SOLAR AND STELLAR MAGNETIC FIELDS AND ATMOSPHERIC STRUCTURES: THEORY*

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Abstract. This presentation reviews selected ideas on the origin of the magnetic field of the Sun, the dynamical behavior of the azimuthal field in the convective zone, the fibril state of the field at the photosphere, the formation of sunspots, prominences, the spontaneous formation of current sheets in the bipolar field above the surface of the Sun, coronal heating, and flares.

1. Introduction

The subject indicated by the title of this review is the basis for all of stellar activity. A balanced assessment of each of the many substantial theoretical scenarios currently available is not possible in so short a space, so this review concentrates on what seems at the moment to be the most likely point of view on each of a limited number of phenomena. It should be emphasized that the shifting nuances of observation have many times in the past sunk a substantial theoretical ship, and the most likely explanation of today may be found washed up on the beach tomorrow. So the theoretical opinions offered here need extensive observational testing before they can be considered hard scientific explanations of stellar activity.

The discussion centers exclusively on the Sun, because the questions posed by the stellar magnetic field, and the attendant atmospheric structures, are too complex to be answered by serendipity alone. The precise observational details are essential to the construction of a scientific theory. The Sun is the only star that can be seen (resolved) so the Sun is necessarily the rosetta stone for stellar fields and stellar activity. We can only remark that most other stars probably create their fields in the same general way as the Sun, and their flares are evidently of the same general nature as the solar flare. The reader is referred to the other papers presented in this IAU Colloquium No. 104 for a survey of present knowledge of the behavior of the fields and flares of the distant stars.

As a matter of fact, the Sun is none too close for scrutiny, because much of the action on the Sun takes place on scales of the order of 10^2 km, well below the limit of resolution of present ground-based telescopes. Fortunately the march of technical development holds promise for resolving 10^2 km within the next decade. So our somewhat blurred rosetta stone may yet be brought into sharp focus before the end of the century.

Speaking in the most general terms it appears that solar activity is primarily the result

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of the displacement of magnetic flux tubes by convective fluid motions beneath the surface of the Sun and consequent displacement of the tenuous fluid by the discontinuities and instabilities of the magnetic field above the surface of the Sun. The process must be viewed as a whole if we are to get the physics properly, and this review is structured on that point of view.

2. Origin of Solar Magnetic Fields

The magnetic field of the Sun evidently has its origins in the convective fluid motions driven by the unstable stratification of the outer 2×10^{10} cm of the solar radius (7×10^{10} cm). The variation of the angular velocity Ω across the convective zone is the essential effect for generating the azimuthal field of the Sun. Helioseismology indicates that there is little or no vertical gradient in the angular velocity Ω (Duvall, Harvey, and Pomerantz, 1986) through the convective zone. The principal variation of Ω is with latitude ψ, in the form

$$\Omega(\psi) = \Omega_0(1 - 0.2 \sin^2 \psi)$$

(Newton and Nunn, 1955; Ward, 1965; Howard and Harvey, 1970; Howard, Gilman, and Gilman 1984; Gilman and Howard, 1984a, b, 1985; Schröter, 1985), where Ω_0 is the equatorial angular velocity ($\Omega_0 \cong 2.93 \times 10^{-6}$ rad s^{-1}). The surface rotation varies somewhat with the phase of the magnetic cycle (Howard and Harvey, 1970; Yoshimura, 1972, 1981; Howard and LaBonte, 1980, 1981; Howard, 1984; Gilman and Howard, 1985) but that is a fine point that need not be considered here.

There is some vague evidence for a poleward meridional flow of the order of 20 m s^{-1} (Durney, 1975; Howard, 1979; Duvall, 1979; Beckers, 1979; Perez Garde *et al.*, 1981; Anderson, 1988) as well as giant convective cells of one form or another (Yoshimura, 1971). The granules and supergranules are the surface manifestation of the general turbulent convective overturning. The mixing length representation of convective heat transport (Schwarzschild, 1958) is used to estimate the convective velocities through the convective zone (Spruit, 1974). Such estimates yield r.m.s. turbulent velocities v_t of the order of 40 m s^{-1} across the middle of the convective zone (at a depth of 10^{10} cm), declining only slowly with depth until near the bottom (at 2×10^{10} cm) where the calculated v_t falls abruptly to zero. The calculated equipartition magnetic field $B_e \equiv (4\pi\rho)^{1/2} v_t$ has a broad maximum of about 3×10^3 G across the lower two-thirds of the convective zone, falling to zero abruptly at the bottom.

Yoshimura (1975) points out that the convection involves converging flows in the lowest levels of the convective zone, so that the Coriolis force causes the rising fluid to rotate more rapidly than the surroundings. Higher up in the convective zone the rising convective plumes expand with the declining density, so that the fluid above some intermediate level rotates more slowly than the surroundings (Steenbeck and Krause, 1969). It follows that the helicity ($\mathbf{v} \cdot \nabla \times \mathbf{v}$) of a rising convective column in the northern hemisphere is positive in the lowest levels of the convective zone and negative above, with the opposite signs prevailing in the southern hemisphere. We presume, then, that the associated downflow is confined to the broad regions between the rising columns, so that the updrafts dominate the helicity, with the sense noted above. Schmitt (1987) considers the helicity in geostrophic waves.

