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THE ORIGIN OF SOLAR FLARES AND THE ACCELERATION OF CHARGED PARTICLES

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I. THE ORIGIN OF OPTICAL SOLAR FLARES

Theories concerning flares have been guided by two major considerations. First, the energy radiated by a large flare has led to postulating a supply of magnetic energy. One must then explain how the required magnetic fields are created, how they are stored in the chromosphere, and how the magnetic energy may suddenly be released at the time of a flare. This release might be in the form of a breakdown when the stored energy exceeds some critical value. Alternatively, it follows the creation of a magnetically neutral point or surface, where the field strength vanishes. The cause of a flare is then assigned essentially to a pinch effect. But even given an unstable situation, a second major consideration has been the rapidity with which the magnetic energy is converted to radiation. So far, no theory naturally explains the duration of the flare and much less the shape of the light curve.

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a) Storage of Magnetic Fields, Formation of Neutral Points

Most theories have been concerned with the very large flares and have, therefore, been based on estimates of the emitted optical energy for such flares. Both Parker (1957a) and Ellison (1963) allowed for ~~have included some factor for~~ white light and have estimated the total optical emission of very large flares to be 10^{32} ergs. This value exceeds by at least two orders of magnitude the thermal energy stored in the flare region and is, in fact, of the order of magnitude of the total heat content of the chromosphere and corona. Conceivably, the energy may arrive in the form of hydromagnetic waves or fast particles from the photosphere, as has been suggested by Piddington (1958) and Warwick (1962), respectively. But aside from some problems in details, it seems difficult to understand the lack of changes in the photosphere due to such a sudden upward surge of so much energy. Therefore, the more common belief is that magnetic energy must have been stored in and near the flare. The required field strengths depend on the assumed volume of storage and the degree to which the fields are dissipated. De Jager (1963) emphasizes the observation by Suemoto, Hiei, and Hirayama (1962) that an Hα flare must consist of a great many small threads with a total volume of only 10^{18} cm^3, and 10^{32} ergs of magnetic energy cannot be stored in this small volume. As an opposite extreme, suppose that the dissipated fields are ~~were~~ stored in a volume of area 10^{20} cm^2 and depth 10^9 cm. Then 10^{32} ergs can be obtained by a complete dissipation of 150 gauss or, more likely, by the reduction of stronger fields, such as from 500 to 475 gauss. Similar estimates have been made by Parker (1957a), Gold and Hoyle (1960), and Ellison (1963).

Few estimates have been made for smaller flares. Because of their smaller volumes, the required fields are not reduced by more than an order of magnitude. However, it is possible that the required energy can be supplied, instead, by influx either from above or below the flare.

The storage of the magnetic fields in the chromosphere presumably requires times of the order of days. During this time, the forces exerted on the chromospheric gas must be very nearly in equilibrium. This can occur only if the magnetic fields are nearly force-free, that is, if the fields $\underline{H}$ and their associated currents $\underline{j} = \text{curl}\ \underline{H}/4\pi$ are nearly parallel to each other. But force-free fields can never exist in isolation. The chromospheric fields must have their roots in the photosphere or below, where the magnetic forces can be fully exerted and where there is also plenty of energy available to actually generate the whole magnetic configuration. Two processes for generating the flare fields have been suggested.

1. Sunspots. Since flares occur near sunspots, their fields may be extensions of the strong sunspot fields. On this view, the occurrence of flares favors complex spot groups because this complexity leads very naturally to the formation of magnetically neutral points. Figure 1 shows a very simple situation in which the opposing fields between two aligned spot pairs form one neutral point (Sweet 1958a). Sweet (1958b) has shown that a more general arrangement of two spot pairs involves two neutral points which lie on the same line of force. Some other arrangements have been considered by Severnyi (1958a).

The influence of external fields in causing a flare near a neutral surface has been investigated by Severnyi (1961, 1962a, 1962b). He shows that even a relatively slow variation of sunspot fields can lead to a rapid and considerable compression of the plasma near a neutral surface, in a time which is comparable with the time of formation of flares. In this model, the energy which is dissipated in the flare is replaced at the expense of the magnetic energy of the sunspot configuration. Gopasyuk (1961, 1962) has estimated that field changes of the required magnitude are in accord with observations. An alternative cause of flares through external influence, suggested by Shabanskii (1961), are ~~is that~~ sudden changes in photospheric magnetic fields which may be propagated into the chromosphere and there initiate a flare at a neutral point.

Severnyi (1958a, 1958b, 1962b) has also investigated the breakdown of an initial equilibrium if the magnetic field strength increases until thermal pressure gradients can no longer balance the magnetic forces. The boundary conditions which should be applied to this stability problem have been the subject of some argument between Syrovatskii (1962) and Severnyi (1962a).

