INTRODUCTION

THE ENIGMA OF SOLAR ACTIVITY

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1. Introduction

The review lectures that make up the basic program of this symposium will cover the most recent observational results, and the present state of theoretical knowledge, of solar activity. It seems, therefore, that the most useful role for the introductory lecture would be to review the outstanding puzzles presented to us by the activity of the Sun so that we may have those numerous dilemmas clearly in mind as the speakers review the accumulated facts and theories.

It has become clear in the last ten years that the cause of all the many different forms of solar activity can be traced to the convection and circulation within the Sun. The convective zone of the Sun is a giant heat engine which converts a small fraction of the outward flowing heat into convective motions, and from there into magnetic fields and hydrodynamic and hydromagnetic waves. From these basic ingredients (of low entropy) there then arises the sunspot, the prominence, the flare, the corona and solar wind, etc.

The most obvious circulation within the Sun is the differential rotation of the visible surface, in which the equator rotates nearly 50% faster than the poles. This nonuniform rotation cannot be an artifact of the formation of the Sun, some 5×10^9 yr ago, for the eddy viscosity of the convective zone would long since have destroyed any initial nonuniform rotation. The present nonuniform rotation is an integral part of the present convection and circulation within the Sun, maintained today by the contemporary thermal gradients and heat fluxes.

The theory of convection, circulation, and nonuniform rotation is fundamental to the understanding of solar activity. Unfortunately, the enormous density variation across the convective zone, from 2×10^{-1} gm cm^{-3} at the bottom (at a depth of 2×10^5 km) to 5×10^{-7} gm cm^{-3} at the top, makes the theoretical treatment of the problem exceedingly difficult. What is difficult but possible in the Boussinesq approximation (uniform density) becomes a formidable task in the real stratified convective zone of the Sun. Some of the review speakers in this symposium will go into the problem in detail. I want to emphasize that the convection and circulation problem is fundamental to our understanding of any, and all, solar activity.

Let me begin, then, with the statement that we now know so much about the Sun that nearly every aspect of the Sun presents a dilemma. There is no other star about which we know enough to be so puzzled.

The most fundamental dilemma with the Sun is the failure to detect the expected neutrinos from the core (Davis and Evans, 1973). That problem, although not obviously central in questions of solar activity, is nonetheless so fundamental that we cannot ignore it. The neutrino dilemma involves the theory of weak interactions, opacity, radiative transfer, circulation and convection and, indeed, the whole

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physical basis for the theory of stellar structure (Bahcall *et al.*, 1973; Ulrich, 1974). We must not forget that our understanding of the convective zone – particularly its depth – is based in large measure on models of the solar interior. What would be the implications for solar activity if the Sun were convective all the way to its center? The explanation of the dilemma may, or may not, prove to be superficial, so far as the Sun is concerned. For instance, the luminosity of the Sun may vary by 5% over 10^4–10^6 yr (Fowler, 1972, 1973). Or it may be only that neutrinos are unstable (i.e., have nonvanishing rest mass) decaying before reaching Earth. This would have tremendous impact on the physics of elementary particles, but might well affect the theory of the solar interior very little. Or there may be some exotic effect that reduces opacity slightly, such as an absence of metals in the core of the Sun, or a convective core. But until the neutrino question is resolved, we cannot be sure of our knowledge of the interior structure of the Sun, and hence cannot be sure that we understand the convective origin of solar activity.

There are some curious questions of climatology that suggest that our knowledge of the solar interior, and the general evolution of a star on the main sequence, is less than complete. For instance, the conventional theory of evolution of the solar interior predicts that 10^9 yr ago the Sun was some 10% less luminous than we find it today; 4×10^9 yr ago it was 30% less luminous. Now the most sophisticated numerical atmospheric models of Earth predict that if the Sun were 6% less luminous, the surface of Earth would freeze over completely, increasing the albedo and further reducing the heating effect of the Sun, etc. But paleoclimatological studies are emphatic in the conclusion that Earth was not cooler 10^9 yr ago. Indeed, the indications are that it was, if anything, a few degrees warmer. Clearly we must keep an open mind when confronted with this problem. We know so little of the Sun and terrestrial climatology that the resolution could lie anywhere, and perhaps everywhere. But clearly something is out of line.

The historical sunspot record shows another gap in our understanding of the convective zone. Sunspots were first discovered and studied in the western world in 1610 with Galileo's application of the telescope to astronomy. Sunspots were considered at the time to be of no intrinsic interest in themselves (after the first trauma of their appearing as a blemish on the face of the 'perfect' sphere of the Sun) and so were not studied systematically. But there were enough records kept to show that the number of sunspots went through two distinct maxima after 1611, and then fell to a minimum at about 1645. The records go on to show that the Sun remained in a state of extreme minimum activity for about 70 yr thereafter, until approximately 1715, after which time activity resumed in the form of the familiar 11-yr cycle that we know so well today (Maunder, 1894, 1922). During the 70 yr of inactivity there was occasionally a sunspot or two, but long years with none at all; there was no white light corona visible during total eclipse by the Moon, whereas the corona is usually so conspicuous then; there were only a few significant auroral events, which are normally so common in clear skies over Scandinavia and Northern England. In view of the absence of a white light corona, we may conjecture whether the Sun was entirely shrouded in a coronal hole, yielding a fast, steady solar wind, or whether there was simply no solar wind at all. I would guess the former, but I know of no way to prove the answer.

