II. 3. SMALL SCALE SOLAR MAGNETIC FIELDS, PLAGES, FILAMENTS: THEORY

Chairman: E. Schatzman, Institut d'Astrophysique, Paris, France

Introductory Report by

Jack B. ZIRKER
Sacramento Peak Observatory, Sunspot, N.M., U.S.A.

This article summarizes theoretical work on the magnetic fields of small-scale structures, plages and filaments.

Since "small-scale" structures includes the calcium coarse network and all smaller details, we shall be considering the magnetic fields of both the quiet sun and the active regions. Sunspots, however, are treated by Danielson, and unipolar fields (i.e., the polar fields of the sun) by Howard, in these proceedings.

In many important areas of our subject, quantitative investigations are lacking. We shall attempt to indicate, in these areas, what are the pressing theoretical problems.

The theory of the magnetic field overlaps, to some extent, with the theories of the energy-balance, of the motion and, of the evolution of the phenomena concerned. Our discussion will touch upon these aspects if necessary.

We shall also be discussing the theoretical implications of high-resolution observations, especially in connection with filaments. We refer the reader to Leighton's article in these proceedings for a more complete discussion of the observations.

1. SMALL-SCALE STRUCTURE

1.1. The coarse network

Outside of active regions, the magnetic field concentrates along the bright coarse network seen on Ca II K_2 spectroheliograms (Leighton 1959; Howard 1959). The diameter of the mesh is \( \sim 3 \times 10^4 \) km, the lifetime is \( \sim 1 \) d (Macris 1962). The magnetic field is of the order of \( 1 - 10 \) g in the network, i.e., \( \sim 10 \) times the average field, and is approximately vertical.

Simon and Leighton (1962) have recently established that the calcium network also coincides with the boundaries of the "supergranulation" cells (Leighton 1960; Leighton, Noyes and Simon 1962), in which the photospheric gas moves horizontally with \( v \sim 0.5 \) km/sec from the center of the cell to the boundary. A physical connection between the gas motion and the concentration of magnetic flux in the network is thus clearly implied.
In their original paper, Leighton and his co-workers suggested that the "supergranulation" represents the surface manifestation of a deep-seated, large-scale convective motion. Pikelnber (1962) pointed out that such convection would tend to concentrate the local magnetic field at the boundaries of the convective cell. Thus, according to Pikelnber, the network is formed at great depths, where the convective cell size (i.e., the scale height) is comparable with the observed width of the network. The cells are assumed to have the observed lifetime $\sim 1$ d. Pikelnber suggested that the transport of the concentration of field up to the photosphere takes place by means of Alfvén waves. At the photosphere, the observed horizontal motion within the supergranulation is to be identified with the transverse motion in the Alfvén wave.

We find difficulty in understanding the picture of outward propagation of the net of Alfvén waves. At the depths Pikelnber is visualizing, a pressure disturbance will propagate mainly in the fast (magnetoacoustic) mode, and essentially isotropically, not in the Alfvén mode. An Alfvén wave also requires equipartition between the perturbations in magnetic and kinetic energy. If we are to picture photospheric motions as the result of an Alfvén wave, we require a field strength of the order of $H = (4\pi \rho \sigma^2)^{1/2} \sim 10^2$ gauss, rather than the observed 10 gauss fields.

Parker (1963a, b) has recently carried the basic idea further. He investigates the interaction of given velocity fields with an initially uniform, weak, large-scale field. The change in the magnetic field is given by

$$\frac{\partial B}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) + \lambda \nabla^2 \vec{B}. \tag{1}$$

He distinguishes four types of motion. Periodic motion, though certainly important, is irrelevant to the present discussion. Motions which are characterized by a time "$t$," a length "$a$" and a velocity "$v$" are termed "turbulent" if $t < a/v$, "persistent" if $a/v < t < a^2/\lambda$, and "stationary" if $t > a^2/\lambda$. Here $\lambda$ is the magnetic diffusivity: $\lambda = c^2/4\pi \sigma$ (cm$^2$/sec), where $\sigma$ is the electrical conductivity. The various kinds of motion correspond, evidently, to the neglect of different terms in eq. (1).

In the present context, the motion within the supergranulation cell is "persistent," i.e., diffusion of the lines of force relative to the gas is negligible, but the motion persists over intervals of time large compared with $a/v$. Parker shows that such motion conserves the vertical component of the magnetic flux on a surface where the vertical component of the velocity vanishes. Thus magnetic flux can be redistributed over such a surface but not increased or decreased.

As an example of such redistribution, he investigates the effect of a spatially periodic upwelling ($\vec{v} = \nabla \times \vec{e}_x V_y \sin kx$) on a uniform vertical field $B_0$. Here the $y$ axis is drawn vertically, the $x$ axis horizontally. The velocity components are

$$v_x = V \sin kx, \quad v_y = -Vky \cos kx.$$ 

Since the horizontal velocity $v_x$ is independent of depth, the field lines
always remain vertical. Moreover, a rapid increase in the field strength occurs at the "boundaries" of the cells, \( kx = (2n + 1)\pi, \ n = 0, \pm 1, \pm 2, \ldots \). A corresponding decrease in the field strength occurs within the boundary.

This simple model demonstrates how the emergence of a large convective cell at the photosphere might sweep a large-scale field to the cell boundary and produce the observed field enhancement there. More theoretical work is needed to establish whether the continual appearance of supergranulation cells at random over the solar surface will result in a network pattern. Parker has assumed that the initial field is uniform; clearly after a period equal to the lifetime of a cell, the field is no longer uniform, but concentrated into vertical sheets. Will the subsequent redistribution of flux result in a network or merely in a quasi-uniform distribution of small patches of field?

What field configuration and velocity field can we expect in the higher levels of the network? The enhanced network fields may be expected to modify the structure of the overlying atmosphere. Can we understand the complex loop structures seen in the corona (Kleczek, 1963) in terms of the network?

The picture of a vertical field being swept to the boundaries of a cell has certain observational consequences which should be checked. The study of the time-development of the magnetic and velocity field inside a supergranule would prove most interesting in this connection.

Note that Parker's approach is explicitly kinematic: the motions are taken as given and the field changes computed. One cannot, therefore, expect the theory to predict the size and lifetime of the coarse network. A dynamical theory, including the large-scale convection, would be required for this. The difficult question of how such large convective cells can persist up to the photospheric level remains to be answered.

1.2. The coarse mottling

The coarse network is composed of coarse mottles (De Jager 1959) \( \sim 8 \times 10^3 \) km in diameter. Howard has shown that the vertical component of the field measured 5 - 25 g in these mottles and that an excellent correspondence exists between the shape of the Ca II mottle and the 5 g isogauss line. Coarse mottles have a lifetime of the order of a half day (Macris 1962). They appear outside the network as well as in it.