2. Filaments. Gold and Hoyle (1960) have emphasized the close relation between flares and chromospheric filamentary structures. They suggest that filaments are magnetic tubes of force which are anchored in the photosphere. It seems possible that such a tube is twisted by photospheric convection cells and that the twist, applied at the feet of a tube, is distributed evenly along the whole tube. The fields

within the tube are thereby strengthened and must be force-free, aside from the small twisting forces. If such twisted flux tubes can migrate, they may occasionally meet each other. If oppositely directed fields come into contact, they will form a neutral point (Fig. 2). Moreover, the motion of the tubes presses the fields toward the neutral point, so that an instability and a flare develop rapidly. The solution of the force-free field presented by Gold and Hoyle is a very special solution, but the physical picture of a chance meeting of oppositely directed fields seems very plausible, in view of the many types of chromospheric motions which have been observed. In fact, I think it must occur very frequently if one wants to explain in this manner the high frequency of small flares.

b) Dissipation Mechanisms

Let me denote the scale of the flare by L and the scale of the magnetic field by ℓ. The field scale is the smaller of the distances over which either the strength or the direction of the field change appreciably. The current density $\underline{j}$ = curl $\underline{H}/4\pi$ will be assumed to have a magnitude $H/4\pi\ell$. The electrical conductivity σ is assumed to be scalar and is evaluated for an ionized gas at an electron temperature of the order of $T = 10^4$ °K, $4\pi\sigma = 2 \times 10^{-7}$ sec cm^{-2} (emu). This value may be lowered by ambipolar diffusion, that is, by dissipation through friction between the ionized and neutral components of the gas. From the structure of the hydromagnetic differential equations one deduces that a time

$$t_{dis} = 4\pi\sigma\ell^2$$

is needed to dissipate a magnetic field. With some care one may speak of the gas and the magnetic lines of force drifting relative to each other at the rate

$$v_d = \ell \;/\; t_{dis} = (4\pi\sigma\ell)^{-1} \quad .$$

The dissipation time has frequently been identified with the rise-time of the flare, which lasts at most a few minutes. I think this is rather incorrect since it assumes that all the magnetic energy has been dissipated into heat shortly after flare maximum and that all subsequent radiation is at the expense of thermal energy. If this were true, flares would be exceedingly hot at times near flare maximum. On the contrary, electron temperatures are observed to be surprisingly constant. A more appropriate decay time may, therefore, be the total flare duration, of the order of an hour. One may then suppose that the heat generated by dissipation is radiated by the dense gas in the flare as quickly as it is produced. This point of view makes the light curve proportional to the rate of magnetic dissipation. If we now blithely set ℓ = L = 10^4 km, we obtain $t_{dis} \simeq 6 \times 10^3$ years, rather than one hour. Flares occurring at magnetically neutral points offer the possibility of greatly reducing the scale of the fields which are to be dissipated. Theories on the motions which may occur at neutral points have been restricted to two types. The first is concerned with a two-dimensional flow which is assumed to be stationary, the second treats the development with time of a one-dimensional collapse toward a neutral surface.

1. Sweet's Mechanism. Mathematically, the most relevant type of neutral point is what has been called x-type, as shown in Figure 3. Suppose that such a neutral point has somehow been formed. The singularity of the kinked lines of force at the neutral point is quickly removed by Ohmic dissipation, and the acting magnetic forces cause the gas and the embedded lines of force to move in a manner such that the lines of force become more parallel to each other. For this reason, the physical condition which has been assumed in many papers is a region in which two anti-parallel magnetic fields meet in a neutral surface, as shown in Figure 4. The magnetic pressure gradients cause the gas to approach the neutral surface until the scale of the fields at this surface is so small that dissipation may not be neglected. A stationary state may then be established in which gas and embedded magnetic field flow toward the neutral surface at such a rate that it is possible both to dissipate the field and also to squeeze the gas out of the ends of the configuration. The region where the fields are being dissipated I shall call the gap. Sweet first discussed the stationary state in 1956, using the analog of hydrodynamical flow between two rigid parallel plates which approach each other (Sweet 1958a). Subsequently, Parker (1957a) obtained some semi-quantitative hydromagnetic solutions.

