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14. Advances in High Resolution Solar Observing Techniques

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14.1. INTRODUCTION

Spatial structures in the solar photosphere are likely to be seen down to scales of the order of the photon mean free path, which is about 70 km in the lower photosphere. This scale corresponds to an angle of 0.″1 at disk center. Structures associated with magnetic fields may be expected on even smaller scales. Existing solar telescopes typically have diameters of slightly less than one meter. Hence, even in the visible part of the spectrum, the scales of solar structures extend out to the diffraction limit of current solar telescopes. Therefore, the achievable spatial resolution is limited by turbulence in the Earth's atmosphere (seeing). This has led to the development of various techniques to overcome this resolution limit and achieve diffraction-limited resolution. This report covers selected highlights and recent work done in the context of high-resolution techniques published in the period from July 1, 1993 to June 30, 1996. Due to the lack of space the report remains necessarily incomplete, and I apologize to all the authors of important contributions that are not cited here. This review does not cover space and balloon-borne instruments that try to achieve high spatial resolution by observing from above the Earth's atmosphere. Recent work on ground-based high-resolution techniques has been collected in the proceedings of the 13th Sacramento Peak Summer Workshop on Real Time and Post Facto Solar Image Correction (Radick 1993).

14.2. CORRELATION TRACKING

The lowest order of wavefront correction is tip-tilt compensation. In the case of solar observations, this technique is often called correlation tracking because the lack of a point source on the sun makes it necessary to use correlation approaches to determine the instantaneous wavefront tilt. The current image is thereby compared with a stored reference image. This reference image needs to be updated periodically to take into account changes in the solar structure itself. One successful implementation of the tip-tilt correction uses a fast Fourier transform scheme to perform the correlation (Rimmele et al. 1993). The shift between the actual image and the reference image is determined by the location of the maximum of the correlation function. A more recent implementation makes use of a video motion estimation processor (Ballesteros et al. 1996). This commercial chip minimizes the sum of the absolute difference between the actual image and the reference image as a function of the shift between the two images. By using a compact electronic component, the hardware complexity of the wavefront tilt estimation circuit is considerably reduced. An interesting approach, to combine the image sensor and the computation capabilities into a single micro-chip, has been proposed and implemented by Strohbehn et al. (1993). This 'silicon retina' tracks subtle, low-contrast features such as solar granulation by using analog current-mode computations that are modeled after the eye's retina.

14.3. ADAPTIVE OPTICS

Unfortunately, there has not been much progress in solar adaptive optics over the last three years as far as higher-order wavefront compensation is concerned. The Lockheed adaptive optics system with its 19-segment mirror is still the only approach in solar physics that has produced images that are better than the uncorrected images (Acton and Dunn 1993). However, this system is limited to observations of pores and small sunspots because the wavefront sensor is based on an array of quad-cells that measure local wavefront tilts of a small, high-contrast object. While the mirror technology has made substantial progress in the last few years due to military and night-time astronomical applications, the wavefront

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sensing issue is unique to solar observations. Again, the absence of a point source on the sun makes the determination of the instantaneous wavefront aberration a formidable task. Various methods have been proposed, but no successful implementation of a general wavefront sensor for low-contrast features has been reported.

14.4. FRAME SELECTION

Since correlation tracking is only correcting the lowest order wavefront aberrations and adaptive optics is still in a very experimental stage, various techniques have been developed to obtain highly resolved images without active, optical correction. A simple and very successful approach is frame selection. Each acquired frame is evaluated in terms of its sharpness. Multiple frame buffers are then used to select a given number of sharpest images out of a larger number of acquired frames. This approach is particularly successful if the exposure times are short and the camera read-out speed is high. Recent applications include observations of bright features in sunspot umbrae (Sobotka et al. 1995) and time series of photospheric bright points (Berger et al. 1995). A correlation tracker can also be used to do frame selection if it is based on an FFT approach (Rimmele et al. 1993).

14.5. DECONVOLUTION

During solar eclipses, the limb of the moon can be used to estimate the instantaneous point-spread function (PSF, e.g. Bonet et al. 1995). However, the PSF can only be determined in the dimension perpendicular to the lunar limb. On the other hand, this approach leads to reliable estimates of the far wings of the PSF, i.e. the stray-light. To apply this PSF estimate to image restoration, it needs to be assumed that the PSF is rotationally symmetric. However, this assumption is not valid any more when the exposure time is not much longer than the correlation time of the atmosphere, which is typically around 20 ms. Modern CCD based cameras very often operate at such short exposure times. Therefore the quality of these reconstructions is of marginal value. Furthermore, the size of the isoplanatic patch is limited to typically a few arcsec, which means that the restoration is only reliable within a small area close to the lunar limb.

Blind deconvolution needs no estimate of the PSF but tries to estimate both the true image and the PSF. Techniques using multiple frames of the same source have a distinctive advantage over single-frame approaches because only the PSF varies from one image to the next. All approaches apply constraints such as non-negativity of the image and the PSF and compact support of the PSF due to the diffraction limit of telescope. A major question concerns the uniqueness of the solutions obtained from blind deconvolution. While Miura and Baba (1995) claim that their reconstructions are unique, Christou et al. (1994) failed to find a converging algorithm for solar images.

