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# FLARE MODELS
## Chapter 9 of SOLAR FLARES
## A Monograph from Skylab
## Solar Workshop II

by

Peter A. Sturrock

SUIPR Report No. 721

February 1979

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Chapter 9

FLARE MODELS

9.1  Introduction

In Chapters 2 through 8, each team has presented an account of a particular aspect of the flare phenomenon, presenting relevant observational data, interpretations of the data, and theoretical concepts which have been advanced to explain the data.  However, these chapters do not reflect some of the inter-team discussion which went on during the Workshop concerning the basic nature of solar flares.  In particular, there was a very lively debate involving Stirling Colgate, Hugh Hudson, Dan Spicer, and Hal Zirin as primary speakers and Zdenek Svestka as moderator, concerning the question of whether current sheets are essential for solar flares.  Unfortunately, no vote was taken at the end of the debate, so the question remains in doubt!  The purpose of this chapter is to review the current status of the modeling of solar flares.  This requires an attempt to address the question of the basic nature of solar flares (if there is one), which is something of a leap in the dark--if this is an appropriate metaphor to use in describing the transition from observational data to theoretical constructs.  As a way of organizing this discussion, Sections 9.2 and 9.3 will propose requirements on flare models which are set by the observational data, and Sections 9.4 and 9.5 will discuss models.  In each case, an arbitrary distinction has been made between "primary" requirements and models and "secondary" requirements and models.

The division of requirements into "primary" and "secondary" is necessarily subjective.  One has in mind that, in some sense, the basic flare problem is "solved" if the primary requirements have been met.  This is

not to say that every flare manifests every primary requirement: for instance, some flares have no impulsive phase. Nevertheless, a flare theory which could not account for the impulsive phase would generally be regarded as unsatisfactory. Similarly, there is no implication that the secondary requirements are not generally required. For instance, the basic definition of a flare has long been expressed in terms of $H\alpha$ emission. The implication is, rather, that if the basic requirements are met by a model, then this model will provide an adequate basis for study of mechanisms for meeting the secondary requirements.

The distinction between "primary" and "secondary" models runs parallel to that between primary and secondary requirements. A primary model addresses the question of the basic nature of flares, and should therefore be tested against the primary requirements. On the other hand, a secondary model attempts to explain one or more of the secondary requirements only. It may or may not be tied to a particular primary model.

Section 9.2 will present a proposed list of "primary requirements" of a flare model. A number of models will be compared with this list in Section 9.4. Section 9.3 offers a list of "secondary requirements." In Section 9.4, a number of models are compared against the primary requirements; there is no corresponding comparison of models against the secondary requirements. The material in Section 9.4 necessarily duplicates to some extent material contained in Section 3.3.1, dealing with "A Brief Survey of Flare Theories," of Chapter III on "Primary Energy Release."

9.2  Primary Requirements

9.2.1  Energy Storage. During a flare, energy suddenly appears in the form of various kinds of radiation and particle emission. The nature of much of the radiation is such that it must originate at the chromosphere

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or above.  In order to escape, the particles must have been accelerated in coronal conditions.  One interpretation of these events, which was generally subscribed to by participants in the Workshop, is that a flare represents the sudden release of energy stored above the photosphere and probably above the chromosphere, i.e. in the corona.  Before space experiments, there was little direct evidence in favor of this proposition, although limb flares and loop-prominence systems showed that coronal events occurred in response to a flare, although they might not be responsible for the flare.

However, space experiments have shown that x-ray emission is a normal, and energetically major, output from flares.  Photographs taken with the x-ray telescopes on board Skylab indicate that much, if not all, of this emission originates at coronal heights.  It is possible to regard the chromospheric manifestations (such as Hα emission) as secondary results of coronal energy release, whereas it would be difficult to interpret the coronal emission in terms of chromospheric energy release, if for no other reason than that it is difficult to store the energy released during a flare in the thin layer of the chromosphere.

These reasons, among others, have led to the prevailing view that a flare represents the sudden release of energy stored (prior to the flare) at coronal heights.  Although in principle one could conceive of alternatives (high-energy particles, gravitational energy, etc.), it is generally believed that, before a flare, the energy exists in the form of the "free" energy of a current-carrying magnetic field.  That is, the magnetic field configuration in the corona involves currents, and that energy can be released by somehow reducing or destroying these currents to convert the field to its "potential" or "current-free" form.  The vertical component

of the magnetic field at the photosphere is assumed to be unchanged since the photosphere is reasonably highly conducting and (compared with the corona) is heavy. Note that the horizontal component of the magnetic field of the photosphere may change, which would lead to changes of the line-of-sight component of the magnetic field if the region is not at the center of the disk.

It was at one time proposed by Piddington (1973, 1974) that a flare represents a sudden efflux of energy from below the photosphere in the form of Alfven waves. There is no evidence for such a wave flux; further-more, such a proposal has the scientific disadvantage of moving the primary cause into a region inaccessible to observations (although, of course, such an argument does not make the hypothesis incorrect--it simply makes it difficult to assess).

The first requirement then is that, before the flare, energy be stored as the free energy of a current-carrying magnetic field in the coronal region of the sun's atmosphere. Note that such a configuration must have some measure of stability. If some processes were to occur which rapidly dissipate the current as soon as non-zero current were to develop, it would be impossible to store the required energy in such a configuration. On the other hand, the spontaneous and sudden release of stored energy is normally interpreted as, or attributed to, an instability. Hence a configuration must in some sense be stable and in another sense unstable. This point will be discussed further in the next section.