A detailed investigation for compressible flow has been presented by Parker very recently (1963a). One can obtain rough estimates of the rate of collapse toward the gap from a few physical principles. For a compressible fluid, the assumption of a stationary state is permitted only if the thermal pressure of the compressed gas in the gap can balance the external magnetic pressure. Unless the temperature varies excessively, the density in the gap, n_g, must greatly exceed the external density, n_o. In turn, the high pressure in the gap causes the gas to flow out of the ends of the gap. This flow takes place at approximately the speed of sound, v_s, and is essentially parallel to the lines of force. The equations for the rate of dissipation, for momentum balance, and for the conservation of mass and of energy suffice to derive the rate of flow toward the gap, v_d, and the total dissipation time, T,

$$v_d = \frac{\ell}{t_{dis}} = \left(\frac{v_s n_g}{4\pi\sigma L n_o}\right)^{1/2} , \quad T = \frac{L}{v_d} = \left(\frac{4\pi\sigma L^3 n_o}{v_s n_g}\right)^{1/2} .$$

If we now substitute $L = 10^4$ km, $n_o = 10^{11}$ cm^{-3}, $T = 10^4$ °K, and an external magnetic pressure corresponding to $H = 150$ gauss, we obtain $n_g = 7 \times 10^{14}$ cm^{-3} and $T = 40$ hours. Parker's analysis, therefore, leads to two main conclusions. First, it is difficult to obtain a sufficiently short total dissipation time for this model of a stationary flow (even if Parker's more favorable values are used). Second, in the gap the required high gas pressures imply densities of the order of 10^{15} atoms cm^{-3}. This is rather larger than indicated by observations.

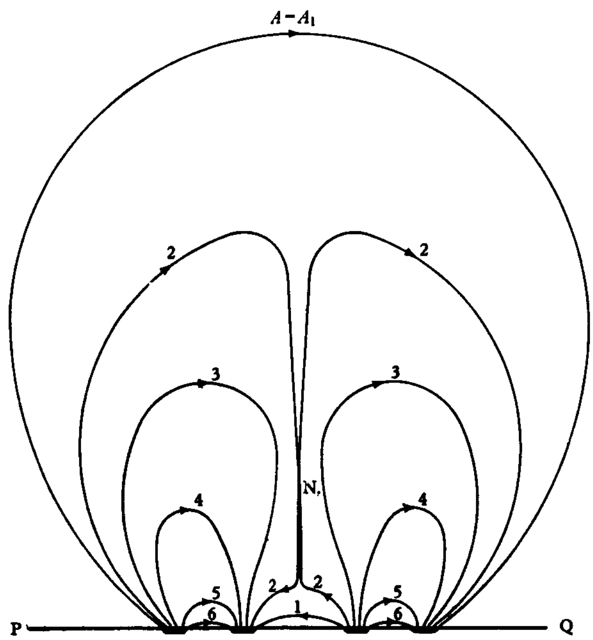
Within the framework of the assumed stationary state there are several possibilities for reducing the dissipation time. First, perhaps solutions exist in which the gas pressure is less important. The fields could then approach each other more closely and they would be dissipated more rapidly. Second, the effective value of σ might be reduced by ambipolar diffusion. However, in a stationary state the invoked friction between ionized and neutral gases requires that the pressure of the neutral gas balances the external magnetic pressure. Parker (1963a) shows that the needed high density of neutral gas in the gap causes such a large friction that little differential motion occurs and, therefore, that the conductivity is not significantly reduced. Third, n_o/n_g might be decreased. Here n_o is determined by the location of the flare and may well be lower than 10^{11} cm^{-3} if the flare occurs very near the corona, but not so near that the temperature and σ are significantly increased. An increase in n_g implies a greater external magnetic pressure. Certainly fields are available to provide larger pressures, but such pressures also imply a noticeable reaction force somewhere in the vicinity of the flare. Perhaps the solar wind and/or the rising cloud of plasma, which produces type IV radio bursts should be considered as evidence for such a reaction force. Fourth, L might be reduced. But if we subdivide the flare into smaller regions, the flow out of the ends of the gaps is soon inhibited and the computations fail. Instead, Parker (1963a) has investigated the effect of a corrugation in the neutral surface. If the amplitude of such a corrugation is sufficiently large, it effectively reduces the field scale ℓ in the gap.

Before turning to other theories, I want to mention two observations which particularly concern the two-dimensional aspects of flare theory. First, Ellison (1963) and others have emphasized the existence of flares which repeat themselves after a time interval of the order of one day. This seems to imply little change in the topology of the field from one flare to the next. But in the two-dimensional flow pattern the lines of force are reconnected across the neutral surface (Fig. 4), so that the field topology does change appreciably. Second, Severnyi (1961, 1961b) has reported that the shape of spectral lines emitted by a laboratory plasma jet depends on the direction of view. If the jet flowing out of the gap in a flare is analogous, perhaps the uncertainties in the assignment of either Doppler or Stark broadening to the emission lines may be resolved by taking into account the direction of view of the jet.

2. <u>One-Dimensional Time-Dependent Models</u>. Both Dungey (1958) and Severnyi (1958a,b) have contended that the collapse toward a neutral surface does not necessarily lead to pressure equilibrium and a stationary

state. As the density increases during a collapse, there results a race between the magnetic and the thermal forces to build up fastest, and it is not obvious which force wins. Let me summarize some of the theoretical aspects of a non-stationary one-dimensional collapse toward a neutral surface. The initial magnetic field may be given by $\underline{H} = H_o\, h(x/L)\, \hat{z}$, H_o = constant, and the simplest choice of the function h is $h = x/L$ for small x.