There are a number of reasons for believing that the magnetic field is generated in the lowest levels of the convective zone (Parker, 1975, 1987a, b) or in the overshoot region below (Golub *et al.*, 1981; Galloway and Weiss, 1981; Spruit and van Ballegooijen, 1982; van Ballegooijen, 1982; Schmitt and Rosner, 1983; Durney, 1981; Gilman, Morrow, and DeLuca, 1989). The idea that the dynamo action occurs at the bottom and perhaps in the overshoot region originally followed from the sign of the helicity of the convection at those levels, providing the observed equatorward migration of the azimuthal field in combination with the downward decrease of Ω indicated by some of the numerical simulations of the large-scale circulation (Gilman, 1983; Glatzmaier, 1985; DeLuca and Gilman, 1986; Parker, 1987a). Golub *et al.* (1981) suggested that the normal active regions appearing at the surface of the Sun are the consequence of the dynamo in the overshoot region, while the small-scale active regions – X-ray bright points and ephemeral active regions – represent the magnetic 'debris' escaping from the dynamo process.

We may wonder if the current results of helioseismology, that Ω varies but little with radius, somehow miss perhaps a thin layer of vertical shear in the deep convective zone. The more definitive results eventually to be hoped for from the GONG observations might possibly change the picture. But for the moment we have no basis for assuming anything beyond the present evidence that Ω seems not to vary significantly with depth, the principal effect being then a decrease of Ω with increasing latitude, as already noted. The variation of Ω with latitude, in combination with the helicity of the convection, provides dynamo waves that migrate vertically instead of horizontally.

Consider, then, the dynamo that results from this combination of fluid motions. The azimuthal field is produced by the latitudinal shear of the latitudinal, or θ, component of the poloidal field. The poloidal field is a consequence of the interaction of the cyclonic convection with the azimuthal field. Combining these effects somewhere in the lower convective zone produces dynamo waves with a natural tendency to migrate vertically downward (Parker, 1955). The migration is blocked by the bottom of the convective zone, of course, so the waves pile up against the bottom. They are deflected north or south, away from their source, depending on the latitudinal distribution of the cyclonic convection and nonuniform rotation. Since both the cyclonic convection and the gradient of Ω are larger at higher latitudes, the dynamo waves apparently issue from higher latitudes and migrate toward the equator. Formal examples illustrating this effect are available in the literature (cf. Parker, 1971, 1979c; Lerche and Parker, 1972).

This provides a self-contained magnetic dynamo system in the lower part of the convective region. The fields created by the dynamo press downward against the bottom so they are relatively unaffected by the opposite dynamo action at higher levels. The convection is strong, with the equipartition field of the order of 3×10^3 G. The dynamo extends into whatever overshoot region there may be below the conventional bottom of the convective zone (at a depth of about 2×10^{10} cm). It remains to be shown what role is played by meridional circulation *vis-à-vis* the dynamo period.

The azimuthal field is held against the bottom of the convective zone by the combined effect of the dynamo migration and the weight of the cool shadow that forms on the upper side of each band of azimuthal field (Parker, 1987a). To elaborate this picture, one infers that the azimuthal field in the lower convective zone has a strength of 3×10^3 G or more (Parker, 1987a) based on the amount of magnetic flux that appears at the surface (Gaizauskas *et al.*, 1983). Hence, the field is strong enough to suppress the convective heat transport to some significant degree. That is to say, each band of azimuthal field represents a major obstacle to the upward convective heat transport. Hence, each band has a cool shadow above and an accumulation of heat underneath. The heat accumulation lies near the bottom of the convective zone where a substantial fraction of the transport is radiative and where the convective transport requires a much smaller difference between the actual and the adiabatic temperature gradients than in the cool shadow region on top of the azimuthal field. Hence, the cool shadow is the larger effect, suppressing the buoyancy of the magnetic field (Parker, 1987a–d). The net result is that the azimuthal field is held down by both the dynamo migration and the cool shadow. However, the under surface of the azimuthal field is subject to a Rayleigh–Taylor instability as a consequence of the local accumulation of heat (Parker, 1987a–e). The instability initiates thermal plumes that penetrate upward through the field and to the surface of the Sun (Parker, 1988a). The plumes carry some of the field with them to the surface, producing the normal active regions. A plume recurs at a given location at intervals of a week or two based on the time required to accumulate the heat to initiate the Rayleigh–Taylor instability across the lower boundary of the magnetic field (Parker, 1987e). Such recurring eruptions from any one location are responsible for the long-lived activity complex (active longitude) with the continuing intermittent emergence of fresh flux at the surface over a period of a year or more (see, for instance, Gaizauskas *et al.*, 1983; Castenmiller, Zwaan, and van der Zalm, 1986).

The rapid disappearance of magnetic flux from the surface of the Sun has long been a puzzling observational fact. Parker (1984a) suggested that most of the emerging bipolar fields are pulled back beneath the surface, so that there is relatively little total azimuthal flux lost into space. This may be understood as a direct consequence of the convective downdraft in the cool shadow above each band of azimuthal field in the convective zone. However, there remains much observational work yet to establish that most of the magnetic flux disappears by retraction (see the review by S. F. Martin in this issue).

