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

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1. INTRODUCTION (J. Harvey)

This report was planned in cooperation with Commission 10. Both this report and the one of Commission 10 together give a coordinated overview of published developments in solar research during the past three years. For several years, the scope of Commission 12 has included not only the areas indicated by the title of the Commission but also the structure of the solar interior. This broadening of coverage has led to a proposed renaming of this Commission: Solar Structure, which is currently under consideration by the IAU Executive Committee.

Highlights of the last three years include continuing progress in understanding the structure and dynamics of the solar interior by the complimentary methods of helioseismology and neutrino flux measurements. Results from both techniques show that our understanding of the interior is still rudimentary. The deficit of high-energy neutrinos has been confirmed and preliminary results suggest that there is also a striking deficit of low-energy neutrinos as well. The latitudinal differential rotation of the convection zone was found to be similar to that observed at the surface. Theoreticians have not yet been able to explain the relative lack of depth variation. Great progress has been made in modeling the structure and dynamics of the upper convection zone and lower photosphere. These efforts have been accompanied by superb observations of the photosphere using new and existing facilities together with advanced instrumentation and data reduction methods. The source of heating of the sun's upper atmosphere still remains a mystery.

I thank the authors of this report for their timely contributions. I also thank the members of the organizing committee for their help and support during the past three years.

2. SPECTRAL IRRADIANCE VARIABILITY (J. M. Pap)

During the past three years considerable effort has been made to understand the real nature and physical origin of solar irradiance variability observed at different wavelengths and in the entire spectral range. Variations on different time scales, from minutes to the 11-year solar cycle, were revealed in solar irradiances (Hudson 1988a). Although the overall pattern of the solar irradiance variability is similar for different spectral bands, being higher during high solar activity conditions, remarkable differences exist between the magnitude and the shape of the observed changes (Donnelly 1989). These differences result from the different physical conditions in the solar atmosphere where the irradiances are emitted (Jordan 1988). Thus, study of solar irradiance variability also has a great importance for astrophysics, besides its terrestrial applications.

2.1 X-ray

The largest variability over the solar cycle is observed in the 1-8 Å soft X-ray flux. The background level can vary a factor of 85 during the solar cycle, while the flux can increase 10^5 above the background, due to flares (Wagner 1988). Intermediate variations (less than a year) are recognized in the background X-ray flux, whose

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major part arises from active regions (Bornmann & Matheson 1990). These variations show the major features seen in chromospheric and coronal indices (Wagner 1988; Feng et al. 1989), such as the CaII K index, He I 1083 nm line equivalent width (EWHe) and 10.7 cm radio flux (F10.7). The observed variations of X-ray flux are attributed to systematic changes in the coronal temperature and density (Hudson 1988a).

2.2 Extreme Ultraviolet Irradiance

A model (SERF2) of the solar EUV irradiance variability, based on the Atmospheric Explorer E (AE-E) satellite data set and rocket measurements (Feng et al. 1989; Woods & Rottman 1990), has been developed for aeronomical use (Tobiska 1988). Model calculations are extremely important at EUV wavelengths because in the 1980s no satellite EUV measurements were made, except for the ASSI experiment on the San Marco D/L satellite launched in March 1988 (Schmidtke et al. 1990). Tobiska & Barth (1990) showed that the Lyman-α emission is a reasonably good proxy for the chromospheric EUV irradiance, while F10.7 is an effective transition region and coronal EUV emission indicator.

2.3 Ultraviolet Irradiance

Recent observations from SME, Nimbus-7, NOAA9 and NOAA11 satellites (Donnelly 1988; Rottman 1988; Schlesinger & Heath 1988) have significantly improved our understanding of UV irradiance variability. Variations over the solar cycle, on intermediate and short time scales are clearly recognized (Simon et al. 1987; Donnelly 1989; Barth et al. 1990). The long-term increase in solar UV irradiance (Mg II core-to-wing ratio and Lyman α) during the rise of solar cycle 22 is comparable to the decrease from the peak of solar cycle 21 (late 1981) to the 1986 minimum (Donnelly 1990; White et al. 1990). Although UV irradiance between 200 and 300 nm represents only 1% of the total solar output, it accounts for a fifth to a third of the decrease of total irradiance during the decline of cycle 21 (Lean 1989; London et al. 1989).

Barth et al. (1990), Pap et al. (1990a) and Donnelly (1990) have pointed out a reasonably good linear relationship between UV irradiance and 10.7 cm radio flux during the declining portion of solar cycle, which breaks down during solar minimum. Both fluxes increase in parallel with the growing activity of cycle 22, however F10.7 shows a faster rise and thus overestimates the actual UV variability (Donnelly 1990; Pap et al. 1990a). Further differences have also been recognized on the active region time scale (Barth et al. 1990) which are attributed to the evolution of active regions (Donnelly 1990).

A reasonably good relationship is found between the changes in the UV irradiance and in the full disk CaII K index (White et al. 1990) and in the He 1083 nm line equivalent width (Pap et al. 1990a). Both indices are used as a measure of the plage and network radiation (Lean 1988). Lean (1988) claims that approximately half of the long-term UV irradiance variability is caused by the network component. Pap et al. (1990a) pointed out that during solar minimum the Ca plages underestimated the observed UV variability and suggested that at this time the bright network gave the major contribution. Photometry of the Ca plage remnants, which are excluded from the present Ca-K plage measurements (Marquette & Martin 1988), shows that the remnants account on average for about 10% of the changes in UV spectral bands and that the remnant contribution changes with time (Pap et al. 1990b).

2.4 Total Irradiance, Visible and Infrared Spectral Bands

The total irradiance showed an early maximum prior to the start of the Nimbus-7 operation in November 1978 (Willson & Hudson 1988, 1990; Hoyt & Kyle 1990) and decreased (0.015% per year) during the declining portion of solar cycle 21 (Willson & Hudson 1988). The rate of increase of total irradiance was substantially greater during the rising portion of solar cycle 22, causing an asymmetry in the temporal variation of total irradiance (Willson & Hudson 1990).

