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IV. SMALL SCALE MAGNETIC FIELDS

(S.K. Solanki)

Considerable progress has been made during the last four years in the theoretical and empirical investigation of the small scale solar magnetic field and associated phenomena. Although the basic outlines established in the 1970s of the structure of the field, namely small fluxtubes or magnetic elements with kilogauss fields embedded in a relatively field free medium have survived, many of the details have changed and some of the large gaps in our knowlegde of these captivating structures have been filled. In the following we briefly outline some of the highlights.

One direction in the thrust for a better understanding of magnetic elements has been towards the construction of comprehensive theoretical models, e.g. by Deinzer et al. (1984a,b) in 2-D slab geometry and by Nordlund (1986) in 3-D. Although these models still lack some essential features (too small spatial resolution in the 3-D models, no proper treatment of the radiative transfer in the 2-D models; the latter shortcoming is being remedied at the moment by a number of groups), they do illustrate the physics and give rise to the hope that within a decade models of magnetic elements of equal detail and generality as the granulation models of Nordlund will be available. However, considerable hurdles must be surmounted first, since magnetic elements are considerably more difficult to model than granulation. Waves, for example, cannot be neglected, since wave heating (perhaps involving dissipation via shocks, cf. Herbold et al., 1984) is probably quite important even in the photospheric layers and is certainly so in the chromosphere. The work of Ayres et al. (1986) actually supports the conclusion that the hot chromosphere only exists within fluxtubes. Another complexity facing 3-D fluxtube modellers is the possible presence of a boundary current sheet, which requires very fine grids for a proper treatment. Two dimensional models, like the ones of Deinzer et al. or of Steiner et al. (1986), have the advantage that they can take such boundary layers into account in detail.

A breakthrough in the radiative transfer of polarized light was achieved by Van Ballegooijen (1985). He presented a method for obtaining the formal solution of the radiative transfer equations for polarized light in the presence of a magnetic field. Besides providing deep insight into the process of solution, his method also allows contribution functions to be defined and calculated. Thus the determination of the heights of formation of the Stokes profiles has been placed on a secure theoretical footing. This advance will play an important role, not only for the proper diagnostics of observations, but also for interpreting the spectra produced by the emerging breed of comprehensive fluxtube models. The one remaining problem with his definition is that it mixes the contribution to the lines with that to the continuum. However, a remedy is already in sight.

Given the present state of theory, observational and empirical work is still indispensible. The main observational advance has come from the extension of the Fourier transform spectrometer (FTS) at the NSO McMath telescope into a spectral polarimeter, which is currently capable of registering Stokes I, V, and Q in thousands of spectral lines simultaneously at very high spectral resolution. Data from this instrument, built by J.W. Brault and converted into a polarimeter by J.W. Harvey and J.O. Stenflo, have led to a considerable fraction of the observational advances concerning small scale magnetic fields in the last three to four years. Although such data do not have high spatial or temporal resolution, the amount of information they contain is still enormous and only a fraction of it has so far been extracted. Some of the progress has been a result of the derivation of an approximate form of the unpolarized line profile, Stokes I, formed exclusively inside the magnetic elements form the observed Stokes V (Solanki and Stenflo, 1984). This allows the rich array of diagnostic techniques available for the unpolarized spectrum to be applied for the first time to light arising solely from inside a magnetic element. When combined with FTS observations this technique yields a complete atlas of a fluxtube spectrum. New empirical models of the fluxtube temperature structure have been deduced from such profiles (Solanki, 1986). It has also been possible to obtain information on the vertical gradient of the magnetic field (Stenflo et al., 1987), as well as the inclination of the fluxtubes to the vertical. Some of the other results obtained from these data are mentioned further below.

Much effort has gone into the (mostly theoretical) investigation of dynamical phenomena associated with a concentrated magnetic field. Of particular importance has been the emergence of the non-linear treatment of such phenomena. For example, the convective collapse of fluxtubes as a means of concentrating the field into small bundles with field strengths well in excess of the value expected through equipartition with photospheric motions, has been studied in detail numerically (e.g. Nordlund, 1986; Hasan, 1985). One outcome of these calculations has been that the final state is one of overstable oscillations. Also, a number of mechanisms for exciting and amplifying the various wave modes and oscillations in fluxtube have been recently proposed. Interesting is the result of Venkatakrishnan (1986), who has found that very high amplitude oscillations and waves can be excited resonantly inside fluxtubes by external pressure fluctuations. In view of such non-linear results and the rich literature on linear calculations of fluxtube waves (see Roberts, 1986 for a review), it appears surprising that until recently no evidence for non-stationary mass motions in fluxtubes, except low amplitude 5-minute oscillations (Giovanelli et al., 1978; Wiehr, 1985), existed at all. The reason is that fluxtubes cannot be resolved, so that usually more than one flux-tube is present in the resolution element. Only the oscillations or waves which are in phase in all of these give an oscillating Doppler shift signal. However, an analysis of line widths by Solanki (1986) has shown that rms velocities of 2-4 km s^{-1} are present inside the magnetic elements, from which he has inferred the presence of non-stationary mass motions with amplitudes (in the vertical direction) larger than in the surrounding quiet photosphere. Unfortunately, such an analysis is not able to differentiate directly between the signatures of different wave modes etc. Very high spatial and temporal resolution observations, as are expected to become available from the Canary islands and perhaps later from space, are required for this. The discovery of an asymmetry in the Stokes V profile by Stenflo et al. (1984) is also suggestive of mass motions, although its proper interpretation is still unclear.

