brandt and Schröter, 1982). These authors come to the conclusion that this latitude dependence may account for the so-called "ears" observed by Howard et al. (1980).

Line asymmetry and blue-shift in plages. The C-shape of line bisector is flatter in plages than in the quiet Sun (Livingston, 1982; Kaisig and Schröter, 1983; Brandt and Schröter, 1984; Cavallini et al., 1984). There is presently disagreement about the relative shift of the line bisector in plage regions compared to the quiet Sun: Livingston (1982), analysing spectra obtained with the FTS at KPNO and Cavallini et al. (1984), analysing the Fabry-Perot measurements made at Arcetri Observatory, find a red-shift; Kaisig and Schröter (1983) find a blue-shift. These authors interpret the blue-shift as a penetration of convective flux into higher photospheric levels in active regions, while the former interpret the measured red-shift as a retardation or an inhibition of convection.

In the quiet network, at supergranular boundaries, the wings of three lines ($g = 0$) are red-shifted by between 75 - 200 m s$^{-1}$ relative to the cell profiles. The cores are relatively unshifted (Miller et al., 1984). Such trends can result if granular convection is suppressed near the network flux tubes, so that there is little downflow in the vicinity of the flux tubes.

Accuracy of absolute measurements. The accuracy of Doppler-shift measurements is limited by uncertainties of the position of reference lines. Causes of reference line shifts are analysed, and solutions allowing an improvement of measurement accuracy are given by Balthasar et al. (1982) for telluric reference lines and by Koch and Wöh (1984) for iodine reference lines.

5. Theoretical models of the solar granulation

We will restrict ourselves to those theoretical models of convection which are closely related to the solar granulation.

Nordling (1982) develops a full three-dimensional numerical simulation of the solar granulation. He solves the hydrodynamic equations, including the radiative transfer equations, in the anelastic approximation; turbulent viscous terms are included in the equation of motion; the importance of spectral lines on the energy balance in the upper photosphere is stressed.

The results of these simulations show the main observed characteristics of the granulation (Dravins et al., 1981; Nordling, 1984b): granules surrounded by intergranular lanes; downward motion in the lanes of larger amplitude than the upward motion in the granules; granules increasing their horizontal dimension in time; larger granules breaking apart into smaller ones, which in turn grow and merge. Synthetic spectral lines calculated both for the solar disc center and for the Sun as a star are in good agreement with the widths, strengths and shapes of observed spectral lines. The spectacular fit of the simulations with observations makes Nordling's tri-dimensional model very appealing, although it is inherent to the model not to be able to predict a turbulent cascade toward the smaller scales. In this model granules are driven by the buoyancy force, horizontal motions are driven by pressure gradients, and the centres of granules are cooled while they expand and brake. The model does not contain any arbitrary parameters: the typical amplitudes of velocity and temperature fluctuations depend only on effective temperature, surface gravity, and the chemical abundance.

Under a different approach (Narasimha and Antia, 1982), convective modes in the solar envelope are investigated in the frame of the mixing length theory. The structure of the convection zone calculated according to this theory is found to be consistent with the transport of convective flux by a linear superposition of statistically independent unstable convective modes, provided the effects of turbulent conductivity and viscosity are taken into account. The resultant vertical velocity is in reasonable agreement with observed granular velocity. In a subsequent paper Antia et al. (1983) investigated the stability of linear convective modes in the solar envelope model by incorporating in a very crude manner the effects of turbulent pressure and eddy transport coefficients calculated in the mixing length approximation. It is demonstrated that for a reasonable choice of parameters there occur two peaks in the plot of growth rate versus horizontal wavenumber, which correspond to the observed features (horizontal size and lifetime) associated with the granulation and supergranulation.

6. Variation of the properties of solar granulation over the activity cycle.

A set of converging results of different origin have recently been published, indicating that the structure of the solar granulation varies over the solar cycle.
The mean size of granules, either measured by the distance between the centres of granules, or by the number of granules per unit surface area, decreases with increasing activity (Macris and Rösch, 1983; Macris et al., 1984, Muller and Roudier, 1984). The granule-intergranular lane intensity ratio at 5200 Å varies with time, being minimum (1.10) around the minimum of activity, and maximum (1.30) around activity maximum. All these measurements were made on high resolution photographs of the solar granulation performed with the 50 cm refractor at Pic du Midi Observatory.

The equivalent width of photospheric lines, measured with the 13.5 m spectrometer at Kitt Peak National Observatory, decreases by a factor ranging from 0 to 2.3% from 1976 to 1980 (Livingston and Holweger, 1982). The authors come to the conclusion that the weakenings are due to global variations of surface properties, namely a reduction of the temperature gradient through the low photosphere. Bisectors of strong iron lines in the full disk Fraunhofer spectrum, measured with the Fourier Transform Spectrometer at Kitt Peak National Observatory, are observed to diminish in curvature as the activity cycle proceeds from minimum (1976) to maximum (1979-1982). The implication is reduced convection on a global scale in response to an increase of total magnetic flux (Livingston et al. 1982; Livingston, 1983, 1984).