Unique solutions can be found in the case of long exposure-time full-disk solar images because of the compact support of the source and the rotational symmetry of the PSF. In particular, the algorithm developed by Toner and Jefferies (1994) has been successfully applied to precise full-disk photometry (Walton et al. 1996), and a modified version is used in the GONG data reduction pipeline (Williams et al. 1995).

14.6. SPECKLE TECHNIQUES

Speckle imaging has been in used to improve the resolution of solar images for almost two decades now. Recent scientific results include the application of speckle masking to the moustache phenomenon (Denker et al. 1995) and of the Knox-Thompson algorithm to small-scale structures in the photosphere (von der Lühe 1994).

For a long time, image reconstruction techniques could not be applied to spectra. Recently, Keller and Johannesson (1995) have developed a technique that uses a rapidly scanning spectrograph and a simultaneously operating slit-jaw camera. The images of the slit-jaw camera are reconstructed in a conventional way. From the slit-jaw images and the reconstruction, the PSF can be determined for every single point in the image. This information coupled with the individual, observed spectra is used to reconstruct the spectra.

14.7. PHASE DIVERSITY

Phase-diversity is an emerging technique that is likely to replace speckle imaging. In contrast to speckle imaging, phase diversity does not rely on a theoretical model of the atmospheric turbulence. Instead, the instantaneous wavefront distortion is determined (e.g. Acton et al. 1996). Phase-diversity, in its simplest form, uses a focused image and a deliberately, simultaneously collected, defocused image. Unique object and wavefront estimates can be obtained from a single image pair. The two most often used algorithms have been developed by Paxman and Seldin (1993, 1994) and Löfdahl and Scharmer (1994). The latter reconstruct single image pairs while the former use a series of pairs to obtain a more reliable estimate. A completely different approach using a transport equation for amplitude and phase has been developed by Restaino (1993).

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15. Advances in Helioseismology

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Helioseismology, the study of wave generation and propagation within the Sun, has led over the last two decades to many new insights concerning the solar interior. This progress has recently accelerated with the advent of new instrument systems that were designed with helioseismology's special requirements in mind, and with the development of effective methods for using sound waves to probe small-scale solar structures. Much of this work is documented in the proceedings of recent conferences (GONG 1994: Ulrich *et al.* 1994, and Fourth SOHO Workshop: Hoeksema *et al.* 1995) and in single-issue summaries of group efforts (Fleck *et al.* 1995, Gough *et al.* 1996b *et seq*). Many exciting results surely lie ahead, especially since the largest of the new instrumentation initiatives have been operating, at this writing, for only a few months.

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15.1. NEW INSTRUMENTATION FOR HELIOSEISMOLOGY

Two major instrumentation projects in helioseismology came to fruition in 1995. The Global Oscillations Network Group (GONG) network of identical Doppler imaging telescopes began operation with all six of its planned sites in October, 1995 (Gough *et al.* 1996b). This network provides near-continuous observations of the Doppler shift at the solar photosphere with a time cadence of one image per minute and a spatial resolution (2 pixel) of about 15 arcsec, good enough to resolve oscillation modes with spherical harmonic degree l as high as 250. The second major observational advance is the SOHO spacecraft, which carries a dozen solar instruments, including a suite of three devoted to helioseismology (Fleck *et al.* 1995). The VIRGO package measures the Sun's irradiance and (with modest spatial resolution) its radiance, with some color discrimination. The GOLF instrument uses a sodium resonance cell to provide very precise measurements of the disk-integrated Doppler shift of the Sun. Finally, the MDI instrument allows Doppler measurements with spatial resolution (2 pixel) of 4 or 1.2 arcsec, as well as providing images of the continuum intensity, absorption line strength, and longitudinal magnetic field. SOHO was launched in Dec 1995, and was successfully inserted into a halo orbit about the L1 Lagrange point in April 1996.

While these major initiatives were under way, several important instrument efforts of smaller scale also reached completion. The LOWL instrument (Tomczyk *et al.* 1995b) uses a potassium-based magneto-optical filter to give Doppler images with moderate spatial resolution and extreme Doppler stability; this instrument has been operating from a site on the island of Hawaii since February 1994. Higher spatial resolution is provided by the High-l Helioseismometer (Bachmann *et al.* 1995), and by the Taiwan Oscillation Network (Chou *et al.* 1995), both of which form Ca II K-line intensity images with 2-pixel resolution of about 4 arcsec.

All of these new instruments, in combination with existing single-site and network facilities, have contributed to a sudden flood of high-quality seismology data. The challenge now is to assimilate these new observations in effective and timely ways, and to coordinate them with other kinds of solar measurements.

15.2. RESULTS FROM ANALYSIS OF GLOBAL MODES

Significant new measurements of the spherical structure of the Sun and of the solar angular velocity have been derived from observations taken with the newer instruments, particularly the LOWL and the GONG network. By design, the LOWL instrument is particularly well suited to measurements of p-modes with large horizontal scale, and hence small values of the angular degree l. Such modes penetrate deeply into the Sun, and provide the only probes except for solar neutrinos that respond to processes within the solar core. Perhaps the most exciting result to come from these and similar data is the conclusion that the angular velocity Ω in the core is not much larger than the mean surface value of Ω (Toutain & Kosovichev 1994, Tomczyk *et al.* 1995a, Appourchaux *et al.* 1995, Thompson *et al.* 1996). This result is contrary to the predictions of some models of the rotational evolution of the Sun (Pinsonneault *et al.* 1989); it suggests that processes that are not included in these models (such as coupling through magnetic fields) may be important in determining the flow of angular momentum within stars.

