COMMISSION 12: SOLAR RADIATION AND STRUCTURE (RADIATION ET STRUCTURE SOLAIRES)

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1. INTRODUCTION (J.O. Stenflo)

At the XXIst IAU General Assembly in Buenos Aires in 1991 the name of Commission 12 was changed from "Radiation and Structure of the Solar Atmosphere" to "Solar Radiation and Structure". The new name better represents our interests, since we are dealing not only with the atmosphere but with the whole sun. An example is the growing field of helioseismology, which during the past decade has played a prominent role in the life of our commission.

As usual the topics for the present report have been selected in coordination with Commission 10 (Solar Activity), to make the two reports as complementary as possible. Due to space limitations we of course cannot attempt to cover all important areas of solar physics. Instead Commission 12 has limited itself to cover six topics of particular current interest, in the form of brief but critical reviews documenting progress made over the past three years (1 July 1990 – 30 June 1993).

This scientific report may in fact be the last one made by Commission 12 as a separate commission. The IAU Executive Committee is currently considering a general overhaul of the now largely outdated commission structure of the union. Through coordinated mergers of previous commissions a much smaller set of new commissions with redefined goals should result. After various consultations within and between the solar-oriented commissions a proposal has been made to merge (in the context of other concerted mergers) Commissions 10, 12, and 49 (The Interplanetary Plasma and the Heliosphere) into a single, new solar commission with the name "The Sun and the Heliosphere". This would allow us to deal with the solar issues in a more unified way.

I would like to thank the authors of this report for their excellent reviews in spite of the severe page limit constraints. I am also grateful to the members of the Organizing Committee and all commission members who have provided feedback and support in dealing with the various issues.

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2. HELIOSEISMOLOGY (J. Toomre)

The oscillations of the sun are being used to study its internal structure and dynamics. A substantial component of the velocity and intensity fluctuations observed in the solar atmosphere result from the interference between about 10^7 resonant modes of oscillation of the interior. The frequency of any given mode is determined mainly by the stratification and dynamics within that portion of the spherical shell where the mode is resonant. Accurate measurement of very large sets of mode frequencies can be used as inputs to inverse theory to obtain detailed deductions about flows and inhomogeneities over a range of depths and latitudes in the solar interior.

From the outset a hallmark of helioseismology has been the close interplay between observations and theory, and this has contributed to rapid advances in the subject in the past three years. This is clearly evident in the recent major conference proceedings dealing with seismic investigations of the sun and stars edited by Berthomieu & Cribier (1990), Osaki & Shibahashi (1990), Gough & Toomre (1991a), Weiss & Baglin (1993) and Brown (1993), and in the large tome assessing advances in solar physics (Cox, Livingston & Matthews 1991). Recent accomplishments in helioseismology, and fundamental issues that can only be addressed by the several new international observational programs now being implemented, are discussed by Gough & Toomre (1991b).

2.1 Ground-Based Networks and Instruments in Space

The central observational issue in helioseismology is how to obtain nearly uninterrupted observations of long duration so that oscillation mode frequencies and their splittings can be determined to high accuracy. Intense efforts have been made in the past few years to addressing this issue, leading to the development of three ground-based networks of observing stations that span the globe, thus mitigating the effects of sidelobes in temporal power spectra (e.g. Hill, Deubner & Isaak 1991). The most ambitious of these is the Global Oscillations Network Group (GONG) project, which has been working to place identical Doppler imaging instruments using solid Michelson interferometers at six sites around the world to study intermediate- and high-degree modes with $\ell \leq 250$ (Harvey *et al.* 1993). Prototype testing is nearly completed, and the GONG stations should become operational in late 1994. Accurate frequencies of low-degree modes are being provided by whole-disk observations from two other ground-based networks called IRIS and BISON (Schmider *et al.* 1990, Elsworth *et al.* 1990).

The ground-based observations must be complemented by space-based instruments in order to remove effects of atmospheric seeing distortions that limit high spatial resolution, and thus major effort has also gone into building these instruments in the past three years. The study of detailed dynamics in the convection zone requires access to very high-degree modes (ℓ up to 4000) that will be provided by the Solar Oscillations Investigation (SOI) using a Michelson Doppler imaging instrument. It will fly on the *SOHO* spacecraft, to be placed at the L_1 Lagrangian point between the earth and the sun (Scherrer, Hoeksema & Bush 1991). The continuous sunlight at L_1 will also be exploited by low-degree helioseismic observations to be conducted with the full-disk atomic resonance scattering instrument (GOLF) (Gabriel *et al.* 1991) and the active cavity radiometer together with photometers (VIRGO) (Andersen 1991). The *SOHO* spacecraft is expected to arrive on station in 1995.

2.2 Theoretical Progress

There have also been substantial advances in many theoretical components that bear on helioseismology, with major refinements in the equation of state and opacity that influence directly the accuracy of solar reference models (e.g. Däppen, Keady & Rogers 1991, Ulrich & Cox 1991, Christensen-Dalsgaard & Däppen 1992, Rogers & Inglesias 1993, Däppen 1993, Seaton 1993), in assessing the sensitivity of mode eigenfunctions and frequencies to changes in solar models (e.g. Christensen-Dalsgaard & Berthomieu 1991), in methods of inversion to deduce mean structure, asphericity and differential rotation (e.g. Christensen-Dalsgaard, Schou & Thompson 1990, Gough & Thompson 1991, Kosovichev *et al.* 1992, Schou, Christensen-Dalsgaard & Thompson 1993, Thompson 1993, Sekii 1993), and in evaluating mechanisms for the excitation and decay of the acoustic modes (e.g. Balmforth & Gough 1990, Osaki 1990, Goldreich & Kumar 1991, Cox *et al.* 1991, Balmforth 1992, Murray 1993). The anticipated arrival of voluminous data sets from GONG and SOI has led to extensive data analysis preparation on diverse aspects such as implementing two-dimensional inversions, devising peak fitting procedures for power spectra with mode crosstalk, and studying the implications of gap filling in time series, with the work carried out by collaborative teams of scientists (e.g. Anderson, Duvall & Jefferies 1990, Brown & Christensen-Dalsgaard 1990, Gough & Toomre 1991c, Harvey *et al.* 1993, Bogart *et al.* 1993).

2.3 Selected Research Highlights from Observations and their Interpretation

The diagnostic potential of helioseismology has been affirmed recently in a number of novel ways, and there have been notable observational discoveries concerning properties of the oscillations. The depth of the solar convection zone has been determined from helioseismic measurement of the gradient in sound speed associated with the transition in the temperature gradient from being adiabatic within the zone to subadiabatic in the stable stratification below. That depth was deduced to be 0.287 solar radii (Christensen-Dalsgaard, Gough & Thompson 1991). The helium abundance within the solar convection zone has been assessed by helioseismic measurements that respond to the variation of the adiabatic compressibility of the material in the second helium ionization zone. The uncertainties in deducing the helium abundance by such methods are substantially less than by any other available observational method (Kosovichev *et al.* 1992). Using the most sophisticated equation of state available, based on the computations of Mihalas, Däppen & Hummer (1988), a value $Y \simeq 0.23$ was found; this is considerably less than the values obtained from stellar evolution calculations with the best estimates of Z/X, suggesting there has been substantial gravitational settling of helium.