An interesting feature of the dynamo driven exclusively by horizontal variation of the angular velocity is that the period is readily adjusted to the observed 22 years. A long standing problem with dynamos based on a radial variation of the angular velocity (Parker, 1955, 1957) is that the theoretical period is much shorter than 22 years – usually 1–5 years – if one employs current estimates of the eddy diffusivity. To elaborate on this problem, suppose that the eddy diffusivity is as small as $1\text{–}4 \times 10^{11}$ cm^2 s^{-1}. Then the turbulent diffusion of field is slow and the theoretical dynamo period is as long as 22 years (Köhler, 1973; Yoshimura, 1975). But a straightforward application of the mixing-length theory, on which the model convective zone is based (Spruit, 1974), yields an eddy diffusivity of about 10^{12} cm^2 s^{-1}, which produces a dynamo period of only a few years (see discussion in Parker, 1979c, p. 762; Rai Choudhuri, 1984). That is to say if the convective helicity and radial shears are strong enough to overcome turbulent diffusion, the phase velocity of the dynamo wave is too fast.

The theoretical dynamo model based on horizontal shear avoids this problem. The migration toward the equator arises only because of the nonuniform distribution of the helicity and horizontal shear. The period depends quantitatively on that distribution and can in principle be arbitrarily long for uniform helicity, uniform boundaries, etc. Such a dynamo provides a ready answer for the well-known variability of the period of the magnetic cycle, being particularly sensitive to the distribution of cyclonic convection, meridional flow, and nonuniform rotation.

The combined horizontal shear, downward migration, and suppression of buoyancy by the cool shadow accounts in a natural way for negligible loss of azimuthal magnetic flux through the surface of the Sun (Parker, 1984b). As pointed out elsewhere (Parker, 1984a), the fields emerging through the surface pull back into the Sun rather than escape into space. The cool shadow plays an important role in the process (Parker, 1987a, 1988a), and we now have the migration of the dynamo wave adding to the suppression of escaping flux.

Note, however, that there is still the possibility that small flux bundles – magnetic debris – may continually escape upward from the lower half of the convective zone, as originally suggested by Golub *et al.* (1981) and Durney (1988), because the cool shadow is ineffective in suppressing the buoyancy of any flux bundle whose horizontal width is small compared to the local pressure scale height (see Parker, 1987a, Figure 4, 1988c). The downward phase velocity of the dynamo wave would be only a few meters s^{-1}, at most, while the rate of buoyant rise of a small flux bundle with a width of, say, 10^3 km, might be as fast as 10^2 m s^{-1}.

The overall picture, then, is one of broad bands of intense ($3–10 \times 10^3$ G) azimuthal magnetic field crawling toward the equator along the bottom of the convective zone. The local dynamics of such bands, with widths of the order of $2–4 \times 10^5$ km, sends thermal plumes to the surface, which carry the magnetic flux responsible for the normal active regions. The associated poloidal field is diffuse and not easily observed. Its most obvious manifestation is in the polar fields, which keep in step with the migrating alternating bands of azimuthal field.

Consider, then, the upper half of the convective zone, where the convective motions are not as robust and where the helicity is presumed to be negative in the northern hemisphere and positive in the southern, as a consequence of the expansion of the thermal plumes rising from below (Steenbeck and Krause, 1969). Again it is assumed that the corresponding subsidence of gas occurs around the periphery of the updrafts, so that its helicity is of opposite sign but so small in magnitude that it can be neglected. The net negative helicity in the northern hemisphere, in combination with the decline of Ω with increasing latitude, causes an upward migration of the dynamo waves.

Now the equipartition field declines from 3×10^3 G at mid level (a depth of 10^{10} cm) to 2×10^3 G at a depth of 0.4×10^{10} cm, to a few hundred gauss at the visible surface.

Hence, the cool shadow cannot effectively suppress the magnetic buoyancy of flux bundles above a depth of the order of 1.5×10^9 cm (Parker, 1988c). So there is no firm barrier for the dynamo wave to push against.

The fields are carried up and out by the combined magnetic buoyancy and migration of the dynamo wave. Consequently it appears that the dynamo action in the upper half of the convective, if it exists at all, can contribute no more than the network fields and the small bipolar regions (e.g., ephemeral active regions). About all that can be said is that these very small magnetic features are the result of the magnetic debris from the lower half of the convective zone, amplified by whatever dynamo action there may be in the upper half. This is, of course, the point of view suggested by Golub *et al.* (1981) many years ago. It is interesting that we are led to the idea by the simple dynamo based on horizontal shear and by a consideration of thermal shadows, which cannot suppress the magnetic buoyancy within about 1.5×10^9 cm of the surface of the Sun. Indeed, the observed behavior of the small flux bundles and the transitory ephemeral active regions are just what would be expected from the theory of cool shadows, thermal plumes, and the retraction of magnetic flux bundles at depths of the order of 2×10^9 cm (Parker, 1988b, c).

With this brief summary of ideas on the origin of magnetic fields, in the convective zone, and their intermittent appearance at the surface, consider some of the dynamical effects of the fields above the surface.