The variation of sound speed and density with depth in the Sun determines the frequencies of the p-modes. A comparison of observed frequencies and those predicted from a solar model therefore provides a sensitive test of the correctness of the model. Early tests of this kind suffered from inconsistencies in the observed mode frequencies; these arose because data from different l ranges were taken with different instruments, and usually at different times (note that different solar activity at different epochs leads to systematic shifts in p-mode frequencies). New data from the LOWL instrument and from the GONG network do not suffer from this problem, and accordingly the precision with which one can compare models and observation has been substantially improved. An analysis of LOWL data (Basu *et al.* 1996) confirms earlier results illustrating the improved fits resulting from new formulations for the equation of state and opacity. In addition, the agreement between models and observed frequencies is much improved if diffusion and gravitational settling of helium is accounted for; there is some evidence that settling of elements heavier than helium may also be important. Similar results emerge from the first 3 months of GONG observations (Gough *et al.* 1996a). The radial variation of sound speed and density predicted by the best models now agree with those estimated from helioseismology to within better than 1% for all radii greater than 0.2 $R_\odot$. This is a substantial improvement over the results of just a few years ago, but the frequency measurements are so precise that the differences remain significant.

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15.3. LOCAL HELIOSEISMOLOGY

Important developments in recent years have emerged from analyses of helioseismic data that treat the oscillations as local waves, taking no cognizance of their global nature. Such an approach is natural and fruitful for the study of small features in the solar envelope, such as those associated with magnetic field concentrations or with localized flows.

Braun and his collaborators (Braun 1995 and references therein) have shown that sunspots absorb and impose phase shifts on the p-modes that are incident upon them. Typical sunspots can absorb up to half of the incident p-mode energy; the absorption is frequency dependent, with a maximum near 3 mHz, a minimum near 5 mHz, and increasing absorption at yet higher frequencies. The observations suggest that phase shifts occur in a rather shallow region of enhanced wave speed that has about the same spatial extent as the visible spot, while absorption takes place over a larger area. The process by which sunspots absorb acoustic waves is now thought to be related to conversion between acoustic and slow-mode waves at boundaries between magnetized and unmagnetized regions (Cally *et al.* 1994). Bogdan & Braun (1995) have reviewed recent progress in this field.

Time-distance helioseismology (Duvall *et al.* 1993) treats each point on the solar surface as a source for acoustic waves that pass through it. By examining the correlation between the oscillating signal at such a point and the signal averaged over an annulus surrounding it, one can estimate the wave travel time along the ray path connecting the point and the annulus. This travel time in turn contains information about physical conditions (particularly temperature and bulk flow velocity) averaged along the path. An ingenious application of this method (Duvall *et al.* 1996) indicates that solar active regions are associated both with subsurface flows and with positive perturbations in the wave propagation speed. By segmenting the annulus over which a signal is averaged, it is possible to estimate the variation of wave propagation speed along several different azimuths. Recently, such techniques applied to data from the MDI experiment on SOHO have revealed direct evidence for the flows connected with supergranulation (Kosovichev *et al.* 1996).

Finally, it has been known for many years that the surface amplitudes of p-modes are systematically reduced in the presence of magnetic fields. Recent theoretical work by Jain *et al.* (1996) and by Hindman *et al.* (1996) suggests that this effect may result from distortions of the p-mode eigenfunctions by magnetic restoring forces in the few scale heights just above and below the photosphere. If this interpretation is correct, then the surface amplitudes may provide a high spatial resolution technique to measure the magnetic field strength in and just below the solar photosphere. The combination of the three methods just described with new, high-quality data from GONG and SOHO promises to yield completely new perspectives on the structure and development of solar activity complexes, especially as they rise through the top few Mm of the solar envelope.

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16. DIAGNOSTICS OF THE VARIATION OF PHYSICAL QUANTITIES THROUGH THE SOLAR PHOTOSPHERE

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Although the debate is very old, theoretical reasons continue to appear in the literature which argue on height variation (or even 2D structure) of the physical parameters to understand particular features of the observed profiles (see, e.g., Solanki & Montavon 1993 for magnetic fields in penumbrae, Thomas 1994 for a discussion on the Evershed effect, and Landolfi & Landi Degl'Innocenti 1996 and Steiner et al. 1996 concerning small-scale elements). During the last three years the transfer of polarized radiation has kept the debate alive (hitherto alive for unpolarized light as well) on the height of formation of lines and measurements. Contribution functions (CFs) of the Stokes profiles have been thoroughly studied (Grossmann-Doerth 1994, Solanki & Bruls 1994, Staude 1996). The authors show the broad range of depths from which information is carried by the line. Ruiz Cobo & del Toro Iniesta (1994), however, propose that the sensitivity of Stokes profiles to the different photospheric quantities is better described by the response functions (RFs). The RF definition avoids ambiguities present in the CF definition and it explicitely shows the variations of Stokes profiles as a consequence of variations of the photospheric quantities (see also del Toro Iniesta & Ruiz Cobo 1995). Moreover, they can also be extended to measurements and not only to profiles and be used in inversion codes of the transfer equation (see del Toro Iniesta & Ruiz Cobo 1996 for a review). The RF approach has been followed by Bellot Rubio, Ruiz Cobo, & Collados (1996) for exploring the diagnostics provided by lines formed in small-scale magnetic elements. These authors use the results of del Toro Iniesta et al. (1995) who study a particular solution of the radiative transfer equation when magnetic and non-magnetic atmospheres are interlaced through the line of sight. Finally, Sánchez Almeida, Ruiz Cobo, & del Toro Iniesta (1996) propose the use of heights of formation for specific measurements which are uniquely defined.