Stratification within the deep solar interior has been evaluated by inversion methods applied to both low-degree p-mode frequency data of whole-disk measurements from the ground (Elsworth *et al.* 1991, Anguera Gubau *et al.* 1992) and from the IPHIR space experiment (Toutain & Fröhlich 1992), joined with the intermediate-ℓ data (Libbrecht, Woodard & Kaufman 1990). The structure inversions by Gough & Kosovichev (1993) indicate that the stratification in the solar radiative envelope is similar to that of a solar model which accounts for helium settling against microscopic diffusion in the absence of turbulent mixing (Christensen-Dalsgaard, Proffitt & Thompson 1993). Although there is still a paucity of data, the inversions suggest that within the energy-generating core the spherically-symmetric hydrostatic structure is largely in accord with that of standard models. This appears to rule out the WIMP models offered to reduce the flux of higher-energy neutrinos from the core. The recent GALLEX and SAGE experimental counts are nearly consistent with standard-model predictions of the lower-energy neutrinos produced by the main $p-p$ chain, leaving a continuing puzzle to explain the apparent low flux of higher-energy neutrinos (e.g. Gough 1993). Though the answer may lie in particle physics, such as neutrino matter-induced transitions, it may also be influenced by local material redistribution in the solar core through dynamical processes, the consequences of which on the stratification in the core should be testable with the low-degree helioseismic data from VIRGO and GOLF.

A clear consensus has emerged that there is a systematic shift in oscillation frequencies associated with changes in solar magnetic activity, increasing by as much as 0.4 μHz from solar activity minimum to maximum (e.g. Elsworth *et al.* 1990, Libbrecht & Woodard 1990, Anguera Gubau *et al.* 1992, Bachmann & Brown 1993). The oscillation frequencies can show shifts over even monthly intervals as the solar activity changes (Woodard *et al.* 1991). The signature of the frequency shifts suggests that the oscillations are sensing changes in conditions near their upper turning point just below the solar surface (e.g. Gough 1990, Kuhn 1993). Rotational frequency splitting also shows temporal variations of statistical significance, indicating that there are small changes (about 1%) in the sun's subsurface angular velocity with the solar cycle, the rotation rate at the higher latitudes having the greater variation (e.g. Woodard & Libbrecht 1993a,b, Gough *et al.* 1993a).

Another recent observational discovery concerns acoustic oscillations of intermediate and high degree that extend as discernible ridges in power spectra to frequencies as great as 10 mHz, well above the acoustic cutoff frequency of about 5.3 mHz for the photosphere (e.g. Duvall *et al.* 1991, Woodard & Libbrecht 1991, Harvey 1991, Fernandes *et al.* 1992, Ronan & LaBonte 1993, Milford *et al.* 1993). Further, the long-noted 3-min chromospheric oscillations, though elusive in helioseismic data, have now been observed to form a broad background feature that underlies the extended ridges at the higher frequencies (Harvey *et al.* 1993). It has been proposed that such high-frequency ridges may result from interference patterns of initially upward and downward-directed waves emitted from subphotospheric sources near the top of the convection zone (e.g. Kumar *et al.* 1990, Brown 1991, Kumar & Lu 1991, Kumar 1993), or from a chromospheric cavity which couples to the deeper acoustic cavity to achieve the resonances (e.g. Balmforth & Gough 1990). The intriguing possibility of directly measuring travel times and distances of individual acoustic waves, now demonstrated using temporal cross-correlations of intensity fluctuations on the solar surface (Duvall *et al.* 1993), may permit detailed studies of local subsurface structures, such as near sunspots. Localized analysis of wave fields has revealed that there is apparent absorption and scattering of p modes both by sunspots and their surrounding active regions (e.g. Braun, LaBonte & Duvall 1990, Braun *et al.* 1992, Braun *et al.* 1993), and this may provide tools for detecting magnetic structures before they emerge through the surface.

The solar differential rotation profile inferred seismologically (e.g. Brown *et al.* 1989, Dziembowski *et al.* 1989, Schou 1991, Sekii 1991, Gough *et al.* 1993b) is still strikingly at variance with predictions based on global simulations of solar convection (e.g. Glatzmaier 1987). Convection models generally favor an angular velocity Ω which is nearly constant on cylinders aligned with the rotation axis, whereas seismic inversions suggest that within the convection zone Ω is more nearly constant on radial lines. However, the resolution provided by current data is poor. Analogy with the differential rotation of the giant planets Jupiter and Saturn suggests that the sun may also possess far more structured zonal flows, and there is some hint of this from local-area ring diagram analyses by Hill (1990), Hill *et al.* (1991), and Patrón *et al.* (1993). The high-resolution data from GONG and SOI will no doubt reveal more subtle details of the dynamics of the convection zone.

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3. MAGNETOCONVECTION (M. Schüssler)

The domain of magnetoconvection embraces all kinds of interaction between convective flows and magnetic fields in an electrically conducting fluid. The origin of the subject lies in the search for an explanation for the darkness of sunspots in the 1930s although the word 'magnetoconvection' was coined only much later by W.V.R. Malkus (1959). Apart from its astrophysical implications the subject has developed a life of its own as an example of structure formation in dissipative dynamical systems. The relevance of magnetoconvection to solar physics is obvious: for investigating processes like the solar dynamo mechanism in the convection zone, the distribution and physical properties of magnetic flux elements in the observable layers of the photosphere, and the structure and dynamics of sunspot umbrae and penumbrae, we need to understand the interaction between convection and magnetic fields. At present, three 'mainstream' lines of research in magnetoconvection can be identified:

a) analytical studies of linear problems and nonlinear dynamics of restricted or truncated systems,
b) numerical experiments for idealized problems,
c) comprehensive simulations.

In what follows these approaches will be discussed briefly. Emphasis will be laid on more recent developments and on work which has implications for the magnetic structure in the convection zone and photosphere of the Sun. More comprehensive reviews have been given by Proctor & Weiss (1982), Hughes & Proctor 1988, Weiss (1990, 1991), and by Proctor (1992).