Although flares can occur in magnetic regions of arbitrarily high complexity, and although complex regions are more likely to flare than simple regions, flares sometimes occur in regions which are basically bipolar. Hence a requirement of a flare model, if it is to have general validity, is that it is applicable to a bipolar magnetic region.

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9.2.2 _Energy Release_.  Although in this section we shall be concerned
with the requirement that stored energy be rapidly released during a flare,
we noted in the previous section that there is an apparently conflicting
requirement.  Namely, that for some time before the flare the energy,
although present and in some sense available, is not released.

These apparently conflicting requirements can in fact be reconciled.
Study of the _onsets_ of instability (Sturrock, 1966a) shows that they may
be classified into two types:  "explosive" or "non-explosive."  [This
characterization is sometimes referred to alternatively as "hard excita-
tion" or "soft excitation" (Kadomtsev, 1965)].  An onset of instability
is "explosive" if the configuration is metastable:  i.e., stable against
small-amplitude perturbations but unstable against sufficiently large
perturbations.  If, on the other hand, the configuration is unstable even
against small-amplitude perturbations, then the onset of instability will
be non-explosive.

However, it is probably a gross oversimplification to refer to "the"
energy-release mechanism.  A large flare seems to display three well identi-
fied release processes.  (This is a simplification of the more complex
breakdown given by Svestka (1976), p. 300 et seq.).  Conceivably these
all represent the same process, but then one needs to understand why the
rates and other properties of these three phases are different.  It is also
possible that there is more than one energy-release process involved in a
flare:  one may be operative in one stage and another in a different stage.

One stage is the "onset stage" which is the first manifestation of a
flare:  it shows up in UV and soft x-ray emission and some Hα brightenings.
In terms of breakdown given by Svestka (1976; pp. 300 et seq.), what is
here termed the "onset phase" corresponds to the interval between the
"onset of the soft x-ray burst" and the impulsive phase.  X-ray emission

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during this phase is in Chapter 5 referred to as a "precursor," meaning "precursor to the impulsive phase or rapid increase," not "precursor to the flare." Since some flares do not have a clearly developed impulsive phase, it appears that (in terms of the present nomenclature) these flares have only an "onset phase." With the assumption that the onset of the soft x-ray burst is closely correlated with "flare start" as determined by Hα observations, we can infer from the study of Harvey (1971) that the duration of the onset phase is typically in the range 0 - 4 m (some flares have almost no onset phase, apparently starting with the impulsive phase), although this duration may be substantially longer for some slow two-ribbon flares.

The most dramatic phase of a solar flare is the "impulsive phase," during which a very large fraction of the total energy of a flare may be released in a time as short as 10s or as long as 10m for some very large and complex flares (see Chapter 5). This phase is typically marked by hard nonthermal x-ray emission as well as UV emission and other chromospheric emission which begins in intense "kernels." The hard x-ray emission is normally attributed to bremsstrahlung from high-energy electrons which may have either a power-law distribution or a high-temperature thermal distribution. During this phase of the flare, the area of Hα brightening may very rapidly increase.

Finally, large two-ribbon flares sometimes show evidence for continued energy release after the impulsive phase (Chapter 7). This phase is often referred to as the "decay phase" which is appropriate enough if all energy is released by the end of the impulsive phase, and x-ray and Hα emission derive their energy from the hot flare plasma produced during the impulsive phase. However, if additional magnetic free energy is released during this phase, the term "decay phase" would seem to be inappropriate. The term

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"thermal phase" is used in Chapter 8 for the extended stage of a flare
after the impulsive phase which produces soft x-ray emission, apparently
from a thermal plasma, and this is clearly to be preferred over the term
"decay phase." There is evidence that, during some flares, there is con-
tinued energy release during the thermal phase, based on the fact that the
estimated energy content of the flare plasma responsible for the soft x-ray
emission sometimes continues to increase during this phase. Furthermore,
their bright ribbons seen in Hα light may slowly separate and drift apart,
indicating that more extended regions of the magnetic-field configuration
are becoming involved in the energy-conversion process. For present pur-
poses, it is convenient to have a term for this phase of energy release
when it occurs, and it will here be referred to as the "late phase."

Another way in which energy release may involve more than one mechanism
is the following: energy release, for instance during the impulsive phase,
seems to involve both macroscopic and microscopic processes. The release
of magnetic energy over a large volume must involve the movement of magnetic
field lines over their volume; it is unlikely that the diffusion coefficient
is increased throughout the volume, so that the bulk of the magnetic-field
readjustment is likely to take place through MHD processes, such as Alfven
waves. The fact that some flares excite waves propagating away from the
flare site, and some flares give rise to coronal transients, may simply be
dramatic manifestations of the general rules that the primary energy release
process involves large-scale mass flow. On the other hand, in order to
reduce or eliminate currents from the coronal magnetic-field structures,
it is apparently essential that there should be localized regions where
magnetic field can diffuse rapidly with respect to the plasma. It is possi-
ble that both requirements, of large-scale diffusionless mass motion and
small regions of rapid diffusion, can be met in one self-consistent model.
However, it may be that two processes are at work which can also occur

independently:  there may be an MHD instability which permits large-scale reorganization of the magnetic field, and this instability may lead to the development of localized regions where rapid diffusion of the magnetic field with respect to the plasma can occur.

To sum up, we need either two or more mechanisms of energy release, or one mechanism flexible enough to behave differently at different stages of a flare, which can explain:  the slow onset phase, the rapid impulsive phase, and the slow late phase when this occurs.  The energy-conversion processes must be capable of converting some energy into mass motion, and some energy into heat and/or the energy of high-energy particles.