No theory has yet been advanced for the coarse mottling, i.e., the existence of a characteristic length some four times smaller than the mesh width of the network. It would be interesting to know whether the mottles first appear when the field strength in the network has reached a critical value (of some 2 to 5 gauss), or whether they form in the network at any field strength, or whether they form inside the supergranulation cell and then are swept to the boundaries. This observation might distinguish among the following hypotheses: (a) the mottles represent a more stable configuration of the field than a constricted sheet of flux does; (b) the mottles are formed by instabilities in the converging flow at the boundary
between two cells; or, (c) the mottles are produced by instabilities in the
horizontal flow of gas.

1.3. The spicules and the fine mottling

Except for some preliminary work by Howard (1962), no magnetic field
measurements with a resolution better than \( \sim 10 \) sec of arc = 7000 km
exist. We must infer what we can about smaller scale, magnetic field
structure from spectroheliograms, therefore. The assumption that the
correspondence between K-brightness and field strength persists to the
smallest structures does not seem to involve a serious extrapolation.

In the Ca II K\(_3\) line (i.e., at \( h \sim 4000 \) km) the coarse mottles appear to
resolve into "fine" mottles, \( \sim 1000 \) km diameter (Hale and Ellerman
1903; D'Azambuja 1930). In addition, a nearly uniform sprinkling of
bright and dark fine mottles appears. A progression with height toward
finer and finer structure seems indicated (De Jager 1959).

Fine dark mottles, seen at \( \pm \Delta \lambda = 0.5 \) \( \AA \) in H\(_\alpha\), have been identified as
spicules on the disk (De Jager, Kiepenheuer, Macris, Bruzek, Beckers).
They are elongated near the limb, circular near the center of the disk, and
occur in clusters of \( \sim 10 \) (i.e., the H\(_\alpha\) dark coarse mottles). Kiepenheuer
(1960) has found that the coarse mottles form a coarse network which
coincides quite well with the center of the corresponding K-network. The
correspondence, he says, extends down to the smallest structures. Beckers
confirms these results and finds (private communication) that each "rosette"
of spicules forming a coarse mottle in H\(_\alpha\) coincides with a coarse K-mottle.
The correspondence of each spicule with a fine K-mottle has not yet been
established, however. Kiepenheuer states that some of the H\(_\alpha\) fine mottles
uniformly distributed over an active region coincide with the K\(_3\) fine
mottles, as well as with photospheric facular granules.

The H\(_\alpha\)-network is also the locus of fine "tunnels" (\( \sim 3 \) sec of arc)
in which the velocity is large (\( \sim 10 \) km/sec) and predominately downward
(Leighton, Noyes, and Simon 1962). Presumably, these are rapidly
moving spicules.

With the resolution of the fine mottles we are presented with yet
another characteristic length (\( \sim 10^3 \) km) and time (\( \sim 10 \) \( r \) \( \eta \)). Theoretical understanding of how these magnitudes arise is no better than for
the coarse mottles.

At the levels where the fine mottling and spicules appear, the gas
pressure no longer dominates the magnetic pressure, as it does in the
photosphere. The motions we observe (e.g., in the spicules) may thus be
a consequence of the changing magnetic fields rather than a cause. Moreover,
the fine mottling appears in the upper levels of a larger and longer-
lived structure (the coarse mottle) that may extend down to levels where
the gas motion can influence the field. Perhaps we may identify the fine
mottles, then, as transient hydromagnetic disturbances whose origin lies
in the lower chromosphere.

The most obvious application of this idea is to the interpretation of
spicules. However, most of the spicule models published to date are
essentially hydrodynamic rather than hydromagnetic (Thomas, 1948; Watanabe, 1958; Osterbrock, 1961; Uchida, 1961). The magnetic field is either neglected (Thomas) or assumed to play no role other than to contain the lateral expansion of the spicule. Thereafter, with varying degrees of success, the spicule is treated as a one-dimensional shock front.

Osterbrock justifies this procedure by identifying the spicule as a slow-mode disturbance (Grad, 1959). Slow-made waves propagate mainly in the direction of the field. If the Alfvén velocity exceeds the sound velocity, the particles move along the direction of propagation. The waves are then essentially sound waves.

From this viewpoint, to account for the needle-like shape of the spicule, one must assume that the source of the spicule disturbance is no wider than the spicule itself. Individual granules have the correct size and appear in roughly equal numbers as the spicules within a mottle (J. Beckers, private communication). However, granulation arises in a region where most of the wave energy is transported by the fast mode (Kulsrud, 1955; Osterbrock, 1961), not the slow one. The problem then is to excite the slow mode somehow. Osterbrock suggests that a transfer of energy from fast to slow modes takes place in the low chromosphere. It is difficult to visualize how this occurs over a dimension comparable with the spicule width, however.

Ferraro and Plumpton (1958) offer another possibility. They consider magnetoacoustic waves, propagating horizontally (i.e., perpendicular to the field) in an isothermal, gravitating atmosphere. In a region where the Alfvén velocity exceeds the sound velocity, the wave creates periodic vertical gas motions whose amplitude increases exponentially with height. In effect, the gas is squeezed vertically by the compression of vertical field lines. The rapidly rising gas may be identified with a spicule. Ferraro's and Plumpton's investigation is essentially a normal-mode analysis of the linearized equations and cannot be expected to yield a realistic spicule model. Nevertheless, their results are very suggestive.

The most important new clue relating to the generation of spicules is the observation that they occur in clusters around or within a larger, more stable mass of chromospheric gas which is permeated by a strong magnetic field. It may prove easier to interpret the cluster than the individual spicule.

1.4. Photospheric granulation

Upper limits on the vertical field strength in individual granules have been set observationally by Steshenko (1960), and Semel (1962). They find $H < 50$ gauss, and $H < 25$ gauss respectively. Howard (1962) found an RMS field of $8.2 \pm 4.4$ gauss, using a scanning aperture of 2 sec of arc.

Parker (1963) has considered the question of why the observed photospheric granulation fields are considerably weaker than the equipartition value ($\sim 2 \times 10^2$ gauss) originally expected (see De Jager, 1959). He follows the changes in a large-scale, weak ($\sim 1$ gauss), vertical field as it
is wound up by the turbulent motions in the convection zone. Amplification of the field strength occurs as a result of the stretching of the field lines. A flux tube is flattened into a folded sheet during the stretching since the flow is assumed incompressible. Eventually the sheet becomes so thin that field lines of neighboring sheets may diffuse and cancel within the period of the convective turnover. At this stage the RMS field is proportional to the original field and to the fourth root of the magnetic Reynolds number: \( \langle B^2 \rangle^{1/2} = B_0 R_m^{1/4} \). Thereafter, the field reverts to its original weak value by rapid diffusion and reconnection of the field lines in neighboring uncorrelated convective cells. The field thus grows by a definite factor only, limited by the finite resistivity \( \sigma \): \( R_m = 4 \pi \rho \sigma / \epsilon^2 \). In order that the field increase to the equipartition value \( B_e = (\alpha R \rho v^2)^{1/2} \), the magnetic Reynolds number must be very large. Indeed, we require \( R_m > (B_e/B_0)^2 \). Parker estimates that amplification factors of \( \sim 5 \) will result, in agreement with the upper limits on the measured fields.