3.1 Linear analysis and nonlinear dynamics

Historically, this line of research began with the linear analysis of convective instability of a Boussinesq fluid in the presence of a magnetic field (for a summary see the book by Chandrasekhar 1961). Linear theory and simple nonlinear models for compressible convection in oblique magnetic fields have been investigated recently by Matthews et al. (1992) who found that the excitation of travelling waves is a general feature in such a situation. Weakly nonlinear theory has been utilized (e.g. Jones et al. 1990; Matthews & Rucklidge 1993) and methods for the analysis of dynamical systems have been applied to determine nonlinear bifurcation structures (e.g. Knobloch et al. 1992; Rucklidge et al. 1993) and the onset of chaos in magnetoconvective flows (Rucklidge 1992, 1993). Kerswell & Childress (1992) have provided an analytical model for the equilibrium structure of a magnetic flux tube sustained by a convective cell in a compressible medium with possible application to solar photospheric magnetic structures.

3.2 Numerical experiments

This approach was initiated by the work of Weiss (1966) on the kinematic expulsion and concentration of magnetic fields by prescribed velocity patterns. Numerical experiments are not intended to directly simulate or represent real (astro-)physical systems; they are used as a tool to investigate basic physical processes which are beyond the limit of analytical tractability. Therefore, complications like radiative energy transport are ignored and simple boundary conditions are used. The results, however, may still have direct implications for astrophysical problems insofar as important processes can be identified.

Oscillations, pulsating and travelling waves in two-dimensional compressible convection with an imposed *horizontal* magnetic field have been found by a number of authors (Brownjohn et al. 1993; Lantz & Sudan 1993; see also Weiss 1991). These results may possibly apply to sunspot penumbrae and the bottom layers of the solar convection zone while the case of an imposed *vertical* field may be relevant for sunspot umbræ (Hurlburt et al. 1989; Weiss et al. 1990; Proctor et al. 1993) and for the formation of concentrated magnetic fields in the photosphere (Hurlburt & Toomre 1988; Fox et al. 1991). Calculations with both kinds of imposed field, vertical and horizontal, have been performed by Fox et al. (1991) and by Hanami & Tajima (1991).

Results of three-dimensional calculations of compressible magnetoconvection in an imposed vertical field have been presented by Matthews (1993). Brandenburg et al. (1990) have studied the case with rotation and determined values for the turbulent α-effect which is important for mean-field dynamo theory. Spontaneous local dynamo action has been found by Meneguzzi & Pouquet (1989) in a three-dimensional simulation of Boussinesq magnetoconvection and by Nordlund et al. (1992) for a compressible medium including a stably stratified overshoot layer. In the latter simulation most of the

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generated magnetic field appears in the form of isolated magnetic flux tubes associated with strong, rotating downdrafts (vortex tubes). The basic field generation process is akin to the stretch-twist-fold dynamo sequence proposed by Vainshtein & Zeldovich (1972). Saturation is reached when the growing magnetic curvature force inhibits further twisting of the flux tube by the flow. The downflows push the generated field towards the bottom of the computational box and into the overshoot layer where it resides in the form of a mainly horizontal field (Stein et al. 1992). The evolution of such a horizontal magnetic flux tube in two-dimensional penetrative convection has been studied by Jennings et al. (1992). Cattaneo et al. (1991) discuss possible pitfalls in numerical simulations of hydromagnetic dynamos and propose a criterion for dynamo action in such simulations.

3.3 Comprehensive simulations

Although the numerical experiments discussed in the preceding section become increasingly sophisticated and 'realistic' we may still distinguish them from simulations which directly aim at modelling structures in the real solar convection zone and atmosphere. Since comparison with observational data is an important aspect for this approach, diagnostic information like intensity or polarization maps and profiles of spectral lines has to be drawn from the numerical results. A problem for this kind of simulations is that due to limited computer speed and storage capacity the whole range of length scales of the real flow and field cannot be encompassed and 'turbulent' or 'sub-grid' diffusivities (e.g. Canuto 1992; Theobald et al. 1993) have to be employed (see also Cattaneo & Vainshtein 1991). The hydrodynamic and magnetic Reynolds numbers which can be effectively achieved by a simulation are orders of magnitude smaller than those of the real astrophysical system. This is probably one reason for the failure of early attempts to comprehensively simulate the solar convection zone and dynamo. Another complication concerns the boundaries of the computational box which in most cases have to be placed at locations where no physical boundaries are. Therefore, boundary conditions are often formulated to be 'transmitting' and 'open' in order to avoid artificial reflection of waves and stagnation of flows. However, since only information from the inside of the computational domain is available during the simulation, some degree of arbitrariness is necessarily introduced and careful tests concerning the influence of the boundary conditions on the results are necessary (cf. Chan & Serizawa 1991). In any case the validity of a code should be ascertained by extensive series of test calculations. A set of test problems well suited for MHD codes has been proposed by Stones et al. (1992).

Simulations of non-magnetic granular convection near the solar surface including non-grey radiative transfer and sophisticated diagnostics (e.g. Steffen 1989, Lites et al. 1989) have evolved quite successfully in recent years (Stein & Nordlund 1989; Steffen et al., 1989; Steffen & Freytag 1991; Rast et al. 1993). Nordlund & Stein (1989, 1990) have included a magnetic field in their three-dimensional code and performed simulations of a sunspot umbra and a very strong plage region. The umbra simulation shows suppression of convective energy transport interrupted by episodic eruptions of convection. In the plage simulation the magnetic flux is rapidly swept to the convective downflows in the intergranular regions. In accordance with observations (e.g. Title et al. 1992) the granular structure is disturbed by the magnetic field and the velocity fluctuations are decreased with respect to non-magnetic granular convection.

The influence of convective motions on the eruption of an initially horizontal flux sheet in the solar atmosphere due to the Parker instability has been investigated by Kaisig et al. (1990). Structure and dynamics of two-dimensional magnetic sheets as models of magnetic flux elements in the solar (sub)photosphere have been simulated and compared to observational data by Knölker et al. (1991) and by Grossmann-Doerth et al. (1993). A strong influence of the magnetic structures on the surrounding convective flow pattern is found: Radiative cooling of the flux sheet drives an external flow which advects heat towards it and forms a high-velocity downflow immediately adjacent to the magnetic structure.

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4. THE SOLAR CYCLE (P.R. Wilson)

Some progress towards an understanding of the solar cycle has been made in several areas but many problems remain.

4.1 Synoptic Observations

4.1.1 The Extended Activity Cycle

K. Harvey (1992) has investigated the overlap of the wings of the butterfly diagram using the criteria of magnetic orientation and latitude of emergence. In an extensive study of magnetic bipoles of all sizes, she has determined that the period between first and last magnetic bipoles of Cycles 14-21 lay in the range 13.2-14.8 yr.