References


V. DYNAMICS OF THE CHROMOSPHERE AND TRANSITION REGION

(R. Grant Athay)

One of the more interesting aspects of the chromosphere-corona transition region is its tendency to exhibit large Doppler shifts. Both the non-thermal velocity component of line widths and the velocity displacement of line positions tend to maximize at temperatures near \(10^5\) K. The increase in velocity amplitudes with increasing temperatures below \(10^5\) K is readily understood in terms of the increasing sound speed and decreasing densities associated with the outwardly increasing temperature. Why the observed velocity amplitudes should decrease at still higher temperatures is not at all clear, however, and it seems very likely that this phenomenon is indicative of fundamental differences in the dynamics of the upper transition region and corona from those in the lower transition region and chromosphere.

The possibility remains, of course, that the apparent velocity decrease at high temperatures is only partially a solar effect. At temperatures above \(10^5\) K, increases in temperature, in general, are associated with increasing amounts of radiating material as a result of the decreasing temperature gradients. The resulting increase in path length over which a given spectral line forms tends to blend together regions of differing Doppler shift. As a result, the lines are broadened in preference to overall wavelength displacements. The apparent decrease in Doppler shifts very likely is due partially to this effect. However, since no marked increase in the non-thermal component of line broadening has been observed for temperatures above \(10^5\) K, it is evident that the steady increase in velocity amplitude up to \(10^5\) K does not continue at the same rate into the \(10^6\) K regime of the corona. Thus, at least part of the effect appears to be of solar origin.

A further unusual property of the temperature regime below about \(10^5\) K is the tendency for the solar plasma to exhibit large scale systematic flows as well as both periodic and highly transient localized flows. This review concentrates on the observational aspects of these flows as reported from 1981 to mid-1984.

Vertical Flow.

A number of observers have continued to report systematic downflows observed in spectral lines formed in the lower transition region and chromosphere. Gebbie et al. (1981) report average downflow velocities for the quiet sun ranging from 1.4 km s\(^{-1}\) in C II to 4.2 km s\(^{-1}\) in C IV, which is consistent with momentum conservation. Roussel-Dupre and Shine (1982) find mean redshifts of 12 km s\(^{-1}\) in C IV and Si IV at disk center, and Dere (1982a) finds an average red shift of 5.4 km s\(^{-1}\) for the quiet sun in C IV.

In active regions, Feldman, Cohen and Doschek (1982) find mean red shifts ranging from 4 to 17 km s\(^{-1}\) in ions formed at different temperatures with the maximum occurring between \(5 \times 10^4\) and \(10^5\) K and decreasing to 2 km s\(^{-1}\) in lines of Si II, S II and C II formed in the upper chromosphere, and Brueckner (1981) finds downflows of 10-60 km s\(^{-1}\) in C IV.

Over sunspot umbrae the situation is less clear. Several authors (Brueckner 1981, Nicholas et al. 1982, Dere 1982b and Athay et al. 1982) have reported downflows in C IV generally exceeding those in the quiet sun. However, in subsequent studies Athay, Gurman and Henze (1983) found several spots with upflow and Gurman and Athay (1983) found from a study of 8 sunspots a small net average upflow. Also, Mein et al. (1982) found strong upflow in C IV in three sunspots;
Kingston et al. (1982) found only a weak net downflow in two sunspots; and Henze et al. (1984) found both upflow and downflow in different portions of a single spot. It seems clear that some sunspots have downflow, but that perhaps an equal number have upflow at transition region temperatures. Within a given spot the flow direction may well be time dependent.

Evidence that the downflows in the quiet sun are associated at least partially with the network seems quite conclusive. Positive correlations between red shift amplitude and intensity of C IV have been found by Gebbie et al. (1981), and Athay et al. (1983). Similar correlations have been found in active regions by Mein et al. (1982), Simon et al. (1982), and Athay et al. (1982, 1983). On the other hand, Dere (1982a) found no correlation between velocity and intensity and Athay et al. (1982, 1983) found that the correlation in C IV was often restricted to intermediate intensities. Furthermore, the latter authors noted that whereas the network features tended to have a red shift the reverse correlation was much weaker. Much of the red shifted areas are near to or below average brightness. Thus, it appears that the red shifted areas include most of the network but, in addition, include much of the supergranule cell interior. Also, the very brightest features in active regions often show blue shifts (Athay et al. 1983). This is consistent with high resolution observations reported by Brueckner (1981) and Dere (1982a, 1982b) that show many bright blue shifted features in C IV.

Although the preponderant downflow at transition region temperatures seems well established in both the quiet and active sun, the form of the downflow is unclear. In both low resolution and high resolution data C IV lines show a variety of profile types ranging from asymmetric profiles composed of a strong unshifted component and weaker Doppler shifted components in the red wing (Dere 1982), to symmetric profiles with notable Doppler shift (Athay et al. 1983). It seems probable, therefore, that the Doppler shifted areas have scale sizes ranging from sub-arcsecond to many arcseconds.