The occurrence of the 70 yr minimum (sometimes called the Maunder minimum), indicates that there is available to the Sun a convective mode of circulation different from its present state. The other mode – let us call it the Maunder mode – is such as to be less effective in the generation of magnetic field. Evidently the Sun can flip-flop back and forth between the Maunder mode and the present mode. Since 1610, some 365 yr ago, the Sun has spent 70 yr in the Maunder mode and about 300 yr in the present mode. On this basis I am tempted to call the present mode the 'normal' mode, but we must be careful not to allow so preliminary an appellation to color our thinking about the physics of the convection. The point is that future theoretical studies of the convection and circulation in the Sun must look not merely for one mode, but for two or more modes, perhaps of distinctly different form.

2. Solar Convection, Circulation and the Dynamo

There are a number of questions that arise concerning the convective zone of the Sun. Present theoretical models of the Sun place the bottom of the convective zone at a depth of about 2×10^5 km (Spruit, 1974), where $\rho\cong0.2$ gm cm^{-3} and $T\cong 2\times10^6$ K. The more rapid rotation of the equatorial surface of the Sun has been explained as a consequence of meridional circulation within the convective zone (Kippenhahn, 1963; Weiss, 1965; Cocke, 1967; Durney, 1968, 1970, 1971, 1972; Osaki, 1970; Busse, 1970; Kohler, 1970; Durney and Roxburgh, 1970; Yoshimura and Kato, 1971; Yoshimura, 1972; Gilman, 1972, 1974; Gierasch, 1974). Unfortunately, the calculations indicate that the meridional circulation must be so strong that a pole-equator difference $\delta\omega/\omega$ in angular velocity is accompanied by a pole-equator energy flux difference $\delta F/F\sim\delta\omega/\omega$ i.e., at least 10%. No such flux difference is observed. Indeed, the recent measurements of Dicke and Goldenberg (1974; Dicke, 1974) indicate that the brightness of the solar disk is circular to within a fraction $\delta R/R\leq4.5\times10^{-5}$. Thus if the brightness W varies with radius r as $W(r)$ out the limb at $r=R$, we have

$$\begin{aligned}\frac{\delta W}{W}&=\frac{1}{W}\frac{\mathrm{d}W}{\mathrm{d}r}\delta R\\&<4.5\times10^{-5}\frac{R}{W}\frac{\mathrm{d}W}{\mathrm{d}r}.\end{aligned}$$

But (Minnaert, 1953)

$$\frac{R}{W}\frac{\mathrm{d}W}{\mathrm{d}r}\sim20$$

near the limb of the Sun, so that, very roughly, $\delta F/F\cong\delta W/W<10^{-3}$.

The brightness at the pole and equator is the same to within one part in 10^3! What then of the meridional circulation and equatorial acceleration? We should note that the calculations to date are based on the Boussinesq approximation, ignoring the enormous density variation across the convective zone. Convection in a stratified layer is *very difficult* to treat mathematically, and progress is only just beginning to be made. But we must have *qualitative* differences to extricate us from the dilemma.

Mere quantitative corrections can hardly be expected to make up the factor of 10^2 in the discrepancy.

There are other difficulties. The hydrodynamic models for the circulation and differential rotation predict that the angular velocity ω at low latitudes declines inward from the surface ($d\omega/dr > 0$) toward the reduced values observed at the surface at high latitudes. There is no direct observational objection to this result. Indeed, it gives the simplest internal variation of ω consistent with the motion of the surface. But there is a severe problem in understanding the generation of the magnetic fields of the Sun. The azimuthal fields beneath the surface of the Sun, whose rise to the surface produces the bipolar magnetic regions, are estimated to be of the order of 10^2 G and are believed to be generated by the combined dynamo effects of the nonuniform rotation and the cyclonic rotation of the rising and falling convective cells (Parker, 1955b, 1970a, b, 1971, 1972, 1975; Steenbeck, Krause and Radler, 1966; Steenbeck and Krause, 1969; Leighton, 1969, Gilman, 1969; Deinzer and Stix, 1971; Deinzer, Kusserow and Stix, 1974; Stix, 1974; Yoshimura, 1972b, 1973).

It is an observed fact that the fields appear first at middle latitudes and then migrate toward the equator. According to the dynamo equations, this requires that the product of $d\omega/dr$ and the helicity $\langle \mathbf{v} \cdot \text{curl}\, \mathbf{v} \rangle$ of the convective motions be positive. But in the northern hemisphere of the Sun a rising convective cell is expanding laterally. We would expect the coriolis forces to cause it to rotate more slowly than its surroundings (Steenbeck, Krause, and Radler, 1966) so that $\langle \mathbf{v} \cdot \text{curl}\, \mathbf{v} \rangle$ is negative. If, then, $d\omega/dr$ is positive, the product has the wrong sign and we would expect the fields to migrate away, rather than toward, the equator (Parker, 1972). We are plagued again with a *qualitative* difficulty.

But there are still more problems. One is the magnetic buoyancy of the fields. A magnetic field is buoyant because the magnetic field exerts pressure and expands, reducing the density of the gas within it (Parker, 1955a). A magnetic flux tube of field density B has a pressure $B^2/8\pi$, which causes a pressure reduction $\Delta p = B^2/8\pi$ in the gas inside the tube. The density reduction is $\Delta\rho/\rho = \Delta p/p = B^2/8\pi p$. There is, then, a buoyancy force $g\Delta\rho = B^2/8\pi\Lambda$ dyne cm^{-3} where $\Lambda \equiv kT/Mg$ is the pressure scale-height of the atmosphere. If the flux tube has a circular cross section of radius a, then the force per unit length is $B^2a^2/8\Lambda$, causing the tube to rise rapidly through the convective zone. The velocity v of rise of a horizontal flux tube is restrained by the aerodynamic drag $C\rho v^2 a$, where the coefficient C is of the order of unity. Hence the terminal speed of rise is $V_A(\pi/2C)^{1/2}(R/\Lambda)^{1/2}$, i.e., of the order of the Alfvén speed. The Alfvén speed computed in 10^2 G at the base of the convective zone is about 60 cm s^{-1}, rising 10^5 km in 5 yr. Higher in the convective zone the rate of rise is faster and the field is lost in periods much less than 5 yr. The characteristic time in which the azimuthal field is generated from the poloidal (meridional) field by $d\omega/dr$ is typically 5 yr. Hence the only place that the magnetic field can possibly remain long enough to be regenerated is near the bottom of the convective zone. The solar dynamo does not extend below the convection, and its possible overshoot, if for no other reason than the absence of turbulent diffusion.