Other groups working in areas such as the coronal green line emission (Altrock 1992), the enhancement of geomagnetic disturbances (Leroy and Neons 1983) and the torsional shear (Snodgrass 1991) have independently suggested that their data were evidence for a high-latitude component of the new solar activity cycle, which begins some 4-5 yr before the appearance of the first sunspots of the new cycle, i.e., shortly after the maximum of the old one, and progresses equatorwards in synchrony with the sunspot butterfly diagram. Their conclusions are supported by synoptic contour maps which exhibit dominant ridges extending from high latitudes through the butterfly diagram to the equator.

Some of these charts also exhibit a polewards bifurcation and several authors, e.g. Sivaraman and Makarova (1992), have studied the poleward evolution of various high-latitude activity phenomena during the cycle. Stenflo (1992) has constructed a 'modally clean' butterfly diagram using the superposition of the first seven odd modes of the spherical harmonic expansion of the radial component of the axisymmetric magnetic field. This clearly shows two components, or branches, one which first appears at latitudes of 40°–50° and extends equatorwards over ~22 yr, overlapping with the butterfly pattern of the cycle associated with the latter part of this period and the other which extends polewards during the first cycle of this period. While this apparently confirms the extended overlap of the cycles, Stenflo (1992) has emphasised that each harmonic of his expansion contributes to *both* the polar and the equatorial branches, noting that such patterns are not uncommon in dynamo theory.

4.1.2 The Evolution of the Large-scale and Polar Fields

The observed evolution of the large-scale field patterns at different phases of the cycle have been compared with the simulated evolution based on solutions of the flux transport equation (Wilson and McIntosh 1991, Murray and Wilson 1993). These have shown several cases in which the large scale patterns cannot be explained in terms of the diffusion and meridional transport of decaying active region fields. Stenflo (1992) has also argued that the large-scale patterns must be maintained by the emergence of magnetic bipoles of all sizes rather than by the decay of surface flux. Legrand and Simon (1991), having reviewed both the geomagnetic and the solar activity data of recent cycles, conclude that the global dipole field is not a surface phenomenon, but one which originates deep within the solar interior. They propose a *two-component* cycle in which the dipole field is generated by a mechanism which is related to the *following* rather than the preceding sunspot cycle.

4.2 Stellar Activity

While the Sun permits the detailed two-dimensional study of cyclic activity phenomena, it exhibits only a single set of stellar parameters. Using the emission cores of the H and K lines of Ca II, and, more recently, of Mg II, as common indicators of stellar activity, many recent studies (e.g. Radick 1992), have revealed important correlations between stellar activity and stellar parameters such as rotation rate, age, and the depth of their convection zones.

Young, fully convective stars exhibit strong but non-cyclic activity which decreases in older stars concurrently with a decrease in their rotational velocity. The *Rossby number* N_R, (the ratio of the rotation period to the turnover time of the largest convective eddies) provides the connection, a low Rossby number (indicating a greater influence of rotation on convection) correlates remarkably well with strong surface activity. Cyclically varying activity is found in older stars with rotation periods of 20 days or longer. Luminosity variations are found to correlate with activity variations in older, cyclically active stars, but anti-correlate in younger, irregularly active, stars.

Baliunas and Jastrow (1990) have proposed that some solar-type stars which exhibit anomalously low levels of activity are, in fact, normal solar-type stars passing through grand minima similar to the Maunder minimum.

These comparisons between solar and stellar activity have implications for the mechanisms which are responsible for the solar activity cycle.

4.3 Dynamos and Chaos

While the above correlations strongly suggest that dynamo action, in one of its several modes, is responsible for stellar activity and activity cycles, the identification of the detailed nature of the solar dynamo remains elusive. Although mathematically attractive, kinematic $\alpha - \omega$ dynamos involve assumptions which do not apply to solar conditions, while the development of non-linear and 'fast' dynamos has far to go (Rosner and Weiss 1992).

Recent advances in the understanding of the *chaotic* properties of solutions to the equations governing non-linear systems, and the recognition that solar magnetoconvective activity is such a system, has initiated studies of the solar cycle as an example of a chaotic system (e.g. Ruzmaikin 1990; Schmalz and Stix 1991). The irregular structure of the sunspot number plot since 1650 and, in particular, the Maunder minimum and the earlier grand minima which have been inferred from proxy data are strongly suggestive of chaotic behaviour. However, attempts to identify the *strange attractor* and to determine its fractal dimension have been frustrated by the inadequate length of the available data string.

4.4 Forecasting and the Parameters of Cycle 22

The possibility that the solar cycle is a chaotic system and, therefore, inherently unpredictable, did not deter a great many forecasters from making predictions regarding the significant parameters of Cycle 22. With the benefit of hindsight one may assess the success or otherwise of the various methods employed.

Cycle 22 began in September 1986, from the highest minimum so far recorded, $R_Z(min) = 12.3$, and the early values of the Zurich sunspot number, R_Z were the highest on record. It also featured the shortest rise time from minimum to maximum (35 months), but the maximum of $R_Z(M) = 158.5$, which was achieved in July, 1989, was disappointing, being ranked third of the modern era, after Cycles 19 ($R_Z(M) = 201.3$), and 21 ($R_Z(M) = 164.5$).

The more successful predictions were those based on the magnitude of the peak in the indices of geomagnetic disturbances occurring during the declining phase of Cycle 21 (Thompson 1988), Thompson's estimate of 159 being the closest. Spectacularly unsuccessful were those forecasts based on the observed polar fields at minimum or on the sunspot numbers observed during the early years of Cycle 22. Indeed, after such a spectacular beginning, the early and disappointingly small maximum of the cycle is more suggestive of a chaotic system than of a regular oscillator. Nevertheless, if the rise of the geomagnetic disturbances during the decline of the old cycle is interpreted as arising from some fundamental changes occurring within the Sun during this phase, then the success of predictions based on these indices supports the arguments of Legrand and Simon regarding the polar field reversals and suggests an interesting avenue for future studies.

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5. HEATING OF THE OUTER SOLAR ATMOSPHERE (U. Narain)

Since the discovery that the temperature of the outer solar atmosphere (corona) is about 10^6 K and is much higher than the regions lying above and below it, various mechanisms have been put forward to explain this phenomenon (see e.g. Narain & Ulmschneider 1990; Ulmschneider et al. 1991 and references contained therein). Because of complexities introduced by magnetic fields the proposed mechanisms could explain this problem with limited success. The attempts in this direction are continuing, theoretically as well as observationally.

It is now believed that acoustic waves can heat the inner solar atmosphere via shock formation (non-magnetic regions only), but magnetic fields play an important role in the heating of the outer solar atmosphere. Different MHD wave modes generated in the presence of magnetic fields are, e.g., slow, fast, and Alfvén modes. If there is a boundary in the medium, surface waves come into existence. These surface waves propagate along the boundary such as the surface of solar coronal loops. Body waves exist in a homogeneous medium. All these waves derive their energy from the subphotospheric convection zone. If the medium is non-uniform, the complexity of the generated wave modes increases (Califano et al. 1990, 1992).