3. Magnetic Activity above the Surface

The structures erected above the surface of the Sun, by the magnetic field emerging through the surface, are subject to direct observation and are consequently well known in general form. We are all familiar with the fibril structure of the magnetic field at the photosphere (Muller, 1985, and references therein) and with the spontaneous clustering of the fibrils to form pores and sunspots (Zwaan, 1985, and references therein). The cause of the fibril structure has yet to be confirmed for lack of the necessary high-resolution observations. Several ideas have been proposed. First of all, the magnetic field energy of a fibril field is larger than a uniform field with the same mean intensity $\langle B \rangle$ by the factor $B_f/\langle B \rangle$ where $B_f = 1\text{–}2 \times 10^3$ G, is the field in the individual fibril. This ratio is of the order of 10^2 in quiet regions and 10 in active regions. On the other hand, the widely separated fibrils offer less impediment to the convective transport of heat than the same total flux spread uniformly. Hence, the heat transport is more effective, and the thermal and gravitational energies are reduced by the fibril state of the field. It can be shown that the minimum total energy occurs for fibrils with B_f of the order of $1\text{–}4 \times 10^3$ G (Parker, 1984c), in rough agreement with the values of $1\text{–}2 \times 10^3$ G inferred from observation. It is interesting, then, that the fibril field observed at the photosphere may represent an energy minimum in the surface layers of the Sun, but, of course, so general a statement does not disclose the physical mechanism that creates the individual fibril.

Nor can it be concluded that the fields are in an intense fibril state throughout the convective zone, with B_f considerably in excess of the equipartition value. Brants (1985) and Zwaan (1985) infer from observation that B_f is only as large as the equipartition value, of about 0.5×10^3 G, in the magnetic flux bundles freshly emerging through the surface of the Sun. This suggests that the intensification to a value several times the equipartition value is intrinsically a surface effect, along the lines suggested by Spruit. That is to say, the global energy minimum can be achieved only where the means to achieve it is available and that is only at the surface.

In general terms, the creation of the fibril at the surface of the Sun requires that the gas pressure p_i within the fibril be reduced to about half the ambient external pressure p_e. Even a very small cooling ΔT may achieve this if it extends over several scale heights, because the pressure scale height is correspondingly reduced and the gas slides down out of the fibril, evacuating the upper regions and compressing the field according to the approximate horizontal equilibrium condition

$$B_f^2 = 8\pi(p_e - p_i)\,.$$

Thus, for instance, a small internal temperature reduction ΔT extending over n scale heights of an isothermal atmosphere reduces the pressure by Δp, where

$$\frac{\Delta p}{p} \cong n\,\frac{\Delta T}{T}\,.$$

Then, if $\Delta T/T$ has the modest value 0.1 extending over 5 scale heights (about 10^3 km), the result is $\Delta p/p \cong 0.5$ and $p_e - p_i \cong 0.5p_e$, yielding $B_f^2 \cong 4\pi p_e \cong 1\text{–}2 \times 10^3$ G.

A modest downdraft within the fibril can easily achieve such a cooling to produce the observed B_f of $1\text{–}2 \times 10^3$ G (Parker, 1978a, 1979c, pp. 260–271). Spruit (1979) has pointed out that the gas pressure reduction $p_e - p_i$, caused by the magnetic pressure $B^2/8\pi$, decreases the opacity and permits a more transparent atmospheric state in which the photospheric surface ($\tau = 1$) lies at a lower level within the fibril. The effect seems to be sufficient to produce the observed concentration of field. Deinzer *et al.* (1984a, b) and Hasan (1985) have explored the idea in some detail. Their modeling shows a quasi-steady state and a vigorously oscillatory state, respectively, for the reduced photospheric gas pressure and compressed magnetic fibril. Detailed studies of line profiles (Stenflo and Harvey, 1985; Stenflo, 1985) suggest that the oscillatory state worked out by Hasan may be more realistic than the quasi-steady model. High-resolution observations, down to 0.1″ (75 km), are necessary to confirm or deny these theoretical ideas.

Priest (1982, pp. 280–324) provides a general description and review of the structure of sunspots. The clustering of magnetic fibrils to form pores and sunspots during (and only during) periods of flux emergence at the surface of the Sun is a puzzling observational fact (Zwaan, 1978, 1985). In as much as the magnetic fibrils expand to fill all the available volume, creating a continuum field, at heights of a few hundred km above the visible surface, the fibrils at the photosphere exert short range repulsive forces on their nearest neighbors. The clustering, in opposition to the magnetic repulsion, must be driven by powerful hydrodynamic forces. There are modest attractive forces arising from the motion of the individual fibrils through the ambient fluid (Parker, 1978b, 1979e), but in order to drive the main event, forming a sunspot with fields compressed to 3×10^3 G, the only possibility seems to be a strong converging flow at depths of several thousand km (Meyer *et al.*, 1974). We suggest that the converging flow feeds a downdraft along the field (Parker, 1979a, b) which sweeps away the thermal energy whose upward convective transport is blocked by the field.

It is an observed fact that magnetic fibrils cluster to form pores and sunspots only while fresh magnetic flux is emerging in the active region, i.e., only while there is azimuthal field being carried to the surface by the thermal eruption from the azimuthal band of field in the lower convective zone. If the idea that the formation of sunspots at the surface is a consequence of a hydrodynamic flow converging on the points of clustering, then it follows that, somehow, there is a tendency for converging flows to form unseen beneath the surface in those regions of thermal upwelling. It is not evident on theoretical grounds why this should occur. We expect (Parker, 1987a–d) a general downdraft, with a converging flow at its upper end, in the cool shadow above each band of azimuthal field. Is there some reason why this general convective flow should become so strong locally in the regions of flux emergence as to sweep the magnetic fibrils into the highly compressed state that forms a pore or sunspot?