2. PLAGES

2.1 Bipolar magnetic regions and the flux-rope model

From the work of the Babcocks (1955) we recognize the existence of extensive bipolar magnetic regions (BMR) which precede and outline visible spot groups. The development of a BMR is accompanied by the successive appearance of white-light faculae, calcium and hydrogen bright plages, the green-line corona, sun-spots and all the transient optical and radio phenomena we associate with an active center. The emergence of the magnetic field of an active center has thus come to be recognized as the primary phenomenon, and all the other striking phenomena as secondary.

As Cowling (1946) has shown, the observed fields cannot grow in place within the observed lifetime of an active center because of the high electrical conductivity of the plasma. The field must, therefore, rise intact from lower depths. To account for the bipolarity of the observed field, a loop of magnetic flux is required. Thus, the basic picture had developed of the emergence of a loop of magnetic flux through the photospheric layers.

Existing observations of the magnetic field, of the chromospheric plage and of the coronal structures overlying the plage, are in qualitative agreement with the picture of a loop of magnetic flux giving form to the active region. For example, the continuity of plage structure with depth, as inferred from spectroheliograms taken in different parts of the Ca K-line (Hale and Ellerman, 1903) argues for the existence of a columnar structure, arranged essentially along the field lines. Leighton (1959) and Howard (1959) have demonstrated directly the excellent correspondence which prevails between the distribution of the vertical component of the photospheric field and chromospheric plage brightness. The form and magnitude of the field in the corona above the plage can only be guessed at present. The existence of loops and arches in the green-line corona is
well known (Lyot, in Kiepenheuer, 1953; Evans, 1957), however, Kleczek (1963) has argued recently that a loop is indeed the fundamental coronal structure. Presumably, these loops outline the coronal magnetic fields.

Why does the flux loop break through the photospheric surface? Perhaps the best answer we have at present was advanced by Parker (1955). He pointed out that a rope of toroidal magnetic flux, generated in some manner in the convective layers below the photosphere, will be buoyant if it lies in thermal and pressure equilibrium with its surroundings. A kink in a rope is unstable. As it rises, the downward flow of material along the lines of force reduces the internal density still further so that the buoyancy persists.

Once the flux tube begins to emerge from the photosphere, buoyancy is no longer required to lift the field higher. When the magnetic pressure exceeds the surrounding gas pressure, the field will expand of its own accord to fill the overlying region. Initially, one might expect the expansion to proceed at the Alfvén velocity. Later, after the field strength in the corona has increased, further expansion of the flux tube into the corona will proceed more slowly.

As the field expands it exerts forces on the gas. It also modifies the energy input and therefore the temperature of the gas. Thus, the expansion of the field will strongly influence the motion of the gas. As a result, it is possible that, after the flux tube breaks through the surface, material is forced to flow into the tube rather than out of it. The net flow may be very slow since eventually the expansion of the field is very slow. However, we can conceive that the density of the material inside the flux tube ultimately exceeds that of the surrounding coronal gas. Such a result is demanded by a great variety of observations which imply that the gas density is higher inside an active region than outside of it.

Such observations as for example, the CaK self-reversal (Jefferies and Thomas, 1960; Obridko, 1963), the Lyman α profile (Morton and Wideng, 1961), the electron scattering continuum in the chromosphere (Athay and Thomas, 1957) and in equatorial streamers (Saito, 1959), the cm and dm radiation from an active region (Christiansen et al., 1960) all imply electron densities anywhere from 2 to 10 times higher than the normal atmosphere at the same height, but equal or lower electron temperatures. Permanent coronal condensations are regions in which both temperature and density are higher than normal (Waldmeier, 1940; Billings, 1957).

We have sketched above the possible expansion of a flux tube in the corona after it reaches the photosphere. A sketch is not a theory, however. We require calculations of the process. Unfortunately, the dynamics of the field and the mass balance are coupled with the energy balance. But some simple model for the energy dissipation and loss may be sufficient to follow the development of the field.

2.2. Force-free fields

So far, we have emphasized the origin and evolution of the plage field.
The field changes relatively slowly, however, and may well be considered as nearly static at any instant. What is the configuration of the field likely to be?

Leighton (1959) has found field strengths of $10 \text{ to } 10^2$ gauss in plages, corresponding to a magnetic pressure of $4 \text{ to } 4 \times 10^2$ dynes. The chromospheric gas pressure is probably less than 10 dynes. Thus, the magnetic pressure may considerably exceed the gas pressure.

According to ideas advanced by Lüst and Schlüter (1954) we should expect such a strong field in a dilute gas to adjust itself until the Lorentz force $(J \times B/c)$ vanishes everywhere. Indeed, Woltjer (1958) has shown that the stability of a bounded, static, hydromagnetic equilibrium configuration requires the field to be force-free. From this standpoint, the question of the support or flow of the gas is secondary and we should concentrate rather on the force-free configuration of the field itself.

A test of the hypothesis of a force-free plage field would be most interesting. The equations for a force-free field

$$\nabla \times \vec{B} = \alpha \vec{B},$$
$$\nabla \times \vec{B} = 0$$

form a mixed hyperbolic-elliptic system (Grad and Rubin, 1958). Hence if the field is known on a boundary (say, the photosphere) it may, in principle, be determined everywhere inside the boundary (i.e., the chromosphere and corona). In order to test whether the actual field is force-free, the following scheme (H. U. Schmidt, private communication) may be helpful. If $\alpha$ depends on the coordinates, we find from the divergence of eq. (1) that

$$\vec{B} \times \nabla \alpha = 0,$$

i.e., that $\alpha$ is constant along a line of force. Moreover, $\alpha$ is determined from observations of $B$ on the boundary by eq. (1). Hence, if the observed field is really force-free, we expect to find the same observed value of $\alpha$ at opposite ends of a computed line of force.

Unfortunately, in order to carry out such a test, it is necessary to have extremely accurate measurements of all three components of the field. A better test must be formulated, therefore.

Stepanov and Gopasyuk (1962) have recently mapped both the longitudinal and transverse components of the photospheric magnetic field in an active region. They claim their results are suggestive of the axi-symmetric force-free fields derived by Lundquist (1950). A quantitative test would be desirable, however.

2.3. Energy balance

No significant advances have been made in the theory of the generation and dissipation of non-radiative energy in plages (or the quiet sun) since Osterbrock's summary was published in 1961. We shall review his results briefly, and emphasize the outstanding difficulties awaiting solution.

Osterbrock traced the flow of acoustic and hydromagnetic energy from its origin in the convective zone to its eventual loss as radiation in the
chromosphere and corona. He found that the amount of acoustic energy
generated by isotropic turbulence (Lighthill and Proudman) in Vitense's
model of the convection zone roughly balances the radiation losses of the
quiet chromosphere. If he assumes that an equipartition field (~ 450 gauss)
prevails in the convection zone underlying plages, then Kulsrud's calcula-
tions provide an additional factor of ten in the amount of acoustic energy
generated, again in rough agreement with the plage radiation losses.