Several ideas and models have been put forward to explain this solar cycle variation (Frölich et al., 1990). Foukal & Lean (1988) and Livingston et al. (1988) attribute it to the changing emission of bright magnetic elements, including faculae and active network. However, the empirical model of total irradiance based on the EWHe (Foukal & Lean 1988) underestimates the observed decrease of total irradiance during solar maximum. Livingston et al. (1988) found that a combination of two lines, Mn 5394 Å and CN 3883 Å were needed to fit the ACRIM signal over the entire solar cycle. Schatten (1988) and Schatten & Orosz (1990) stress that the high contrast of white-light faculae near the solar limb and of polar faculae at the beginning of a cycle may cause an early increase and thus an asymmetry of total irradiance variations relative to solar activity. Recently Kuhn et al. (1988) reported temperature changes with latitude over the solar cycle, based on broad-band, two-color photometric observations of the brightness distribution just inside the solar limb. This temperature change may explain the irradiance variations over the solar cycle, but it is not clear yet whether it may be linked to the bright network component (Fröhlich et al. 1990).

Several efforts have been made to study the changes in total irradiance on active region time scale, using estimates of sunspot and facular areas. Willson & Hudson (1988) found that the simple Photometric Sunspot Index (PSI) model, which is based on sunspot areas and their contrast, can explain approximately half of the variance in the ACRIM data. Faculae are considered as potential contributors of excess luminosity (Chapman 1988; Hudson 1988a). LaBonte (1987) suggested that the photospheric network may contribute as much to irradiance fluctuations as the faculae. Fröhlich & Pap (1989), using multivariate spectral analysis, pointed out that during solar maximum more than 90% of short-term irradiance variations were related to sunspots and bright magnetic elements, while during solar minimum the main contribution arose from the active network. Their analysis shows that after removing the effect of sunspots and bright elements from total irradiance, changes still remain with periods around 27 and 9 days. This may result from currently unknown processes within the convective zone.

Photometric measurements of sunspots and plages are in progress at the San Fernando Observatory (Chapman 1988, 1990) and at the Kiepenheuer-Institut (Steinegger et al. 1990; Brandt et al. 1990). The "Photometric Sunspot Deficit (PSD)" (Chapman 1988) shows the same major fluctuations as seen in the ACRIM data. Chapman (1988) pointed out that the PSD and the PSI are well correlated but in a slightly non-linear fashion. From photometric measurements Lawrence (1987) estimates the mean delay between sunspot luminosity deficit and the facular excess at about 0.7 solar rotations. Steinegger et al. (1990) and Brandt et al. (1990) found that the umbral/penumbral area and temperature ratios change from spot to spot, and these photometric values on the average yield lower irradiance deficit than using the PSI model. Incorporation of real photometric measurements into the PSI model may help to clarify the question to what extent the facular emission compensates the sunspot deficit (Chapman 1988; Brandt et al. 1990).

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3. THEORY AND MODELING OF SOLAR CONVECTION (W. J. Merryfield)

Turbulent convection such as occurs in the outer 30% or so by radius of the sun is such a rich and complicated phenomenon that numerical computations are invaluable for its study. Although we cannot yet encompass within a single computation the considerable range of spatial scales exhibited by convective motions in the sun, much progress has been made, particularly in understanding the dynamics of the smallest (granular) scales. Such progress has been aided considerably by the increase in performance of the fastest computers, as measured in floating point operations per second, by a factor of about 20 during each of the last four decades (Kerner 1990). This trend, should it continue, bodes well for the continued rapid development of this subject, particularly as massively parallel computers such as the Connection Machine become available.

3.1 Modelling of Compressible Convection in Three Dimensions; Nature of the Solar Granulation

Convection in the sun is a turbulent, three-dimensional flow in a highly stratified medium, and thus presents substantial challenges to the modeller. In addition, the Mach number in the surface layers is of order unity, so that compressive effects, including shocks, become important there. In recent years there have been primarily two approaches to studying such flows: simulating the dynamics of the solar granulation in as detailed a manner as is feasible, and examining the generic properties of convection in an idealized system as various dimensionless parameters are varied.

The former approach is exemplified by the recent work of Nordlund & Stein, who consider surface convection in a small volume, say 6 x 6 Mm in cross section, extending 3 Mm downward from the temperature minimum. They treat radiative transfer and the equation of state realistically, and adopt permeable upper and lower boundaries, allowing material and disturbances such as waves to exit nearly unimpeded. The computational domain encompasses several granules, and is taken to be horizontally periodic. The equations of motion typically are solved on a 63x63x63 grid.

Some of their most striking results concern the topology of convective flows beneath the photosphere (Stein & Nordlund 1989). They find that the cool, sheet-like descending flows which define the intergranular lanes soon collapse into filamentary downdrafts, this process becoming important already just 500 km beneath the photosphere. Thus, the granulation pattern observed at the surface, exhibiting warm, topologically disconnected upflows and cool, topologically connected downflows, may be purely a surface phenomenon. Further beneath the photosphere, the filamentary downdrafts begin to merge in a hierarchical, tree-like manner. The authors speculate that this hierarchical merging extends to scales comparable to the 200 Mm depth of the convection zone, and question whether there indeed exists a clear distinction between mesogranular and supergranular scales of convection.

Another series of simulations examines three-dimensional compressible convection in the absence of complexities such as those introduced by radiative transfer, now treated in the diffusion approximation, and ionization effects (Toomre et al. 1990; Cattaneo et al. 1990). Particular attention is given to the variation of flow properties as the Prandtl number, describing the ratio of viscous to thermal diffusion, is reduced from unity to 0.01. (The characteristic Prandtl number in the convection zone is of order 10^{-6}). In contrast to the simulations of Nordlund & Stein, the top and bottom boundaries are taken to be impermeable. The system is again horizontally periodic, and up to 96x96x96 grid points are employed.

The simulations exhibit a flow topology much like that seen by Stein & Nordlund (1989), with connected downflows and disconnected upflows near the surface, the reverse of this topology being observed at greater depths. At Prandtl numbers of order unity, the flow is characterized by relatively smooth, laminar structures throughout the domain. However, at lower Prandtl numbers of 0.01-0.1, the coherent downdrafts found beneath the surface persist, but the surrounding flow becomes increasingly disordered and turbulent. Furthermore, the downward kinetic energy flux carried by concentrated downdrafts becomes so large that it largely cancels the substantial upward enthalpy flux carried by these structures. This leads to the rather surprising result that convective energy transport occurs primarily in the relatively feeble and disorganized upflows, in which the spatial correlation between vertical velocity and entropy fluctuations, necessary for thermal energy transport to occur, is comparatively weak.