(i) The rise-time of a flare is comparable to the time needed by a hydromagnetic wave to traverse the flare. Therefore, Severnyi has identified the rise-time of the flare with the time needed for the collapse to the neutral surface, since this collapse is likely to proceed at roughly the hydromagnetic velocity. Severnyi (1958a,b) and Severnyi and Shabanskii (1961) have investigated three stages of a collapse toward a neutral surface. First occurs an adiabatic contraction of the whole region. For this stage, some special solutions have been derived by Severnyi (1962b). Later a shock forms on each side of the neutral surface. Finally, the reverse pressure gradients behind the shocks cause the surrounding plasma to expand, while the shocks themselves collide. In this model, the magnetic energy is first converted to kinetic energy of motion toward the neutral surface, and then the resulting shocks convert the kinetic energy into heat and radiation. Temperatures in excess of 10^6 °K are produced in a layer which is of the order of 10 km thick. Perhaps such conditions are applicable to the moustaches which are the subject of some of these investigations, but it seems difficult to account for normal flares on this basis.



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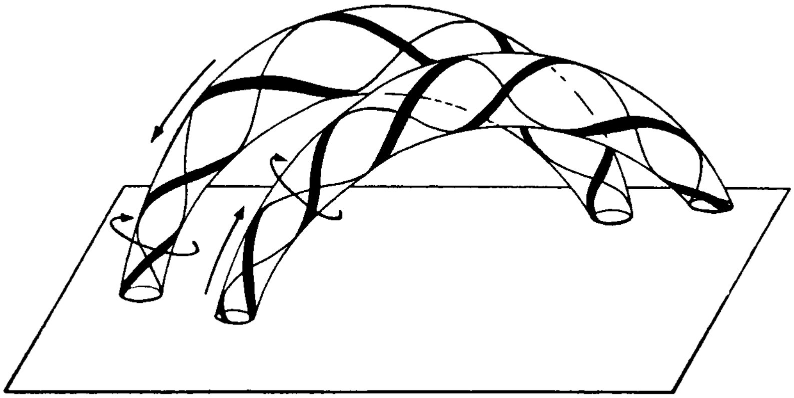

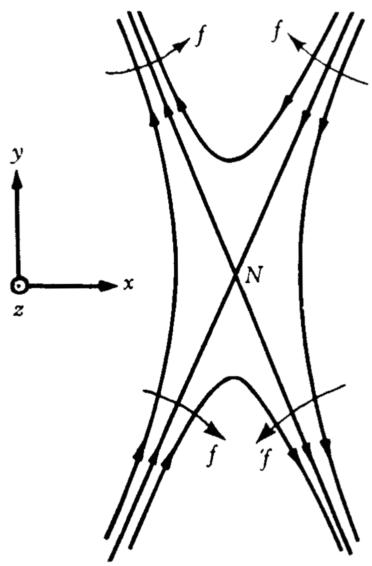

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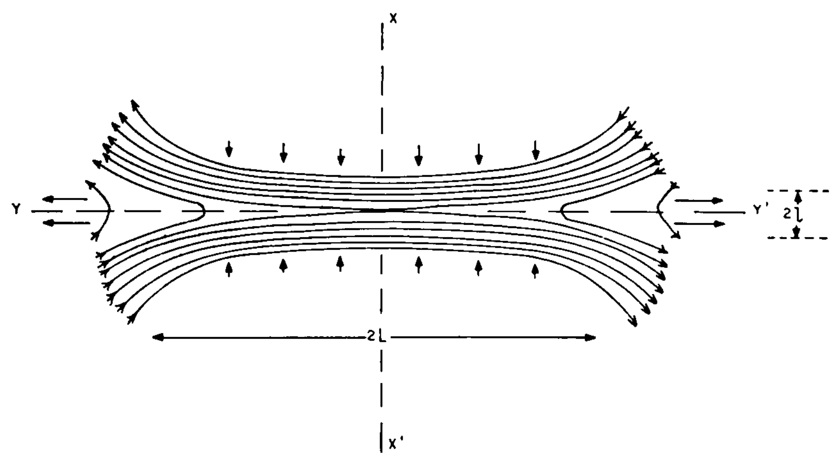
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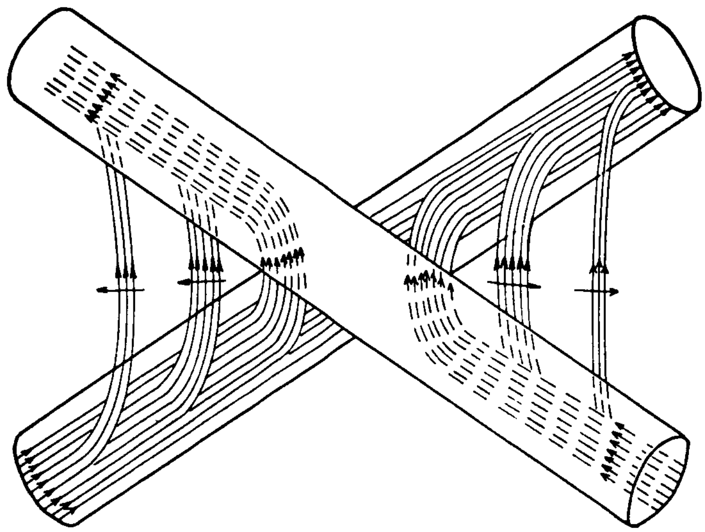