X-ray pictures of the corona contain a variety of structures. The coronal loops are characterized by closed magnetic field lines, whereas the coronal holes have open magnetic field lines extending to interplanetary space. These are the basic building blocks of the corona. Once we know with certainty the basic mechanism(s) of their heating, the coronal heating problem would come to its logical conclusion. These basic structures may be heated through the dissipation of MHD waves as well as currents/magnetic fields.

5.1 Heating of Coronal Loops

Unlike other MHD modes, the Alfvén waves reach coronal heights even after passing through the photosphere, chromosphere and transition region. In coronal loops these waves may dissipate via resonant absorption, phase mixing, mode conversion, Kolmogoroff turbulent cascade, etc., to heat the coronal plasma contained in them.

For simplicity, loops are approximated by straight, cylindrical, axisymmetric plasma columns with equilibrium quantities varying only in the radial direction. There exist a continuum of oscillation frequencies of such a plasma. If this plasma is forced to oscillate at some frequency by photospheric mass motions (convection), resonance may occur in some layer where the local Alfvén frequency equals the frequency of the external (photospheric) source. Energy is thus transferred from the photospheric source to the coronal loop. Since the spectrum of photospheric frequencies is not known, Poedts et al. (1990) could estimate only the efficiency of this heating mechanism and found it to be a viable mechanism for heating coronal loops.

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Alternatively, coronal loops may be heated via episodic dissipation of magnetic fields in current sheets (Parker 1991a). Granular motions shuffle the coronal fields' footpoints, and braiding of coronal loops takes place. As a consequence of this non-potential energy is stored in the system. Eventually, a critical threshold is reached and reconnection of coronal fields occurs in thin current sheets. The released energy heats the loop impulsively creating a tiny flare. Parker calls it a nanoflare, in which about 10^{23}–10^{25} ergs of energy is released. Thus the X-ray corona is heated by 'swarms' of nanoflares. Taking 10^{23} ergs per nanoflare as an average, the mean output of 10^7 ergs cm^{-2} s^{-1} requires about one new nanoflare per second per area 1 Mm × 1 Mm, where Mm stands for 10^3 km. Nanoflares may, alternatively, be produced by the twisting of loop footpoints. Both mechanisms, twisting and braiding, are equally effective in producing nanoflares (Zirker & Cleveland 1993). Sturrock et al. (1990) also propose episodic heating, where each short burst of heating is followed by a long period of radiative cooling but they do not specify the mechanism. The spectrum, computed by Raymond (1990) for this model, agrees with the observations qualitatively.

Due to microturbulence the coronal medium may be endowed with an effective viscosity and resistivity (different from the molecular one). When the boundary motions stress such a dissipative medium, turbulence is generated. After some time equilibrium is established. This approach is different from the usual frozen-in assumption. There is a net flow of energy from the photosphere to the coronal loop, where it is dissipated. In 2-D MHD Heyvaerts & Priest (1992) find a DC flux of 5×10^5 erg cm^{-2} s^{-1} for quiet region loops and 2×10^6 erg cm^{-2} s^{-1} for active region loops. The rms velocities are 20 and 30 km s^{-1}, respectively. There is a free parameter, C, in the expression for energy flux, which cannot be specified unambiguously.

5.2 Heating of Coronal Holes

It is obvious from the observational analysis of Withbroe (1988) that a coronal hole requires a heat input of about 5×10^5 erg cm^{-2} s^{-1}, the major portion of which is deposited within 1–2$R_\odot$. A recent review by Parker (1991b) infers an upper limit of 1×10^5 erg cm^{-2} s^{-1} for the Alfvén wave flux in a coronal hole. The agitation observed in the photosphere suggests characteristic wave periods in the range 50–300 s, which correspond to a granule size of about 500 km and characteristic velocities of 1 km s^{-1}. Phase mixing and other known mechanisms are not able to damp these waves within 1–2$R_\odot$ (Parker 1991c). Kolmogoroff turbulent cascade could deposit energy in the first 1–2 solar radii provided the turbulence could be produced by standing Alfvén waves. However, for open-ended coronal holes inward flux is not expected at periods of 100 s, which would be essential for the formation of standing waves. Photospheric motions generate an estimated Alfvén flux of the order of 5×10^8 erg cm^{-2} s^{-1}. Obviously, the entire generated flux cannot be transported to the corona. Thus a coronal hole is not heated principally by the dissipation of Alfvén waves produced in the subphotospheric convection. Only in the fibril photospheric field of 10^3 G an adequate amount of Alfvén wave flux could be generated.

For a simple class of spherical sources, adopted as a model for oscillating solar granules with a five minute period, Collins (1992) finds that the generated Alfvén fluxes are comparable to those required to heat active regions. This may not be true for coronal holes.

Under isothermal hydrostatic conditions Moore et al. (1991) find that for a base radius of 1.15 $R_\odot$, base field strength of 10 G and a base electron density of 3×10^7 cm^{-3} the waves with periods of about 5 minutes are trapped within the hole and heat it if its temperature is slightly less than one million Kelvin. They escape to the solar wind and accelerate it for coronal holes of higher temperatures. The potential magnetic field is assumed to decrease according to $B \sim R^{-m}$, where R is the radial distance from the Sun centre, and m is an even integer such that for $m = 2$ the field spreads radially.

A new mechanism called 'intermittent magnetic levitation' for the dissipation of reflected Alfvén waves has been proposed (Moore et al. 1992), for which the waves propagate from the sites of their generation to the coronal hole plasma in a flux tube. The waves with periods exceeding a critical period get reflected by the density gradients and push up against the coronal plasma. Consequently a quasi-hydrostatic vertical distribution of plasma could result such that there would be more supported plasma than in the absence of the reflecting waves. Because the events (granules, microflares and spicules) that generate the Alfvén waves are episodic and intermittent, it is expected that the coronal plasma in the flux tubes at any instant would be rising or falling. During rise the plasma gains gravitational potential

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energy which, during fall, gets converted into thermal energy. The viability of this mechanism is yet to be established.