Downflows inside fluxtubes and in their immediate surroundings were widely observed in the 1960s and 1970s, but more recently Stenflo and Harvey (1985) and Solanki (1986) among others have ruled out flows faster than 0.25 km s^{-1} in the photospheric layers of fluxtubes. Miller et al. (1984) and Solanki and Stenflo (1986) have shown that the previous positive detections of downflows were due to poor spectral resolution and a neglect of the (then partly unknown) asymmetry in the unpolarized (Stokes I) and polarized (Stokes V) line profiles. Hasan and Schüssler (1985) have provided theoretical support for the absence of net downflows.

A field of ever-growing importance concerns the interaction of the magnetic field with its surroundings. Observational evidence for such interaction is still sparse, but the investigation is gaining momentum. The classical study of line bisectors has shown that convection is affected quite strongly by magnetic fields (Cavallini et al., 1985, 1987) as theoretically predicted earlier. An analysis of time sequences of white light pictures from Spacelab 2 also beautifully demonstrates that the granulation changes dramatically in character in the vicinity of magnetic elements (Title et al., 1987a). The convection pattern in magnetic regions is considerably more stable than in non-magnetic regions. Individual granules appear to live almost twice as long as on the quiet Sun. Furthermore, Title et al. (1987b) have found that magnetic elements are mainly concentrated in the intergranular lanes, as had been previously theoretically anticipated, e.g. by Nordlund's (1986) 3-D calculations of fluxtube convective collapse. His models as well as those of Deinzer et al. (1984b) take the interaction with the non-magnetic atmosphere into account in detail. Deinzer et al. have stressed the presence of a convective cell surrounding the fluxtubes, produced by the inclination of the surfaces of constant temperature in the immediate vicinity of the fluxtubes. This inclination is due to the cooling of this region by the magnetic elements through the influx of radiation and the inhibition of convection.

The Sun, being the only resolvable star, plays a central role in our understanding of stellar magnetic activity as a whole. Thus it is the only star on which the detailed structure of the magnetic field can be investigated more or less directly. Furthermore, since the solar fluxtubes are spatially unresolved, their study has often led to the development of instrumentation and techniques which can be applied to the measurement of stellar magnetic fields or stellar activity. Older examples are the Babcock magnetograph (used to measure the field on Ap stars) and the use of Ca II H and K flux as a measure of stellar activity. Newer examples are the use of powerful statistical techniques, originally developed for the analysis of solar spectra, to Ap stars (Mathys and Stenflo, 1986) and to active G and K main sequence stars.

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V. HEATING AND DYNAMICS OF CHROMOSPHERE AND CORONA

(G.E. Brueckner)

The crucial role of magnetic fields in any mechanism to heat the outer solar atmosphere has been generally accepted by all authors. However, there is still no agreement about the detailed function of the magnetic field. Heating mechanisms can be divided up into 4 classes: (I) The magnetic field plays a passive role as a suitable medium for the propagation of Alfvén waves from the convection zone into the corona (Ionson, 1984). (II) In closed magnetic structures the slow random shuffling of field lines by convective motions below the surface induces electric currents in the corona which heat it by Joule dissipation (Heyvaerts and Priest, 1984). (III) Emerging flux which is generated in the convection zone reacts with ionized material while magnetic field lines move through the chromosphere, transition zone and corona. Rapid field line annihilation, reconnection and drift currents result in heating and material ejection (Brueckner, 1987; Brueckner et al., 1987; Cook et al., 1987). (IV) Acoustic waves which could heat the corona can be guided by magnetic fields. Temperature distribution, wave motions and shock formation are highly dependent on the geometry of the flux tubes (Ulmschneider and Muchmore, 1986; Ulmschneider, Muchmore and Kalkofen, 1987).

The emphasis of the literature, both theoretical and observational, is shifting to detailed investigations of fine structures, inhomogeneities, assymetries, singularities and the interaction of waves with changing conditions in the surrounding media (Steinolfson et al., 1986; Lou and Rosner, 1986; Van Ballegooijen, 1985; Einaudi and Mok, Yung, 1987; Davila, 1987). In order to explain the increase of the smeared out emission measure distribution function Q(T) at lower temperatures, a mixture of cool and hot loops has been introduced (Antiochos and Noci, 1986). Low lying, small scale loops ($h < 5000$ km) are assumed to be the main source of the cooler emission. A possible explanation of the dominant redshifted 100,000° K emission is based on assymetries in the loop geometry or heating rate (McClymont and Graig, 1987). Spicules are possible manifestations of upflows over regions of increased heating rate in a similar model invoking inhomogeneous heating (Athay, 1984). An analysis of high resolution C IV transition zone spectra showed that blueshifted (upward moving) material at 100,000° K cannot compensate for the observed predominant redshifted (downward moving) material at the same temperature. The upward mass flow is 3 orders of magnitude lower than the downward mass flux (Dere, Bartoe and Brueckner, 1986).

The role of transition zone explosive events and jets in the heating process of the transition zone and corona has been reevaluated using much more comprehensive observations from Spacelab-2 (Cook et al., 1987). Although there are many more events present on the sun than earlier estimates from sounding rockets indicated, their total kinetic energy is only 2.5×10^4 ergs cm^{-2} s^{-1}, which seems to be insufficient to compensate for the energy losses of the corona. However, these estimates are based on an analysis of a rather narrow temperature regime, therefore they represent only a lower limit. An analysis of intensity fluctuations and Doppler-shifts of the NV lines ($T \sim 250{,}000$ K°) results in an upward energy flow of 10^3 ergs cm^{-2} s^{-1} if interpreted as acoustic waves (Bruner and Polleto, 1984). This is again a lower limit because of the rather coarse spatial resolution (3×3 arc sec^2) of the Solar Maximum Mission observations. Microwave solar radiation at 6.3 cm displays fluctuation, which has been observed simultaneously

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