16.1. NON-POLARIZED LIGHT DIAGNOSTICS

The only attempt during the period covered by this report to diagnose other thermodynamic variables than temperature is the remarkable paper by Kneer & Nolte (1994). Based on a RF analysis, they propose the wing fluctuation of lines as a good indicator of the photospheric pressure. Most of the work aimed at diagnosing the depth dependence of velocity fields has been devoted to the Evershed effect in penumbrae. Synthesis of line profiles allows Degenhardt (1993) to suggest that a decrease of the filling factor of flowing material with height may account for the observed line asymmetries. These results are confirmed by Degenhardt & Wiehr (1994a,b), and by Wiehr (1996) who, besides, finds no trace of the Evershed effect outside the outer boundary of the penumbra. This last result is opposite to those of Rimmele (1995) who finds velocities well beyond the spot and estimates the height of the arch through which material is flowing. The temperature and velocity stratification of penumbrae is studied by del Toro Iniesta, Tarbell, & Ruiz Cobo (1994). Diagnostics of temperature/intensity and velocity fluctuations of convective motions are carried out through the use of RFs (Salucci et al. 1994, Rodríguez Hidalgo, Collados, & Vázquez 1994, Volmöller, Komm, & Mattig 1996, Márquez, Bonet, & Vázquez 1996a) and of CFs (Hanslmeier, Nesis, & Mattig 1993, 94). Correlation tracking techniques along with theoretical arguments are used by November (1994) to show that the horizontal supergranular flow cannot extend much more than one e-fold increase in the density scale height below the visible surface. The information content on temperature of infrared continua is displayed through plots of CFs by Jefferies (1994) and Lindsey (1994). Finally, NLTE analyses show that the flanks of alkali lines are good indicators of temperature in the upper photosphere (Caccin, Gomez, & Severino 1993, Severino, Gomez, & Caccin 1994), that NLTE is crucial in the upper

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photosphere/lower chromosphere diagnostics (Rutten & Carlsson 1994), and that the weaker infrared H I lines are indeed formed in the photosphere (Carlsson & Rutten 1994).

16.2. POLARIZED DIAGNOSTICS

Estimates of the vertical gradient of the magnetic field strength are made in plages (Martínez Pillet, Lites, & Skumanich 1996), in pores (Muglach, Solanki, & Livingston 1995), in umbrae (Hewagama et al. 1993, Wiehr & Degenhardt 1993, Schmidt & Balthasar 1994), and in the whole spot (Balthasar & Schmidt 1993). A diagnostic study of several spectral lines to constrain MHD models of umbral dots is presented by Degenhardt & Lites (1993a,b). Model atmospheres of umbrae are proposed which include thermodynamic, dynamic and magnetic parameter stratifications, after the inversion of Stokes I- and V-profiles (Collados et al. 1994). The upper photospheric and lower chromospheric layers of penumbrae are studied by Bruls et al. (1995) and by Rüedi, Solanki, & Livingston (1995). One of the most exciting realizations during this period is the association of polarization beyond the visual, outer penumbral boundary of sunspots with superpenumbral canopies. Adams et al. (1993) and Zhang (1994) detect them on vector magnetograms, Solanki, Montavon, & Livingston (1994) do the same from inversion of infrared observations of the Evershed effect; finally, Solanki, Finsterle, & Rüedi (1996) use them to diagnose possible errors in determining the inclination of plage small-scale magnetic elements. The stratification of physical parameters of these flux tubes is studied by calculating synthetic Stokes profiles in MHD simulations (Grossmann-Doerth et al. 1994, Steiner et al. 1996) and by NLTE analyses (Solanki et al. 1994, Briand & Solanki 1995, Márquez, Bonet, & Vázquez 1996b). Challenging new views of the problem of height variation of physical quantities continue to appear as the recently proposed micro-structured magnetic atmospheres (MISMA, Sánchez Almeida & Landi Degl'Innocenti 1996, Sánchez Almeida et al. 1996; for the non-polarized case see also Lindsey, Gu, & Jefferies 1995 and Gu, Lindsey, & Jefferies 1995).

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17. Solar Atmospheric Dynamics

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In the last years, studies of the structure of the solar atmosphere have demonstrated — yet more than before — that the solar atmosphere is so intrinsically dynamic in nature that it is a fallacy to speak of "the quiet solar atmosphere". The term denotes areas where magnetism is not obviously dominating, but even there the atmosphere is far from the classic paradigm of stably stratified plane-parallel layers in hydrostatic equilibrium. In fact, even the existence of a ubiquitous "temperature minimum" between photosphere and chromosphere has now been put into doubt (Carlsson & Stein 1995).

The major current improvement in this regard is the advent of realistic numerical simulations. Time-dependent hydrodynamics modeling including detailed radiative transfer, currently cast in 1D, 2D and 3D versions with different capabilities, now enable solar astrophysics to finally leave the one-dimensional standard modeling that was so long required for tractability. In addition, new groundbased techniques (see report by Keller) provide the high spatial and temporal resolution needed to properly appreciate the dynamic nature of the photosphere. The spate of instruments onboard the SOHO mission furnishes unprecedented long-duration views of chromospheric dynamics from space.