An attempt by Rottman, Orrall and Klimchuk (1981) to measure the radial flow velocity in a coronal hole in OV showed a blue shift of 3 km s\(^{-1}\) in the coronal hole relative to the average of the observed area outside the coronal hole. Since the average sun is very probably redshifted in OV, as in other lines formed at similar temperatures, it is unclear whether, in fact, the observed coronal hole had a net outflow in OV or just a reduced redshift.

The high spatial resolution HRTS data from the U.S. Naval Research Laboratory reveal a complex array of moving features including small blue shifted jets of relatively short lifetime. Brueckner (1981), Dere (1982a, 1982b) and Brueckner and Bartoe (1983) identify "chromospheric jets" as a class of objects with blue shifts at 10-20 km s\(^{-1}\) and "coronal jets" as a second class with blue shifts up to 400 km s\(^{-1}\). Little is known about the morphology and the associations of these jets with other solar features due to the limited spatial sampling in the HRTS data. The discovery of these interesting high speed jets together with the unanswered questions about the structure of the downflows underscores the need to pursue high resolution studies of the highly dynamic transition region.

**Horizontal Flow.**

As is clear on general physical grounds and supported for some time by observations, flows with dominant horizontal components play an important role in the dynamics of the solar atmosphere. The difficulty of observing such flows has notably restricted what is known concerning them. Again, however, recent transition region studies have provided interesting new results.

Nicholas and Kjeldseth-Moe (1981) and Athay et al. (1982, 1983) report flow patterns observed in C IV around large sunspots indicative of a reverse Evershed effect. On the sun-center sides of the spots, the gas is red shifted, and on the limbward side it is blue shifted. The red shifted area is usually larger in size than the blue shifted area and the red shift amplitude usually exceeds the blue shift amplitude, which suggests that the flow follows a pronounced Wilson depression.

At transition region temperatures, active regions show horizontal flow patterns that are coherent over large spatial domains and that are closely associated with the overall magnetic field structure of the active region (Athay et al. 1982, Athay, Gurman and Henze 1983). Near the magnetic neutral line separating strong field regions of opposite polarity the flow is usually divergent with opposite sign either side of the neutral line. However, near the neutral lines separating the weaker field areas of opposite polarity bordering the strong field areas the flow is often convergent.
towards the neutral line. In many cases the local flow around individual spots appears to be a coherent part of the large scale pattern, but in other cases the flow appears to be peculiar to the spot itself.

Oscillations.

Periodic oscillations in a sunspot umbra were reported by Zhugzhda and Makarov (1982). Brightness fluctuations observed in the Hα and K lines show series of wave trains lasting for 1.5 to 2 hours. Individual wave trains start at periods near 200 s and decrease to about 150 s as the train dies out. The wave trains are somewhat less pronounced in Hα than in the K line, but otherwise they are very similar in the two lines. The authors interpret the pulses of wave trains and the changing wave period in terms of an alternate compression and expansion of the chromospheric resonant cavity.

Umbral oscillations in C IV have been reported by Gurman et al. (1982) and Henze et al. (1984). Of the eight sunspots studied by Gurman et al., all showed velocity and brightness oscillations. Periods ranged from 130 to 170 s and velocity amplitudes from 0.8 to 3.5 km s⁻¹. For four of the spots, maximum velocity and maximum blue shift were in phase, consistent with adiabatic acoustic waves. In the one spot studied by Henze et al. different umbral pixels showed oscillatory periods from 110 to 200 s in both brightness and velocity. The pixel with the best defined period showed peak intensity leading peak blue shift approximately 45°.

Successful attempts to construct quiet sun k - ω diagrams in the chromospheric components of the K line have been reported by Kneer and von Uexküll (1983) and by Dame, Gouttebroze and Malherbe (1984). Both sets of observations show modal structure in the approximate wave number ranges 0.25 to 2.5 Mm⁻¹ and at frequencies beginning near 15 mHz (P ≈ 420 s). Modal structure is resolved up to frequencies of approximately 30 mHz (P ≈ 210 s) in the observations of Kneer and von Uexküll and to approximately 45 mHz (140 s) in those of Dame, Gouttebroze and Malherbe. The latter authors also find faint but inconclusive evidence for longer period waves in the gravity wave regime.

References


VI. THE PHYSICS OF CORONAL FLUX TUBES

(B. Robert)

Recent texts dealing with background aspects of this topic include Priest (1982), Noyes (1982) and Giovanelli (1984). Here we concentrate on the equilibrium structure of coronal loops, their oscillations and instabilities, and their heating.
**Equilibrium Structure of Loops**

The structuring of the coronal atmosphere by magnetic fields, with density, pressure and temperature differences giving rise to the appearance in X-ray and EUV-lines of individual loops, has drawn attention to the need to explore magnetic equilibria and their stability properties. Loops are undoubtedly not static, exhibiting both flows and variations in intensity on a variety of timescales. Nonetheless, it is important to understand the simplest static behavior that is possible under coronal conditions, and to inquire as to the limitations imposed by stability.