Altogether, then, it appears that, if the solar dynamo is to function at all, it must be in the lowest level of the convective zone (Parker, 1975b). According to Spruit's (1974) model of the convective zone, this would be at a depth of 1.5–2×10^5 km.

Higher up in the convective zone the magnetic flux tubes are merely rising to the surface with little time for regeneration. We see the activity at the surface caused by the continual arrival of tubes of magnetic flux from below.

What then, is the resolution of these many problems and contradictions? How must our ideas be modified to make sense of the rotation, convection, and dynamo effects in the Sun? Is it possible, for instance, that the circulation was in another mode, perhaps with a 5–10% pole-equator brightness difference from 1645 to 1715? Could it have been noticed by the sharp eyes of the 17th-century astronomer looking at an image of the Sun projected from the eyepiece of his telescope onto a screen? Perhaps in a few more years when adequate codes are available to explore the properties of convection in a rotating, deeply stratified, convecting atmosphere it will be possible to explore this question (see review by Gilman, these Proceedings). The general point that I want to make here is that we must search over a wide range of possibilities if we are ever to develop an understanding of what was happening at the Sun during the Maunder minimum

Turning to more concrete ideas, Durney (1975) (see review, these Proceedings) suggests that there may perhaps be a simple resolution of the whole puzzle. His first point is that there appear to be solutions of the hydrodynamic equations in a stratified rotating sphere in which the equatorial surface rotates more rapidly than the rest, but which exhibits no pole-equator difference in convected energy flux. The solutions are of the nature of rotation in cylinders, with ω a function only of the distance $\tilde{\omega}$ from the axis of rotation. If correct, this resolves the question of $\delta\omega/\omega$ without $\delta F/F$. Durney goes on to point out that the work of Yoshimura (1975) suggests that the direction of rotation of the cyclonic motions in the *lowest* level of the convective zone is ***reversed*** from the conventional considerations on local Coriolis force. If this is correct, then the product of $\mathrm{d}\omega/\mathrm{d}r$ and the helicity is positive in the lower convective zone where we now think the dynamo functions, and the migration of sunspots toward the equator follows from the dynamo equations. Thus, the annoying restriction of dynamo activity to the lowest levels of the convective zone, together with the resolution of the equatorial acceleration problem, appears to resolve the dynamo dilemma with the migration of solar fields toward, rather than away from, the equator. Durney's synthesis points the way for the development of a complete, deductive, self consistent theory.

3. Sunspots and Intense Flux Tubes

The activity that we see at the Sun is caused by the continual emergence of magnetic fields through the surface of the Sun. The fields come up through the surface in complicated forms, contorted by the fluid motions in the convective zone from which they spring. It can be shown that the topology of most field configurations admits of no hydrostatic equilibrium, there being instead rapid reconnection and dissipation (Parker, 1972). It is the dissipation of these nonequilibrium fields, sometimes by explosive reconnection, that produces the boisterous activity where the fields are freed at the photosphere. One of the most remarkable properties of the magnetic field at the photosphere is the tendency to compress itself into extremely dense flux tubes, with little or no field in the regions between tubes.

When we remember that the stresses in a magnetic field consist of a tension $B^2/4\pi$ along the lines of force, and an isotropic pressure $B^2/8\pi$, we expect the magnetic field to behave much like a gas, expanding to fill all the available space.

What is it on the Sun, then, that causes the fields to contract into isolated bundles? The effect is remarkable and merits serious attention.

The sunspot is the most conspicuous example of the self-confinement of the magnetic field, producing fields of 1500 G in pores, to 3000–4500 G in the fully developed spot. One of the most startling developments in solar physics has been the growing realization over the past decade that even the general 1–2 G magnetic field of the Sun in quiet regions is almost entirely composed of flux tubes of 2000 G, or more, compressed into tubes of 400 km diameter. This conclusion is not a direct observation, of course. It is a sophisticated inference drawn from the theoretical interpretation of a number of independent observational studies of the Zeeman broadening of various spectral lines in both weak and strong fields (Sheeley, 1967; Livingston and Harvey, 1969, 1971; Sawyer, 1971; Simon and Noyes, 1971; Howard and Stenflo, 1972; Frazier and Stenflo, 1972; Chapman, 1973; Stenflo, 1975). But the conclusion now appears to be inescapable. I am sure that we will hear more about it in this meeting.

Why, or how, can a magnetic field gather itself into a dense bundle, in opposition to its own enormous pressure? The pressure of a 3000 G field is a little more than the gas pressure at the surface of the Sun, where the number density N is 2×10^{17} cm^{-3} and $T=6\times10^3$ K.

The sunspot provides what appears to be the basic clue. The sunspot is cool, some 3900 K at the surface within the magnetic field. The reduced temperature means a reduced scale height, presumably over a depth of several scale heights, so that the gas within the field drops down out of the magnetic field, and the field is compressed into its dense form by the surrounding gas (Parker, 1955a; Schlüter and Temesvary, 1958). In this way we can understand an equilibrium configuration in which the total pressure, composed of the magnetic pressure of the vertical magnetic field $B(x, y)$ and the gas pressure $p(x, y)$ is uniform across the photosphere $p(x, y)+B^2(x, y)/8\pi=$ *constant* (ignoring the tension and the curvature of the lines of force).