This section covers the so highly unquiet behavior of the "quiet" photosphere and chromosphere. For subsurface dynamics see Brown's report; dynamics of magnetic structures is covered by Solanki; coronal dynamics is treated by Hammer.

17.1. PHOTOSPHERIC GRANULATION

In essence, the hydrodynamics of the solar granulation has been understood in the past decade (see reviews in Rutten & Severino 1989 and by Spruit et al. 1990) and translated to stellar granulation as well (Nordlund & Dravins 1990). Currently, simulations are used to detail the turbulent convective processes. An issue is the occurrence of supersonic flows, both in the fast downflow plumes ("fingers", Stein & Nordlund 1989) where partial hydrogen ionization contributes appreciably to the dynamical topology (Rast et al. 1993) and which act as the major scale-setting agent (Rast 1995), and in the horizontal flows at the edges of large granules near downdraft sites (Malagoli et al. 1990). Rimmele et al. (1995) found that exceptionally dark intergranular lanes accompany the acoustic events that are thought to mark p-mode excitation sites. Nesis et al. (1992) have claimed that supersonic flows are actually observable as post-shock intergranular line broadening, but Solanki et al. (1996) disagree and suggest instead that the

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predicted supersonic horizontal flows themselves may be diagnosed from excessive line broadening along slanted lines of sight.

17.2. PHOTOSPHERIC FLOWS

The emphasis in studying photospheric dynamics has moved to the effects of turbulent convection on the structures and patterns of magnetic activity. At the smallest scale, current efforts concentrate on the Muller bright points seen in the G–band (CH lines around 430.5 nm), which for a not-understood reason brighten considerably in the smallest flux concentrations. They appear to furnish direct diagnostics of the basic components of solar magnetism, so far observed only indirectly through Stokes polarimetry — but nevertheless modeled in great detail as flux "tubes" (*e.g.*, Spruit et al. 1991, Buente et al. 1993) or "sheets" (*e.g.*, Steiner et al. 1994, Grossmann-Doerth et al. 1994). The G–band points are tiny (0.1–0.2 arcsec) and stand out only when the seeing is excellent (Title & Berger 1996), but they then provide direct views of the highly dynamical nature and topology of the photosphere as experienced by flux concentrations (Berger et al. 1995). The current frontier is to enhance their visibility through sophisticated image restoration (speckle plus phase diversity, Paxman et al. 1996).

The phenomenon of mesogranulation (*e.g.*, Muller et al. 1992) is still being debated. It is seen clearest in the vorticity and divergence patterning of granular flow motions (Wang et al. 1995). November (1994) has proposed that it drives the supergranulation, while Straus & Bonaccini (1996, cf. Straus et al. 1992) doubt its existence, and Rast (1995) attributes it to granular downflow topology.

The larger-scale topology of the supergranulation and the roughly (but not exactly) corresponding magnetic and chromospheric network is actively studied using various diffusion formalisms (percolation, Voronoi tessellation; Balke et al. 1993, Lawrence & Schrijver 1993, Lawrence et al. 1993, Tao et al. 1995, Lawrence et al. 1996, Schrijver et al. 1996). Currently, space observation with SOHO's MDI supplies long-term distortion-free measurements that enable quantitative analyses of this type. A major goal is to ascertain the field topology at emergence in order to derive subsurface dynamo patterning.

17.3. CHROMOSPHERIC OSCILLATIONS

A recent breakthrough in chromospheric dynamics is the identification of the oscillatory phenomena that constitute the so-called Ca II H_{2V} and K_{2V} internetwork grains. A review of the extensive literature on this subject led Rutten & Uitenbroek (1991) to propose that these portray three-minute shock formation with *p*-mode excitation and interference, of purely acoustic nature rather than marking fluxtubes as claimed by Sivaraman & Livingston (1982), Kalkofen (1989) and Kariyappa et al. (1994). Extensive observational studies (Kulaczewski 1992, Von Uexkuell & Kneer 1995, Steffens et al. 1996, Hofmann et al. 1996) have confirmed that internetwork K_{2V} grains are tip-of-the-iceberg extrema of oscillation interference patterns. At the same time, numerical simulations by different groups (Carlsson & Stein 1992, Kalkofen et al. 1994, Schmitz & Fleck 1995, Ulmschneider & Sutmann 1995a, 1995b) have culminated in the qualitative reproduction of observed H_{2V} behavior by Carlsson & Stein (1994). Using a broad-band subphotospheric piston derived from the actual Doppler excursions of a photospheric line observed by Lites et al. (1993) they established that the K_{2V} grains indeed betray shock interference between upward propagating acoustic disturbances and backfalling matter from previous shock passages. Issues now under study are the signatures of reflection from higher layers (Kumar et al. 1994, Steffens et al. 1995, Deubner et al. 1996) and the signatures of the shocks within higher layers (Cook et al. 1996, Hoekzema et al. 1996). An open question is yet how much these acoustic phenomena contribute to the "basal" heating of the solar chromosphere (cf. Schrijver 1995).