Static configurations give rise to simple scaling relations (e.g. Rosner, Tucker, and Vaiana 1978; Chiuderi, Einaudi, and Torricelli-Ciamponi 1981; Pallavicini et al. 1981; Withbroe 1981). A number of extensions are possible, such as the inclusion of gravity (Wragg and Priest 1981; Serio et al. 1981). In uniform (zero gravity) pressure loops, simple power-law scalings pertain (e.g. \( T \sim (pL)^{1/3} \)). Gravity is important in long loops, with lengths exceeding the coronal scale-height. In loops longer than about \( 10^8 \) cm, the hydrostatic fall-off in height of density and pressure modifies the simple power laws by the inclusion of an exponential dependence of temperature upon the loop length (Wragg and Priest 1981).

Scaling relations originally offered the hope of providing detailed information on the physical mechanisms at work in heating the coronal atmosphere. However, it has transpired that such relations are somewhat insensitive to direct testing against the observations and, moreover, the temperature structure along a loop is poorly determined. Golub (1982, 1983) has reviewed the matter and emphasized the possible use of stellar data, including relations which depend upon magnetic field strength. For stellar sources, Galeev et al. (1981) argue that quiescent emission levels arise principally from loops of length comparable with the atmosphere's pressure scale-height; shorter, newly emerged, loops tend to give rise to fluctuations in emission. The use of emission measure as a diagnostic tool, rather than direct use of temperature, length, etc., has been emphasized by Torricelli-Ciamponi, Einaudi, and Chiuderi (1982).

Magnetic equilibria are of obvious general interest, and so have been investigated for a variety of circumstances, including force-free (Sakurai 1981; Low 1982; Low and Hundhausen 1983; Melville, Hood, and Priest 1983; Browning and Priest 1983) and gravitational (Melville, Hood, and Priest 1984; Browning and Priest 1984a) equilibria.

1. **Instabilities**

Loops and arcades of loops are subject to a number of instabilities, including both hydromagnetic and thermal. Ideal magnetic instabilities have been reviewed by Van Hoven (1981), Hood and Priest (1981), Priest (1981, 1983a, b, 1984), and Einaudi (1984). Regarding a loop as a twisted magnetic cylinder, and including the important stabilizing influence of line-tying in the dense photosphere (e.g. Raadu 1972; Hood and Priest 1981; An 1982, 1984; Spicer 1982), allows a rather full analysis of the possible ideal magnetohydrodynamic instabilities (Raadu 1972; Hood and Priest 1979, 1981; Van Hoven, Ma, and Einaudi 1981; Priest 1981, 1983; Einaudi and Van Hoven 1983). Similarly, arcades of loops have been investigated in some detail (Hood and Priest 1980; Ray and Van Hoven 1982; Hood 1983; Schindler, Birn, and Janicke 1983; Migliuolo and Cargill 1983; Migliuolo, Cargill, and Hood 1984) as also the question of a general magnetic atmosphere (Birn and Schindler 1981; Heyvaerts et al. 1982; Zweibel and Hundhausen 1982; Priest 1983a, b).

The aim of instability studies is to understand how, on the one hand, loops and arcades may be stable on timescales of perhaps a day and, on the other hand, may cause or contribute to the onset of flares or other dynamical events. The main difficulty in these analyses is in a realistic modeling of the equilibria, the choice of boundary conditions at the footpoints of loops, and the appropriate treatment of the transition zone. Uncertainties on all these issues remain.

Analysis of magnetic instabilities is generally based upon two standard approaches: either method of normal modes or the energy principle, the latter usually being simpler. There are several obvious similarities with analyses of laboratory plasmas but the coronal case provides a distinct set of problems in its own right, so it is not possible simply to transpose results from the laboratory to the coronal plasma (see reviews by Spicer 1982, Priest 1983a, b, and Einaudi 1984).

A loop may be free from hydromagnetic instabilities and yet liable to thermal instabilities (or nonequilibrium) if the optically-thin radiation is insufficient to balance with heating. Some analytical (Wragg and Priest 1982, Martens and Kuperus 1982) and numerical (McClymont and Canfield...
1982) studies are available (see the review by Craig (1981)) but, as with hydromagnetic instabilities, it is presently unclear how to treat properly the footpoints of loops and how sensitive results are to such a treatment of boundary conditions.

2. Oscillations in the Corona

A. Observations

Oscillations are reported in a variety of coronal structures and possess a variety of periodicities, from seconds to tens of minutes. Oscillations have been detected in hard X-ray wavelengths (Orwig, Frost, and Dennis 1981; Dennis, Frost, and Orwig 1981; Kiplinger et al. 1983a, b), simultaneously in hard X-ray and microwave (Takakura et al. 1983; Kane et al. 1983), in EUV emission (Antonucci, Gabriel, and Patchett 1984), and in the green coronal line (Koutchmy, Zhugzhda, and Locans 1983; Pasachoff and Landman 1984). Radio wavelengths have revealed coronal oscillations for over a decade; recent reports include a moving Type IV event (Trottet et al. 1981). Prominences are also seen to oscillate (Strauss, Kaufman, and Opher 1980; Malville and Schindler 1981; Malherbe, Schmieder, and Mein 1981; Bashkirtsev, Kopanov, and Mashnic 1983; Bashkirtsev and Mashnic 1984), with periods typically in tens of minutes.