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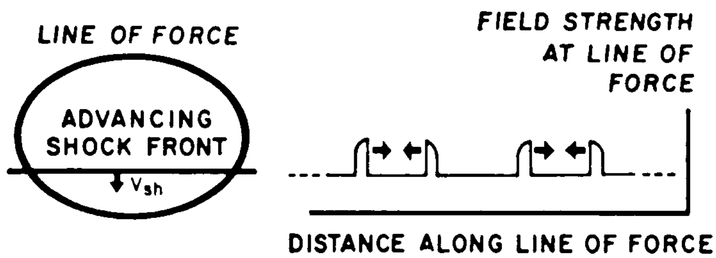

LINE OF FORCE
ADVANCING
SHOCK FRONT
V_{sh}
FIELD STRENGTH
AT LINE OF
FORCE
DISTANCE ALONG LINE OF FORCE

b

(ii) Gold and Hoyle (1960) explain the short rise-time of the flare on the basis of ambipolar diffusion. When two twisted magnetic filaments first meet, the gas densities are low and ambipolar diffusion may indeed by important. In this case, the effective conductivity and the time scale of dissipation are proportional to H^{-2}. The dissipation time at first is long since the fields on the outside of the filaments are weak. But when these are dissipated, stronger fields are pushed together by the motion of the filaments, these dissipate more rapidly, and thus a vicious circle ensues. The rapid increase in the rate of dissipation causes a very sudden brightening of the flare. This process depends on a continued low degree of ionization, since otherwise ambipolar diffusion ceases to be dominant.

In the same paper Gold and Hoyle also suggest that the two touching filaments may be magnetically connected to each other during the flare, so that the lines of force can quickly unravel. This would make more magnetic energy available for dissipation.

(iii) I have recently looked into some of the effects of invoking turbulence in a flare (Wentzel 1963b). Perhaps most important is an adequate rate of dissipation for plausible sizes of the turbulent eddies. Differing magnetic fields must frequently meet at eddy boundaries. If the eddies have a scale D and typical velocities v_t, then the boundaries are in contact only for a time D/v_t. This limits dissipation to a skin depth, ℓ, given by $D/v_t = t_{dis} = 4\pi\sigma\ell^2$. A local, but high, rate of dissipation is thereby assured. The total dissipation time is t_{dis} multiplied by the number of boundary skin layers that fit into an eddy,

$$T = \frac{D}{v_t}\,\frac{D}{\lambda} = \left(\frac{4\pi\sigma D^3}{v_t}\right)^{1/2} .$$

All the field can be dissipated in about one hour if the eddies have scales $D = 100$ km and turbulent speeds $v_t = 200$ km/sec, which seems plausible. There is, however, no theoretical reason for choosing such a D. With these values the width of the current systems is about $\lambda = 17$ meters. If these eddy boundaries are sufficiently dense that they can immediately radiate away the generated heat, then the flare emission should come from roughly 10^{-4} of the total flare volume. The corresponding fraction deduced observationally by Hirayama (1961) and Suemoto <u>et al.</u> (1962) is only of the order of 10^{-9}.

Turbulent dissipation and flaring cannot occur until kinetic energy is available to twist the magnetic fields, that is, until the velocity of collapse has reached some appreciable fraction of the hydromagnetic velocity. The rise-time of the flare may then be identified with the time interval needed to start turbulence in most of the collapsing gas. The collapse and the increase in density ~~may~~ must begin some time before they become visible. In this turbulence model, the magnetic energy of initially large-scale fields is rapidly transformed into magnetic and kinetic turbulent energy during the collapse, and is then stored in this form for gradual dissipation throughout the flare duration.