Kulsrud's results indicate that almost all hydromagnetic energy gener-
ated by turbulence will be fed into the fast mode and none into the transverse
(Alfvén) or slow modes. Osterbrock found that at the depths where the fast
mode is essentially hydrodynamic (sound waves), the viscous losses are
negligible, while at higher levels, where the fast mode is essentially
hydromagnetic, losses by resistivity or by Piddington's mechanism, are
negligible. Hence, the dominant mechanism of dissipation is the formation
of hydromagnetic shocks.

Utilizing Bazer's and Ericson's theory of hydromagnetic shocks,
Schatzman's approximate energy transfer equation, and Van de Hulst's
chromospheric model, Osterbrock calculated the height-dependence of the
dissipation per gram. The dissipation is a peaked function of height. In
plages, where a field strength of 50 gauss was assumed, the peak dissipa-
tion falls at a lower height than in the quiet chromosphere (B ~ 1 gauss).
Moreover, significant dissipation occurs in the photosphere below a plage,
but not enough to account for the radiative losses of white-light faculae.

The main difficulty Osterbrock encountered was in supplying sufficient
energy to the high chromosphere and corona. Virtually all the fast-mode
wave energy has dissipated at a height of only a few thousand kilometers.
Osterbrock therefore suggests that a portion of the fast-mode energy is
converted into the slow and Alfvén modes, somewhere in the upper chro-
mosphere. The slow mode (hydrodynamic shocks) he identifies with spicules
(see our discussion in the preceding chapter) but these carry insufficient
energy to heat the corona. The Alfvén waves must therefore be responsible
for coronal heating. The dissipation of Alfvén waves in the corona by
ordinary processes (Joule losses, Piddington's mechanism) is negligible,
however. Parker has suggested that the dispersion of Alfvén waves in the
compressible coronal gas leads to the formation of steep wave fronts and
subsequent dissipation.

In summary, then, it seems possible to account for the great bulk of
the energy losses of the quiet and active chromosphere in a semi-quantita-
tive fashion. The main gap in the chain of physical processes is a means of
transporting sufficient energy to the high chromosphere and corona. If
Osterbrock's suggestion is to bear fruit, the basic physics of the excitation
of one hydromagnetic mode by the decay of another must be explored
further. Naturally, other processes should be considered. We note that
De Jager and Kuperus (1961) find no difficulty in extending the energy input
to coronal heights, even though they neglect the field completely. This
result is somewhat surprising, since they utilize the same basic theory
that Osterbrock did. Clearly, these independent estimates must be re-
conciled.
2.4. Fine structure

Up to this point, we have discussed mainly the large-scale properties of the plage field. Leighton's work (1959) has demonstrated in a striking manner, however, that nearly every small feature (i.e., coarse mottle) resolvable on a K-spectroheliogram of a plage represents a local enhancement of the magnetic field. First-rate spectroheliograms reveal even smaller details (~1 sec of arc) (Hale and Ellerman, 1903; Azambuja, 1930). It is a fair guess (though, admittedly only a guess) that the correspondence between field and plage brightness extends down even to these small features.

Then, as with the coarse network, we must account for the existence of at least two characteristic lengths in the plage: a) the diameter of a coarse mottle, ~7000 km, and b) the diameter of a fine mottle ~1000 km. Moreover, the fine structure of the plage exhibits an unexplained height variation similar to that of the network: at the level of K_2 (h~1000 km) only coarse mottles are resolvable, while at the level of K_3 (h~3000 km) the plage consists mainly of fine mottles, both in the massive clumps around the spots and as a uniform distribution over the whole active region.

Leighton's results, together with the evidence of high-resolution spectroheliograms, raise a host of questions concerning the manner in which the magnetic field modifies the "normal" chromosphere and, indirectly, the emission in the cores of strong Fraunhofer lines. These questions fall properly within the theories of line formation and stellar atmospheres and to that extent, are irrelevant to our main purpose here. Still, there are several problems so intimately connected with the presence or orientation of the field that they deserve mention.

Both the Babcocks (1955) and the Crimean observers (Stepanov and Petrova, 1959) have indicated a rough proportionality between the vertical component of the field strength and the brightness of the plage in the K_232 line. According to current ideas of the formation of the K-line core (Jefferies and Thomas, 1960; Obridko, 1963) the brightness of the plage reflects the details of its temperature gradient, and therefore, presumably, of the release of non-radiative energy. Moreover, the separation of the K_2 peaks is observed to diminish in the vicinity of a sunspot (Smith, 1960), i.e., the Doppler width seems to decrease with increasing field strength. Thus, the dependence of the energy dissipation and the associated microscopic velocity fields on magnetic field strength may, in principle, be extracted from a study of the K-line profiles in plages. Such an investigation seems worthwhile.

More observational work is needed to establish the height variation and continuity of the fine structure, particularly downward toward the photosphere. It is still not clear for example, whether any vertical connection exists between the white-light facular granules and the overlying K-mottles. Hale's and Ellerman's spectroheliograms in K_1 and in the continuum suggest such a connection but Rogerson (1961) would disagree. The important question involved here is the height at which significant energy dissipation and modification of the chromosphere begins. As we saw
in the last section, some sort of theoretical estimate of the height distribution of energy dissipation is now available. A comparison with observation would be interesting.

On an Hα spectroheliogram, the coarse and fine mottles also appear, but the appearance of dark filamentary structure is much more striking. The Babcocks (1955) and Stepanov (1958) agree that the filamentary structure is oriented along the field (or, at least, runs perpendicular to the lines of constant longitudinal magnetic field). Indeed, Stepanov has traced "streams" of filamentary structure (i.e., a magnetic flux tube) between the active centers in different hemispheres. Kiepenheuer (1960) has also tentatively identified bright Hα threads and loops as visible flux tubes. Studies of the time development of the Hα filamentary structure (Lippincott, 1955; Tsap, 1962) also suggest motion along the direction of the field.

The question naturally arises as to why the horizontal component of the field is visible in Hα, but not in K. What information concerning the thermodynamic structure of the plage may be extracted from this observation? Is there a relation between the darkness of the Hα filamentation and the magnitude of the transverse field? (Such a relation would prove extremely useful, since transverse field measurements are very difficult and uncertain at present.) We recommend these problems to the observers.

3. FILAMENTS

3.1. Observations

Most of the published theoretical work on the magnetic fields in filaments (i.e., quiescent prominences seen on the solar disk) is directed toward explaining a single observation: the filament gas is denser than its surroundings and requires support against gravity. Considerably progress has been made on this problem and it seems an appropriate time to direct attention to other questions. For the purpose, a brief summary of the main observational features of filaments is relevant. Our review is not intended as an exhaustive historical survey, but merely to provide a measure of how successful are current theories of filaments and what aspects need further work. Many of the ideas and relations expressed here have appeared in the literature before, but are as pertinent as ever. The reader is directed to the excellent summaries by Kiepenheuer (1953) and De Jager (1959), and to the article in these proceedings by Leighton.