B. Theoretical Aspects

Magnetically Structured Atmosphere. The behavior of magnetoacoustic waves in a magnetically structured atmosphere has been investigated by Roberts (1981), Spruit (1981, 1982), Edwin and Roberts (1982, 1983), Ray and Roberts (1982, 1983a, b), Gordon and Hollweg (1983), Roberts, Edwin, and Benz (1983, 1984), following on from earlier studies (e.g., Wentzel 1979, Wilson 1980). The general conclusion is that structured media support both body waves and surface waves, the forms and speeds of which depend upon the particular values of sound and Alfvén speeds. Both slab and cylinder geometries are amenable to investigation, with applications to uniform pressure coronal loops as well as chromospheric fibrils and photospheric flux tubes. In addition to the sound and Alfvén speeds, two other velocities turn out to be important in structured media: a tube or cusp speed, which is both subsonic and subAlfvénic; and a mean Alfvén speed, which is associated with both a single magnetic interface and with asymmetrical (kink) modes in tubes. Reviews are available in Spruit (1981), Roberts (1982, 1984) and Spruit and Roberts (1983).

The inhomogeneous nature of the corona means that regions of low Alfvén speed may act as wave guides. In particular, dense loops may act as ducts for fast magnetoacoustic waves. Roberts, Edwin, and Benz (1983, 1984) have worked out the temporal signature of an impulsively generated fast wave in a magnetic slab or cylinder. The signature of the wave exhibits short timescales, roughly the loop diameter divided by the internal Alfvén speed. The signature exhibits three phases: first a periodic phase, then a quasi-periodic phase of higher frequency and stronger amplitude and, finally, a rapid decay phase (with the frequency of the oscillation maintained). The explanation for this distinctive signature lies in the dispersive nature of the mode in a duct. Periods in the event are typically on the order of a second (assuming loop diameters of \( \sim 10^8 \) km and Alfvén speed \( \sim 10^8 \) km s\(^{-1}\)). Such signatures offer the possibility of use as a diagnostic of in situ coronal conditions (such as the magnetic field strength). Dissipative effects have yet to be incorporated in the calculations of the dynamical response, but the analysis by Gordon and Hollweg (1983) suggests that these modes are most likely to persist and propagate for long distances in regions of strong (above 10 gauss) field strengths.

Ducted waves may be either kink or sausage modes, accordingly as the tube's axis is displaced or undisturbed in the oscillation (e.g., Roberts 1981). The above described signature is specifically for the sausage mode but higher harmonics than the first of the kink wave will behave similarly. The exception is the principal kink mode which is only weakly dispersive and so may propagate as a single pulse. Both sausage and kink modes are analogous to other, non-magnetic, systems; the sausage mode to Pekene waves in oceanography and the kink modes to Love waves in seismology (Edwin and Roberts 1982, 1983). Additionally, there are close analogies with fibre optics (Roberts, Edwin, and Benz 1983, 1984). Loops may also act as ducts for sound waves but these are virtually non-dispersive.

The oscillation of a loop as a whole is also of general interest. The period is given by the length of the loop and the mean Alfvén speed; for a dense loop of length \( L \) the period is \( 2L/v_A \), where \( v_A \) is the Alfvén speed within the loop (Spruit 1982; Edwin and Roberts 1983; Roberts, Edwin, and Benz 1984). Thus periods of the order of minutes may arise.
Stratified Atmospheres. The above discussion concentrates on the role of magnetic structuring, ignoring gravity. Other aspects of wave behavior have been investigated by ignoring structuring and instead retaining the effect of gravity. Leroy (1981) has examined the propagation of Alfvén waves in a stratified medium and concluded that Alfvén waves observed in interplanetary space cannot have been generated in the convection zone. Bel and Leroy (1981) have argued that sunspots are not the seat of, nor are cooled by, a large flux of outwardly propagating Alfvén waves. (This is at variance with the suggestion of Mullen and Owens (1984) that observed interplanetary Alfvén waves may have arisen from sunspots.) Schwartz, Cally, and Bel (1984) have examined Alfvén waves in an oblique field, showing that a two-layer model atmosphere represents remarkably well the behavior in multi-layered media. They go on to analyze the behavior of a spreading magnetic field (see also Cally 1983), demonstrating an order-of-magnitude increase in coronal flux when field strengths are high (∼3000 gauss).