(iv) The magnetic fields need not be exactly anti-parallel. Parker (1957b, 1963a) has considered configurations such as shown in Figure 5. The field direction changes gradually across a surface where the magnetic pressure attains a finite minimum. A simple representation of a similar field is $\underline{H} = H_o\, h(x/L)\, \hat{z} + \text{constant} \times \hat{y}$. If a collapse occurs with such

multiplication x

a configuration, new magnetic pressure gradients are set up near x = 0 which counteract and stop the collapse. The violence attained during the collapse depends on the value of the initial pressure minimum. I hope to report on my computations concerning such a collapse later in this session.

Until now I have emphasized problems related to the energy supply and to the rate of dissipation. Let me briefly mention a few other features of flares which should be explainable within the framework of hydromagnetics. First, the relative frequency of flares of different importance should follow from theory. What happens in the case of the thousands of small flares? Second, ~~Why~~ why does the density in a flare exceed that in the surrounding chromosphere? De Jager (1963) considers the suddenly acquired density as the essential feature of a flare. Third, what clues can we derive from flares which occur in the form of two parallel filaments and from others which start in many points and then coalesce? Fourth, we have not exhausted the possible magnetic geometries that can lead to instabilities. Ultimately the magnetic configurations should, of course, correspond to the maps of the observed magnetic fields and of their changes during a flare.

II. ACCELERATION OF CHARGED PARTICLES

The observed phenomena which are associated with optical flares force us to ask the question: Is the optical flare the major phenomenon, and must we search for the cause of shocks and fast charged particles in the optical flare? Or are the flare and the associated phenomena together evidence of a much more extensive event than the optical flare indicates? All the theories that I have treated so far have been restricted to explaining just the optical flare. But in recent years many phenomena have been observed which are very difficult to reconcile with the dominance of the optical event. Perhaps the strongest arguments rest on energy considerations, which have been reviewed by Warwick (1962), De Jager (1963), and Parker (1963a). These indicate that the flare-associated phenomena, such as the enhanced solar wind, involve more energy than the optical emission. A plausible picture which de-emphasizes the optical flare has been presented by Wild (1962). He considers a neutral point between two spot pairs as the source of all the phenomena. The instability first causes the ejection of fast electrons. This is followed by shock waves, which accelerate other particles, and by the generation of the optical flare in a lower and denser region.

My own impression is that the collapse toward a neutral surface between spot pairs may involve regions of greatly differing heights and densities. Where the collapse increases the density above some critical value, radiative losses cool the gas and an optical flare arises; where this critical density is not reached, the collapse causes strong heating, particle acceleration, and radio events.

These arguments show primarily that the location of particle acceleration is still quite unknown. Many physical conditions suitable for acceleration have been and may be invoked. A check on theories must concentrate on the deduced energy ranges, on the time scales, and, if the theory provides it, on the intensities and spectra of the particles which are produced. The observed intensities and spectra also depend on the manner of propagation in interplanetary space.

A crucial parameter for any theory of particle acceleration is the injection energy. The faster the particle when it is first accelerated, the smaller are its energy losses by Coulomb collisions. Supra-thermal particles may be produced by plasma phenomena, by shock waves, or possibly by thermonuclear reactions, but the quantities of the particles so produced are practically unknown. Let me simply assume that collisional losses of energy are negligible and summarize the methods of acceleration which have been suggested.

a) Electric Fields

The original discharge theory of flares ascribed the heating of the flare region to electrons which had been accelerated in electric fields. Normally, such high electric fields cannot be built up in ionized gases. But they may be by-products of a flare which is started by other causes. The observed extremely short time scales of some of the phenomena and the periodic repetition of bursts in some groups of radio bursts certainly make an electric discharge seem very plausible. However, it is also possible that the particles are continuously accelerated and then pulsed by some sort of instability.

If an observer sees a conducting fluid move with velocity $\underline{v}_f$, then he sees an induced electric field $\underline{E}_i = -\underline{v}_f \times \underline{H}$ as well as the electric field $\underline{E}_d$ which is due to dissipative processes. Let me suppose first that $\underline{E}_d = 0$, in the limit of infinite conductivity. The particle velocity $\underline{v}_p$ consists of the Larmor motion $\underline{v}_L$ and any drifts $\underline{u}$, $\underline{v}_p = \underline{u} + \underline{v}_L$. The total force on the particle is $q(\underline{E}_i + \underline{v}_p \times \underline{H})$. The electric drift is $\underline{u} = \underline{E}_i \times \underline{H}/H^2$, so that $\underline{u} = \underline{v}_f$ and $\underline{E}_i + \underline{u} \times \underline{H} = 0$. The particle simply moves with the fluid and the induced electric field is ineffective in accelerating the particle (compare Parker 1963b, p. 7), except indirectly: The total force exerted on the particle is just $q\underline{v}_L \times \underline{H}$ and the energy gained is $\underline{u} \cdot (q\underline{v}_L \times \underline{H}) = q\underline{v}_L \cdot (-\underline{v}_f \times \underline{H})$, which represents betatron acceleration and is treated separately below.