Chan & Sofia (1989) also simulate compressible convection in three dimensions, and derive from their results a number of quantitative relationships between horizontally averaged flow variables, residual rms fluctuations, and spatial correlations between such quantities. Their results show, in concurrence with Cattaneo et al., that the downward kinetic energy flux, ordinarily neglected by mixing-length theory, can offset considerably the upward transport of heat via enthalpy flux. The authors note that mixing-length theory might be modified to include such effects if a relation between the kinetic energy flux and the local mean stratification could be found. After carefully analyzing their data, however, they conclude that no such relation is evident.

3.2 Interaction of Solar Granulation with Magnetic Fields

Recent high-resolution observations (e.g. Title et al. 1990) have revealed with unprecedented clarity the rich and complicated interplay between convection and magnetic fields in the surface layers of the sun. It is seen, for example, that in regions having a comparatively large (> 75 Gauss) mean field, granules live perhaps twice as long as in non-magnetic regions. Also, horizontal flow speeds are somewhat reduced in magnetic regions, and the granulation there appears odd and fragmented in comparison to magnetically quiet regions.

In a preliminary attempt to understand such observations, Nordlund & Stein (1989, 1990) have incorporated magnetic fields into the granulation model described above. One such computation begins by superimposing a vertical 500 Gauss field on a previously computed non-magnetic flow. As the solution evolves over about 40 minutes of solar time, the field becomes concentrated into intergranular lanes, especially at cell vertices. The resultant girdling of granules by nearly vertical magnetic sheets dynamically isolates them from one another, and shields them from being buffeted or engulfed by adjacent cells. Such granules therefore live longer than granules in non-magnetic regions, in agreement with observations. In a second computation a field of 2000 Gauss, comparable to that in a sunspot, is imposed. In this instance granular convection is immediately suppressed, and within a few minutes the photosphere cools and dims to 20% of its initial intensity. Intermittent episodes of subsurface convection follow, occurring at intervals of about an hour. Such behavior may provide clues to the nature of vertical energy transport in sunspots, and to the origin of umbral dots. Additional studies along this line should further improve our understanding of sunspots and other magnetic structures, such as plages and pores.

3.3 Giant Cell Convection

At present, the nature of convective motions on scales comparable to the depth of the convection zone (the so-called giant cells) remains unclear. Numerical simulations and a space-borne experiment exhibit banana-like cells aligned with the rotation axis (Glatzmaier 1984; Gilman & Miller 1986; Hart et al. 1986), yet observers report instead evidence for toroidal giant cells resembling donuts which migrate either toward the equator (Snodgrass & Wilson 1987), or toward the poles (Ribes & Laclare 1988). The dynamical influence of rotation would tend to favor the former pattern; indeed, it is difficult to see how donut-like rolls could be present unless a toroidal magnetic field, which would suppress banana cells via the Lorentz force, resided within the convection zone. That such a field exists with sufficient strength to alter the pattern of convection has been hypothesized by Parker (1987) to account for why the sun's toroidal field is not rapidly expelled by magnetic buoyancy.

One is thus led to ask what pattern would be selected by large-scale motions in a rotating convection zone in which a horizontal magnetic field is present. Perhaps the most fundamental approach to this problem is to perform a linear stability analysis. This has been done for a Boussinesq plane layer by Jones & Galloway (1988), and for a polytropic atmosphere by Jones, Roberts & Galloway (1990). They model convection at the solar equator, and so consider gravity, the rotation axis, and the magnetic field to be mutually perpendicular. In both instances it is found that convection sets in as rolls aligned with the magnetic field if the Elsasser number, which measures the ratio of the Lorentz force to the Coriolis force, much exceeds unity. In addition, in the polytropic atmosphere convection sets in not as steady motions, but as traveling waves. This suggests that if toroidal convective rolls were to be present in the sun, they indeed would migrate in such a manner as described above.

Mildly nonlinear computations have been performed by Merryfield (1990). He considers convection in a Boussinesq plane layer which contains a horizontal magnetic field and rotates about an axis perpendicular to the field, with an inclination corresponding to a solar latitude of 30 degrees N. It is found that convective rolls aligned with the field are preferred over a larger parameter range than linear theory would suggest, and that the solutions are strongly hysteretic, so that such rolls tend to persist, even when the horizontal field is reduced somewhat. However, when the field falls below a critical value the motions switch to rotationally-aligned rolls, and the magnetic field is annihilated. Such a transition appears permanent, as the magnetic field would seemingly have to be regenerated on the overturning time scale, a factor of one hundred or so shorter than the solar cycle, for the field-aligned pattern to be regained. This perhaps discourages suggestions that such transitions are related to Maunder-type minima in solar activity (e.g. Parker 1979, Dogiel 1980).

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4. PROBING THE SOLAR INTERIOR (S. Vorontsov & W. Däppen)

Solar seismology has progressed significantly in the last few years. A large number of new observational and theoretical results are found in the proceedings of the three most recent major conferences, the IAU Symposium 123 *Advances in Helio- and Asteroseismology* (I), the symposium *Seismology of the Sun and Sun-Like Stars* (II), and the IAU Colloquium 121 *Inside the Sun* (III). Current reviews of the field are Bahcall & Ulrich (1988), Libbrecht (1988), Vorontsov & Zharkov (1989) and the newly added chapter on solar seismology in the 2nd edition of the monograph *Nonradial Oscillations of Stars* by Unno et al. (1989).

Thousands of solar acoustic oscillation frequencies, measured with a relative accuracy of up to 10^{-4}, are now available (Duvall et al. 1988; Libbrecht & Kaufman 1988; Pallé et al. 1989a). The latest frequency tables are published in Libbrecht et al. (1990). Despite intensive theoretical efforts in modelling the solar interior, there are still significant discrepancies between observational and theoretically computed frequencies. Extensive studies of different solar models have been continued, concentrating on the effects of opacities (Korzennik & Ulrich 1989), the equation of state (Christensen-Dalsgaard et al. 1988; Stix & Scaley 1990), and, beyond the standard model, the possibilities of element diffusion (Cox et al. 1989) or WIMPs (Gilliland & Däppen 1988).