9.2.3 <u>Acceleration</u>.  The fact that any primary energy-release mechanism is likely to involve large-scale reorganization of magnetic field makes it almost inevitable that mass motions will develop, so that some of the flare energy is likely to go into the kinetic energy of plasma motion.  Furthermore, since the currents must be dissipated in regions where the effective resistivity becomes high, it seems inevitable that some of the free magnetic energy must heat the plasma by way of Joule heating or its equivalent.  However, it is not so obvious that primary energy release should <u>necessarily</u> accelerate electrons and/or ions to high energies.

It appears from observational data that the onset phase does not intrinsically involve particle acceleration.  The soft x-ray emission and related chromospheric emissions can be ascribed to sudden heating of coronal gas.  Whether or not the impulsive phase necessarily involves acceleration is to some extent a matter of semantics.  If the hard, impulsive x-ray burst is produced by a non-thermal spectrum of electrons (such as a power-law spectrum), one would normally say that acceleration has occurred.  On the other hand, if the hard-x-ray emission may be attributed to one or more groups of electrons, each of which has a thermal (Maxwellian) distribution,

one person may regard this as "acceleration" whereas another regards it as "heating." If, in the latter case, electrons in the coronal gas are energized preferentially over the ions, it does seem fair to use the term "acceleration."

The energization of electrons during the impulsive phase is usually ascribed to "first-phase" acceleration (see Chapter 4). The major requirement of a theory of first-phase acceleration is that it should rapidly (in a few minutes) accelerate large numbers of electrons to energies of order 10 to 100 keV. The number of electrons required to explain the nonthermal impulsive x-ray bursts depends upon the model (Brown, 1975). For "thick target" emission, it ranges from about $10^{36}$ for small flares to about $10^{39}$ for large flares (Hoyng et al., 1976; for "thin target" emission, the numbers would be larger). This is a substantial fraction of the electron content of the corresponding coronal region before the flare.

It seems likely--but not certain--that Type III radio bursts are a manifestation of first-phase acceleration: the electron energies are in the same range, and some flares show a close correspondence between the timing of Type III bursts and fine structure in the impulsive nonthermal x-ray emission. If it does represent the same process, one needs to understand why a number ($10^{32} - 10^{33}$) which is small compared with the total number of accelerated electrons participate in the Type III bursts. In order to produce a Type III burst, there must be a certain increase in the number of electrons escaping along open field lines; since fast electrons run ahead of slow ones, this will automatically lead to a two-stream situation. Lin (1974) has found that spacecraft data indicate that for flares manifesting both impulsive x-ray bursts and Type III radio bursts, the electrons which escape into interplanetary space are comparable in

number (of order $10^{33}$) with the number of electrons estimated to be involved
in Type III bursts. This suggests that, even when escape occurs, only a
small fraction of the electrons accelerated during the impulsive phase escape
into interplanetary space. This suggests that the relevant criterion is
one of access: of all the electrons accelerated during first phase
acceleration, only a very small fraction have access into interplanetary
space, and these typically produce Type III radio bursts.

The acceleration of ions and electrons to relativistic energies is
currently attributed to a "second phase" of acceleration (Chapter IV;
Sturrock, 1974a). As originally proposed by Wild, Smerd, and Weiss (1963)
and by de Jager (1969), the second phase occurs some minutes after the
first phase and is associated with the shock front responsible for a
Type II radio burst. However, as pointed out by Svestka (1976, p. 290),
the 2.23 Mev gamma-ray flux detected by Chupp et al. (1973, 1975) from
the flare of 1972 August 4 was almost simultaneous with the impulsive
x-ray burst. More recently, Hudson (1978a) has reported the detection
of gamma rays from flares by means of instruments on the HEAO-1 spacecraft.
His results also indicate that gamma rays are produced simultaneously
with the impulsive x-ray burst. These more recent data strengthen Svestka's
assertion that the second phase of acceleration immediately follows the
first (or is contemporaneous with it) or there is only one phase of acceler-
ation.

When large fluxes of high-energy ions are detected in interplanetary
space, there is usually evidence for mass motion from the flare through the
corona into interplanetary space. For instance, of the 18 prompt solar
proton events observed during the Skylab period, Kahler et al. (1978) found
that 14 were associated with coronal transients, and infer that mass ejection

is a necessary condition for the occurrence of a prompt proton event.

Furthermore, there is a high correlation between particle events and Type II radio bursts, which are attributed to shock waves ("bow shocks") moving ahead of ejected plasmoids, and this is one of the factors which led to the view that there exists a "second phase" of acceleration. This phase predominantly accelerates ions, sometimes to several GeV, and accelerates to a few MeV or more a small fraction (of order 1%) of electrons accelerated to 10 - 100 keV during the first phase. The close association with mass motions in the corona, especially with Type II radio bursts, has been taken to indicate (Chapter 4) that a second-phase of acceleration may occur at the shock front. [The possibility that acceleration of cosmic rays may occur in the intense shock waves produced by supernovae has recently been proposed and examined by Blandford and Ostriker (1978)]. However, this interpretation is somewhat difficult to reconcile with the gamma-ray data previously cited, which indicates that ion acceleration occurs contemporaneously with the impulsive phase, which occurs before a shock wave forms (as inferred from Type II bursts).

The situation now appears to be that the relative timing of gamma rays and impulsive x-rays do not support the proposition that there are two phases of acceleration which are clearly separated in time. On the other hand, theoretical considerations give some support to the existence of two modes of acceleration. For instance, stochastic acceleration processes such as might accelerate ions to high energies seem to require high injection energies such as particles might acquire from another process which accelerated particles to lower energies (Sturrock, 1974a). Hence it seems prudent to continue to entertain the possibility that there are two distinct phases of acceleration, even though some of the arguments originally given for this thesis now appear to be invalid.