Observations of filaments may be conveniently grouped in the following categories: a) shape, b) lifetime, c) association with magnetic regions, d) magnetic field strength and orientation, e) temperature and density, f) energy balance, g) mass balance, and h) association with larger structures. We shall omit any discussion of the evolution, sudden disappearance or eruption, brightness or migration in latitude of filaments, except where it is relevant.

It is well to keep in mind that the filament described here is an abstrac-
tion - a synthesis of many observations. A real filament may depart in several aspects from the idealization we present.

3.1.1. Shape

From the work of Pettit (1932) and the D'Azambujas (1948), the following picture has emerged for the shape of a filament. It is a nearly vertical blade of gas with the following dimensions:
Height: 15 - 120 × 10³ km (mean = 42 × 10³ km).
Length: 60 - 600 × 10³ km (mean = 2 × 10⁵ km).
Thickness: 4 - 15 × 10³ km (mean = 6600 ± 1500 km).

A mature filament may be built up of a series of arches, whose span may measure ~ 60 × 10³ km. The feet of the arches may appear as knobs along the length of the filament when viewed from above (D'Azambuja). The lower boundary of the filament (i.e., the top of the underside of the arch) is quite sharp. The space under the filament is presumably filled with gas at coronal temperatures.

A filament may, on the other hand, have no visible connection with the chromosphere, but hang suspended some 10⁴ km above it. Or, the filament may sit solidly on the chromosphere, with no arch structure.

All filaments possess a fine structure of narrow, vertical, bright threads or fibers, separated by darker lanes. The fine structure seems to appear coarser at the top and finer at the bottom (R.B. Dunn, private communication). No measurements exist of thread widths but they approach the resolution permitted by seeing (~ 10³ km). There is no indication the fibers run parallel to the arches at the lower edge of the filament.

3.1.2. Lifetime

D'Azambuja gives the mean lifetime of a filament as 3 rotations, the range being 1 to 12. During this period the filament changes form, increases in length, approaches the direction of the solar equator, and finally disintegrates - but is always a unique identifiable object. The stability of filaments is the single most important datum.

The fine structure changes in appearance within the order of half an hour, Knots in the fibers occasionally have downward velocities of ~ 1 km/sec. In other fibers of the same filament, the gas appears absolutely motionless during the entire period of good seeing (~ 1 hour). Severny (1953) has reported random ("turbulent") motions of knots in quiescent prominences.

3.1.3. Association with magnetic regions

The association of filaments with active centers has been known for many years. The Babcocks (1955) first pointed out, however, that some mature filaments divide a bipolar magnetic region (bmr) into two regions of opposite polarity. The rest form a poleward border of a bmr, partly encircling it. Stepanov (1958) and Howard (1959) confirm these findings.

When a filament first appears in a bipolar spot group, it points toward the preceding spot, and lies poleward of the bipolar group (D'Azambuja, 1948).
3.1.4. Magnetic field

To this date, the only published measurements of magnetic field strength in a filament are those of Zirin (1961). He measured fields of 25 - 100 g perpendicular to the blade of a large filament at the limb. A longitudinal (i.e., horizontal) field of such strength seems remarkably high, since the vertical photospheric fields measured by Babcock amounted to only a few gauss. Estimates by a variety of means (Idliss et al., 1955) suggest fields of a few gauss.

3.1.5. Temperature and density

The determinations by Jefferies and Orrall (1963) indicate \( T_e \approx 8000 - 15000^\circ \), \( N_e \approx 1 - 5 \times 10^{10} \). The prominence material is thus \( 10^2 \) times denser than the normal corona at the same height and requires support against gravity. The hydrogen is between 10% and 100% ionized.

3.1.6. Energy balance

We wish only to point out here that the lifetime of a knot of filament gas (\( 10^3 \) sec) exceeds the time required to radiate its thermal energy (\( 10^4 \) sec) by a factor of ten. Some energy input is required to maintain a steady state. Orrall and Zirker (1962) considered heat conduction as a possible mode of energy transport from the corona, but heating by hydromagnetic waves (Obashev, 1959), Joule losses, and compression are all possible.

3.1.7. Mass balance

Similarly, the observed downward velocities in filaments imply an appreciable mass loss. If \( v = 1 \) km/s, a filament \( 3 \times 10^4 \) km high loses all its mass in \( 3 \times 10^4 \) sec. only 8 hours. The only likely source of mass is the corona, through the condensation process (Kiepenheuer, 1953, 1959a; Parker, 1953).

3.1.8. Structures of larger scale

Finally, it should be noted that filaments are part of the internal structure of coronal (white light) streamers (Bugoslavskaya, 1950). A filament when seen edge on at the limb during an eclipse, is surrounded by a dark dome (presumably coronal gas at low density) which is encased in series of bright loops. The whole nest of loops is in turn imbedded in the base of a coronal streamer. Bugoslavskaya suggests an invariant association of filaments with streamers. Saito (1959) found streamers more often associated with active coronal regions than with filaments, however.

3.2. Magnetostatic models

The theoretical models of filaments we discuss here try to explain the support of the prominence against the force of gravity by magnetic fields.

Brown (1958) has related the solutions of a number of investigators to a single partial differential equation, first derived by Dungey (1953). It is convenient to review some early models using Brown's notation.

The balance of forces in a filament required that

\[-\nabla \phi - \rho g \hat{k} + \frac{1}{4\pi} (\nabla \times \vec{B}) \times \vec{B} = 0\]

with

\[\nabla \cdot \vec{B} = 0.\]
If the temperature is uniform throughout the gas,

\[ p = \rho \frac{RT}{\mu} = g \rho h_0, \]

where \( h_0 \) is the scale height in the absence of the field. Let all quantities be independent of the \( x \) coordinate. Then \( \vec{B} \) can be represented by a potential \( F(y,z) \):

\[ B = (0, \frac{\partial F}{\partial Z}, \frac{\partial F}{\partial y}). \]

Hence,

\[ \nabla (pe^{Z/h_0}) = \frac{1}{4\pi} \left[ (\nabla^2 F) e^{Z/h_0} \right] \nabla F \]

or \( pe^{Z/h_0} \) is a function of \( F \) (say \( G(F) \)),

\[ G(F) = \frac{\nabla^2 F}{4\pi} (e^{Z/h_0}) \]

or finally

\[ \nabla^2 F = M(F)e^{-Z/h_0}, \tag{3} \]

where \( M(F) \) is some arbitrary function.

Eq. (3) is the fundamental equation of the problem, and different solutions arise depending upon the choice of \( M(F) \) and the boundary conditions.

We shall summarize only the essential features of a few models, review the criticisms which have been raised toward them and then concentrate on a particularly useful model.

Menzel (1951) discovered the fundamental support mechanism by magnetic forces. He chose \( M(F) = AF^{1-(2h/h_0)} \), in effect, which yields lines of force periodic in \( y \) and \( B \) decreasing exponentially with height. The density of the gas is larger than average at the places where the lines of force sag. The weight of the gas is supported by the tension \( (B^2/4\pi) \) in the lines of force.