The amount and quality of the observational data have stimulated the development of suitable inversion techniques to probe the internal structure of the sun (with a first target being the sound speed distribution) directly from the observational frequencies (Christensen-Dalsgaard et al. 1989; Dziembowski et al. 1990; Gough & Kosovichev 1990; Sekii & Shibahashi 1989; Vorontsov 1989). The results of the different inversions are in reasonable agreement. In the outer two thirds of the solar radius, sound speed can now accurately be inferred from oscillation frequencies, with small but significant (within 1 percent) deviations from model predictions in the radiative interior, which put constraints on the opacity. Of course, the central solar regions are the most difficult to study using p-mode frequencies; however, there are consistent indications that in the standard evolutionary models problems exist with the description of the energy-generating core, probably connected to some sort of element mixing. The main sources of the discrepancies appear to be related to the structure of the outermost solar layers. Theoretical techniques to study this problem are now under development (e.g. Brodsky & Vorontsov 1989; Baturin & Mironova 1990; Marchenkov & Vorontsov 1990). From the sound-speed inversions, the depth of the convection zone was estimated to be 30 ± 1 percent of the solar radius (Vorontsov 1989). Very recently, Christensen-Dalsgaard et al. (1990) obtained a slightly lower value, 28.7 ± 0.3 percent.

New, accurate measurements of the rotational splitting of p-mode frequencies have led to significant progress in the study of the solar internal rotation. Within the convection zone, the angular velocity appears to be almost independent on depth, the latitudinal variation being that observed at the surface; near the base of the convection zone, there is a transition to uniform (rigid) rotation in the radiative interior (Brown et al. 1989; Dziembowski et al. 1989; Kosovichev 1988; Rhodes et al. 1990). Theoretical studies of possible effects of a magnetic field on solar oscillation frequencies were continued by Campbell & Roberts (1989), Gough & Thompson (1990) and Zweibel & Däppen(1989). Dziembowski & Goode (1989) found some evidence for a toroidal magnetic field concentrated near the base of the solar convection zone while analyzing the even component of the frequency splittings measured by Libbrecht (1989). F. Hill (1989) has developed a technique of "ring diagrams" of high-degree modes to study the large-scale convective flows beneath the solar surface.

With accurate observational data now being around for more than ten years, it is beyond any doubt that there are small variations of the oscillation frequencies that correlate with the solar cycle (Gelly et al. 1988; Libbrecht & Woodard 1990: Pallé et al. 1989b; Rhodes et al. 1988). The detailed frequency dependence of the frequency variations indicate that the perturbations in the solar structure are located near the surface (Libbrecht & Woodard 1989).

Linewidths of solar p modes were measured by Libbrecht (1989) and Elsworth et al. (1990), and they serve for a better understanding of mode damping and excitation. The oscillation amplitudes and their frequency dependence appears to be in reasonable agreement with the mechanism of stochastic excitation of p-modes by acoustic turbulence (Goldreich & Kumar 1988). A further diagnostic is given by measurements of the phase shift between intensity and velocity observations (Jiménez et al. 1989).

Up to now, all the information about the solar interior has come from high-frequency acoustic modes. Although no decisive observational results have been reached about possible long-period oscillations, the theoretical studies were continued, including the problem of g-modes excitation (Merryfield et al. 1990), visibility of g-modes (Berthomieu & Provost 1990) and a possible explanation of the 160-minute oscillation (Vandakurov 1987), whose existence remains doubtful (van der Raay 1989).

Solar neutrinos have challenged both astrophysics and particle physics. The well known discrepancy between the high-energy neutrinos observed in Davis' chlorine experiment (Davis et al. 1990), which has recently been confirmed by the Kamiokande group (Hirata et al. 1990a,b), and the predictions from the standard solar model (e.g. Bahcall & Ulrich 1988) has led to the so-called solar neutrino problem. In the near future, the results from the low-energy neutrino experiments using gallium will be known [for a detailed discussion see Kirsten 1990 (GALLEX); Gavrin 1990 (Baksan)].

The theoretical prediction of the high-energy neutrino flux is a subtle affair (Bahcall & Ulrich 1988), since with slightly non-standard models one can reduce the predicted neutrino flux by the required amount. However, this is not possible for low-energy neutrinos, which are tightly constrained by the observed solar luminosity. Should the results of the gallium experiment also turn out to be similarly deficient, then it would be virtually inevitable to consider neutrino oscillations (for instance by the MSW mechanism, see e.g. the review by Smirnov 1990). However, although there is no fundamental reason for neutrinos to be massless, their actual mass can be in a huge range of more than 10 orders of magnitude, and it would be a remarkable coincidence if they lied within the rather narrow window required for the MSW mechanism (Harari 1990).

Finally, we mention the interest in detecting possible time variations of the neutrino flux (Davis et al. 1990; Hirata et al. 1990b). Such variations are relevant both for solar physics (especially if they could be correlated to the variation of other quantities such as the radius or the sunspot number), but also for the propagation of neutrinos between the sun and Earth. For instance, neutrino enrichment within the Earth would cause a day-night modulation of the neutrino flux (Spiro et al. 1990).

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5. CHROMOSPHERIC AND CORONAL HEATING (P. Ulmschneider)

The heating phenomenon in chromospheres and coronae very likely cannot be explained by a single process but is rather due to a *multitude of mechanisms*. Some of these operate globally, others only in particular physical situations and magnetic field geometries. At the present time it is not possible to decide which mechanisms are the important ones. This is due to the thin observational basis and the poor state of theoretical development of many mechanisms. A comprehensive review up to mid 1989 is given by Narain & Ulmschneider (1990) and the proceedings of a recent conference is a nice summary of work in this field (Ulmschneider et al. 1990). Based on the mechanical energy input, the various processes are broadly classified as *wave mechanisms* and *electrodynamic mechanisms*. The wave mechanisms comprise acoustic waves, fast-, slow magnetoacoustic and Alfvén body and surface waves. Waves in late-type stars are excited by fast turbulent motions at the top of the convection zone, by small-scale instabilities, or by mode-coupling from other waves. The electrodynamic mechanisms are current dissipation, micro/nanoflares and magnetic flux emergence. Here the energy is introduced into the magnetic field by slow convective motions of the photospheric foot points or by buoyancy.