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If there is indeed only one phase of acceleration, or if there are two phases but they normally (but not necessarily always) occur simultaneously, the association between particle events and evidence for ejecta may require reinterpretation. It may be that this association is indicative of escape conditions rather than of acceleration. The requirements concerning acceleration, as they are presently perceived by the writer, may be summarized as follows:

(a) There is a first phase of acceleration which accelerates, during the impulsive phase of the flare, a large fraction of the electrons in the coronal region before the flare to energies of order 10 - 100 keV.

(b) The bulk of these electrons are trapped, but a small fraction may escape, possibly along open current sheets, into the outer corona and interplanetary space.

(c) There is probably (but not certainly) a second phase of acceleration which can occur at the same time as the first phase, possibly in the same volume. This phase preferentially accelerates ions (to many MeV) but also accelerates some electrons to MeV energy. (This second phase may also occur near a flare-produced shock wave, but at this time there is no fully convincing evidence for this.)

(d) The ions and electrons accelerated by the second phase can escape in appreciable numbers if there is an eruption of the magnetic field pattern leading to the ejection into interplanetary space of a plasmoid containing these accelerated ions and electrons.

(e) Type II radio bursts indicate that electrons are accelerated to energies of order 10 keV or more at a shock front propagating through the corona. The "herring-bone structure" (Kundu, 1965, p. 339) and also the interpretation of Smerd et al. (1974) of the frequency splitting both indicate that electrons propagate both upstream into the unshocked plasma

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and downstream into the shocked plasma. Since there is no reason to identify this acceleration of electrons to keV energies with the acceleration of ions and electrons to relativistic energies, we should perhaps regard this as a separate acceleration process which might be termed "third-phase acceleration." However, since this appears to be a property of shock waves rather than of the flare itself, and since these keV electrons are energetically insignificant, this phase will not be regarded as a "primary" requirement of a model of solar flares.

9.2.4 Mass Ejection. Mass ejections are important in themselves, and in addition are related either to a "second-phase" acceleration process or to escape conditions for accelerated particles.

Although only a small fraction of flares show evidence for mass ejections, when this does occur a large fraction of the total energy released appears to be in the form of the kinetic energy of mass motion (Chapter 7). For this reason, it seems appropriate to regard mass ejection as a primary requirement rather than a secondary one. (Just as the impulsive phase is regarded as a primary requirement, even though not all flares have an impulsive phase.) One requirement of a primary flare theory is to explain why mass ejections occur for only a small fraction of flares.

It is known that filament eruptions precede some flares, especially two-ribbon flares (Chapter 2). Although one could develop a scenario for solar flares in which filament eruption might play an essential role in some flares, this would perhaps stretch the definition of a flare beyond that usually adopted. The more usual interpretation is that a filament eruption either "triggers" an existing unstable magnetic field configuration, which then is recognized as a flare, or that the filament eruption changes the magnetic field configuration into one which is subject to the type of instability responsible for a flare. One would like to see a primary flare

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model explain whether filament eruption triggers an instability or whether it changes the magnetic field configuration into one subject to a flare-producing instability.

Many transients are associated with filament eruptions. Some transients are associated with flares, most of which involve filament eruptions (Munro, 1979). It is possible that the remainder involve the eruption of a similar magnetic field configuration, but that this configuration does not contain sufficient cool gas to produce the absorption which is the usual evidence of a filament. Hence it is quite possible that coronal transients are due intrinsically to the process of filament eruption, not to the flare process per se. On the other hand, there is some indication that transients produced by filament eruptions without flares differ from those produced by regions in which flares occur: the latter tend to have higher velocities (Chapter 7). A primary flare theory might therefore explain whether all coronal transients are produced by some form of filament eruption, or whether some transients are produced by another process which is intrinsic to a solar flare.

It appears (Svestka, 1976, p. 197) that Type II bursts are always associated with flares, never simply with filament eruptions, and this suggests (but does not establish) that there is a mass ejection process which occurs in flares but not in filament eruptions.

In addition to the questions concerning mass ejection listed above, one is faced with the more basic question of determining the mass-ejection mechanism, which may in turn be broken down into the following questions:

(a) What is the structure of an ejected plasmoid; what gives it cohesion, and is it magnetically attached to or detached from the sun? (b) What are the forces (or what is the force) which accelerates the plasmoid and over what range of distance or time do they act? and (c) What

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is the origin of the mass ejection in the plasmoid, and what is its state
(density, temperature, etc.)? However, as we shall see in Section 9.4,
most current models have not yet been developed in sufficient detail to
address such specific questions.

9.2.5 <u>Heating of the Temperature Minimum Region</u>. The work of Team 5
(see Chapter 6) was concerned in part with radiations, such as the Si I
continuum and the wings of the Cα II K line, which are believed to originate
primarily from the upper photosphere. This radiation is confined to small
regions (possibly the flare "kernels") and to the impulsive phase. It is
not certain that all flares would exhibit such radiation.

Some of the radiation apparently originates in the "temperature minimum"
region; the difficulty in understanding the origin of this radiation is
discussed in Chapter 6. The conventional view concerning solar flares has
been that the primary energy release occurs in the upper atmosphere, most
likely in the corona. If this is the case, heating of the temperature-
minimum region must be due to a flux of radiation or of particles origi-
nating in the corona and propagating down to the upper photosphere.
Machado et al. (1978) have shown that electrons or ions or fluxes of soft
x-rays would be scattered and absorbed at levels well above the temperature
minimum. It is possible that energy transfer from coronal heights to the
temperature-minimum region occurs through a flux of EUV photons, or through
a flux of protons with energies in the range 10 - 20 MeV. However, another
possibility is that there may be an "<u>in situ</u>" mechanism of energy release
in this part of the sun's atmosphere.