If the \( y \) direction coincides with the length of the prominence, the periodic density might conceivably represent the arches, but then the narrow thickness of the filament (in the \( x \)-direction) is unexplained. Alternatively, if the \( x \)-direction represents the filament's length, we are presented with a whole set of parallel filaments. The model is clearly too crude, but gives insight into how a filament can be supported.

Dungey (1953) found closed field lines which lie on concentric cylinders by choosing \( M(F) = A = \) constant. He pictured the field as vanishing outside some outer cylinder and inside some inner cylinder. The density within the smaller cylinders is higher than average, while the density within the boundary cylinder is smaller than the external density. Thus, the nest of cylinders forms a buoyant "bubble" which can support the weight of dense material at its core.

Once again, the form of the filament is unexplained. Moreover, Dungey pointed out that his model, like all those with unlinked lines of force, is energetically unstable. The configuration he pictures is basically a pinch discharge, and this has been shown to be plagued by a variety of instabilities (Kruskal and Schwarzschild, 1954; Johnson, Oberman, Kulsrud and Frieman, 1958).
Bhatnagar and Chakraborty (1959) generated a solution by the choice 
\( M(F) = -A = a \) constant. In their model the field lines run _along_ the length 
of the prominence (the \( y \)-direction) and terminate in a point under the solar 
surface. The thickness of the filament remains unspecified.

A model which explains a wide variety of observations was published by 
Kippenhahn and Schlüter (1957). They picture the filament as lying across 
the field lines which pass between the two halves of a bipolar magnetic re-
gion. Thus, as in Menzel's model, the weight of the filament is supported 
by the tension of sagging field lines.

Considering a simple model, valid only in the vicinity of the filament 
plane, they determined the density distribution along the field lines, i.e., 
perpendicular to the filament plane. In effect, they chose 
\( M(F) = B e^{(F/Ak_0)} \), 
with \( F = Ax + N(y) \). The resulting density profile falls off rapidly from the 
central plane, and leads to a filament thickness and a central density in 
good agreement with the observations, for a reasonable choice of field 
strength and temperature. Thus the blade-like form of the filament is ex-
plained.

Kippenhahn and Schlüter also investigated the stability of such a fila-
ment. They examined infinitely thin sheets supported at the median plane of 
a symmetrical potential field by a discontinuity in the vertical field compo-
nent. The electrical conductivity was assumed infinite and small perturba-
tions in the \( y \) and \( z \) direction (but independent of the \( x \) direction) were 
considered. They found the filament is always stable against non-uniform 
vertical displacements from its equilibrium position. Stability against hori-
zontal displacements is ensured if, before the filament condenses, the lines 
of force of the original potential field form a depression at the median plane. 
Thus, at least some regions of simple potential fields approximating a bi-
polar region can support a filament in stable equilibrium.

Recently, Anzer (1963) has reexamined the stability of such an infinitely 
thin sheet by the use of the energy principle (Johnson et al., 1958; Hain, 
Lüst and Schlüter, 1957). Completely arbitrary displacements, dependent 
on all three dimensions, are included. Necessary and sufficient conditions 
for stability are: a) the original field must curve upward at the place where 
the filament forms and, b) the current must decrease with height in the 
sheet.

Kippenhahn and Schlüter found that the drift of material across the lines 
of force would be too slow to be observable. The finite resistivity of the gas 
results in a drift of \( \sim 0.1 \) mm/sec. The ambipolar diffusion of the neutral 
components is larger (\( \sim 10 \) m/sec), but still small. One can easily show that, 
with such small drift velocities, the filament will not be subject to the 
Rayleigh-Taylor instability in the long dimension of the filament. The ma-
terial is too well "frozen" to the lines of force to slip into any depression 
which might develop between layers of different density. Moreover, the 
tension in the lines of force will suppress Rayleigh-Taylor instabilities 
with dimensions comparable to the width of the prominence.

Thus the Kippenhahn-Schlüter model seems to account, in a self-con-
sistent manner, for the static support of the filament, its stability, its quiescence, its width, and its association with bmr.

We have only a few comments to add. These are directed not so much at what the theory explains as at what it ignores. Our aim is to try to fit more of the observations into the framework of the theory.

The most substantial omission from the model seems to be any mention of the vertical, down-streaming motion in the fine structure. This structure is so characteristic of stable, quiet filaments that we cannot conceive that it represents merely a terminal phase of instability. The downward uniform velocity (~ 1 km/sec) suggests that most of the material we see in a filament either (a) moves along the lines of force, i.e., that the sag in the field lines is very deep, or (b) is diffusing more rapidly across the lines of force than Kippenhahn and Schluter calculate.

The first hypothesis would imply an accumulation of material in the bottoms of the magnetic troughs unless some process of mass loss (such as evaporation, perhaps) removes it. It is possible that the filament is, in fact, not in mass-equilibrium and, as Kippenhahn and Schluter suggest, that it must shed material occasionally by collapsing at particularly heavy places. This process is fairly rapid, however. We estimate that the entire filament would be flattened to half its height in about five days. Clearly, before we can arrive at definite conclusions on the mass-balance, we must evaluate the rates of evaporation and condensation more carefully. If we follow the procedure used by Kippenhahn and Schluter, equating the mass-flux to the product of density and thermal velocity we find $m_p n_c v_m^2 = 1.6 \times 10^{-24} \times 10^8 \times 2 \times 10^7 = 3 \times 10^{-9}$ g/cm$^2$ sec$^{-1}$ arrive from the corona while $m_p n_p v_m^2 = 3 \times 10^{-8}$ g/cm$^2$ - sec leave the prominence. The rates differ by a mere factor of ten. A more careful calculation may show them to be comparable.

The second hypothesis, that the influx of condensing coronal material is balanced by a kind of dribbling across the lines of force, is not hopeless. It is well known from experiments in the laboratory that the diffusion of plasma across the field can exceed the prediction based on the resistivity. Biermann and Pfirsch (1960a, 1960b) discuss possible cooperative mechanisms for this phenomenon. Possibly, such processes are active in filaments. If they are, we must replace our notions of a static equilibrium by a steady-state pattern of flow.

There are two dimensions of the filament which a satisfactory theory must predict: the diameter of a vertical fiber (~ 10$^3$ km), and the length of an arch along the filament. Orrall and Zirker (1962) suggested that the fiber diameters are fixed by the energy balance within them: heat conduction from the corona is balanced by radiation. The radius of a fiber is essentially the distance over which the temperature falls from the coronal value to the prominence value, the temperature gradient being fixed by the radiative losses in the fiber. Thus $R \sim T/\nabla T$. The results depend critically on the direction of the field and the opacity of the fiber, but diameters of the correct order of magnitude have been predicted. Of course, the fiber sizes may depend solely on hydromagnetic considerations.
The arches of a filament represent the sharp lower boundary between the filament and the invisible coronal gas. It is difficult to avoid the impression that material flows down along the arch to the chromosphere. Again the question of the direction of the field arises: is it along the arch, or perpendicular to it (as the Kippenhahn-Schlüter model suggests)? If we assume for the moment it is along the arch, the following connection to a Rayleigh-Taylor instability becomes plausible. Assume the dense prominence gas is separated from the underlying corona by a sinusoidal interface and that a uniform horizontal magnetic field runs parallel to the length of the filament, at least near its lower boundary. The situation is unstable for sufficiently long wavelengths. Moreover, a wavelength of maximum instability exists (Chandrasekhar, 1961). This wavelength, \( \lambda = \frac{3H^2}{g\rho} \) is \( 10^{10} \) cm (for \( H = 1 \) gauss, \( \rho = 10^{-14} \) grams/cm\(^3\)), in reasonable agreement with the observations.