5.1 Wave heating

Acoustic waves are an important chromospheric heating mechanism locally for nonmagnetic areas and globally for very slowly rotating stars (Ulmschneider et al. 1987; Ulmschneider 1989, 1990). Schrijver (1987) observed that there are *two basic contributions* to the chromospheric heating: the acoustic heating which is independent of rotation and is a minimum contribution for a given T_{eff} and the efficient rotation related magnetic heating. Sterling & Hollweg (1988), Sterling & Mariska (1990) discuss wave heating by spicules. Cuntz & Muchmore (1989) studied dynamical effects of acoustic waves in α Boo with radiation damping by CO and SiO molecules. Cuntz (1990) computed acoustic waves in α Boo, α Tau, α Ori. Musielak & Rosner (1987, 1988) as well as Musielak et al. (1987, 1989) calculate the generation of mhd waves by turbulent motions in a gravitationally stratified medium and of longitudinal mhd waves in flux tubes. They do not find enough energy to explain the observed stellar coronal emission. Bogdan & Knölker (1989) discuss the propagation of compressive waves in a radiating, uniformly magnetized, homogeneous fluid. Musielak et al. (1989) and Musielak (1990) studied propagating and nonpropagating compression waves in an isothermal atmosphere with uniform horizontal magnetic field.

Zähringer & Ulmschneider (1987) and Ulmschneider & Zähringer (1987) computed the propagation of nonlinear time-dependent adiabatic longitudinal and transverse mhd waves along vertical flux tubes. Ferriz-Mas et al. (1989) discussed linear wave modes in thin magnetic flux tubes up to second order. V. Uexküll et al. (1989) found that the observed network oscillations supply enough energy to balance the radiation losses of the high chromosphere. Similon & Sudan (1989) studied the energy dissipation of Alfvén wave packets in coronal arches. They find that more realistic stochastic magnetic geometries will dramatically increase the heating. Wentzel (1989) discussed the conversion of Alfvén waves to fast-mode waves and their subsequent Landau damping near the height where the coronal-hole nozzle diverges rapidly. Refraction can cause the conversion of up to half the Alfvén wave energy to fast-mode energy. Abdelatif (1987) investigated the dissipation by phase-mixing of shear Alfvén waves in a coronal loop driven externally. He finds that the total energy deposited in the loop depends on the magnetic diffusivity and viscosity, contrary to conclusions of other authors. Poedts & Goossens (1987, 1988) investigate poloidal wavenumber coupling of ideal mhd continuum modes in two-dimensional models for coronal loops and arcades. They find the efficiency of phase-mixing is increased and that the heating is larger at the top of the coronal loops, in agreement with observations. Combining basic electric circuit theory with the linearized mhd equations, Scheurwater & Kuperus (1988) calculate the input impedance for weakly damped monochromatic Alfvén waves traveling in a magnetoplasma. An et al. (1989, 1990) studied the reflection and trapping of transient Alfvén waves propagating in an isothermal atmosphere with constant gravity and a uniform magnetic field, and in a spherically symmetric atmosphere. Poedts et al. (1989) numerically simulated the coronal heating by resonant absorption of Alfvén waves. They consider compressible resistive mhd.

Assis & Busnardo-neto (1987) calculated the Cherenkov damping of low-frequency surface waves. Davila (1987) investigated the heating of the solar corona by resonant absorption of surface Alfvén waves. He calculates the heating rate by an improved method, compares his results with observations and concludes that resonant absorption is a viable mechanism for the heating of the solar corona. Mok (1987), Einaudi & Mok (1987), and Mok & Einaudi (1990) studied dissipation by viscous and resistive damping of surface Alfvén waves in a non-uniform plasma by using a normal mode analysis. Hollweg (1987a,b,c) studied resonant absorption of surface waves using the incompressible mhd approximation in detail. He shows that the energy of the surface wave gets deposited near the resonant field line within the boundary layer. Grossmann & Smith (1988) study resonant absorption of a spectrum of standing Alfvén waves in coronal loops. They conclude that resonant absorption of Alfvén waves is a viable mechanism for coronal loop heating. Hollweg et al. (1990) computed the effect of velocity shear on resonance absorption of incompressible mhd surface waves. Miles & Roberts (1989) investigated the properties of magnetoacoustic surface waves. Amendt & Benford (1989) discuss the heating of coronal loops by turbulent ion-cyclotron waves together with the cross-field wave transport.

5.2 Electrodynamic heating

Bodo et al. (1987) investigated current-driven mhd thermal instabilities in sheared fields. Vekstein (1987) extended the theory of Browning et al. and obtains an expression for the coronal heating rate. Strauss (1988) calculated the reconnection rate in a current sheet in the presence of tearing mode turbulence. He finds a large heating rate for the current sheet. Strauss & Otani (1988) noticed that when the twisting of the coronal magnetic fields by the photospheric motions exceeds a critical amount, kink-ballooning instabilities occur which lead to the formation of current sheets. Dahlburg et al. (1988) by fully three-dimensional numerical simulation, studied the time-dependent relaxation of a coronal gas column permeated by a force-free magnetic field. Vortex structures are almost as important for the heating as electric current sheets. Mikic et al. (1989) discuss the formation and heating by current filaments. Coronal heating by selective decay of MHD turbulence was also discussed by Gomez & Ferro Fontan (1988). Zuccarello et al. (1987) utilize an electric circuit analogy to model the build up and storage of magnetic energy in solar coronal loops. Antiochos (1987) proposed a coronal heating model which uses the hypothesis that magnetic reconnection acts as a catalyst to initiate the formation of current sheets. Chiueh & Zweibel (1987), Zweibel (1989) studied reconnection and the general equilibrium structure of current sheets produced by global mhd forces and magnetic reconnection in these sheets. Aly & Amari (1989), Amari & Aly (1990) computed current sheets in 2-D potential magnetic fields. Vainshtein (1990) discussed cusp point and current sheet dynamics. Low (1989) discussed the spontaneous formation of current sheets by the expulsion of magnetic flux. Wolfson (1989) studied the current sheet formation in a sheared force-free magnetic field.