We have suggested that the subsurface magnetic field of a sunspot is a loose assembly of intense ($\sim 10^4$ G) nearly vertical magnetic fibrils, with field-free fluid flowing in and down between the fibrils (Parker, 1979a–d). The fibrils flare out at the visible surface to fill the available space and to provide a nearly continuous umbral field. We suggest that the bright umbral dots are a result of the transitory upward intrusion of the field-free fluid (Parker, 1979e). High-resolution observations of sunspot umbrae appear to support this picture of the sunspot (Garcia de la Rosa, 1987). The influence of the subsurface magnetic field structure on the local p-mode oscillations holds promise for helioseismological probing of the subsurface structure (Thomas, Lites, and Nye, 1982; Thomas and Scheuer, 1982; Thomas *et al.*, 1987; Bogdan and Zweibel, 1987; Bogdan, 1987a, b; Abdelatif and Thomas, 1989). It is clear from observation that the sunspot has profound effects on the local oscillations (cf. Balthasar, Küveler, and Wiehr, 1987, and references therein).

Moving up into the atmosphere above the surface of the Sun there is the quiescent prominence, representing a quasi-stable condensation of gas suspended on the magnetic field protruding upward from the surface (see, for instance, Tandberg-Hanssen, 1974; Hirayama, 1985; Sakai, Colin, and Priest, 1987; Wu and Low, 1987; Ballester and Priest, 1987, and references therein).

The coronal mass ejections have become an active subject for researrch, since their discovery a few years ago. It appears that the coronal mass ejection arises when a bipolar magnetic arcade, or similar structure, anchored in the surface of the Sun, is sheared lengthwise beyond a critical amount so that there is no longer a closed magnetic equilibrium (Low, 1977a, b, 1981, 1984, 1985, 1986; Jockers, 1978; Birn, Goldstein, and Schindler, 1978; Parker, 1981a; Seehafer, 1985; Browning and Priest, 1986, and references therein; Biskamp and Welter, 1988). To put the matter in its simplest terms, the magnetic energy of a magnetic arcade confined to a long quonset hut (horizontal semi-circular cylinder) can be increased linearly without bound as the lengthwise shearing increases. On the other hand, an elemental magnetic flux tube can be extended radially from the surface of the Sun to infinity with a finite amount of energy. In particular, a field B_0 extending radially from the surface of the Sun ($r = R$) to infinity possesses a magnetic energy $\mathrm{d}E$ in the solid angle $\mathrm{d}\omega$, given by

$$\mathrm{d}E = \frac{B_0^2}{8\pi} R^3 \,\mathrm{d}\omega \,.$$

The energy between R and r is proportional to $(1/R - 1/r)$, so it does not matter how the field is deflected at $r = \infty$ to other directions. It follows, therefore, that beyond a critical shear, the field can reduce its energy if it expands upward from the original arcade and extends to infinity. One imagines, then, that a magnetic arcade, or similar structure, at the surface of the Sun is progressively and slowly sheared by the massive motions of the photosphere. When the shearing reaches some critical value, the lowest energy state of the field involves an increasing radial extension, which reaches to infinity for finite shear. That is to say, quasi-static magnetic equilibria form discontinuous families in configuration space, so that continuous deformation beyond a given point introduces a discontinuous – and in this case infinite – jump in the equilibrium configuration. The equilibrium ceases to exist in the form of an arcade and is replaced by an equilibrium which extends far out into space. The coronal gas tied to the field is pitched outward with the expanding field, creating the spectacular coronal mass ejection. Once underway the ejection is no longer near quasi-static equilibrium because the velocity of expulsion is comparable to the Alfvén speed. The finite kinetic energy of the catapulted coronal gas permits at least some portion of the gas and field to move to infinity.

4. Spontaneous Formation of Current Sheets

Solar flares, microflares, and the active X-ray corona appear to be a consequence of magnetic neutral point reconnection. The essential point is that these extreme suprathermal phenomena are the result of intense, localized dissipation of magnetic field energy, producing high speed jets (10^2–10^3 km s^{-1}), fast particles, and generally intense heating of the ambient gas. They occur in regions where the temperature is already quite high (10^5–10^6 K) and the resistivity of the gas is low. The classical resistive diffusion coefficient $\eta = c^2/4\pi\sigma$ is 10^3–10^5 cm^2 s^{-1}, so that the characteristic resistive dissipation time over typical granule scales of 500 km is 10^{10}–10^{12} s (3×10^2–3×10^5 years). Dissipation on so long a time-scale is uninteresting.

The current ideas on wave heating of the X-ray corona appear to be ruled out by the observation (Rosner, Tucker, and Vaiana, 1978) that the surface brightness of the X-ray corona is essentially independent of the scale of the emitting region, from the normal active region at 2×10^5 km down to the smallest resolvable emitting regions of

$2–4 \times 10^3$ km. Waves with periods of 1–2 s or less would be required to accomplish the heating of the smallest regions. Waves with such power at such high frequencies would be a revelation in themselves. In any case, the large active regions would then be heated by all waves with lengths equal to or less than the dimensions of the active region, rendering the longer magnetic loops much brighter than the shorter loops.

The essential point is that the random displacement of the footpoints (the magnetic fibrils) by the photospheric convection deforms the bipolar magnetic fields that extend outward from the photosphere. Large-scale shears produce the abrupt outward expansion of the static equilibrium of the field, as described in the preceding section. The large-scale motion may also be responsible for the large current sheet believed to produce the hard component of the flare emission. The reader is referred to the general studies of flares by Švestka (1976), Sturrock (1980), Priest (1980), and de Jager and Švestka (1985), and to the specific ideas spelled out by Priest (1982, pp. 344–381) and Seehafer (1985, 1986).