The dynamics of the chromospheric network, mapped by bright elements in Ca II K, differs strongly from the non-magnetic internetwork domains (or at least less magnetic, see Keller et al. 1994 and Lites et al. 1996). Lites et al. (1993) confirmed the dichotomy between three-minute internetwork oscillations and the long-period modulations displayed by network elements (cf. Bocchialini et al. 1994). However, Volkmer et al. (1995) have found evidence for 100 s oscillation within a small-scale magnetic element.

17.4. CHROMOSPHERIC FLOWS

A topic where much is to be expected now that SOHO provides extended coverage with short-wavelength diagnostics (SUMER, CDS and EIT) is the dynamical behavior of the magnetically structured middle

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and upper chromosphere. Current ground-based studies of mottle flows lead the way (*e.g.*, Heinzel & Schmieder 1994, Tsiropoula et al. 1994). Elaborate radiative transfer modeling is required (Mein et al. 1996) — if not detailed hydrodynamical simulation, for example to establish the importance of siphon flows (*e.g.*, Degenhardt et al. 1993, Montesinos & Thomas 1993).

Finally, two topics of chromospheric dynamics should be pointed out that merit focus in the coming years. The first consists of spicules, a subject largely been neglected since the sixties (Beckers 1968, cf. Gaizauskas 1994) but bound to resurface while chromospheric dynamics is detailed SOHO-wise. The second is the FIP-flip observed in the closed-field corona and the slow solar wind (and even in energetic cosmic rays). This fractionation between low and high first ionization energy species must occur where hydrogen is yet mainly neutral, so that transport across field lines is easy for C, N and O but not for the charged ions of Mg, Fe, Si etc. (Marsch et al. 1995).

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18. FLOWS AND OSCILLATIONS IN SMALL-SCALE MAGNETIC STRUCTURES

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Small-scale magnetic features (or magnetic elements) contain most of the magnetic energy and flux on the solar surface, and play, through their dynamics, a dominant role in channelling energy into the upper atmospheric layers. First a brief review is given of the work done in the last 3 years on stationary flows.

On average, magnetic elements are well known to be free of substantial steady flows. Recently Montagne et al. (1996) confirmed these results, although their line shifts were derived from Stokes I profiles alone. The redshift of roughly 200 m s^{-1} they observe in and around magnetic features relative to the quiet sun corresponds to no flow when corrected for the granular blueshift. Amer & Kneer (1993) and Kneer & Stolpe (1996) also find little net shift of the Stokes V zero-crossing when averaged over a few arc sec on the solar surface. Individual high-spatial-resolution profiles can be shifted by up to 1 km s^{-1}, however (both blue- and redshifts being common).

Even stronger flows within magnetic elements have been detected on both sides of a magnetic neutral line and have been interpreted as the footpoints of a siphon flow. Degenhardt et al. (1993) showed from the comparison of model calculations with infrared (1.56 μm) observations that this siphon flow is supersonic near the top of the loop connecting the footpoints and shocks above the downstream footpoint. The models they used were developed by Montesinos & Thomas (1993) and include the effects of partial ionization and lateral radiative exchange (via Newton's law of cooling).

Magnetic elements are surrounded by fast, quasi-stationary flows concentrated in narrow lanes, which are fed by horizontal inflows. This picture is substantiated by both empirical modelling of the Stokes V and I profile asymmetry (Bünte et al. 1993, Márquez et al. 1996) and in still greater detail by theoretical simulations (Steiner et al. 1995, 1996). A radically different view of how the Stokes V asymmetry is produced is proposed by Sánchez Almeida & Landi Degl'Innocenti (1996), who argue that the magnetic features are composed of many strands of field, each thinner than the photon mean-free-path. These strands are interleaved with flows.

In the following, recent advances in the theory and observation of oscillations and waves related to magnetic elements are reviewed.

Lundberg (1994) derived the non-linear dispersion relation of a weakly non-linear slow sausage surface wave travelling along a magnetized slab (considered as a simple model of a flux tube, which is thought to be the basic physical structure underlying magnetic elements), and Goossens et al. (1995) obtained dissipative MHD solutions for resonant Alfvén waves in a cylindrical model of a flux tube, while Nakariakov & Roberts (1995) have worked out the theory of magnetosonic waves in magnetic slabs, including the influence of steady flows. On applying their results to photospheric conditions they find that downflows of 1–3 km s^{-1} around flux tubes (i.e. downflows of the observed magnitude) lead to the disappearance of certain wave modes in the flux tube. All these investigations do not take the effects of gravity into account, however. The theory of magneto-atmospheric waves subject to Newtonian cooling (including the influence of gravity) was developed further by Bünte & Bogdan (1994). Finally, an important step

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towards a generalized linear theory of the wave modes in slender magnetic flux tubes was taken by Zhugzhda (1996), who extended earlier work and combined the description of longitudinal and torsional waves into a single (linear) formalism.

Waves in or interacting with small-scale magnetic features are of particular interest in the context of chromospheric and coronal heating. Jordan (1993) makes use of a low-lying magnetic canopy in an attempt to keep acoustic waves from dissipating through shocks too low in the atmosphere. Such canopies are produced by the rapid expansion of the magnetic elements with height. Choudhuri et al. (1993) consider the propagation of kink waves and wave pulses along thin flux tubes in an atmosphere including a temperature jump between the chromosphere and corona. They calculate the upward propagating energy flux expected from the the rapid horizontal movement of bright points (identified with magnetic features), such as those observed by Muller et al. (1994). Choudhuri et al. (1993) conclude that this energy flux is still sufficient to heat the quiet corona even in the presence of reflections at the transition zone.