Let me now neglect any induced fields $\underline{E}_i$ and consider only the electric field $\underline{E}_d = \underline{j}/\sigma$. Any component of $\underline{E}_d$ which is perpendicular to $\underline{H}$ causes a drift velocity $\underline{E}_d \times \underline{H}/H^2$, which is generally of the order of $v_d = (4\pi\sigma\ell)^{-1} = 5 \times 10^{12}/(T^{3/2}\ell)$ cm/sec. This motion is generally subsonic and is simply the drift velocity of the magnetic lines of force, with which the charged particle moves, relative to the gas. Much higher drift velocities occur at neutral points, where $\underline{E}_d$ may be finite while $\underline{H}$ becomes vanishingly small. Until the particle reaches these high drift velocities, or until it leaves the neutral region, the acceleration takes place as if there were no magnetic field. The same is true for any component of $\underline{E}_d$ which is parallel to $\underline{H}$. Where the electric field thus accelerates the particle, the gain of energy is of the order of

$$1.6 \times 10^{-20}\ H\ v_d\ \text{erg/cm} \simeq 0.05\ H/\ell\ \text{ev/cm (for } T = 10^4\ {}^\circ\text{K);}$$

note that the drift velocity $v_d = \ell\ /\ t_{dis}$ enters, but not the fluid velocity. The current density has again been assumed to be $H/4\pi\ell$, where H now is the field strength external to the neutral region. Effective acceleration requires very narrow current systems. With $H = 1000$ gauss and $\ell = 1$ km, a distance of 20,000 km is needed to obtain 1 Mev. To find ℓ of the order of meters, we must look for effective accelerating fields in more complicated situations, including turbulence, shocks, and plasma phenomena. Since the electric fields under such conditions are not likely to act over large distances, we should ask, following de Jager (1960), for the probability that a given particle sees sufficiently many accelerating electric fields in order to attain high energy, within the time allowed by the observations. Sweet (1958a,b), Dungey (1958), and de Jager (1960) have deduced electric fields of the order of 1 ev/cm for several situations. It seems probable that in each case only a small fraction of these fields is really effective in accelerating particles.

b) Betatron Acceleration

An increase in field strength increases the kinetic energy of Larmor gyration of a charged particle proportionately. As an upper limit to the increase in energy which can be obtained in this way, suppose that the magnetic field strength is proportional to the gas density. Then the increase in particle energy due to the collapse of flare material is at most about 3 orders of magnitude, and most probably it is smaller. De Jager (1963) has proposed acceleration of protons to cosmic ray energies by what amounts to betatron acceleration. He has estimated the induced electric field from the rate of change of magnetic flux through a surface fixed in space. But charged particles travel with the field lines, which in turn travel with the gas, and hence the appropriate surface to integrate over is one fixed in the fluid. The magnetic flux is then found to be constant and only the normal betatron acceleration occurs. Dissipation and $\underline{E}_d$ are ~~induced electric field is~~ zero in the limit of infinite conductivity, ~~This limit~~ which is an excellent approximation in the situation envisaged by de Jager.

c) Fermi Acceleration

On the basis of the guiding-center approximation, a particle which enters a sufficiently strong magnetic field is reflected by this field. If the magnetic "wall" moves with speed w, then the particle energy and its speed, v, are increased or decreased by a fraction of the order of w/v, depending on whether the collision is a head-on or an overtaking collision (Fermi 1949). Normally one assumes $w \ll v$, but in general only $w \lesssim 0.5\ v$ is required (Wentzel 1963a). Two important conditions must be satisfied for successful acceleration of particles by this mechanism.

1. Re-Alignment of Pitch Angles. Reflection by any given magnetic inhomogeneity requires that the pitch angle (angle between $\underline{v}$ and $\underline{H}$) exceed some critical value before the reflection occurs. But the Fermi acceleration decreases this angle and, therefore, tends to be self-defeating. To obtain repeated Fermi acceleration it is necessary that the pitch angle is repeatedly increased, without an associated deceleration. For this purpose Davis (1956) proposed betatron acceleration between hydromagnetic waves which cross each other. More usually it has been assumed that pitch angles are redistributed through violations of the guiding-center approximation. Takakura (1961, 1962) pointed out that a fast electron may be appreciably deflected by Coulomb collisions without losing appreciable energy, and that this mechanism may be effective for acceleration in the upper chromosphere. Alternatively, one may suppose that a particle crosses a hydromagnetic shock front which is thinner than the Larmor radius of the particle. The resulting distribution of pitch angles has been assumed to be random (Parker 1958, 1963b; Wentzel 1963a), but this is certainly not exact.