The principal source for coronal holes could be the dissipation of quasi-static magnetic fields, which contain thin current sheets to provide enhanced dissipation. The statement that almost all field topologies produce internal current sheets as an intrinsic part of static equilibrium is not true for coronal holes, because the transverse components of the field are free to propagate away to infinity along the field. Since the energy requirement of a coronal hole is smaller (about 1/20) than that of the active X-ray corona it is quite reasonable to look for small-scale magnetic fields that appear at the supergranule boundaries. This idea has already been put to practice (Parker 1991b and references contained therein). The emerging picture is that the small-scale (2–4×10^3 km) magnetic bipoles are jostled together by subphotospheric convection. They develop internal, tangential discontinuities, where magnetic dissipation heats the gas trapped in the bipole. The small bipoles reconnect where they are pushed against other bipoles or against unipolar fields. The magnetic energy is continually replenished by the emergence of new flux bundles and by the continual deformation of the bipolar fields by the subphotospheric mass motions. This magnetic energy of the small-scale fields is converted into thermal energy at thin current sheets in the usual way. Porter & Moore (1988) estimate an average overall magnetic dissipation rate of 5×10^5 erg cm^{-2} s^{-1} in coronal holes. Most of this energy is injected into the coronal hole, in the form of jets of gas, lashing flux bundles and superheated plasma from a bipole interior suddenly freed by reconnection into the ambient unipolar field.

5.3 Heating in General

The smallness of dissipative coefficients in many astrophysical situations requires that large gradients should develop in the dynamical evolution of the system (i.e., small spatial scales are formed), so that efficient dissipation may take place. Within the framework of normal mode analysis and incompressible MHD, Califano et al. (1990) establish the existence of a new class of resistive (nonresonant) solutions, which are characterized by the explicit appearance of resistivity in their asymptotic form and the formation of small scales over the entire inhomogeneous region. This feature of the solutions distinguishes them from the more familiar resonant solutions that obey ideal asymptotic boundary conditions and develop large gradients at particular spatial locations.

In the more realistic compressible case, adopting slab geometry (where relevant quantities depend on a single coordinate normal to the magnetic field direction) Califano et al. (1992) arrive at similar solutions. For shear Alfvén waves the smallest damping length turns out to be of the order of the scale of the non-uniformity. The existence of small spatial scales is supported by the numerical simulation of Malara et al. (1992) for shear Alfvén waves with phase-mixing as the damping mechanism, within the frame work of incompressible MHD. Further support will be available when numerical simulation of the more realistic compressible case is attempted.

5.4 Observational Aspect(s)

Cook & Ewing (1990), by examining Kitt Peak magnetograms and spectroheliograph observations at 1600 Å, find that the brightness temperature above 4400 K is linearly related to the magnetic field strength. Alfvén waves seem to be the most obvious candidate, as their flux $\rho v^2 V_A$ (where ρ is the matter density, v is the driving, photospheric velocity, and V_A is the Alfvén velocity) is proportional to B, the magnetic field strength. The structures so heated are found to be bright points.

As a result of an analysis of Solar Maximum Mission data on coronal X-ray line broadening of the Mg XI ion in a nonflaring active region Saba & Strong (1991) are tempted to conclude that the heating of the active region takes place either by Alfvén waves directly or as a side effect of magnetic reconnection and current dissipation.

Parker (1993) has suggested that resistive dissipation and rapid reconnection at the current sheets is the major heat source for the active X-ray corona of the Sun or any star, through flaring on all scales from nanoflares to microflares to major flares. In view of this, observations providing insight into small-scale magnetic activity seem quite crucial, although they are hampered by limited spatial and temporal resolution (Stenflo 1989).

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6.1 Instrumentation

Most solar telescopes have large effective focal lengths to achieve high spatial resolution. This results in rather complicated optical constructions with beam-folding mirrors inside the telescope or in front of static image-forming optics. Hence, we often face complicated instrumental polarization patterns in the final focus due to oblique reflections. In addition, solar post-focus instruments often have strongly polarizing properties, e.g. spectrograph gratings or birefringent filters. This requires that the polarization analysis is done, at least, in front of the post-focus instrument. Modern solar telescope designs even place the polarization analysis as early in the optical train as possible where the optics is still cylindrically symmetric. This spatial separation of the polarization analysis optics from the detector system in the final focus avoids instrument-induced cross-talk between the various Stokes parameters, which is essential for highly sensitive and accurate solar polarimetry.

Polarization measurements always involve the detection of intensity differences, i.e. at least two measurements are needed to determine a polarization signal. Reliable polarimetry requires that the

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Polarization measurements always involve the detection of intensity differences, i.e. at least two measurements are needed to determine a polarization signal. Reliable polarimetry requires that the

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two intensities are detected within a period that is short with respect to the fastest changes of seeing. This can be achieved either by spatial modulation (with our terminology including the case of static beam splitters), which guarantees absolutely simultaneous measurements, or temporal modulation. Spatial modulation has the drawback that the two (or more) beams do not pass the optics along the same optical path, and differential aberrations may become crucial. Furthermore, spatial modulation requires that the various beams are detected by different detectors or detector areas, which makes the measurements susceptible to differential gain effects. Temporal modulation should be performed at frequencies well above the fastest changes due to seeing (typically a few 100 Hz). Unfortunately this is well above the current read-out rate of large CCD array detectors, which are now employed in almost all solar polarimeters. In this context we may distinguish between slow and fast temporal modulation schemes, where the latter uses frequencies well above the seeing frequencies. Finally any purely temporal modulation scheme requires that about half of the light remains unused to eventually achieve a temporal intensity variation. In conclusion, technological limitations always impose some compromises in the design, which has resulted in a large variety of polarimeter schemes. In the following I discuss some of the most recently designed or constructed solar polarimeters.

Most modern, precise solar polarimeters employ a temporal modulation scheme in combination with sensitive CCD array detectors. Single exposures of CCD detectors have the disadvantage of a relatively low S/N ratio (typically several hundred). Therefore high frame read-out rates (often at video frequency) and on-line digital summation is combined to obtain the high S/N ratio required for solar polarimetry. Fast tip-tilt mirrors can significantly reduce image motion, which is important when the temporal modulation frequency is comparable to the seeing frequencies. Powerful real-time image processing hardware may perform sophisticated on-line analysis.

The High Altitude Observatory/National Solar Observatory Advanced Stokes Polarimeter (Elmore *et al.* 1992) is a spectrograph-based vector polarimeter. A mechanically rotating retarder and a polarizing beam-splitter system combine temporal and spatial modulation with CCD imagers that are read out at video frequency. The combination of the two modulation schemes leads to a nearly optimum use of the photons entering the polarimeter. Two spectral lines may be observed simultaneously and the full line profiles recorded by the instrument makes it particularly useful to determine physical quantities of solar magnetic features.

Another spectrograph-based polarimeter is the NASA/NSO Spectromagnetograph (Jones *et al.* 1992), which has recently replaced the old 512-channel Diode Array Magnetograph that produced the widely distributed daily Kitt Peak magnetograms. This instrument employs a Kerr cell to modulate the circular polarization. A video CCD array records alternate states of polarization in the spectrogram. A sophisticated real-time image processing system extracts the line-of-sight velocity and magnetogram signals, the continuum intensity, the equivalent width, and the line depth.