Porter & Moore (1987) make an order of magnitude estimate of about 10^4 microflares at any one time and suggest that microflares can supply the necessary energy to heat the corona (Porter et al. 1987). Parker (1988) suggests that the X-ray corona is heated by reconnective dissipation at many small current sheets which are formed all the time as tangential discontinuities between interweaving and winding magnetic filaments. He suggested that the observed X-ray corona is simply the superposition of a very large number of nanoflares. Harrison et al. (1988) investigate the correlations between flaring rates, flare power and quiescent X-ray background of solar active regions and compare them to relations found for dMe stars.

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6. SOLAR OPTICAL INSTRUMENT DEVELOPMENT (O. Engvold)

During the past few years, several large solar observing facilities have become fully operational. This fact, plus the rise of solar activity and the availability of new detectors and computing equipment have led to new focal plane instrumentation at many observatories. The following are examples of development within the field of solar optical instrumentation in the past 2-3 years.

6.1 Universal Narrow-band Filters

The birefringent type of narrow-band filter consists of stacks of polaroids, calcite, and quartz plates and can isolate a wavelength with a spectral bandwidth between 15mÅ and about 100mÅ, in the spectral range from the visible to the infrared. Modern universal filters are tunable from about 3800Å to 7000Å. The development of *Universal Narrow-band Filters* is very promising and offers good possibilities for highly improved bi-dimensional, monochromatic, imaging in solar observations.

A *Universal Birefringent Filter* in tandem with a *Fabry-Perot* interferometer is being developed for 2-D spectroscopy by Bonaccini et al. (1989) at Arcetri. The filter has a spectral bandwidth of ~20mÅ and positioning accuracy of 1mÅ in the visible (4200 - 7000 Å), and its net peak transmission is 4% - 12%. This filter has been used and tested at the Vacuum Tower Telescope (VTT) of NSO/Sac Peak and gives high quality maps of intensity and velocity, and simultaneous magnetic fields (Cauzzi & Smaldone 1990). An upgraded version of the SOUP filter of Lockheed has been installed and operated successfully at the Swedish and German solar telescopes in the Canary Islands during summer periods in 1989 and 1990 (Title et al. 1989). A similar type filter is developed by the Göttingen group for use in the German telescopes in the Canary Islands. A *Triple-Fabry-Perot Universal Filter* is installed and tested on the 30 cm refractor of the CSIRO Solar Observatory (Bray 1988).

Some versions of the birefringent type filter are being designed to isolate several spectral windows simultaneously (multi channel). A 9-channel filter is put into operation during 1990 at the Huairou Solar Observatory, as part of a 60-cm vacuum "Solar Magnetic Field Telescope" (Ai 1990). A 64-channel version has been designed and is expected to be operable by end of 1992 (Ai & Hu 1987).

Birefringent filters are also manufactured for observations at fixed wavelengths. An Hα filter tunable over ±1.5Å, with FWHM=0.24Å, has been made for a high resolution solar telescope at Yunnan Observatory (Acta Astr. Sinica **31**, 180, 1990).

6.2 High Dispersion Spectrographs

High dispersion spectrographs, with spectral resolution $\lambda/\Delta\lambda \geq 500{,}000$ are highly desirable for solar work. The main instrument of the German Vacuum Tower Telescope (VTT) at Izaña, Canary Islands, is a vertically mounted spectrograph (15 m focal length, a grating with 79 g/mm, 220×440 mm ruled area, and blaze angle 63.5°). The system contains a slit jaw camera (Hα, Ca K, and white light) and a low dispersion predisperser (Soltau 1989). The spectrograph can be run in a *Multi-channel Subtractive Double Pass (MSDP)* mode which is provided by the Meudon group. In the French MSDP system (Mein 1989a, b) the image of the spectrographic slit is first dispersed onto an array of slits which isolate the desired spectral regions. At this point, all spatial detail perpendicular to the slit is smeared by the spectral dispersion. A second pass through the spectrograph removes this smear so that the spatial size of the detail is restored. The horizontal Littrow type spectrograph of the Swedish telescope in La Palma was upgraded in 1990 and mounted on a stable optical bench. It is equipped with a holographic grating (2400 g/mm and 220 mm ruled length). An InSb dewar is now operational on the 13.5 m vertical spectrograph of the McMath telescope. The long wavelength limit of the instrument is ~ 2.8 μm, set by the 600 g/mm grating. Two other gratings from the Milton Roy Harrison ruling lab are becoming available for this spectrograph (one grating 320×420 mm, 632 g/mm, with 57° blaze angle, for the UV and visible; and one 368×470 mm, 121 g/mm, 45° blaze angle for the near IR to 12μm wavelength range).

6.3 Polarimetry Systems

A number of polarimetry systems are being developed at various observatories. A general, high-precision Stokes polarimeter is built for the NSO Vacuum Tower Telescope at Sac Peak (Dunn et al. 1989). A new two-channel solar magnetograph for the Crimea Observatory is described by Li Rufeng (1989).

A magneto-optic filter for measurements of the solar vector magnetic field was recently put into operation at Big Bear Solar Observatory (Cacciani et al. 1990). A high resolution 2-D video magnetograph using a 500×582 CCD camera is installed at Beijing solar observatory (Ming Chang-rong 1988). Video magnetographs operate with a modulator, or a beam splitter, to separate the right and left circular polarized light, whose difference is used to infer the line-of-sight component of the magnetic flux. The modulation is done at video rate which lessens seeing noise in the data. During 1989 a multi-channel polarimeter (Stokes V) was installed at the Sayan Observatory (Markov and Likhte 1990). The system uses a low-frequency, electro-optical modulator (KD^*P crystal) (Markov et al. 1988). The Stokes polarimetry system being developed at ETH in Switzerland (Povel et al. 1989) utilizes an optical modulation package, which is based on two piezo-elastic modulators, and demodulation by synchronous shift of charges of the CCD detector arrays. The Swiss system offers a very high frequency modulation which eliminates spurious polarization caused by seeing effects at lower frequencies.