But what makes the gas cool? It has been suggested (Biermann, 1941) that the magnetic field inhibits the convective transport of heat in the sunspot. That is to say, the region of intense field is a thermal insulator. The result is clearly a reduction of temperature at the surface. Unfortunately it is not always appreciated that it also means an enhanced temperature *under* the insulator. When we put on a coat, we become warm underneath, rather than cool. I have examined a number of models of reduced heat transport and have been unable to construct one in which the cooling is of such form as to cause the field to concentrate. The enhanced temperature beneath the region of concentrated field *increases* the gas pressure extending up along the field and *disperses* the field. A deep inverted cone of reduced heat transport seems to come closest to solving the problem, because the heat flow is easily diverted around to the sides. Perhaps someone with deeper insight can construct a situation where reduced heat transport is able to concentrate the field. This has not been done so far, and it appears to me that either it must be done soon or we are forced to the view that some other effect is largely responsible for the cooling. The only available idea is overstability, with vigorous production of Alfvén waves in the upper $1\text{–}2\times10^3$ km of the convective zone immediately below the photosphere. The thermal convective forces act as a heat engine converting a major function of the heat flow into Alfvén waves and actively refrigerating the gas in the field. The overstability was pursued originally by Danielson (1965), Musman (1967), and Savage (1969) as an explanation for the missing flux from a sunspot produced by the inhibition of convective heat transport. We have used their calculations (Parker, 1974, 1975a) as a basis for arguing that the production of Alfvén waves is the *principal cause* of the sunspot. The spot is cool because the energy flux is converted from heat into mobile waves, so that the heat transport is *enhanced* rather than inhibited. The Alfvén waves carry the energy (some 5×10^{10} erg cm^{-2} s^{-1}) out of the region both upward and downward along the magnetic lines of force. The waves are dissipated elsewhere around, and in, the Sun. One fundamental question in the theory of the sunspot, then, is the reality of the Alfvén waves presumed to be responsible for the cooling. If they exist, then the cooling and intense magnetic field can be understood (see, for instance, the recent observations of Phillis, 1975; Beckers, 1975). If they do not exist, then we must find another explanation and *demonstrate* it.

There is another fundamental question, however, to which we must address ourselves. Until it is answered, understanding of the sunspot cannot be complete. It is not enough to establish the existence of a theoretical equilibrium configuration to understand the sunspot. We must also show how the configuration can be assembled from the gas and field in the first place, and why it is stable once assembled. These two points are probably closely related; if we knew the answer to one, we would probably be able to construct the answer to the other. The difficulty is that a magnetic field constricted by gas pressure to a small throat (the umbra of the sunspot) is unstable to the hydromagnetic exchange instability (fluting instability). The magnetic lines of force are concave toward the gas, so that the tension along the lines of force tends to pull individual flux tubes out of the larger tube as sketched in Figure 1. The characteristic time for the instability is the Alfvén transit time across the tube, of the order of an hour. The effect is well known in the plasma laboratory where one tries to confine a gas by wrapping a field around it. We must not confuse the equilibrium and the instability. The magnetic field is compressed by the reduced pressure of the cool sunken gas level within the field. The reduced gravitational potential energy of the depressed area of cool gas within the field compensates for the increased energy of the magnetic field, and the gas confines a magnetic flux tube of *circular* cross section in a state of *hydrostatic equilibrium.* However, if the circular cross section is perturbed, the balance is upset by the tension along the magnetic lines of force. The field is free to break up into a number of individual tubes which separate from each other and shorten, thereby reducing their energy. We would expect that a sunspot in the course of an hour or so should split across and break into many small spots, each carrying its cool depressed umbra with it, and each breaking into smaller tubes, quickly obliterating the intense fields. When a sunspot is young, the opposite happens. The individual magnetic knots stream into the spot and add to its field (Beckers and Shröter, 1969). When the spot is old, it breaks up into small pieces, but

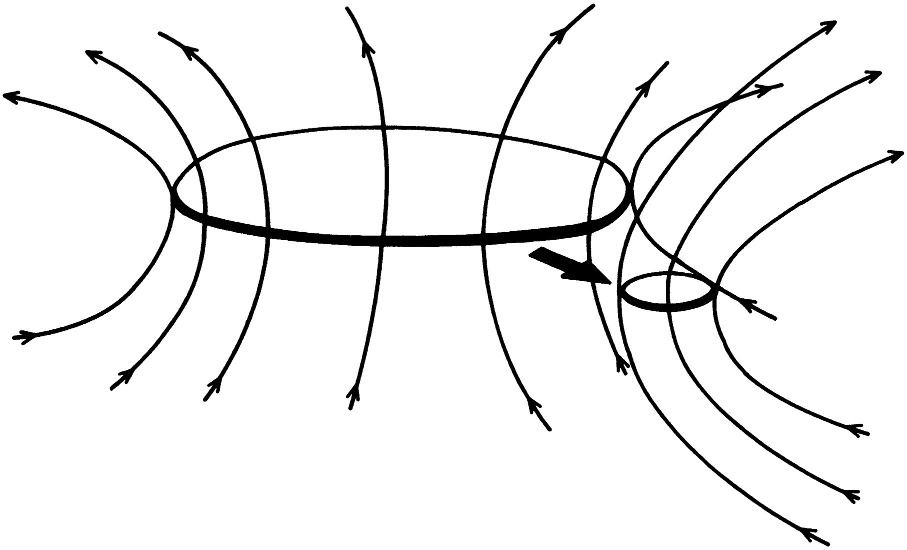

Fig. 1. A sketch of the magnetic field through a sunspot, illustrating the tendency for the tension along the magnetic lines of force to pull tubes of flux out the side of the sunspot.

even this final disintegration takes days instead of hours. The mechanism for stabilizing the spots observed on the Sun has not been demonstrated, so the sunspot is an enigma.