More pertinent to the problem of suprathermal heating is the fine-scale winding and interweaving of the lines of force of a bipolar field as a consequence of the continuous random walk of the footpoints of the field carried about in the granules. The small-scale winding and interweaving leads to the spontaneous formation of current sheets (tangential discontinuities) in the field (Parker, 1972, 1979c, pp. 359–391, 1987c, 1988d, e; Tsinganos, 1982; Tsinganos, Distler, and Rosner, 1984, and references therein). The heat input responsible for the X-ray corona and a large part of the solar flare appears to be a consequence of the dissipation of these spontaneous current sheets (Parker, 1972, 1979c, pp. 359, 391, 1981a, b; 1983a, b, 1987f, g, 1988d). The dissipation arises from the rapid (neutral point) reconnection of the fields across each current sheet, which is essentially independent of the very large electrical conductivity of the medium.

Figure 1 is a sketch of the lines of force of a simple bipolar field of length L. Figure 2 is a convenient idealization of that field in which the overall curvature has been removed so that the initial unperturbed field extends uniformly with intensity B_0 from the 'photosphere' at $z = 0$ to the 'photosphere' at $z = L$. Suppose, then, that the footpoints of the field at $z = L$ are fixed while the footpoints at $z = 0$ are transported in a random continuous velocity field with r.m.s. velocity u, correlation length λ, and correlation time

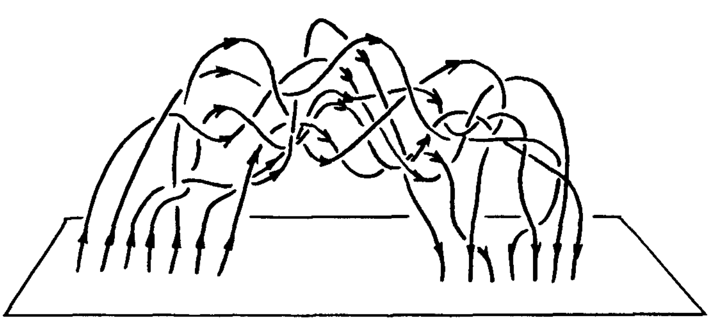

Fig. 1. A schematic drawing of the lines of force of a bipolar magnetic region above the surface of the Sun.

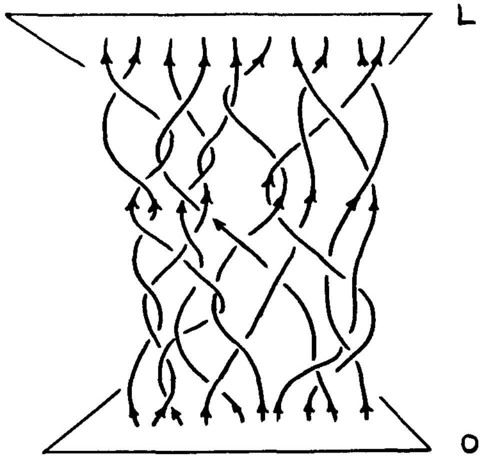

Fig. 2. A schematic drawing of the idealized form of a bipolar field.

$\tau \cong \lambda/u$ (which we identify with the granule motions for which $\lambda = 500$ km, $u = 0.5$ km s^{-1}). Thus, in a time t the typical footpoint travels a distance $s = ut$ along a random path composed of $n \cong t/\tau$ statistically independent steps of length λ. The lines of force trail out behind the moving footpoint at $z = 0$, as sketched in Figure 3, following the same general pattern throughout $0 < z < L$ as traced out by the moving footpoint at $z = 0$. Hence, the mean inclination θ of the line to the original z-direction is given by $\tan\theta = ut/L$. The mean value of the z-component of the field is unaffected by this winding and interweaving of the lines of force and remains equal to B_0, while the mean transverse component is $B_t = B_0 \tan\theta$. The tension in the field opposes the forward random march of the footpoint with the Maxwell stress $B_t B_0/4\pi$ so that the motion of

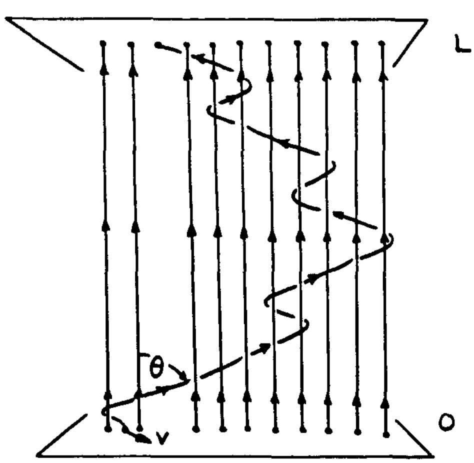

Fig. 3. A schematic drawing of the wandering of a single line of force among neighboring lines of force.

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the footpoint does work on the field at the rate (Parker, 1983a)

$$W = uB_tB_0/4\pi = B_0^2u^2t/4\pi L \quad \text{ergs cm}^{-2}\,\text{s}^{-1}\,.$$

The result is a progressive internal small-scale winding and interweaving of the lines of force of the re-entrant fields extending above the surface of the Sun. The rate of energy input by the convective motions of the footpoints is of the order of $uB_0^2 \tan\theta/4\pi$ ergs cm^{-2} s^{-1}.