A new polarimeter system is presently under development by the High Altitude Observatory (HAO) in Boulder and NSO/Sac Peak, and another at the Institute for Astronomy, University of Hawaii. In both systems the polarization modulation is performed by mechanical rotation of a retardation plate (Lites 1987). The HAO system, called the *Advanced Stokes Polarimeter*, was recently tested with good results at the NSO/Sac Peak VTT. It will use a spectrometer (1-dimensional imaging) with moderately high spectral resolution emphasizing high quality line profile information for quantitative flux tube analysis and Stokes inversion techniques. When fully operable, the instrument will provide magnetograms of 90×90 arc s^2 area with 0.4 arc s pixels every 10 minutes. The University of Hawaii system, on the other hand, called the *Imaging Vector Magnetograph*, uses a tunable narrow-band filter, thereby sacrificing some the spectral information in order to obtain fast 2-D spatial imaging of the Stokes parameters, with the aim of relating the changing morphology and vector magnetic fields to solar flares. The monochromator in this polarimeter is a servo-controlled Fabry-Perot etalon with finesse about 50, stability of plate spacing λ/2000 and tunable spectral range 5000 - 7000Å . Similarly, a vector magnetograph for high resolution polarimetric measurements of solar active regions and flares (Max 91 program) has been developed by the Applied Solar Physics group of the Johns Hopkins University (Rust & O'Byrne 1988, 1989) and installed at NSO. This system is operational and incorporates a tunable solid Fabry-Perot filter.

6.4 Image Motion Compensators and Correlation Trackers

Image motion compensators are becoming standard equipment of solar observatories. A sunspot tracker of the Lockheed group is being used successfully at the Swedish solar telescope at La Palma. A photoelectric sunspot tracker of the Sayan Observatory is described by Druzhinin et al. (1988). A correlation tracker that performs effectively on solar granulation has been developed jointly at NSO/Sac Peak and the Kiepenheuer-Institut, Freiburg (Rimmele 1989; von der Lühe 1989). The system incorporates a 32×32 Reticon diode array that operates on a rate of 971 frames/s. Changes in the morphology of the granulation are traced by continuous updating of the reference frame. A version of the NSO/KIS system is being built for the ASP/JHU group (Rust & O'Byrne 1989).

6.5 Other

An instrument for measurement of solar differential rotation is built by Grigoryev and Ilganov (1988). A high precision CCD photometer for measurements of irradiance variations is developed for the National Astronomical Observatory, Mitaka, Japan (Nishikawa 1990). The photometer measures the intensity distribution to an accuracy of 0.07%.

Solid-state detectors have almost entirely replaced photographic emulsions in solar imaging. A survey of CCD detector systems used at solar observatories is made by H. Wöhl, Kiepenheuer-Institut, Freiburg (unpublished). See also Coulter and Stauffer (1990).

Image processing, in real-time as well as after the observations, has become a major issue because of the increasing amount of data being produced with modern detector systems. In the case observations are done broad band ($\Delta\lambda \geq 10$ Å) one may reduce the amount of data by continuously making short exposures and keeping only the sharpest ones. A real-time image selection system (best image every 10s) has been operated successfully at the Swedish solar telescope on La Palma to obtain extended time series of photospheric granulation (Scharmer 1989). The Lockheed group has developed fast routines for data handling after the observations. This involves flat fielding, noise filtering, image de-rotation, and "de-stretching" of images distorted by seeing (Title et al. 1990).

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7. SOLAR OBSERVATIONS WITH HIGH SPATIAL RESOLUTION (O. von der Lühe)

The commissioning of new solar telescopes as well as substantial improvements of instrumentation and data analysis techniques have led to significant progress when observing the sun with high angular resolution at various wavelengths. Several conferences address the issue of high resolution observations within their scope (I, II, III), and the reader is also referred to reviews therein. Since the resolution varies inversely with wavelength and the technical implications of high angular resolution is a strong function of the spectral regime observed, it is appropriate to address those separately.

7.1 Radio

The Very Large Array (VLA) of the National Radio Astronomy Observatory continues to be the prime instrument for solar observations with appreciable angular resolution. Typical radio wavelengths used range from 2 cm to 92 cm. Depending on the array configuration (with baselines up to 32 km), the resolution achievable for $\lambda = 2$ cm varies from 3 arc s to 70 arc s for high temporal resolution snapshots, and improves when aperture synthesis imaging is performed over longer periods of time. The VLA has been frequently used in a multi-wavelength mode, where two groups of antennae were used at different wavelengths.

Some observations address transient phenomena such as flares with high temporal as well as high angular resolution (Velusamy et al. 1987; Kundu et al. 1987; Alissandrakis 1988); the latter with the Westerbork Synthesis Radio Telescope). Lang & Wilson (1987) report observations of noise storms with an angular resolution of 5 arc s at 92 cm.

Substantial work has been done correlating observations in the radio regime with those in other wavelength regions, such as infra-red (Habbal & Harvey 1988) and the visible (Gary & Zirin 1988; Gary et al. 1990). Habbal and Harvey (1988) find a deviation from a strict one-to-one correspondence between radio bright points observed a 20 cm and dark points observed in the He I 10830 Å line. Gary & Zirin (1988) and Gary et al. (1990) find close correspondence between the microwave structure of the quiet sun at 6 cm and 3.5 cm compared to the quiet sun Hα and Ca II network and magnetograms.

Lindsey et al. (1990) report the first sub-millimeter (850 μm) images of solar structure - solar limb, supergranular network, and sunspots - with the good angular resolution of 14 arc s of the 15 m James Clerk Maxwell Telescope on Mauna Kea.

7.2 Infrared

The importance of the near infra-red spectral regime is currently increasing as usable IR array detectors become available for solar imaging. Foukal et al. (1990) report observations of faculae at the McMath telescope with the NOAO 58x62 InSb array at 1.63 μm, with a resolution of 2.7 arc s per pixel. Koutchmy (1990) has observed the solar granulation at the same wavelength with an IR video camera system that offers a resolution better than 1 arc s at the NSO/Sac Peak vacuum tower telescope.

7.3 Visible

Observations with high angular resolution have made substantial progress during the last three years, due to major developments in improving handling and analyzing large amounts of high-quality data, due to progress in active and passive methods to overcome the atmosphere in ground-based observations, and due to commissioning of major solar facilities located at high quality sites on the Canary islands.