Finally, we should comment on the connection of the filament to the active center in which it forms. As we have seen in connection with our discussion of plages, we have, at present, no accurate picture of the field configuration in an active center. If we imagine the field as roughly multipolar, however, it is difficult to reconcile D'Azambuja's and Stepanov's observations that filaments first appear pointing toward a spot (i.e., roughly along the field) with the Kippenhahn-Schlüter model, which provides support against gravity only across the field. Why don't prominences form preferentially on the neutral line of a bipolar field? The answer may be connected with Kiepenheuer's (1959 b) suggestion (see also Lüst and Zirin, 1960) that magnetic compression of the coronal gas is required to initiate the condensation process. Some quantitative investigation of this process is needed.

REFERENCES

Lundquist, S., 1950, Arkiv Fysik 2 361.
Semel, M., 1962, Compt. rend. 254 3978.
DISCUSSIONS

Parker

Dr. Zirker is correct in noting that the gas density in the field above a bi-polar spot is higher than the density of the surrounding coronal gas and so provides no buoyant lift to the field. I think, however, that we should look to the dense fields and gas below the photosphere to provide the real buoyant forces which heave the sunspot flux through the photosphere.

Unno

I have two comments on the convection theory of supergranulations. The large horizontal dimension of the convection cell enables it to penetrate deep into the upper stable atmosphere. In other words, the velocity amplitude of a super granulation does not decrease rapidly with height. This is in favour of the convection theory. On the other hand, even for the convection cells extending deep into the convection zone, the one which is most predominantly accelerated has the horizontal dimension of the order of the scale height of relatively shallow layer. It is, therefore, doubtful that the super granulation may obtain appreciable energy in the convection zone. The reason is that the turbulent diffusion resisting the convective instability works practically within relatively shallow layer and, therefore, the minimum resistance is realized for the cell with horizontal size of a few scale heights of shallow layer. Quantitative study is required.

Öhman

I would like to comment on some details in Dr. Zirker's excellent picture of the prominence. In many of these objects I think one can see also dark structures. When coming close to your picture, it is not so evident as from some distance. I think one can see very narrow structures appearing as dark threads. It is perhaps not an easy thing to connect such a picture with your model of a filament.

In my opinion we often have in these bodies also a real "filamentary" structure which we perhaps forget, and it would be interesting to hear if Dr. Zirker has considered also these formations, if they can fit into the picture of the filaments and, assuming the dark structure to be real, on which side in the picture they might be situated, on the front side or in the middle.

Zirker

I have usually thought of these dark threads as "holes" in the sheet of the filament.
Öhman

You see we have often cases where we can see them on the disk crossing the limb at a point where we might have a prominence. In this way a dark filament may be followed as a dark feature also in the prominence. We have reason to believe, therefore, that they may appear quite often.

Gold

I would like to point out that the explanation of filaments in terms of a trough developing in the field lines is by no means at variance with the observations. Sometimes the filaments appear to lie in the direction which would have been judged a direction along the field and not across it. At first this seems impossible with an explanation of the type suggested by Schlüter and Kippenhahn. There is, however, no real conflict if one supposes that the field lines can make twisted instead of paralles bundles. A twisted bundle will place adjacent troughs along the length of the bundle, like the bottom edge of a twisted rope held horizontally, and extra mass can concentrate there. The overall appearance would then be that the extra mass runs largely along the direction of the field. The twisted bundle as a whole can develop a sag in the middle just as in the other model so that the material cannot flow down at the ends. I would claim that a twisted bundle is quite the normal thing, not by any means the exception, and I would therefore regard this discussion as a generalization of the particular untwisted case discussed by Schlüter and Kippenhahn.

Zirker

How do you picture the currents to flow in such bundles?

Gold

If there are currents flowing along the field, a helical shape of the field lines will result. So long as there is no extra weight lying in this field the currents must flow exactly along it. If there is extra weight, then the currents will be displaced somewhat from flowing exactly along the field and will therefore exert a force. Such a twisted bundle is sewn together by the peripheral component of the field and the twists will probably increase and not decrease the general stability.

Kahn

In your model of a prominence, you allow material to hang at the bottom of trough of the magnetic field and slowly to escape across the lines of force by some instability phenomenon. Can you give values for its density and its velocity relative to the lines of force? Further, if you allow the material to stream across the lines of force in this particular case, is it consistent to assume that the material is well confined when it comes to constructing a spicule? We don't seem to allow any flow across the lines of force there.

Zirker

As the answer to the first one, I think the observed velocities are between a few tenths and ten km/sec. The order of the number density is say $10^{10}$ or a few times $10^{10}$.

I have no good answer to your second question. You are right, an incon-
sistency is there. But as I pointed out, the only alternative to the flow of ma-
terial across the field lines is to assume that the field is essentially vertical
in the filament plane. This has many difficulties also.

Woltjer
Concerning your comment about the energy supply by hydromagnetic
heating and any other processes that you need to keep the prominence radia-
ting. Isn’t it true that if you have the matter streaming down through the
prominence with a constant velocity of 3 km/sec, you get all the energy you
need out of the potential energy or release in the gravitational field, at least
if I haven’t dropped a few powers of ten?

Zirker
Yes, the gravitational energy could be sufficient.

Orrall
Dr. Öhmans "dark prominence features" are almost certainly real and
not just holes in the prominence. They, of course, have a lower excitation
temperature but we have no evidence that their kinetic temperature is lower
than in other prominences. We have looked for the near ultra-violet CN bands
in prominences, some having dark features, but have not as yet detected
them.

Biermann
I would like to say a few words on the possibility of connecting the ob-
served dimensions and the life time of the chromospheric net work with the
properties of the deep convection zones. It was of course always tempting
to look for relations between the turbulence in the deep layers with the large
scale surface features (see the early literature on the subject (1938/39)).
The scale height in these deep layers should be 100 or some 100 times that
of the photosphere and the turbulent velocity \( \frac{1}{10} \) or \( \frac{1}{20} \) or so. The time scale as
well as the linear extent of the long lived chromospheric network would
therefore seem to be roughly as expected, if we would associate them tenta-
tively with the scale and the turbulent velocity in the deep layers as given by
the usual theory.