Recently Meyer *et al.* (1974) have proposed that a swift (0.5 km s^{-1}) converging, horizontal flow, and associated downdraft, at depths of $1\text{–}2\times 10^4$ km where $\rho \cong 2\times 10^{-4}$ gm cm^{-3}) play a fundamental role in assembling the magnetic field into the concentrate sunspot. They suggest that the otherwise inexplicable 'attraction' of magnetic knots toward each other and toward the sunspot is one of the direct consequences of the converging flow. Certainly some such drastic assumption is needed to account for the behavior of the spot. They also suggest that in some way the geometry of the depressed umbra is such as to aid in stabilization of the sunspot once it is formed.

It is difficult to think of alternatives to their suggestions (Parker, 1975a). Unfortunately any such hypothesis of subsurface dynamical effects can be established only by theoretical calculation, and that is a difficult task in the unstable stratified convective zone of the Sun.

Now consider the isolated flux tubes of 2000 G that make up the general field of the Sun. They appear in the supergranule boundaries. Their magnetic pressure is comparable to the gas pressure in the photosphere, and very much in excess of the dynamical pressure of any of the fluid motions observed at the surface. For instance the 0.5 km s^{-1} of the supergranule in the surface density of $\rho = 3\times 10^{-7}$ gm cm^{-3}; corresponding to a dynamical pressure of $p = 0.7\times 10^3$ dyne cm^{-2}, is equivalent to the pressure $B^2/8\pi$ of a field of about 10^2 G. Granule motions of 3 km/sec correspond only to 700 G. How, then, are we to understand such intense concentration of magnetic field?

I have spent a long period of time exploring the many ‘beautiful’ ideas for producing intense magnetic fields (Parker, 1976). Some have suggested that the flux tubes are self-confined force-free magnetic fields. Unfortunately, there is no such thing. Magnetic fields expand. They do not confine themselves. In each case I have been obliged to abandon the ‘beautiful’ idea as inadequate, for one reason or another, except the possibility that the small flux tubes (of 400 km diameter and 3×10^{13} Mx) are cooled and concentrated in much the same manner as sunspots. Roberts (1976) has shown that the overstability is just as strong in a slender flux tube as in a broad one, so the same basic idea as the sunspot appears to be tenable. But, of course, the same questions of initial assembly and long term stability arise too.

Presumably no cool spot in the small flux tubes is visible at the surface because the cooling need not be as severe as in the sunspot, and because the active cooling does not extend above the top of the active convective zone, terminating several hundred km beneath the visible surface of the photosphere. The surrounding photosphere closes in over the small 200 km radius of the flux tube, partially obliterating the coolness. A temperature reduction of 500–800 K over a diameter of 400 km at the surface would not be conspicuous in the general granule pattern of 500 K temperature variation. It would be interesting to see what a careful search might turn up, because we need an explanation for the general occurrence of intense isolated flux tubes in the solar photosphere. If active cooling by the overstable production of Alfvén waves is *not* the correct explanation, then we need to discover what is. And even if cooling is the answer for their compressed equilibrium, what provides the necessary stability of that equilibrium?

4. Flares, X-rays, and Eruptions

The solar flare has for decades occupied a prominent position in the thoughts of both observers and theoreticians. It is generally agreed – through the absence of alternatives – that the flare is caused by the annihilation of magnetic field, presumably the Dungey-Sweet-Petschek mechanism of rapid reconnection of opposite fields. The theory of rapid reconnection has been carried forward in the past few years (Dungey, 1955; Sweet, 1958; Parker, 1963, 1973a; Petschek, 1964; Green and Sweet, 1967; Petschek and Thorne, 1967; Sonnerup, 1970, 1971; Yeh and Axford, 1970; Priest, 1972a, b, 1973; Fukao and Tsuda, 1974a, b; Vasyliunas, 1975) to the point that it has now been demonstrated that there are circumstances under which opposite fields can reconnect and merge at a significant fraction of the Alfvén speed (computed in the opposite fields). It is not entirely clear just what external boundary conditions yield the highest reconnection rates, but speeds of the order of $0.1\,V_A$ are to be expected, and $0.5\,V_A$ can be accomplished under special circumstances. Altogether, then, the idea of magnetic merging as the cause of the solar flare is not without a substantial theoretical foundation. However, it is not clear to me that there is anything that can be called observational proof. Perhaps we will hear more on that question in this Symposium.

It is abundantly clear that flares have complicated personalities, providing endless combinations of temporal and spatial form, radio emission, X-ray emission, fast particle emission, and interplanetary blast waves. For instance, flares occurring at the prow of moving sunspots appear to produce more type III radio bursts (Zirin and Lazareff, 1975; Takakura and Yousef, 1975). The outward shock waves (observed in Hα) are closely associated with type II bursts (Harvey *et al.* 1974). Particles appear to be accelerated in two or three stages, producing X-rays after the first stage and 'cosmic rays' after the second (Kane, 1974; Rust and Hegwer, 1975; Tanaka and Enome, 1975). At least half of the energy release of the flare is in the form of fast particles. Theory does not provide any ready explanation for such complete conversion of magnetic energy into accelerated particles. There are a variety of ideas on particle acceleration in solar flares, beginning with the Fermi mechanism (Fermi, 1949, 1954; Parker, 1958) over twenty-five years ago, acceleration in plasma turbulence (Kadomtsev and Tsytovich, 1969; Tsytovich, 1973) and acceleration in neutral sheets (Speiser, 1965, 1967; Coppi and Friedland, 1971; Low, 1975). All of these ideas have merit and may contribute, but in no case, of which we are aware, has it been possible to demonstrate that more than a tiny fraction of the energy release goes into fast – often relativistic – electrons and protons. It is clear that there is much work yet to be done in the theory of particle acceleration that is so central to the outbursts of solar activity.