Leroy and Schwartz (1982), Schwartz and Leroy (1982), and Zhugzhda and Dshalilov (1984) take up the question of the propagation of magnetoacoustic waves, examining the non-WKB limit. Leroy and Schwartz conclude that such modes make only a small contribution to coronal energetics. Schwartz and Bel (1984a,b) examine propagation in an oblique field, concluding that Alfvén waves are the most viable wave option for coronal heating. When the oblique field is almost horizontal, Schwartz and Bel (1984b) find that there is little evidence of the singular critical level behavior associated with the horizontal field case. This raises the question of how physically relevant is the usual treatment of the horizontal case. General reviews of magnetic waves in stratified media have been given by Adam (1981), Thomas (1983), and Campos (1983a,b).

2. Coronal Heating

With the recognition that acoustic waves are not responsible for the heating of the corona (Athay and White 1978; Mein and Mein 1980) has come a general effort to understand the waves in which magnetic fields may prove an essential ingredient. There has been good progress, with a number of promising effects explored in enough detail that they can no longer be described as "hand-waving." The most popular means of heating the corona! Nonetheless, a clear picture of how the corona is in fact heated has yet to emerge and so a description of the various contenders must suffice for the present. Recent reviews are: Kuperus, Ionson, and Spicer (1981), Chiuderi (1983), Hollweg (1983), Priest (1983a,b), and Heyvaerts (1984).

Two processes have been explored for coronal heating: the dissipation of hydromagnetic waves, and the continuous reconnection of stressed magnetic fields.

A. Hydromagnetic Waves

The equations of magnetohydrodynamics admit an Alfvén wave and two compressive (fast and slow) waves. The properties of these waves in a uniform medium are well known but in a non-uniform medium (such as in loops or flux tubes) require re-appraisal (see, for example, Roberts 1981, 1984). Strong inhomogeneities render the propagation of characteristics more complex; indeed, the behavior of mhd waves in a nonuniform media is not fully understood (Goedbloed 1984). The simplest mode to investigate is the Alfvén wave. Heyvaerts and Priest (1983) have demonstrated the phase-mixing of an Alfvén wave propagating in an inhomogeneous medium. Phase-mixing leads to the reduction of the effective length-scale of the wave and consequently to dissipation under the enhanced effectiveness of viscosity and diffusivity (see also Nocera, Leroy, and Priest 1983). Damping of propagating waves by phase-mixing is most efficient for short-period (10 s) waves in a weak (1 gauss) magnetic field; longer periods or stronger fields the mechanism is not efficient enough to heat the corona (e.g., Priest 1983a,b).

In loops standing waves are important and these are also damped by phase-mixing, but now in time rather than in space. Estimates (e.g. Priest 1983a) give a time of typically 20 wave periods for damping under coronal conditions. Dissipation may be further enhanced by local Kelvin-Helmholtz instabilities generating turbulence (Heyvaerts and Priest 1983; Browning and Priest 1983) and a turbulent cascade (Hollweg 1983).

In addition to the Alfvén wave a non-uniform medium supports compressive modes. The presence of inhomogeneities again allows the build-up of sharp velocity gradients and thus enhanced dissipation (Rae and Roberts 1981, 1982), making magnetoacoustic waves a candidate for coronal heating. The complexity of the behavior of magnetoacoustic waves in a nonuniform medium makes the complementary approaches of analytical (e.g., Sakurai and Granik 1984) and numerical (e.g., Steinolfsson 1984) analyses here invaluable.
A somewhat different approach to the coronal heating problem has been taken by Ionson (1982, 1983, 1984), who has argued that the linear MHD equations may be cast in the form of an equivalent LRC circuit, with the circuit's coefficients being determined by the plasma's geometry and physical state; photospheric conditions provide a driver. The use of equivalent circuits has also been discussed by Spicer (1981, 1982). Because of the general complexity of the problem, the application of equivalent circuit concepts provides a valuable means of investigating the physics of coronal heating. Though it remains presently unclear how representative such circuits are of the actual coronal physics, and how much of that physics is averaged-out in the derivation of the circuit equations, quite separate analyses by Heyvaerts and Priest (1983, 1984) would seem to provide strong support for the circuit approach.

Waves may also heat coronal loops by damping in a resonant cavity (Hollweg 1981, 1983, 1984; Zhugzhda and Locans 1982). Hollweg (1984) has considered a three-layer model of a coronal loop, the two end layers representing the photosphere and the middle layer the corona. Resonant transmission peaks arise if the middle-layer cavity is driven externally by incident waves from the photosphere. The analysis permits a derivation of the heating rate which agrees with that obtained by Ionson (1982) from a circuit approach. However, estimates of values are much smaller than those in the circuit approach of Ionson (1982), though an allowance for leakages is possible (Ionson 1984). Hollweg and Sterling (1983) have compared the predictions of the resonant loop model with available coronal loop data, finding agreement.