Cowling
Could I make just a couple of comments? First, the mere existence of
the filamentary structure which has been described has to be regarded as
something of a headache to theorists. A filament is seen on the limb as
bright compared with the corona. It seems bright because it is cooler than
the corona and as a consequence can manage to produce radiation by the re-
combination of hydrogen, which cannot occur in the remainder. Now it ap-
ppears as a filament, because when you have got enough material together
then the atoms by their collisions are able to assist in each other's cooling.
The filament is able to cool itself because of its increased density and be-
cause each part of the filament enables the rest of the filament to remain
cooler, whatever is inside being shielded by what is outside from any heating
source. As soon as you produce a stringlike structure running through and
so expose more of the material to the corona, you have more difficulty in
getting the requisite coolness of the structure. So one has got to remember
that by introducing the stringlike structure, one is introducing a further
difficulty into the theory of a filament. The other point is simply this. We
find ourselves in these days tempted regularly to invoke motions across the
lines of force. Well, such motions are met in certain circumstances, and
we have to reckon with them. But I think one should regard it as the last
confession of weakness rather than the first straw to be clutched at.

Michard

I think we have been hearing of some attempts to put into a general pic-
ture called the supergranulation a number of different facts - observational
facts - and I think we really should not forget that it might be too far an ex-
trapolation to assume that all those facts can really be worked together. It
is squeezing much too far the observations. Now what are the really observ-
ed facts as presented by Leighton essentially in his lecture this morning.
The first fact is, that we have a coarse mottling in the $K_3$-spectroheliogram.
We have a system of little bright cells, and it seems to be organized into a
more or less general pattern. And what we know from Leighton's observa-
tions too, is that in these bright $K_3$ flocculi we have magnetic fields. That
we know from Leighton's observations because he has observations of both,
the $K_3$ flocculi and also the magnetic field. Now we heard something else.
There is a supergranulation which as described by Leighton, is a particular
velocity field. And then we have some people, and Leighton himself, I am
not quite sure, saying that these two structures are the same thing and that
they are something fundamental to the solar atmosphere. And on that point
I am not sure that we have the observational evidence. Because what is the
supergranulation as initially described by Leighton? It is a field of horizon-
tal velocities observed. Inside the cells we have according to Leighton radial
motions. We then may ask ourselves: If we have radial motions, what hap-
pened with the material? We should expect that the matter will be flowing
down somewhere in between the cells and flowing up at the center of the cell.
But we have absolutely no proof that the velocity structure is like that and
we have no proof, no observational evidence for a downward flow of material
between the cells or for an upward flow of material in the center of the cell.
We have, it is true, some evidence of a downward flow at the limit of kind
of cells in the $H\alpha$ mottling. Then I ask, if the downward flow is observed in
the $H\alpha$ line, why is it not observed in other photopheric lines? The difference
of levels are may be a few hundred km and they are not relevant if these
things are really a fundamental phenomenon of the stellar atmosphere: This
downward flow should be observed in all Fraunhofer lines, and we should
actually see this flow also at the center of the disk. Then we have added to
that the idea that the spicules actually do come from clusters surrounding
the cells. But again we have no direct evidence that it is so. So we must be
very prudent.

Leighton

Dr. Michard has made a very important point, and perhaps I passed too
hastily over such things this morning. Dr. George Simon, who made the a-
alysis of the correspondence between the emission network and the supergranulation field, actually established that these bright emission network features tend to surround the supergranulation cells by two different methods. One method was that which I described earlier. In the second analysis, he searched for a correspondence between a K-spectroheliogram with its network, and the Doppler picture with its velocity cells, by placing one plate directly on the other and measuring the cross correlation between the two. He did this in three regions: In one region near one limb, in another region near the opposite limb, and in a third region in the center, and he did it with several different plates. Because of the fact that, near the limb, a velocity cell is dark on one side and light on the other, it represents what we might call an "antisymmetric" function in a system of coordinates that is lined up along the radius and centered on the cell, whereas the corresponding network emission is a "symmetric" function in this same sense. The cross correlation function of these two fields should be an antisymmetric function of the displacement of the two plates; the plates are evidently in correct register at the displacement corresponding to the center of this antisymmetric curve. The physical location of the zero had to be found in this way since he did not know a priori exactly where the plates were in correspondence. He did this for each side of the solar disk. Having thereby established the position in which the two photographs are in perfect register, he then measured the cross correlation function between the two for a central region in which one does not see any large scale velocity field with the eye alone. He obtained on several occasions a cross correlation function which, although very weak and subject to noise fluctuations, always had a maximum at a position which corresponded exactly to the same zero that he had already found. So, having predicted where the peak should be, sure enough there was a correlation! This is now a direct correlation between currents which are flowing up at the centre of the cell and down at the edges, (now a symmetric velocity function) against the network brightness function. I am reasonably well convinced that such a correlation exists. The size of the velocity necessary to account for the peak was about 0.1 km/sec, which is approximately our noise level. Clearly there has to be a supply of material to replenish the horizontally moving material, and clearly it must go somewhere when the currents collide.

Schatzman

I would like to have an answer to the following questions.

a) What is the energy balance in the spicules? Can we say that the energy loss per ccm in the spicules is larger or smaller than in the surrounding dark chromospheric regions?

b) What about the flux of energy per cm² going into the spicules, compared to the flux per cm² going into the surrounding dark chromospheric regions?

Zirker

I can give sort of an answer to your first question and no answer at all to your second. I would say unquestionably that the radiative leak from the spicule is larger than that in the surrounding corona. But I have no really quantitative estimate, what energy is going into the spicule per ccm.
Schatzman
That would mean that we have to supply energy to the spicule to keep it cooler in the surrounding regions.

Zirker
Cooler? Why, it is radiating at a greater rate than the surrounding material.

Schatzman
Are the spicules the hot or the cool components of the chromosphere?

Zirker
I would say that they are cooler than the corona certainly. They may possess a's has been suggested by a number of people, a hot sheath, but ultimately you tag on to the corona at the altitude that you really see them, say 5000 km and up. So I would say that the temperature in the surrounding atmosphere is higher, but the radiative loss per ccm from the spicules is larger.

Schatzman
If we consider the picture that you showed where we have the bright regions in the K-spectroheliogram surrounded on the disk by the dark regions of the spicules, we should raise the question whether the energy flux coming from the photosphere is larger or smaller. Because then we would have three values for the flux coming from below the photosphere, in the bright region, at the edge of the bright region and in the dark region. As we know that these regions adjust extremely fast to the change of flux, we might raise the question whether this difference in structure is not reflecting some difference in the flux of energy which is coming from below.

Zirker
Yes. My own comment would be that such an idea would be attractive to me to explain the presence of the plages and the coarse motting perhaps. But to me the spicules are strictly a secondary dynamic phenomenon.

Schatzman
Yes, but we might supply dynamical energy to the corona with them.

Zirker
I think probably much more energy is being dissipated in the underlying chromosphere, say below 5000 km or so, than in the very tall spicules themselves. The spicules themselves e.g. are subsonic with respect to the corona. They cannot be heating the corona directly.