The discovery by Skylab of repeated eruptions from the Sun into interplanetary space, in the absence of visible flaring on the surface, adds a new dimension to the quandary. The X-ray bright spots, associated with the tiny bipolar magnetic regions – the pepper and salt effect in magnetograms – are another curiosity (Krieger *et al.*, 1971; Vaiana, Krieger, and Timothy, 1973; Harvey and Martin, 1973; Golub *et al.*, 1974; Harvey *et al.*, 1975; Parker, 1975c) behaving much like little bipolar sunspot groups, including miniature flares.

5. General Comments

Altogether, I am awed and challenged by the tricks displayed by the Sun. The Solar magician is clever indeed. Sunspots have been studied, and thought about, for the better part of a century, and I cannot tell you that I understand much of their behavior in terms of physics. The flare is a turbulent phenomenon, which, therefore, may never be reduced to quantitative theoretical understanding. But I think we can understand more about the magnetic activity of the Sun than at present if we put serious effort into recognizing and distinguishing the fundamental problems. We must develop the habit of recognizing what is not understood, and what promises, therefore, to teach us new physics. Unfortunately, the literature is full of folklore on the various aspects of the activity of the Sun. There is no phenomenon that does not have an 'explanation', and a retinue of followers of that explanation.

Perhaps the most illusive aspect of all in the great riddle of solar activity is the seeming relation between activity on the Sun and unusual environmental conditions at the surface of Earth (Willett, 1965; Bray, 1968; Wilcox, 1968; Woodbridge, 1971; Shapiro, 1972; Hines, 1973; Roberts and Olsen, 1973a, b; Bandeen and Maran, 1974). It is noteworthy that the annual tree rings were unusually uniform during the Maunder minimum (Douglass, 1919; Maunder, 1922) while the Baltic sea froze over in the winter, something that has not happened at any other time within historical memory. No physical connection has yet been established, leaving one with the uneasy feeling that much of it may be coincidence. But to explain all as coincidence appears to be even more difficult than hunting for missing physical connections. It is a complicated subject to approach, but its fundamental importance to our lives, as well as our scientific knowledge, requires that the subject be pursued until it can be discarded with confidence, or established and understood. Success will involve the cooperation of individuals working in the physics of the Sun, interplanetary space, and the terrestrial magnetosphere, ionosphere, and atmosphere, as well as the geophysicist and biologist studying conditions at ground level.

Altogether the fundamental problems that confront us are (a) the convection and circulation in the ionization zone of the Sun, (b) the generation of magnetic fields, (c) the properties of the merging fields, forming active regions, (d) the frequent solar eruptions, (e) the coronal hole and the high speed wind, and the suppression of the coronal hole by magnetic fields, and finally (f) the complicated climatological effects of the solar luminosity and solar activity. Together these problems make solar physics the most exciting and challenging field of astrophysics. Unlike the other subjects in astrophysics we have learned enough to get our teeth into the physics of the Sun. The basic theoretical problems are difficult but not impossible. We have a good idea of the crucial observations that have yet to be carried out, from coordinated high resolution X-ray, XUV, visible, Doppler, and magnetograph studies of flares and active regions, to global studies of the circulation at the visible surface, global studies of the corona and solar wind from the equator to the poles, to accurate (1 part in 10^3) absolute synoptic measurement of the solar luminosity. The necessary instrumentation and technology is presently tractable. Spacecraft observations and very high resolution ground based observations are essential, with careful coordination between them on many occasions. If there ever was an urgent program that needs worldwide cooperation for its solution it is the present problem of understanding the Sun. It is in recognition of this state of urgency and complexity that we are all here in Prague. I look forward very much to the next few days to hear how the various aspects of the problem are being developed in so many places around the world.

References

Bahcall, J. N., Heubner, W. F., Magee, N. H., Merts, A. L., and Ulrich, R. K.: 1973, *Astrophys. J.* **184**, 1.
Bandeen, W. R. and Maran, S. P.: 1974, *Possible Relationships between Solar Activity and Meteorological Phenomena, NASA Symposium,* Goddard Space Flight Center (X-901-74-156).
Beckers, J. M.: 1975, *Astrophys. J.* (in press).
Beckers, J. M. and Schröter, E. H.: 1969, *Solar Phys.* **4**, 192, 303.
Biermann, L.: 1941, *Vierteljahrsschr. Astron. Gessellsch.* **76**, 194.
Bray, J. R.: 1968, *Nature* **220**, 672.
Busse, F. H.: 1970, *Astrophys. J.* **159**, 629.
Chapman, G. A.: 1973, *Astrophys. J.* **191**, 255.
Cocke, W. J.: 1967, *Astrophys. J.* **150**, 1041.
Coppi, B. and Friedland, A. B.: 1971, *Astrophys. J.* **169**, 379.
Danielson, R. E.: 1965, *IAU Symp.* **22**, 315; *Handbuch der Physik,* **52**, 151.
Davis, R. and Evans, J. M.: 1973, *Proc.* 13*th Int. Cosmic Ray Conf.*, Denver, Colorado.
Deinzer, W., Kusserow, H. U. V. and Stix, M.: 1974, *Astron. Astrophys.* **36**, 69.