If it turns out, as a result of further data and model analysis, that
energy is released at photospheric levels during some flares, or during
all flares, the explanation of this fact will certainly qualify as a
"primary requirement" of flare models. However, since this requirement is
still in doubt, it must be left in abeyance at this time, although it may

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be interesting to consider whether or not proposed models might lead to such energy release.

9.3  Secondary Requirements

In this section we discuss requirements which are believed to be secondary. This is unavoidably an intrusion of theoretical considerations into a section which should be devoted purely to observational requirements. The general consensus that the energy released in a solar flare is before the flare in magnetic form already leads to some limitation on what might be the outputs from the primary energy-release mechanisms. A plasma instability can convert stored energy into high-energy particles, mass motion, MHD turbulence, etc., but it would not in itself, give rise to-- for instance--Hα radiation.

In this section we discuss some of the requirements for providing some of the radiations which are believed to be secondary in character.

9.3.1  X-Ray and EUV Radiation. X-ray emission is typically divided into two types: "hard" (E > 10 keV) and "soft" (E < 10 keV). The hard radiation is normally produced only during the impulsive phase of a flare, and therefore is produced only for that subcategory of flares which have an impulsive phase. The order of magnitude of the photon flux is well known for various classes of flares. The spectrum is frequently believed to be power-law in form, although for some cases it appears that the spectrum could be fit by a thermal bremsstrahlung spectrum. To date, only one experiment has sought to determine whether or not hard x-ray emission is polarized (Tindo et al, 1970, 1972a,b, 1973). These results indicate that some of the hard x-ray emission is polarized, but the result has not yet been confirmed by independent experiments. As a way of determining whether hard x-ray emission is "beamed" or not, there has been some atten-tion to studying the distribution of hard x-ray events on the disk of the

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sun (Datlowe et al., 1974; Petrosian, 1975; Langer and Petrosian, 1977; Datlowe et al., 1977). Results to date appear to be compatible with almost iso-tropic radiation.

Hard-x-ray detectors which have been in operation to date accept the entire radiation from the sun. As a result, there is no direct evidence for the height at which hard x-rays are produced. However, some studies of hard x-ray emission from flares which appear to be located just over the limb (McKenzie, 1975; Roy and Datlowe, 1975; Hudson, 1978b) indicate that, in certain cases, part of the hard x-ray emission originates at heights of some tens of thousands of kilometers above the photosphere.

A theory of hard x-ray emission should explain the flux, spectrum, polarization, beaming, and location.

As mentioned in Section 9.2.2, all flares appear to begin with EUV and soft x-ray emission during the "onset phase," and some flares never get beyond this phase. However, all flares which have an impulsive phase seem also to have a "thermal phase" during which emission continues. Soft x-ray and EUV emission is observed during the onset phase, begins during the impulsive phase, and extends into the thermal phase.

A requirement of a flare theory is therefore to explain the time-evolution, flux, and spectrum of soft x-ray and EUV emission at various stages of a flare, realizing that there may be one mechanism for one phase and another for a different phase.

9.3.2  UV and Visible Radiation. The bulk of our information con-cerning solar flares is still obtained by patrol cameras which have been photographing the sun in Hα light every few seconds for many years. The bulk of this radiation must originate from gas at chromospheric temperatures (10,000 to a few times 10,000° K). It appears that the chromosphere is greatly disturbed during a flare leading to greatly enhanced radiation in

lines such as Hα in the visible part of the spectrum and also in UV lines such as Lyα. On rare occasions, flares are visible also in white light. It seems likely that in these cases the chromosphere is very greatly disturbed so that the density of a given temperature level is greatly increased.

Consideration of the UV and visible radiations from flares may therefore be interpreted as the question of determining the change in the chromosphere necessary to explain these radiations and understanding the processes by which these changes occur.

A great deal of information has been derived from the morphology of chromospheric radiation such as Hα light. Viewed in Hα light, the first manifestation of a flare may be two bright "kernels" located close to the magnetic reversal line. Flare kernels typically have much broader wings than later Hα emission, probably indicating that this radiation originates deeper in the atmosphere of the sun. Hence a separate question to be asked of flare models is the distinction between the mechanism for the production of Hα (and other lines) in flare kernels and in other phases of a flare.

Study of the morphology of Hα emitting regions gives a great deal of additional information concerning flares. Some of this has already been discussed in Section 9.2 dealing with primary requirements. Other aspects will be mentioned briefly in Section 9.3.4 dealing with mass flow.

9.3.3 Radio Emission. Radio emissions of wide variety are produced by solar flares, the detailed study of which could well occupy another workshop of comparable manpower and duration. As it was, only limited attention was given to radio bursts, primarily by Team 3 (see Chapter 4). Solar radio bursts have been categorized into five types (Kundu, 1965), the first of which is not specific to flares.

Type II bursts have already been mentioned. It is widely accepted that they are produced by radiation from plasma oscillations, these oscil-

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lations being excited by streams of electrons accelerated in a collision-
free shock front. A major question concerning the shock front is the
following:

Is the shock front which gives rise to a Type II burst a "blast wave"
produced by impulsive energy release, or is it a "bow shock" which forms
ahead of a moving plasmoid?
The answer to this question has important bearing on energy release and/or
mass motion produced by flares.