Many data analysis methods were developed while analyzing the white-light movie produced by the Spacelab II SOUP experiment (November & Simon 1988; Bogart et al. 1988; Simon et al. 1988; Title et al. 1989), and were subsequently applied to high-quality data from various ground-based telescopes (Zirin & Wang 1989; Lites et al. 1990; Bonaccini & Stauffer 1990). For high-resolution ground-based time series of images, the development of local correlation methods (so-called ''destretching'') allows one to remove atmospheric distortion (differential image wander) which has a short time scale compared to the evolution of solar small scale structure. Data from a large aperture telescope that has been prepared in this way can have a resolution which is better than the data taken with the 30 cm SOUP telescope. After careful removal of intensity fluctuations ascribed to solar oscillations, the time series serve to study the dynamics of the fine structure by measuring the phase velocity of the intensity pattern, using the same local correlation techniques for longer time scales. The phase velocity is usually interpreted as mass motion. Most notable results from this kind of work are the revived concept of mesogranulation, evident as a medium-scale horizontal velocity pattern (November 1989), and the observation of strong vortex flows in the photosphere (Brandt et al. 1988).

New technological concepts for improving observations of ground-based instruments include computerized real-time frame selection (Scharmer 1989), rapid guiding using any small-scale structure (''correlation tracking''; von der Lühe et al. 1989), and adaptive optics to compensate distorted wavefronts in the telescope pupil, allowing diffraction-limited observations (Acton 1989). Scharmer (1989) has demonstrated that an excellent telescope at an excellent site, in combination with real-time image selection, can produce dramatically improved resolution in images and spectra. The image selection system consists of a solid-state video camera, a buffer into which digitized images are written, and an analog system that monitors the camera video signal and derives a sharpness measure from each frame. The typical sharpness measure is the power integrated over a (temporal) passband of the video signal, corresponding to a passband integral of the angular power spectrum of the intensity fluctuation in the fast scanning direction of the camera. The frame that maximizes this sharpness criterion within a specified period of time (e.g. 10 s) is retained in memory. Time series of optimized images are recorded this way and later written to mass storage. This kind of data serves well as input for the analysis methods described in the previous paragraph.

Fast guiders are particularly important for long exposure observations, where they significantly improve resolution by removing instrumental and atmospheric image jitter. These systems comprise the first step towards full real-time compensation of instrumental and atmospheric wavefront errors, i. e., adaptive optics. The capability to guide the image with any fine structure as a tracer including the ubiquitous granulation is particularly attractive, so a number of feature trackers (''correlation trackers'') have been developed. First results using a tracker on a ground-based telescope have been reported by von der Lühe, et al. (1989). The successful application of a higher-order adaptive optic constructed by the Lockheed group has been reported by Acton (1989). The system consists of a Hartmann-Shack wavefront sensor based on a multiple spot tracker approach, and a 19-element, segmented deformable mirror connected to the wavefront sensor by servo electronics. The images of sunspots and their immediate surroundings can be restored with the adaptive optic. The system has shown consistent image improvement during an engineering run at the NSO/Sac Peak vacuum telescope in 1988.

Passive methods for improving the resolution include various image restoration methods, such as interferometric techniques. Speckle methods can produce nearly diffraction-limited results. Druesne et al. (1989) present the speckle-interferometric analysis of the CLV of the statistics of solar granulation. Von der Lühe (1989) describes results of speckle imaging of photospheric fine structure. Högbom (1989a,b) proposed to use the information present at several positions in the vicinity of the focus of an aberrated telescope, the ''focal volume'', for restoring the original object intensity. Zirker (1989) discussed the use of multiple, two-dimensional, non-redundant arrays for recovery of information at high angular frequencies.

First high-resolution observations are now reported from the new facilities in the Canaries, most notably from the Swedish telescope on La Palma (Lites et al. 1990) and from the Gregory-Coudé telescope on Tenerife (Nesis et al. 1987; Wiehr & Stellmacher 1989). Démoulin et al. (1987) report on the analysis of high-resolution observations taken with the Multi-channel Subtractive Double Pass (MSDP) on Pic-du-Midi. Preliminary reports from those new facilities make one curious about further results in the near future (e.g., Soltau 1989).

Much work has been reported on more traditional varieties of high-resolution observations such as thorough analysis of the generic one-chance-in-a-lifetime high-quality single selected picture or spectrum. The relation between the convective granular pattern and magnetic activity has received a lot of interest; some papers deal with the statistical properties of granules near sunspots (Schmidt et al. 1988; Macris et al. 1989), and the sunspot moat (Muller & Mena 1987; Simon et al. 1988). Muller et al. (1989) suggest that network bright points might distort locally the granular pattern. Some results seem to be related to this topic, such as the relation of the lifetime and the size of granules and their location (Dialetis et al. 1988; Muller et al. 1990).

7.4 EUV and X-ray

Major developments in the area of multi-coated normal-incidence optics are beginning to dramatically improve the quality of observations in the EUV and X-Ray spectral regime, which will help exploiting much better the intrinsic resolution possible at these short wavelengths. Particularly remarkable examples are the pictures obtained by Golub et al. (1990) with the rocket-borne Normal-Incidence X-Ray Telescope (NIXT) in 1989. Multi-layer coatings on the mirror optics restricted the spectral band to 1.4 Å at about 63.5 Å, in the vicinity of the Fe XVI and Mg X emission lines, with a peak efficiency of 4%. The camera was located in the prime focus during the 5 minute flight, and several exposures were taken on two types of film with different grain sizes, resulting in a resolution of 2 and 0.75 arc s, respectively. It was noted that the higher resolution pictures show considerably more detail at the 1 arc s scale, indicating that further detail awaits discovery at even smaller scales.

A number of EUV experiments on the Solar and Heliospheric Observatory (SOHO) satellite, due for launch in 1995, will improve the spatial resolution in the 150 Å to 1600 Å region to about 1 arc s (SOHO 1989). Walker et al. (1990) describe an XUV Spectroheliograph which has been selected as one of the first scientific instruments for the space station. Nine multi-layer Ritchey-Chrétien telescopes, and three spectroscopic telescopes will be used to image the sun in the 70 Å to 350 Å region with a resolution as good as 0.1 arc s. Prince et al. (1988) discuss techniques for high-resolution imaging of solar flares with hard X-rays and gamma-rays (10 kev to several Mev).

Cook & Ewing (1990) report studies of the correlation between the fine structure brightness in the temperature minimum region at 1600 Å, observed with the High Resolution Telescope and Spectrograph (HRTS) experiment, and the magnetic field strength at scales down to 1 arc s.

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