Deinzer, W. and Stix, M.: 1971, *Astron. Astrophys.* **12**, 111.
Dicke, R. H.: 1974, *Astrophys. J.* **190**, 187.
Dicke, R. H. and Goldenberg, H. M.: 1974, *Astrophys. J. Suppl.* No. 241.
Douglass, A. E.: 1919, 'Climatic Cycles and Tree Growth', Carnegie Institution.
Dungey, J. W.: 1953, *Phil. Mag.* **44**, 725.
Durney, B.: 1968, *J. Atmos. Sci.* **25**, 372.
Durney, B.: 1970, *Astrophys. J.* **161**, 1115.
Durney, B.: 1971, *Astrophys. J.* **163**, 353.
Durney, B.: 1972, *Solar Phys.* **26**, 3.
Durney, B.: 1975, *Astrophys. J.* (in press).
Durney, B. R. and Roxburgh, I. W.: 1971, *Solar Phys.* **16**, 3.
Fermi, E.: 1949, *Phys. Rev.* **75**, 1169.
Fermi, E.: 1954, *Astrophys. J.* **119**, 1.
Fowler, W. A.: 1972, *Nature* **238**, 24; 1973, *Nature* **242**, 424.
Frazier, E. N. and Stenflo, J. O.: 1972, *Solar Phys.* **27**, 330.
Fukao, S. and Tsuda, T.: 1973a, *Planetary Space Sci.* **21**, 1151.
Fukao, S. and Tsuda, T.: 1973b, *J. Plasma Phys.* **9**, 409.
Gierasch, P. J.: 1974, *Astrophys. J.* **190**, 199.
Gilman, P. A.: 1969, *Solar Phys.* **8**, 316; **9**, 3.
Gilman, P. A.: 1972, *Solar Phys.* **27**, 3.
Gilman, P. A.: 1974, *Ann. Rev. Astron. Astrophys.* **12**, 47.
Golub, L., Krieger, A. S., Silk, J. K., Timothy, A. F., and Vaiana, G. S.: 1974, *Astrophys. J. Letters* **189**, L93.
Green, R. M. and Sweet, P. A.: 1967, *Astrophys. J.* **147**, 1153.
Harvey, K. L., Harvey, J. W., and Martin, S. F.: 1975, *Solar Phys.* **40**, 87.
Harvey, K. L. and Martin, S. F.: 1973, *Solar Phys.* **32**, 389.
Harvey, K. L., Martin, S. F., and Riddle, A. C.: 1974, *Solar Phys.* **36**, 151.
Hines, C. O.: 1973, *J. Atmospheric Sci.* **30**, 739.
Howard, R. and Stenflo, J. O.: 1972, *Solar Phys.* **22**, 402.
Kadomtsev. B. B. and Tsytovich, V. N.: 1969, *IAU Symp.* **39**, 108.
Kane, S. R.: 1974, 'Coronal Disturbances', *IAU Symp.* **57** (Dordrecht: D. Reidel), ed. by G. Newkirk, p. 105.
Kippenhahn, R.: 1963, *Astrophys. J.* **137**, 664.
Kohler, H.: 1970, *Solar Phys.* **13**, 3.
Krieger, A. S., Vaiana, G. S., and van Speybroeck, L. P.: 1971, *IAU Symp.* **43**, 397.
Leighton, R. B.: 1969, *Astrophys. J.* **156**, 1.
Livingston, W. and Harvey, J.: 1969, *Solar Phys.* **10**, 294.
Livingston, W. and Harvey, J.: 1971, *IAU Symp.* **43**, 51.
Low, B. C.: 1974, *Astrophys. J.* **189**, 353.
Maunder, E. W.: 1894, *J. British Astron. Assoc.* **5**, 47.
Maunder, E. W.: 1922, *J. British Astron. Assoc.* **32**, 140, 223.
Meyer, F., Schmidt, H. U., Weiss, N. O., and Wilson, P. R.: 1974, *Monthly Notices Roy. Astron. Soc.* **169**, 35.
Minnaert, M.: 1953, in G. P. Kniper (ed.), *The Sun*, University of Chicago Press, Chicago, Chap. 3, p. 100.
Musman, S.: 1967, *Astrophys. J.* **149**, 201.
Osaki, Y.: 1970, *Monthly Notices Roy. Astron. Soc.* **131**, 407.
Parker, E. N.: 1955a, *Astrophys. J.* **121**, 491.
Parker, E. N.: 1955b, *Astrophys. J.* **122**, 293.
Parker, E. N.: 1958, *Phys. Rev.* **109**, 1328.
Parker, E. N.: 1963, *Astrophys. J. Suppl.* **8**, 177.
Parker, E. N.: 1970a, *Astrophys. J. Suppl.* **160**, 383; **162**, 665.
Parker, E. N., 1970b, *Ann. Rev. Astron. Astrophys.* **8**, 1.
Parker, E. N.: 1971, *Astrophys. J.* **164**, 491.
Parker, E. N.: 1972, *Astrophys, J.* **176**, 213.
Parker, E. N.: 1973a, *Astrophys. J.* **180**, 247.
Parker, E. N.: 1973b, *J. Plasma Phys.* **9**, 49.
Parker, E. N.: 1974, *Solar Phys.* **36**, 249; **37**, 127.
Parker, E. N.: 1975a, *Solar Phys.* **40**, 275; 291.
Parker, E. N.: 1975b, *Astrophys. J.* **198**, 205.
Parker, E. N.: 1975c, *Astrophys. J.* **201**, 494.
Parker, E. N.: 1976, *Astrophys. J.* **204**, 259.