B. DC Currents

Rapid motions in the photosphere may give rise to waves which propagate into the corona and dissipate their energy in the various ways outlined in (A). On the other hand, slow photospheric motions may build up stresses in the corona, the resulting field perhaps being force-free. Such DC current systems represent a source of energy for heating the corona if the stressed field can be dissipated or reconnected at an adequate rate (as compared with the rate for build-up of the field stresses). Direct dissipation of magnetic energy by Joule heating is inadequate to meet the coronal power needs unless scales as small as centimeters (or meters, if microturbulence is admitted) are envisaged (Heyvaerts and Priest 1984). Heating may also result from the resistive tearing modes (Galeev et al. 1981; Chiuderi 1981; Kuperus, Ionson, and Spicer 1981; Sturrock and Uchida 1981; Parker 1984).

Heyvaerts and Priest (1984) have recently considered the application of Taylor’s hypothesis (familiar in laboratory plasma physics; Taylor 1974) to solar or stellar conditions (see also Norman and Heyvaerts 1983). The application of the hypothesis implies that at any given time the coronal magnetic field is a linear force-free one, determined from the evolution of magnetic helicity (see also Berger 1988). Heyvaerts and Priest demonstrate that in this theory heating results from photospheric motions which build-up field stresses at just that rate which is comparable to the rate at which the field is relaxed by reconnection; in this theory, photospheric motions that are either too fast or too slow give negligible heating. The efficiency of heating is limited by the geometrical ratio of the scale of the driving velocity cells to the scale of the magnetic field, and also by the ratio of the reconnection (dissipation) timescale to the transit time of the driving velocity across the base of the magnetic structure (Parker 1983a, b; Heyvaerts and Priest 1984). Thus, for loops with very small cross-sections in the photospheric base the efficiency of this process is strongly reduced.

In general terms, the view that slow small-scale shufflings of magnetic fields in the photosphere results in a significant heating in the corona has been advocated by Parker (1982, 1983a, b), without reference to Taylor’s hypothesis. Parker demonstrates that wrapping and winding of magnetic field at the structure’s footpoints inevitably leads to reconnection, there being no static equilibrium available to the field (Parker 1972). This, Parker concludes, is the basic cause of the X-ray corona. Parker (1984) points out that the nonequilibrium of the magnetic field is closely akin to the phenomenon of magnetohydrodynamic turbulence (Matthaeus and Montgomery 1981).

Both Parker (1982) and Heyvaerts and Priest (1984) build their scenarios of coronal heating on the transference and subsequent dissipation of magnetic stresses in the corona, the stresses being induced by motions in the photosphere. Consequently, the heating rate is essentially the same in both calculations, though the geometrical scaling factor (between the velocity cells and the scale of the magnetic field) is squared in Heyvaerts and Priest (1984), presumably as a consequence of the restrictions brought about by the Taylor hypothesis, and linear in Parker (1982). Since this factor is small, such a difference may be important.
The notion that the manipulated photospheric field is inevitably subject to nonequilibrium (Parker 1972, 1981, 1982; Tsinganos 1982) has been taken up by others, who point out that small motions of the footpoints may in fact result in fields which possess large variations in boundary layers near the footpoints (Sakurai and Levine 1981), and that small perturbations which change the field's topology are in fact excluded in Parker's discussion (Rosner and Knobloch 1982; see also Priest 1984).

Finally, it should be noted that DC heating can also be treated from a circuit viewpoint (Johnson 1982, 1984), though two or more circuits may be needed for an adequate representation; see the discussion in Heyvaerts and Priest (1984).

References

Priest, E.R. 1984, Reports Progress Physics, in press.
Steinolfson, R.S. 1984, Phys. Fluids, 27, 781.

VII. THE SUN AS A STAR

(K. R. Sivaraman)

An important topic of current interest both in solar and stellar physics is the possibility of identifying solar phenomena in stars through an understanding of these on a global scale on the sun. We concentrate here on the recent research concerning the variability in solar irradiance from disc integrated observations (sun as a star) in the white light as well as in monochromatic wavelengths.

1. Luminosity variation in white light

The principal scientific motivation for monitoring the solar constant is to detect any variability that could explain the climate changes over the earth. For an excellent review see Newkirk (1983). Measurements in 1980 by the precision radiometers on NIMBUS-7 and SMM have revealed temporal dips of 0.1 to 0.3% in the measured solar irradiance which had eluded previous detection. An empirical model ascribing 90% of the short time irradiance fluctuations to sunspot blocking reproduces best the ACRIM data between 1980-1982. The solar irradiance reconstructed from the archived sunspot areas from 1874 through 1981 using this model imply that the average solar constant during an active year can be as much as 0.1% lower than during a quiet year (Hoyt and Eddy, 1983). Photospheric heat flow can also be modulated by large laminar convective cells causing temperature perturbations between up and down flowing regions on scales of \( \sim 1 \times 10^5 \) km and life times of months (Gilman, 1978). Also the subsurface magnetic concentrations might cause 'thermal shadows' on the photosphere (Spruit, 1977, Foukal et al. 1983). But the continuum maps outside spots and faculae show that temperature inhomogeneities on these scales are below 2–3° K, which is far below the spot signal (Foukal and Fowler, 1984). The heat blocked by
sunspots is apparently rapidly redistributed for storage throughout the convection zone over time scales at least comparable to the spot life times. The efficient storage and slow release explains the spot induced dips in the radiometry data. (Foukal et al. 1983).