An interesting polarimetry set-up was used by Rust and Keil (1992). A Ronchi ruling provides a mask that covers every other pixel row of the CCD camera from direct illumination. The adjacent lithium niobate polarizing beam-splitter produces two orthogonally polarized beams, one of which is displaced by the width of one pixel row. The tiny displacement of the two beams minimizes differential aberrations. However, differential gain effects remain and the exact positioning of the ruling with respect to the CCD array structure is crucial.

The Zürich imaging Stokes Polarimeter ZIMPOL I (Keller *et al.* 1992) combines modulation of all Stokes parameters at 42 and 84 kHz with CCD arrays by synchronous charge shifting in specially masked CCD arrays. It will be capable of measuring all four Stokes parameters through the same optics. While this design allows extremely sensitive and accurate polarimetry down to the 10^{-4} level, the opaque mask covering every other CCD row and the beam-splitting system needed to feed three CCD arrays to measure all four Stokes parameters simultaneously makes the system rather inefficient as compared with other designs. Based on ZIMPOL I a new imaging vector polarimeter scheme (ZIMPOL II) has been presented by Stenflo *et al.* (1992). Only a single array is needed to detect all four Stokes parameters. Together with a micro-lens array in front of the CCD imager this design increases the sensitivity with respect to ZIMPOL I by at least a factor of six.

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The National Solar Observatory's Near Infrared Magnetograph (NIM) is a spectrograph-based polarimeter (Rabin 1992b, private communication). It builds up a two-dimensional array of polarized line profiles by scanning the solar image across the slit of a high-dispersion grating spectrograph. Polarization analysis is accomplished by liquid-crystal variable retarders and an infrared linear polarizer. It is mostly used to record Stokes I and V, but it can also be used to record the full set of Stokes parameters. The detector, a 256×256 indium antimonide array, is fed by anamorphic transfer optics that match the spatial and spectral scales to the 38×38 μm pixels. At each slit position, 8 polarization pairs for each Stokes parameter are acquired at 7 Hz, averaged, and recorded on tape.

6.2 Observational methods

We see a continuous increase in spatial and temporal resolution as well as coverage in the visible part of the solar spectrum. Most observations focus on sunspot regions. The Lockheed group continuously provides high spatial resolution results from La Palma (e.g. Title *et al.* 1993). A significant improvement in the spatial resolution of magnetic field measurements has been achieved by eliminating the influence of the Earth's atmosphere with speckle-interferometric methods (Keller and von der Lühe 1992). Speckle polarimetry is based on a two-channel system where one channel measures the instantaneous point spread function while the other records the polarization in the wing of a Zeeman sensitive spectral line. It has led to the first resolution of solar magnetic fluxtubes (Keller 1992). Almost continuous time series of vector magnetic field measurements over several day periods are now collected by the combination of the Big Bear and Huairou Solar Observatories (Zhang *et al.* 1992). Finally it has been recognized that spectral lines without intrinsic linear polarization due to the Zeeman effect (e.g. FeII 6149 Å) might play a key role in measuring instrumental polarization (Lites 1993).

The near-infrared has the major advantage of being able to directly indicate the field strength in the deep solar photosphere. NIM has found weak fields, i.e. fields with strengths below 1 kG (Rabin 1992a). NIM exploits the high Zeeman sensitivity of the line Fe I 15648.5 Å to measure $\vec{B}$. For $|B| \gtrsim 800$ G, the magnitude of the field is derived, without adjustable parameters, from the strong splitting of the Zeeman components. The relative strengths of the Stokes components indicate the direction of the field. Livingston (1991) has brought back into operation the two decades old Baboquivari infrared detector at Kitt Peak. Although this instrument contains only a single InSb diode detector, its simplicity and ease of use has led to a variety of scientific results (e.g. Solanki *et al.* 1992).

A recently developed far infrared detector system has been used to sequentially record the full Stokes vector in the extremely Zeeman-sensitive MgI 12.3 μm line (Hewagama *et al.* 1993). Since the spatial resolution of the 1.5 m McMath-Pierce facility is limited by the diffraction at these wavelengths, and not by seeing, the sequential recording of Fourier Transform Spectrometer interferograms in six polarization states (12 minutes for the full Stokes vector) is not crucial when observing sunspots. Furthermore, instrumental polarization due to oblique reflections is very small as compared to the visible.

6.3 Developments

Solar polarimetry will mostly be ground-based in the rest of this decade. An instrument that will be particularly suited for polarimetry is the 90 cm THEMIS (Rayrole 1991). It belongs to a new class of large-diameter solar telescopes that are virtually free from instrumental polarization and instrument induced cross-talk between the Stokes parameters. Among these designs is also LEST, the Large Earth-based Solar Telescope (Engvold and Andersen 1990). It will become the largest solar telescope and it is designed with high priority on sensitive and accurate polarimetry. Instead of going into space it is cheaper to use balloons to leave most of the atmosphere behind. The GENESIS telescope (Rust *et al.* 1991) will circle the South Pole during 2 weeks and collect magnetograms with an 80 cm telescope. This instrument may deliver the highest spatial resolution magnetograms in the near future.

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7. ADVANCES IN INFRARED SOLAR PHYSICS (D. Rabin)

Although infrared observations have long played a role in the study of the Sun, it is only during the last five years that infrared solar physics has emerged as a vigorous subdiscipline. The explosive development of infrared array technology has contributed to this development by greatly expanding the range of feasible measurements in the 1–30 μm spectral band. However, as with infrared astronomy generally, unifying physical themes are at least as important as techniques—for example: a simple continuum opacity dominated by H^- and H free-free absorption; an approximately linear relationship between temperature and continuum intensity; the importance of rotation and vibration-rotation transitions of simple molecules; the quadratic wavelength dependence of the Zeeman effect.

IAU Symposium 154, the first international meeting devoted to infrared solar physics, took place during 1992. The symposium proceedings (I) provide the most comprehensive picture to date of current research and possible initiatives in this young field. The review by Deming *et al.* (1991) is a good introduction to the physics of the infrared spectrum.

7.1 Total Solar Eclipse of 11 July 1991

There was unprecedented coverage of the 1-μm to 3-mm spectral region during this favorable eclipse. Three experiments searched for thermal emission from dust in the range 1–6 $R_\odot$ (Kuhn *et al.* 1993; MacQueen *et al.* 1993; Tollestrup *et al.* 1993); each group employed an infrared array camera and filters in the 1–2.5 μm range. Kuhn *et al.* and MacQueen *et al.* found no evidence for coronal dust emission; Tollestrup *et al.* reported a marginal detection. MacQueen *et al.* hypothesize that the much stronger emission observed during the 1966 eclipse arose from dust supplied by one or more Sun-grazing comets.