Petschek, H. E.: 1964, *Physics of Solar Flares*, AAS-NASA Symposium (NASA, SP-50), p. 425.
Petschek, H. E. and Thorne, R. M.: 1967, *Astrophys. J.* **147**, 1157.
Phillis, G. L.: 1975, *Solar Phys.* **41**, 71.
Priest, E. R.: 1971a, *Quart. J. Mech. Appl. Math.* **25**, 319.
Priest, E. R.: 1972b, *Monthly Notices Roy. Astron. Soc.* **159**, 389.
Priest, E. R.: 1973, *Astrophys. J.* **181**, 227.
Roberts, B.: 1976, *Astrophys. J.* **204**, 268.
Roberts, W. O. and Olson, R. H.: 1973a, *Rev. Geophys. Space Phys.* **11**, 731.
Roberts, W. O. and Olson, R. H.: 1973b, *J. Atmospheric Sci.* **30**, 135.
Rust, D. M. and Hegwer, F.: 1975, *Solar Phys.* **40**, 141.
Savage, B. D.: 1969, *Astrophys. J.* **156**, 707.
Sawyer, C.: 1971, *IAU Symp.* **43**, 316.
Schluter, A. and Temesvary, St.: 1958, *IAU Symp.* **6**, 263.
Shapiro, R.: 1972, *J. Atmospheric Sci.* **29**, 1213.
Sheeley, N. R.: 1967, *Solar Phys.* **1**, 171.
Simon, G. W. and Noyers, R. W.: 1971, *IAU Symp.* **43**, 663.
Sonnerup, B. U. O.: 1970, *J. Plasma Phys.* **4**, 161.
Sonnerup, B. U. O.: 1971, *J. Geophys. Res.* **76**, 8211.
Speiser, T. W.: 1965, *J. Geophys. Res.* **70**, 1717, 4219.
Speiser, T. W.: 1967, *J. Geophys. Res.* **72**, 3919.
Spruit, H. C.: 1974, *Solar Phys.* **34**, 277.
Steenbeck, M. and Krause, F.: 1969, *Astron. Nachr.* **291**, 49, 271.
Steenbeck, M., Krause, F., and Radler, K. H.: 1966, *Z. Naturforsch.* **21a**, 369.
Stenflo, J. O.: 1973, *Solar Phys.* **32**, 41.
Stix, M.: 1974, *Astron. Astrophys*, **37**, 121.
Sweet, P. A.: 1958, *Nuovo Cimento* **8**, 188.
Takakura, T. and Yousef, S.: 1975, *Solar Phys.* **40**, 421.
Tanaka, H. and Enome, S.: 1975, *Solar Phys.* **40**, 123.
Tsytovich, V. N.: 1973, *Annual Rev. Astron. Astrophys.* **11**, 363.
Ulrich, R. K.: 1974, *Astrophys. J.* **188**, 369.
Vaiana, G. S., Krieger, A. S., and Timothy, A. F.: 1973, *Solar Phys.* **32**, 81.
Vasyliunas, V. M.: 1975, *Rev. Geophys. Space Physics* **13**, 303.
Weiss, N. O.: 1965, *Observatory* **85**, 37.
Wilcox, J. M.: 1968, *Space Sci. Rev.* **8**, 258.
Willett, H. C.: 1965, *J. Atmospheric Sci.* **22**, 120.
Woodbridge, D. D.: 1971, *Planetary Space Sci.* **19**, 821.
Yeh, T. and Axford, W. I.: 1970, *J. Plasma Phys.* **4**, 207.
Yoshimura, H.: 1972a, *Solar Phys.* **22**, 20.
Yoshimura, H.: 1972b, *Astrophys. J.* **178**, 863.
Yoshimura, H.: 1973, *Solar Phys.* **33**, 131.
Yoshimura, H.: 1975, *Astrophys. J. Suppl.* **29**, 467.
Yoshimura, H. and Kato, S.: 1971, *Publ. Astron. Soc. Japan* **23**, 57.
Zirin, H. and Lazareff, B.: 1975, *Solar Phys.* **41**, 425.

DISCUSSION

Gilman: Let me comment on your second dilemma, that of the long sunspot minimum in the 17th century. Jack Eddy, Dorothy Trotter and I have been looking at the sunspot rotation rate just prior to the beginning of that period. From data collected by J. Hevelius in 1643–45, we find no strong differences in rotation rate from modern values.

Stix: You said that the long activity minimum during the 17th century might have been caused by a different mode of *convection*. Could the cause also be a different mode of the *magnetic field*, with the motion field remaining the same?

Parker: That is certainly another possibility. A slight change in the level of convection might well shift the dynamo to another mode.

Mestel: Your remark about a magnetic field's finding it hard to reach hydrostatic equilibrium: doesn't this apply primarily to convective zones with a nearly adiabatic pressure-density relation? In a sub-adiabatic, relative zone, arbitrary fields of moderate strength may be balanced by pressure and gravity, provided temperature and density vary independently. This may be the situation in the envelopes of early-type stars, and indeed in the core of the Sun. The question then arises of the stability of such fields. For dynamical stability (against adiabatic motions), one almost certainly needs a complex topology, with linked flux. Stability against the much slower modes which depend on heat exchange – of which magnetic buoyancy in a radiative zone is an example – may require an inward gradient of mean molecular weight. The question is not irrelevant to a Symposium on 'Solar Activity': magnetic flux from the solar core could be significant for surface phenomena.

Parker: Generally speaking, the magnetic fields in nature lack the perfect symmetry that is necessary for equilibrium. Any deviations from perfect symmetry permit their buoyancy to carry them upward to the surface of the Sun, or other astrophysical body. I should add that any field topology that varies along the lines of force, produces a nonequilibrium in the form of neutral point reconnection of the lines of force. It is on this general basis that I made the statement that magnetic fields have no equilibrium and so necessarily produce activity.