Now the field, with its random internal winding and wrapping is in quasi-static equilibrium, with u of the order of 10^{-3} of the Alfvén speed $V_{\rm A}$ ($= 10^3$ km s^{-1} in the corona). The gas pressure is approximately 10^{-2} of the magnetic pressure, so that the field satisfies the familiar force-free equations

$$\nabla \times \mathbf{B} = \alpha\mathbf{B}\,, \quad \mathbf{B}\cdot\nabla\alpha = 0\,,$$

where α is the helicity of the field,

$$\alpha = \mathbf{B}\cdot\nabla \times \mathbf{B}/B^2\,.$$

Note, then, that α is rigorously constant along each line of force. On the other hand, the random field shown in Figure 2 involves a random sequence of right- and left-hand winding of the individual line of force about its neighbors. The helicity α cannot follow these changes in the geometrical helicity of the various independent windings along a given line of force. The field resolves the issue by developing internal tangential discontinuities, across which the magnitude of the field is continuous but the direction changes discontinuously (by an amount of the order of θ) so as to accommodate the successive right- and left-handed winding among the neighboring flux bundles (Parker, 1985, 1986a, b, 1988e). The tangential discontinuity occupies no volume and contains no magnetic flux (in the limiting case that the fluid has infinite electrical conductivity). Hence, the equilibrium equations are satisfied everywhere except on a set of points of measure (volume) zero.

The reader may wish to consult the work of van Ballegooijen (1988) who holds that tangential discontinuities do not occur under these circumstances. His numerical simulations provide a vivid illustration of the rapid development of current sheets in a field subject to successive winding and interweaving operations, which, however, he asserts is not the same effect as discussed above.

Another way to understand the formation of the tangential discontinuities (current sheets) is to consider a continuous static equilibrium field involving one or more separatrices between regions or lobes of field. It is readily demonstrated that any nonuniform deformation or squashing of the field (by motion of the footpoints or further twisting, etc.) produces tangential discontinuities at the separatrices (Syrovatskii, 1971, 1978, 1981; Parker, 1972, 1979c, pp. 378–383, 1982, 1983b, 1987c; Rosenbluth, Dagazian, and Rutherford, 1973; Waddell *et al.*, 1976; Hu and Low, 1982; Low and Hu, 1983; Moffatt, 1987; Steinolfson and Tajima, 1987; Low, 1987, 1988; Low and Wolfson, 1988; Otani and Strauss, 1988; Strauss and Otani, 1988).

It must also be remembered that the footpoints of the coronal magnetic fields of the

Sun are separated into the individual fibrils, each of which may move independently of its nearest neighbors. This introduces discontinuities directly into the field above, without any consideration for the winding and interweaving of the flux bundles from the separate fibrils. Whole flux tubes may be displaced relative to the ambient field, producing tangential discontinuities along the entire length of the displaced flux bundle (Parker, 1981a, b).

The spontaneous appearance of tangential discontinuities through the re-entrant field of the solar atmosphere introduces dissipation, where none of any significance is otherwise expected. These current sheets are subject to resistive instabilities, leading to rapid reconnection of the fields across the current sheet. The high electric current densities in the discontinuity suggest the possibility of plasma turbulence and anomalous resistivity, although it must be remembered that this requires the electron conduction velocities to exceed at least the ion, if not the electron, thermal velocity.

Laboratory experience and numerical simulation indicates that the reconnection progresses only very slowly until the discontinuity θ exceeds some critical value, θ_c, whereupon there is a burst of reconnection, reducing θ to some fraction of θ_c (Rosenbluth, Dagazian, and Rutherford, 1973; Kadomtsev, 1975, 1984; Waddell *et al.*, 1976; Finn and Kaw, 1977; Montgomery, 1982; Seehafer, 1985; Lichtenburg, 1984; Dahlburg *et al.*, 1986).

Heyvaerts and Priest (1984) and Dixon, Browning, and Priest (1987) suggest that the reconnection proceeds in such a way as to satisfy Taylor's hypothesis (Taylor, 1974, 1986). That is to say, the total helicity $\int d^3\mathbf{r}B^2/8\pi$ declines to the minimum allowed by the given total helicity. With this constraint the minimum energy occurs for uniform α. Seehafer (1985, 1986) has studied the evolution of force-free fields with uniform but time varying α, showing the various singular transitions in the topology of the field with a continuously increasing $\alpha(t)$. He suggests that major flares may be associated with these transitions.

The central point is then that, with the continual shuffling and intermixing of the footpoints of the field, one has the picture of the gradual increase of θ (over a period of hours in a normal active region with a scale $L = 10^{10}$ cm) until some critical value θ_c is exceed, whereupon the individual current sheets undergo random transient bursts of dissipation, and a statistically steady state is reached with the mean θ (over the field) of the same order as θ_c. Withbroe and Noyes (1977) estimate an energy input of the order of 10^7 ergs cm^{-2} s^{-1} to the brighter regions of the solar X-ray corona. With a typical field $B_0 = 10^2$ G and an assumed $u = 0.5$ km s^{-1}, the result is $\tan\theta \cong \frac{1}{4}(\theta \cong 14°)$. The energy of each individual burst is some fraction of the energy associated with the characteristic volume $\lambda^3 \cot\theta$ and transverse magnetic energy density $B_0^2 \tan^2\theta/8\pi$. With $\lambda = 500$ km and $\tan\theta = \frac{1}{4}$, the characteristic energy is 10^{25} ergs. The characteristic burst, then, might involve 10^{24} ergs, which we have referred to as a *nanoflare*, it being about 10^{-3} of the typical 10^{27} ergs of the microflare (Parker, 1987g, 1988d).