Highly dynamical 2-dimensional radiation MHD simulations of magnetic elements have been presented by Steiner et al. (1993, 1995, 1996). They find that the magnetic elements are strongly affected by the surrounding granules. These push the magnetic elements backwards and forwards, producing considerable inclination of the field lines. Although the motions are not strictly periodic they are associated with a time-scale of 5–10 min (the granular time scale) and thus should produce propagating kink waves, such as the ones investigated by Choudhuri et al. (1993). The quasiperiodic horizontal oscillations of a magnetic feature observed by Volkmer et al. (1995) may be of this type. The simulations of Steiner et al. (1993, 1995, 1996) also produce intense, upward travelling shocks followed by downflows, presumably caused by material returning to its original location, at intervals of 2–3 minutes. The shocks produce episodes of intense heating in the upper photosphere and transport considerable energy into the lower chromosphere.

Direct observations of waves in magnetic elements have been relatively rare and have in general detected only 5min oscillations. Thus, these were the only oscillations detected by Muglach et al. (1995) in the deep layers of magnetic elements observed at infrared wavelengths. Volkmer et al. (1995), however, present the first evidence for short period (100 s) waves in magnetic elements. The significance of this detection is that according to linear theory only the short period longitudinal flux-tube waves are expected to propagate. Unfortunately, only a single structure was found to exhibit such oscillations and a confirmation is important.

More common than observations in the polarized Stokes parameters are oscillation measurements of the intensity spectrum in magnetic regions, such as the network. Lites et al. (1993), Kariyappa (1994) and Bocchialini et al. (1994) have observed waves in the intranetwork and the network and have confirmed previous observations that the chromospheric oscillations in the network possess longer periods. Bocchialini & Baudin (1994), applying a wavelet analysis to the data of Bocchialini et al. (1994), also confirmed earlier conclusions of downward propagating waves in the network.

Finally, line broadening still suggests that large non-stationary velocities are present in magnetic elements. NLTE calculations have confirmed that the Stokes V profiles of photospheric lines need to be broadened by 2–2.5 km s^{-1} (Bruls & Solanki 1993) and the Mg I b line requires a broadening of 1.6–1.8 km s^{-1} (Briand & Solanki 1995), values that are larger than quiet sun Stokes I profiles, once again indicating the presence of strong dynamics within small-scale magnetic structures.

The literature prior to 1993 on flows and oscillations in small-scale magnetic features has been reviewed by Solanki (1993). An up to date review of coronal heating processes is provided by Narain & Ulmschneider (1995).

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19. The Non-Active Corona

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The physics of magnetically closed and open structures in the solar corona is quite different. This applies in particular to the energy balance and possible heating mechanisms. In magnetically closed regions, footpoint motions can easily build up stress in the magnetic field, while in open regions perturbations tend to escape with the high Alfvén speed. This makes different dissipation mechanisms likely. The emphasis of this section lies on recent progress in our understanding of the magnetically open corona, which manifests itself most prominently in coronal holes, although open regions exist also in the so-called quiet corona.

19.1. OBSERVATIONAL ASPECTS

Coronal holes are not homogeneous, but structured on various scales. Spicules reach larger heights, and macrospicules are more frequent than outside of coronal holes, probably since the essentially vertical magnetic fields in coronal holes permit these jet-like phenomena to ascend higher (Johannesson and Zirin 1996). Polar plumes are well-known ray-like density enhancements that could recently be traced out to heliocentric heights of 5 $R_\odot$ in images taken with the white-light coronagraph aboard the *Spartan 201* spacecraft (Fisher and Guhathakurta 1995). The angular half-width was found to be constant with height; it corresponds roughly to the supergranular scale at the solar surface. On the basis of radio ranging measurements obtained during the 1991 solar conjunction of *Ulysses*, Woo (1996) showed that such structures exist also in equatorial coronal holes (see also Wang and Sheeley 1995a) and extend out to at least 42 $R_\odot$. *In situ* spacecraft measurements found possible signatures of these structures out to 0.5 AU in the ecliptic plane.

One of the most unexpected observational results during the reporting period is evidence that protons in the inner corona may be much hotter than previously thought. This was suggested by measurements of H I Lyα line profiles above the solar limb with the *Ultraviolet Coronal Spectrometer* on *Spartan 201* (Kohl et al. 1995, 1996). The profiles cannot be represented by a single Gaussian function, but rather by two Gaussians, of which the broader component has a width of about 300 km s^{-1}, corresponding to roughly 5×10^6 K if interpreted as temperature. This is much higher than the electron temperature, which is of the order of 1×10^6 K (Habbal et al. 1993). It is not clear if the enhanced line wings really necessitate such hot plasma along the line of sight. If so, this would point to a coronal heating mechanism that preferentially heats ions (e.g., cyclotron heating by waves of very high frequencies, McKenzie et al. 1995). Alternative explanations are non-Maxwellian velocity distributions (Scudder 1994), or a combination of thermal velocities, transverse wave motions (e.g., Olsen et al. 1994) and the line of sight component of longitudinal motions. The improved version of this instrument on *SOHO* will certainly provide more details.