2. Luminosity variations in monochromatic radiation

2.1. Photospheric variability

Changes in luminosity are intimately related to the possible slow global changes in photospheric temperature which can be detected by monitoring the equivalent widths of temperature sensitive spectral lines originating in the photosphere. During the ascending phase of solar activity (1976-1980) the full disc equivalent widths of C1 5380A and four Fe I lines representing the low and high photosphere showed a steady decrease, but remained constant since 1980 (Livingston and Holweger, 1982; Holweger et al. 1983). This calls for more data to decide the presence of any 11-year cycle modulation. Similar behaviour of all the diagnostic lines can be reconciled only by a slight flattening of the photospheric temperature gradient as the carbon line has a temperature sensitivity opposite to that of iron lines. Since the temporal behaviour of these lines has no correlation with short lived features like active regions, it seems to reflect true global changes accompanying solar activity.

Another diagnostic is the spectral line asymmetry which is a measure of the granular convection. The C-shaped line bisector is more blue shifted relative to the core over quiet regions than in magnetic regions. The full disc Fe I 5250.6 mean bisectors from the Kitt Peak 13.5m spectrograph show a mid-C shift towards the core by ~ 2mA between 1976 and 1981. Better observations with the FTS of ten similar Fe I lines confirm this trend between 1980-1982, suggesting a global decrease in the net upward velocity of convection in the photosphere with increase in solar activity (Livingston, 1982). Pic du Midi observations showing that the size of granules is reduced at that time support this (Macris and Rösch, 1983). Far infrared radiometry of the full disc indicates a warming of the temperature minimum accompanying solar activity (Müller et al. level in the atmosphere contradicts this finding (Cook et al. 1980).

2.2. Chromospheric variability

K-emission. The first attempt to demonstrate the variability in the Ca II K line emission from the 'Sun as a star' was by Bumba and Topolova (1967). The continuing disc integrated K emission measurements commencing in 1969 at Kodaikanal provide data on the variability of the K-line parameters over a full cycle (Bappu and Sivaraman, 1971; Sivaraman et al. 1984). Other published results, although for a limited period are those of White and Livingston (1978) and Keil and Worden (1984). The 1A emission index for the years 1975-1981 suggest that the excess emission in the ascending phase of the solar cycle arises from plages (White and Livingston, 1978). The quiet sun is represented well by the summation of the contributions from the network and the cell interior forming one component. The addition of two or more components, the plages and the active network (remnants of decayed plages) gives good agreement with full disc emission except near the solar maximum (Skumanich et al. 1984).

He I 10830A. Full disc He I 10830A equivalent width measurements since 1974 show it was lowest at 24 mA in mid 1975, a year earlier than sunspot minimum and steadily rose afterwards to 83 mA in late 1981, two years after the sunspot minimum. The rotational modulation reveals active longitudes. The apparent rotation period increased from 1977 to 1981 and has been shorter since 1981 which contradicts the equatorial migration of active regions during the course of solar cycle (Harvey, 1983).

Lyman Alpha. The ground based K index serves as a good proxy to space measures of Lyα and the EUV. The Lyα flux computed using a three component model of K with the photometric contrasts at Lyα agrees well with the measured flux in the years 1969-1980 except near the solar maximum. High resolution observations may bring better agreement as, at 1"×1" resolution 33% of the disc would have enhanced Lyα emission at solar maximum (Lean and Skumanich, 1983).

3. Radius variation

A change in the solar output would require a change in the solar radius. A day to day variation of 0.4" is detected by the dedicated solar diameter telescope in Boulder (Brown 1982). LaBonte and Howard (1981) from analysis of 5 years magnetograph data report that R is constant to within ±0.1". The main problem is to be able to relate any apparent diameter change to change in lumi-
nymity with certainty. To what accuracy must $\Delta R/R$ be measured to produce a change of $\Delta L/L \sim 0.1\%$? Unless this is settled, the results of the radius change measurements cannot be linked to luminosity changes.

4. **Rotation**

A plot of the daily mean plage areas would reveal the 27 day modulation (Bappu and Sivaraman, 1971). Temporal power spectra of the daily plage index for the period 1976-1982 as a whole as well as of the broken data of one year each show only two peaks at 27 day and 13 day periods, (Keil and Worden, 1984). Analysis of the Mt. Wilson disc integrated magnetic flux also shows the 27 day and its harmonics with an accuracy of $\sim 2\%$ (LaBonte, 1982). But none of the attempts have revealed the differential rotation of the Sun from full disc data.

5. **Solar mean magnetic field**

The only measurement of the magnetic field of the sun integrated over the entire disc is the one using the Fe I $3250\AA$ line for the years 1968-1981 due to Severny and his co-workers. Year to year values of the yearly means of the mean magnetic field show changes as much as by factors 3 to 4 (Kotov and Severny, 1983).

**References**