It follows from these theoretical considerations that the individual X-ray coronal region represents a cloud of nanoflares (Parker, 1983a). Observations of the X-ray corona without high resolution show only the general glow of the individual X-ray loops.

But increasing resolution in space and in time progressively shows increasing spatial structure and rapid time variation. On scales of 1–2 × 10^3 km the X-ray corona is, in fact, a rapidly flickering spotty structure with correlation times 20–200 s (Golub, Krieger, and Vaiana, 1976a, b; Sheeley and Golub, 1979; Nolte, Solodyna, and Gerassimenko, 1979; Habbal and Withbroe, 1981; Brueckner, 1981; Brueckner and Bartoe, 1983; Lin *et al.*, 1984; Porter, Toomre, and Gebbie, 1984; Dere, Bartoe, and Brueckner, 1986; Porter *et al.*, 1987). The observations of Brueckner and Bartoe (1983) and Porter, Toomre, and Gebbie (1984) show that the individual nanoflare is of the general order of 10^{24} ergs, with a characteristic time of 10^2 sec. Thus, the theory appears to be borne out in detail by the observations (see discussion in Porter, Toomre, and Gebbie, 1984). The coronal emission rate of 10^7 ergs cm^{-2} s^{-1} requires about one nanoflare per square second of arc (0.5×10^{16} cm^2) in progress at any given point in time.

We have suggested (Parker, 1987b) on the basis of the high-resolution observations of Machado *et al.* (1988a, b) that the typical solar flare represents a coordinated burst of nanoflares throughout a finite volume of field. Machado *et al.* point out that "The basic structure of a flare usually consists of an initiating closed bipole plus one or more adjacent closed bipoles impacted against it... The flare energy release begins either within the initiating bipole or at the interaction site between it and the impacted bipole. The initiating and impacted bipoles interact strongly in the impulsive phase of the flare [during which] most of the energy... is released inside the initiating bipole and/or inside one or more of the adjacent bipoles rather than at the interacting site between these." They point out that most of the hardest radiation may be emitted from the interaction site, but constitutes only a small fraction of the total X-ray energy.

It appears from this vivid description that the flare is a consequence of the large number of tangential discontinuities in the bipoles prior to the interaction, i.e., mutual deformation, of the bipoles. The flare occurs when the large-scale motion of the footpoints squashes two or more bipoles together, creating further current sheets and setting off a major portion of the pre-existing small-scale current sheets in a coordinated burst of nanoflares. The deformation of the bipoles may lead to rapid instabilities, violently shaking and squashing the bipoles along the lines described by Seehafer (1985, 1986). Further observational study of the initiating deformation is an essential step in understanding the diverse natures of individual flares. Indeed, the initial magnetic configuration, the intensity of the small-scale internal current sheets, and the particular mode of deformation are presumably the key to the nature of the flare.

It is interesting to note that Sturrock *et al.* (1984) pointed out several years earlier that the extremely spiky nature of the X-ray and microwave emission from solar flares suggests that the flare is a consequence of many very small reconnection events. They suggested that the individual magnetic fibrils rotate independently of each other, with the result that current sheets are produced at the contact surfaces between the individual flux bundles at coronal altitudes. Our own work has modified this concept by adding the spontaneous current sheets that arise throughout the field subject to any continuous random displacement of the footpoints at the photosphere. The observations of

Machado *et al.* (1988a, b) have placed the whole picture of the flare, as a coordinated burst of nanoflares, on a firm footing.

It is obvious that (a) further theoretical work needs to be done (see Parker, 1987f, and references therein) and (b) the final proof of the nature of the flare and the X-ray corona must come from detailed observation. Not only is it necessary to extend the present preliminary observational studies of individual microflares and nanoflares in the X-ray corona and in the flare itself, but much of the basic data on the structure and the motions of the individual magnetic fibrils (which are the footpoints of the coronal fields) have yet to be determined. The numbers employed in the present discussion ($\lambda = 500$ km, $u = 0.5$ km s^{-1}) are conjectures based on the observed granule motions. These observations will have to be done from an orbiting diffraction-limited mirror of 1 m diameter or more, or failing that, employing active optics on a large ground-based telescope.

The necessary optics have yet to be fully developed, although the technology holds great promise. The nature of the solar flare and the solar X-ray emission is fundamental to the terrestrial environment, to X-ray astronomy, and to the activity of all stars. It is not possible to extract much science from the extensive recording of the X-ray emission from the distant stars, until we have exploited the nearest star to understand what physical process is implied by the X-ray emission.

Finally, note that we have said nothing about the heating in coronal holes, which are responsible for the fast streams in the solar wind. The recent work by Withbroe (1988) indicates substantial energy deposition within the first few hundred thousand km. Current sheets do not form spontaneously in the open fields of the coronal hole. It remains to be shown what hydromagnetic wave spectrum might accomplish the heating close to the Sun where phase mixing is presumably not effective. It is essential that we take a hard headed attitude toward this problem, because for too many years now we have been without a real scientific understanding of the energy source for the solar wind. It is time that we recognize the problem and attack it on realistic terms.

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