19.2. ENERGY BALANCE

The heating mechanism remains the most outstanding problem in the physics of the open corona. But although it has not yet been identified, there has been some progress in constraining it. In particular, we know much better now where the heating must occur. This has been brought about by theoretical models that parametrize the heating law and try to adjust the parameters until agreement is achieved with observational information (such as the mass flux and flow speed of the solar wind as measured by spacecraft, density profiles and the geometry of coronal holes derived from coronagraph observations, or constraints on the electron temperature derived from EUV measurements and from the frozen-in ionization state of various atomic species in the solar wind plasma). It is crucially important that the energy balance of theoretical models accounts for the downward thermal conduction into the chromospheric-coronal transition region because this process determines the long-term coronal base pressure. Previously, self-consistent models of this kind assumed a single-fluid gas (i.e., electrons and protons have the same temperature). Withbroe (1988) and Wang (1993) showed that the best agreement with observations is achieved when an energy flux of a few times 10^5 erg cm^{-2} s^{-1} is dissipated in the inner corona over a characteristic damping length L of somewhat less than a solar radius $R_\odot$. The higher density in plumes can be reproduced by assuming an additional heating component at the very base of the corona, perhaps related to bipolar magnetic fields in bright points that are often found at the base of coronal plumes (Wang 1994). More recently, self-consistent two-fluid models of the combined heating and wind problem became also available (Hansteen and Leer 1995). They confirm the basic characteristics of one-fluid models, such as the dominance of wind (radiation) for large (small) L, and the insensitivity of the mass flux with respect to the location of the heat deposition. The main new effects in two-fluid models occur when a significant fraction of the available energy heats the protons. They can then reach much higher temperatures than the electrons since their conductivity is smaller and thus less efficient in redistributing the energy. The high proton temperature leads *(i)* to a more efficient acceleration of the wind by the thermal pressure gradient, and *(ii)* to significant amounts of enthalpy that can be converted to potential and kinetic energy beyond the temperature maximum. Thus the latter lies at lower heights, and hence the damping length is smaller, than in one-fluid models.

Sturrock et al. (1996) found evidence from YOHKOH observations that even in a magnetically closed, but very extended region in the quiet corona under a coronal streamer the main heating took place beyond 0.5 $R_\odot$ above the surface.

The reason for a damping length that is neither larger nor much smaller than the solar radius is well understood (cf. Hammer 1994): A major energy loss in the open corona is the potential energy required to lift the solar wind out of the gravitational well. This energy is needed over a characteristic scale of $R_\odot$. If the heating occurs over a significantly different scale, the energy must be redistributed within the corona. This can be done efficiently by thermal conduction. However, the ratio of outward to inward conducted energy depends on the location of the temperature maximum and thus on L; and if L is not of order $R_\odot$, conduction tends to transport the energy further away from where it is needed (Hammer et al. 1996). As discussed above, in models with high maximum temperature at relatively low heights, enthalpy can also become an efficient energy redistribution mechanism.

Sandbæk et al. (1994) pointed out that the relatively constant wind mass flux at Earth implies that the total energy input into coronal holes must vary linearly with the magnetic field in the inner corona, which has an average value of 10 G in polar coronal holes (Wang and Sheeley 1995b). Even though this points (again) to a magnetic heating mechanism, this mechanism has not yet been identified. The relatively short damping length L excludes many suggested heating mechanisms, in particular those for monochromatic Alfvén waves of periods expected to be generated in the convection zone (i.e., several minutes), as Parker (1991) has shown. Several authors (e.g., Velli 1993, Krogulec et al. 1994, Lou and Rosner 1994, MacGregor and Charbonneau 1994, Musielak and Moore 1995, Stark-Kublin 1995) have discussed if non-WKB effects can lead to a trapping, or at least partial reflection, of Alfvén waves, with possibly new dissipation mechanisms. Ofman and Davila investigated the dissipation of shear Alfvén waves in the presence of inhomogeneities (plumes). McKenzie et al. suggested heating by high frequency waves (.01 — 10 kHz), which might be produced in small-scale reconnection events in the chromospheric network, and which could dissipate by cyclotron heating. For extensive reviews on heating mechanisms, see Marsch (1994) and Narain and Ulmschneider (1996).

19.3. NONCOLLISIONAL EFFECTS

Scudder (1994) applied his "velocity filtration model" to coronal holes. This model postulates a strong overpopulation of energetic particles at the top of the chromosphere, which is able to maintain the corona without further heating. In its current state, the model neglects Coulomb collisions, leading to theoretical inconsistencies (Anderson 1994). It is also inconsistent with a number of empirical constraints: For the middle and upper transition region, it can neither explain the observed emission as a function of temperature T (Anderson et al. 1996) nor as a function of height (∇T is too flat at higher T). Moreover, in a coronal hole model with the correct mass flux and line widths, the energy flux is too large. Despite these current deficiencies, the theory should be further explored since it points correctly to the need for a better understanding of noncollisional effects and the heights where they become important.

It has long been known that such effects are very important in the outer corona. In particular the classical description of the heat flux must break down at a few solar radii. Canullo et al. (1996) provided an expression for the heat transport that interpolates between the collision dominated regime in the inner, and the collisionless saturated heat flux in the outer corona. Olsen and Leer (1996a,b) use a set of eight-moment transport equations to show that an improved treatment of the heat flux leads to higher temperatures and a faster wind acceleration.

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