Type III radio bursts often occur without visible manifestation of
flares, but they also frequently occur at or somewhat before the impulsive
phase of flares. They are attributed to electron beams with energies in
the range 10 to 100 keV moving outward through the corona where they excite
plasma oscillations. Hence the existence of Type III bursts has imposed
one of the primary requirements of flare theory, that is, the requirement
for the acceleration of electrons in the range 10 to 100 keV in such a
location that they can move out through the corona. This implies that,
for these flares at least, either there are open field lines before the
flare occurs, or these open field lines form shortly before the impulsive
phase of the flare. The occurrence of "U-bursts" indicates that, in some
cases, electrons are moving along closed field lines rather than open
field lines, but the scale of these closed field lines appears to be
larger than that of any stable closed loops visible (through eclipse
photographs, etc.) on the sun. This suggests that before Type III bursts
occur there may often--if not typically--be magnetic-field rearrangements
leading to erupting and expanding flux loops, which might indeed become
so expanded that the field lines become esentially "open."

Although details remain to be examined, the mechanism by which electron
streams produce Type III radio bursts appears, in principle, to be under-

stood. Hence these bursts, per se, do not at this time present a major
unsolved problem concerning secondary energy release in solar flares.

There are several types of Type IV radio bursts. Two of these are
stationary and moving meter-wave bursts. These are both attributed to
gyrocyclotron radiation by high-energy electrons (in the MeV range) moving
in magnetic-trap configurations. Electrons responsible for stationary
Type IV bursts are probably contained by mirror-action due to the increase
in magnetic field as one follows flux tubes down to the photosphere.
Moving Type IV bursts may represent electrons trapped in magnetic-field
configurations which are essentially closed. At least one radio burst
(the event of 1969 March 1; Riddle, 1970) appears to have involved a
toroidal magnetic-field configuration. This may or may not be typical of
moving Type IV meter-wave bursts.

Since the radiation mechanism of meter-wave bursts is generally believed
to be the synchrotron process, the main interest concerning meter-wave
bursts is now in its implications for acceleration and for trapping.

Type IV microwave bursts correlate in time very closely with impul-
sive hard x-ray bursts. It seems likely that both are caused by a single
electron stream with energies in the range 10 to 100 keV or more. The
hard x-ray burst is generally attributed to bremsstrahlung as an electron
stream is scattered in the chromosphere and possibly also in the corona.
Hence, Type IV microwave bursts are interesting in that, when information
from them is combined with information from impulsive hard x-ray bursts,
we have a more complete specification of the requirements concerning
electron acceleration during the impulsive phase of solar flares. On the
other hand, our understanding of the spectrum of microwave bursts is a
nontrivial problem (Holt and Ramaty, 1969; Kruger, 1972; Takakura, 1972),
so that analysis of microwave spectra can provide useful information about

conditions in which accelerated electrons may be trapped.

Type III bursts (which typically occur in groups) are often followed by emission, in the same part of the spectrum, which persists for a few minutes. This emission, when it occurs, is called a Type V burst. According to Kundu (1965), there is no accepted interpretation of these bursts. Lacking an interpretation, we cannot stipulate a corresponding requirement of flare models.

An interpretation of Type V bursts can, however, be proposed. We know that the excitation of Type V radio bursts depends upon the development of a two-stream instability. If an electron stream is produced with a well defined velocity, then this beam, together with the coronal electron plasma, can meet a necessary (but not sufficient) condition for two-stream instability, that is, that the one-dimensional velocity distribution function (v) should have a minimum for some value of v (Schmidt, 1966).

However, the acceleration processes which one expects to be operative in astrophysical situations are more likely to produce electron distribution functions which fall off monotonically with $|v|$. Such a distribution, taken together with the near-Maxwellian control distribution, would not satisfy the condition for two-stream instability. However, it was realized some time ago (Baldwin, 1964) that if a symmetrical single-humped distribution is generated instantaneously, the two-stream instability will be satisfied at some distance from the source since the fast electrons will run ahead of the slow ones.

It appears that this model can offer an explanation of both Type III and Type V bursts. If acceleration begins suddenly and continues for a few minutes, there will initially be a strong instability as the fast electrons run ahead of the slow ones. One may attribute the Type III bursts to radiation generated at this "leading edge" of the electron beam.

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If the beam were to continue without any change in intensity or spectrum, no further instability would develop. However, in the more likely case that the beam continues but displays fluctuations in intensity or spectrum, then one must expect that the condition for two-stream instability will be met sporadically, preferentially at large distances from the source. This would then show up as sporadic radiation, similar to Type III radiation, concentrated at lower frequencies than a normal Type III burst.

Inspection of data presented by Kundu (1965) indicates that this inperpretation fits the observational facts reasonably well. Furthermore, some of the Type V spectrographic data show fine structure consistent with the occurrence of a large number of Type III bursts. This fine structure is just as one would expect on the basis of the proposed model.

This interpretation of Type V radio bursts, if correct, has an important implication concerning the number of electrons accelerated during the impulsive phase which escape out through the corona. If one assumes that a Type III radio burst is produced by an electron stream which exists for only a second or a few seconds and then ceases, the number of electrons typically produced by such a burst is quite small, of order $10^{31}$ (Smith, 1979). On the other hand, if one assumes that, as indicated by the above interpretation of Type V bursts, acceleration normally continues for a few minutes, then the number of electrons accelerated during such a stage, which escape through the corona, is increased by a factor of order 100 to about $10^{33}$.

Estimates of the number of electrons escaping into interplanetary space have been made by Lin et al. (1973) who give estimates of order $10^{33}$. This number is inconsistent with the above estimate for Type III bursts, assuming that the electron stream lasts only for a duration of a Type III burst, but is reasonably consistent with estimates based on the above

interpretation of Type V bursts.