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Jennings *et al.* (1993) studied the limb profile of the 12.32 μm Mg I emission line at the IRTF. They found the emission peaks within ~ 300 km of the 12-μm continuum limb, consistent with new radiative-transfer models of the formation of this line (section 7.2). However, line emission can be traced to heights as great as 2000 km, indicating spatial inhomogeneities or departures from hydrostatic equilibrium.

Limb observations at submillimeter and millimeter wavelengths directly probe the vertical structure of the temperature minimum region and chromosphere. There was excellent coverage of the 1991 eclipse by four observatories: JCMT (Lindsey *et al.* 1992), CSO (Ewell *et al.* 1993), OVRO (Belkora *et al.* 1992), and BIMA (White & Kundu 1993). The results confirm and extend previous indications that chromospheric emission extends 1.5–3 times higher (depending on wavelength) than predicted by standard one-dimensional models in hydrostatic equilibrium. It is not yet certain that spicules (as seen in off-band Hα images) cause the extended submillimeter emission; if so, the spicules are rather cool, 6000–7000 K.

7.2 Atomic Physics and Line Formation

A highlight of the last triennium has been the explanation of the 12-μm emission lines and related high-l atomic Rydberg transitions. Detailed radiative transfer models establish that the Mg I emission lines are formed in the upper photosphere (Chang *et al.* 1991; Carlsson *et al.* 1992). The NLTE processes that affect them are now understood, as are their susceptibilities to the Zeeman and Stark effects (Chang 1993). This new understanding enhances the value of the 12-μm lines for magnetic observations (section 7.3).

The ATMOS atlas of the solar spectrum between 2 μm and 16 μm has proven to be an invaluable source of high-resolution spectra that are free of atmospheric contamination (Farmer 1993). ATMOS profiles of lines unobservable from the ground were instrumental in confirming the interpretation of the 12-μm lines. ATMOS profiles of some H I lines differ significantly from the predictions of current radiative transfer models (Avrett *et al.* 1993; Carlsson & Rutten 1993). As the models are notably sensitive to atmospheric structure, the infrared H I lines will be a valuable chromospheric diagnostic when they are better understood. Biémont (1993) and Sauval & Grevesse (1993) have reviewed recent progress in solar infrared spectroscopy of atoms and molecules, respectively.

7.3 Magnetic Fields

In an important series of papers, Solanki and colleagues have investigated the diagnostic power of near-infrared spectral lines, especially Fe I 15648.5 Å and 15652.9 Å, and used these diagnostics to probe solar magnetic features (Muglach & Solanki 1992; Solanki *et al.* 1992a,b,c; Rüedi *et al.* 1992a,b). The results include: evidence for the existence of stable "weak-field" flux tubes ($B \lesssim 1200$ G); evidence against a significant return flux in either small-scale flux tubes or sunspots; detection of a siphon flow in a small magnetic arch; and confirmation of the nonlinear field-strength vs. temperature relationship in sunspots reported by Kopp & Rabin (1992), together with a linear relationship between magnetic inclination angle and temperature.

An investigation of the spatial and statistical distribution of the properties of plage flux tubes was initiated by Rabin (1992a,b) using an array-based Near Infrared Magnetograph (described in section 4). This instrument produced the first two-dimensional map of plage magnetic fields in the deep photosphere. Field strengths in the range 1000–1600 G accounted for more than 90% of the magnetic flux, as expected from the work of earlier investigators. Within this range, the observed field strength varied coherently on several spatial scales within the field of view. A statistical relationship between magnetic field strength and magnetic flux was apparent, in the sense that strong magnetic fields are found at all magnetic flux densities, but weak fields ($B \lesssim 1200$ G) are found only in weak-flux areas; Rüedi *et al.* (1992a) report a similar result.

Polarimetric observations of the Mg I emission line at 12.32 μm have been used to study the structure of sunspot fields down to a field strength of 300 Gauss, well outside the radius of the penumbra-photosphere boundary, R_p (Hewagama 1991; Deming *et al.* 1993). The precise (±50 G) measurements of field strength clearly show departures from azimuthal symmetry. The average field strength at R_p is weaker than predicted by the relation of Beckers & Schröter (1969), but the field in the high photosphere

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persists to $R \sim 1.5R_p$, consistent with inferences from visible-light polarimetry. Measurements of the inclination and azimuth of sunspot fields from 12-μm data have been carried out but are still preliminary in character. An array-based imaging magnetometer operating at 12 μm is under construction (Deming *et al.* 1993). Now that the formation of these lines is understood (section 7.2), simultaneous observations at 12 μm and 1.56 μm should allow accurate measurements of flux-tube expansion from the bottom to the top of the photosphere.

Infrared observations have provided important constraints on theoretical models of magnetic flux tubes, as reviewed by Steiner (1993). Future measurements of thermal inhomogeneities in the temperature-minimum region and chromosphere should prove particularly useful; imaging observations in the millimeter and submillimeter continuum (Lindsey 1993) and in the carbon monoxide lines near 4.7 μm are now possible.

7.4 The Opacity Minimum

The solar atmosphere is most transparent at $\sim$ 1.6 μm. Although continuum radiation at 1.6 μm is formed only 30–40 km below the $\tau_{0.5\mu m} = 1$ level, this region is interesting because the balance between convective transport and radiative transport changes rapidly with height. Observations of granules and other convective structures at the opacity minimum have so far revealed small but significant differences from their visible-light properties (Koutchmy 1993; Keil *et al.* 1993); Stein & Nordlund (1993) review theoretical simulations. Moran *et al.* (1992) have investigated the 1.6-μm contrast of faculae and pores observed near disk center and find that the contrast depends on magnetic flux: $< 0.2\%$ for values below 2×10^{18} Mx but increasingly dark for stronger flux concentrations. These observations include both unresolved flux tubes and the atmosphere immediately around them, so a comparison with flux-tube models is not straightforward. Continuum observations in the 1–4 μm range are also valuable diagnostics for differentiating among models of sunspot atmospheres (Maltby 1993).

7.5 Solar Activity

Beyond extensive and useful observations in He I 10830 Å (Jones 1993), observations of solar activity and flares in the infrared and submillimeter spectrum are scarce. Falchi *et al.* (1993) review the potential value of various diagnostics, emphasizing infrared continuum windows. Petrosian (1993) discusses flare emission mechanisms in the range 10^{11}–10^{14} Hz (3 μm–3 mm), including non-thermal synchrotron emission in the impulsive phase and, in the gradual phase, free-free and thermal gyrosynchrotron emissions. According to recent observations with the Itapetinga antenna (Correia *et al.* 1993), $\sim$ 25% of solar bursts show a rising spectrum (flux increasing with frequency) in the range 35–90 GHz. The BIMA interferometer detected both impulsive and gradual emission at 86 GHz from many flares during a Max '91 campaign (White & Kundu 1992). Thus, there appears to be a promising future for millimeter and submillimeter observations of flares.

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