2. Accelerations Must Outnumber Decelerations. If regions of acceleration and of deceleration occur in equal numbers, then the net efficiency of Fermi acceleration is small. Parker (1958) showed that hydromagnetic shocks which cross each other can provide very efficient acceleration (Fig. 6). Particles are swept ahead of the shocks, so that the density of particles being accelerated is generally greater than the density of particles being decelerated. Moreover, the length of the accelerating trap shrinks to zero, so that all particles in the trap must necessarily be accelerated up to their escape energy. In contrast, particles which have crossed a shock find themselves in a decelerating trap whose length is increasing, so that decelerations become progressively less frequent. Finally, the shocks cross each other and all particles again are in an accelerating trap. I have extended Parker's analysis (Wentzel 1963a) and have shown that a net acceleration occurs even if the shocks are very weak. A shock-like structure is then needed only for the scattering of the pitch angles. In the same paper I also showed that acceleration in non-uniform fields can be very efficient. If a shock moving into stronger fields becomes stronger with time, then the shock simply pushes the particle ahead of it and acceleration is greatly prolonged. A similar shock moving into weaker fields yields no corresponding deceleration.

Let me emphasize that Fermi acceleration can provide energy for both protons and electrons. A given magnetic trap multiplies the particle energy by a given fraction, independent of particle mass. If protons and electrons are injected with the same velocity and different energies, then indeed the protons gain much more energy than the electrons, but if they are injected with the same energy, then both gain the same amount of energy.

It is usually stated that Fermi acceleration produces an energy spectrum. Even this need not always be the case. The Fermi acceleration depends on the reflection of a particle by a strong magnetic field. If this field is a shock, then the efficiency of reflection may depend on the ratio of the Larmor radius of the particle to the thickness of the shock front. The guiding-center approximation strictly requires that this ratio be small. The opposite extreme, the transmission of particles across a sharp magnetic discontinuity, has been considered by Parker (1963b, p. 166-170). His results depend on the assumption that an isotropic velocity distribution is maintained as the particles across the discontinuity.

The conclusion from these arguments is that we cannot yet predict what types of charged particles can or cannot be produced by Fermi acceleration. I am sure that we have not yet imagined all possible efficient field configurations. The energies achieved depend on the injection energies, and, if acceleration occurs by hydromagnetic shock, the spectra may depend also on the particle rigidity.

Finally, I should summarize the specific situations that have been proposed for specific types of charged particles. Most of these proposals have been limited to stating that the conditions are favorable for some one accelerating process. Only few detailed analyses have been made. Parker (1957a) proposed that cosmic ray protons from the flare of February 23, 1956 were accelerated by Fermi mechanism within the region of the optical flare. He assumed injection of protons at hydromagnetic velocities and obtained a reasonable energy spectrum. He had to postulate somewhat extreme parameters, but these might be made more plausible by invoking a more efficient Fermi acceleration. Severnyi and Shabanskii (1960, 1961) and Shabanskii (1961) have proposed the Fermi acceleration of protons between two magnetic walls which are collapsing toward each other ~~and a neutral surface~~ during a flare. Thermonuclear reactions in the center of the collapsing region may serve as particle injectors. Takakura (1962) has suggested that fast electrons are accelerated by hydromagnetic waves over sunspots. There the waves are so fast that just a few accelerations suffice to achieve the desired energies, and no great efficiency of acceleration is needed. It seems probable to me that such acceleration becomes much less efficient when the electron Larmor radii become greater than the thickness of hydromagnetic shocks, which is presumably a few Larmor radii of thermal protons. In regions with temperatures between 5×10^4 and 2×10^6 °K, one would then expect electrons in the energy range from 10 to 500 kev, which corresponds well to the energies required by x-ray and radio observations (Wentzel 1963a). The flaw in all of these specific theories is that each explains only one type of particle. I think no theory can be convincing unless it includes as an essential ingredient the explanation of at least several of the many phenomena that are associated with a flare.

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CAPTIONS

Fig. 1. Lines of force of two aligned bipolar spot-pairs (Sweet 1958a).

Fig. 2. Two bundles of lines of force, both twisted up. The arrows indicate the components of the fields (Gold and Hoyle 1960).

Fig. 3. The direction of the magnetic force, $\underline{f} = \underline{j} \times \underline{H}$, near an x-type neutral point (Dungey 1958).

Fig. 4. Schematic representation of the magnetic lines of force of two antiparallel regions of magnetic field pressed firmly together, with the fluid caught between free to escape out the ends Y and Y' (Parker 1963a).

Fig. 5. Schematic drawing of the merging of two perpendicular flux tubes by Sweet's mechanism (Parker 1957b).

Fig. 6. Field strength measured along a line of force with two pairs of interpenetrating shocks (right), and the equivalent situation of a shock crossing a closed line of force (Wentzel 1963a).