9.3.4  Mass Flow.  We have already discussed some aspects of mass flow in Section 9.2.4 as part of the "primary" requirements of a flare model.  There are however other forms of mass flow which seem more appropriately considered as "secondary."

Even before observations were made by means of spacecraft such as Skylab, it was clear that large masses of gas somehow appear at coronal heights as the result of a flare.  Thus observations of limb flares often show extensive and dramatic "loop prominence systems," in which large amounts of gas appear (in Hα) at coronal heights and stream down curved paths which may naturally be interpreted as magnetic field lines.  There is no evidence for such large masses of gas being present in the corona before such a flare.  It follows therefore that this gas is somehow injected into the coronal volume of the active region during the flare, and the only source of such large masses of gas in the lower atmosphere--the chromosphere and (if necessary) the photosphere.

Until spacecraft observations were made, the above interpretation may have been reasonable but it was still conjectural.  However, Skylab observations completely resolved the issue.  Observations made by means of the two x-ray telescopes made it abundantly clear that large masses of hot, dense plasma appear at coronal heights in the course of a typical flare. The temperature is normally several million degrees which explains why the gas is invisible in Hα light.  It becomes visible only if conditions are such that the plasma becomes thermally unstable (Goldsmith, 1971; Antiochos, 1976), in which case "knots" of gas spontaneously cool to a few thousand degrees so that they emit Hα light and, because of the result-ing densification, stream down towards the chromosphere.

Hence it is now clear that, during a typical flare, mass first flows

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from the chromosphere into the corona and subsequently flows back down to
the chromosphere. It is believed that such mass flow occurs as a natural
consequence of sudden energy release at chromospheric levels, by a process
which has been termed "chromospheric evaporation" (Neupert, 1968; Hudson
and Ohki, 1972; Chapter 7, Chapter 8). It is believed that such upward
mass flow can occur either as a result of bombardment of the chromosphere
by energetic particles or through the conduction of large amounts of heat
from the corona to the chromosphere. Although bombardment of the chromo-
sphere by high-energy particles is likely to occur only during the impul-
sive phase, heat conduction will occur as long as the coronal plasma can-
not get rid of its energy by radiation, and therefore may extend long
after the impulsive phase has ended.

According to current theory, the requirements on a flare model for
the production of chromospheric evaporation seem not to be stringent:
sudd    release of energy at coronal heights in almost any form appears
adequate for the production of such transfer of mass from the chromosphere
into the corona.

Another form of mass flow which frequently occurs in association with
flares (but sometimes occurs without flares) is the surge (Svestka, 1976,
p. 221). Surges are visible in Hα light and other chromospheric-type
lines, and there is no evidence for strong heating. Surges often occur
at "satellite sunspots" (Rust, 1968; Roy, 1973), and surge activity ceases
when the satellite sunspot finally disappears. Flare activity may or may
not be associated with the surges.

It is possible that surges are due to some mechanism which may occur
during a flare, but could also occur when no flare is in progress. However,
it is also possible that a surge is an independent phenomenon, giving rise
to changes in the magnetic field which may sometimes lead to magnetic-

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field conditions appropriate for the occurrence of flares.

A basic question concerning surges is whether the mass flow is driven by a pressure gradient or by magnetic forces, in which case it might be attributed either to magnetic pressure or to magnetic tension. This question must be answered in order to determine a requirement on flare models. The relationship between surges and satellite sunspots suggests that the driving force is magnetic. Possibly a magnetic group of field lines are "hooked" into the photosphere; then flare action may occur in this current-carrying magnetic-field configuration (Sturrock, 1972). This scenario for surge-related flares is closely related to the "emerging-flux" model of solar flares to be discussed in Section 9.4.5.

9.4 Models

9.4.1 Gold-Hoyle Model. It is interesting to consider a model proposed some time ago by Gold and Hoyle (1960) since it is the earliest model which comes close to meeting the primary requirements set out in Section 9.2. In a sense, it may be viewed as the first "modern" model of solar flares.

The basic form of the model is shown in Figure 9.1. The model comprises a pair of twisted flux tubes in proximity to each other. The sense of the longitudinal field is different in the two tubes, but the sense of the toroidal field is the same. Hence the electric current responsible for the toroidal component is in the same direction in both flux tubes. It is argued that, if the two filaments remain pressed together for a length of time, they must begin to penetrate into each other. Interpenetration tends to augment the toroidal component and annihilate the longitudinal component, so that toroidal magnetic-field linkage occurs which tends to produce the "pinch effect." The field and current configuration which exists between the two flux tubes would not be termed a "current sheet";

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hence the Gold-Hoyle model is closely related to models such as those discussed in Section 9.4.3.

It is recognized clearly by Gold and Hoyle that there must be a process producing a catastrophic effect. This means that the axial parts of the filaments, where the fields are most intense, must approach each other at an increasing rate. Gold and Hoyle further realized that this requires a rapid increase in the diffusivity which is equivalent to a rapid increase in electrical resistivity or a rapid decrease in the electrical conductivity. At this point, Gold and Hoyle quote the following formula for the conductivity of a plasma in the presence of a magnetic field of strength B:

$$\sigma = 10^{-32} c^2 n^2 x B^{-2} \qquad (9.4.1)$$

where n is the number density of ions and atoms and x is the degree of ionization. It is clear that Gold and Hoyle are considering conditions in the chromosphere. This formula represents the conductivity coefficient which gives the current parallel to an electric field produced in the plasma when the electric field is orthogonal to the magnetic field. However, linkage of magnetic field requires the development of neutral points at which $\vec{B} = 0$ and the conductivity at these points is not given by the above formula. In the case that reconnection occurs where $\vec{B} \neq 0$, there is a current parallel to B which is driven by an electric field parallel to B. Hence the formula adopted by Gold and Hoyle does not fit with the present-day concept of the mechanism of magnetic field reconnection, as developed for instance by Furth, Killeen, and Rosenbluth (1963). Hence it is worthwhile to consider how the Gold-Hoyle model compares with the primary requirements set out in Section 9.3, realizing that our understanding of the reconnection process has improved since Gold and Hoyle originally developed their model.

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The basic requirement of energy storage set out in Section 9.2.1 is met by their model, although Gold and Hoyle imagine that the storage occurs at chromospheric heights rather than coronal heights. However, their model requires a quadrupolar field pattern at the photosphere, whereas we know that flares can occur in situations which are basically bipolar. That is, the Gold-Hoyle model does not meet the requirement of a general model that it should be possible for flares to occur in a bipolar configuration.

We have already discussed the question of energy release and noted that Gold and Hoyle realized the requirements but do not propose what would nowadays be an acceptable mechanism. Gold and Hoyle were implicitly attempting to explain only the rapid impulsive phase of a flare, probably being unaware of the prevalent slower onset phase or of the occasional slow phase.

There was no discussion of acceleration or of mass ejection or of possible photospheric heating in the Gold-Hoyle presentation, since these requirements were not realized at that time. It seems unlikely, but not impossible, that acceleration of particles to high energy can occur at chromospheric densities. Studies (Mogro-Campero and Simpson, 1972; Cartwright and Mogro-Campero, 1972) of the abundances of ions accelerated during solar flares indicates that, before acceleration, the particles are in a plasma with a temperature of some millions of degrees, necessarily at coronal height. Nevertheless, there is no reason why a model of the form proposed by Gold and Hoyle could not extend into the corona.

Gold and Hoyle did not discuss the magnetohydrodynamic effects of their reconnection process, but there is nothing in the model which would obviously lead to an explosion with a sudden ejection of material. The model therefore appears not to be compatible with known ejection phenomena.

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To sum up, the Gold-Hoyle model was an important advance on previous ideas in suggesting a specific magnetic-field configuration and emphasizing that a flare might basically be an explosive reconnection of magnetic field. There certainly exist flares which occur in basically bipolar configurations which are incompatible with the Gold-Hoyle model. On the other hand, it is possible that some class of flares do occur in a configuration not unlike that proposed by Gold and Hoyle. (See, for instance, the "emerging flux" models discussed in Section 9.4.5.)

9.4.2 Alfven-Carlqvist Model. The short article by Alfven and Carlqvist (1967) represents an important contribution to developing ideas of solar flares. The authors emphasize the role of currents in the sun's atmosphere and state clearly that the problem of rapid energy release is equivalent to the problem of rapid current dissipation. Another important lesson in the Alfven-Carlqvist article is that it stresses the importance of the current circuit: the problem is not simply one of the in situ dissipation of magnetic energy; rather, one should look for the localized release of energy stored over a large volume.

The analogy made by Alfven and Carlqvist is that of energy release in a circuit containing a mercury-vapor rectifier. The plasma in the rectifier can, under certain conditions, make a sudden transition from a highly conducting to a highly resistive state. When this occurs, energy stored in the inductance leads to arcing, that is the development of very high electric potentials, which leads to the breakdown of a circuit element parallel to the rectifier. The details of the rectifier operation are not relevant to conditions which would occur in the sun's atmosphere. Alfven and Carlqvist (1967) and more recently Carlqvist (1972) argue that, if the current density in the sun's atmosphere exceeds a critical value, an ion-acoustic instability will develop which leads to a sudden increase

in the resistivity of the plasma. This sudden increase in resistivity necessarily leads to the development of high electric fields in order to maintain (or attempt to maintain) the original current. This region (or regions) may develop into a "double layer" (or array of double layers) in which stored magnetic energy goes to accelerate large numbers of electrons and/or ions. (Concerning double layers, see for instance the review by Goertz, 1978.)

In comparing the Alfven-Carlqvist model with the primary requirements set out earlier in this chapter, we find that energy is stored, as required, in a current-carrying coronal magnetic field. Furthermore, it is possible for the topology to be that of a simple dipole or something more complex.

In considering the energy release requirements, we note that Alfven and Carlqvist consider only a rapid stage of energy release which is presumably to be identified with the impulsive phase. There is no discussion of a slower onset phase or of a slow late phase. If the sudden change of state of the plasma occurs in a single localized region, it is difficult to see how an onset phase can fit into their model. If on the other hand the anomalous regions permitting the dissipation of magnetic energy are many in number, building up in the form of a cascade, then we might interpret the onset phase as the creation of more and more regions of localized dissipation, and the impulsive phase as the "avalanche" which occurs when the number of dissipation regions reaches saturation. Since the potential developed across a double layer is limited to a few times the thermal energy, there must be very many double layers in the flare region if energy release is to occur by double-layer formation.

Although the mercury rectifier circuit is known to be explosively unstable, it does not follow that the solar model proposed by Alfven and Carlqvist will also manifest an explosive instability. An ion acoustic

instability is a special form of a two-stream instability which is typi-
cally nonexplosive (Sturrock, 1966a). Hence the Alfven-Carlqvist model,
in its present form, appears not to meet this requirement. Alfven and
Carlqvist stress that the development of regions of high resistivity will
tend to promote acceleration and this point seems well taken. It is not
so clear (but it may be true) that the energy release may on some occa-
sions produce heating (Maxwellian distributions) rather than power-law
electron beams. It does not seem at all likely that the configuration
which they propose could convert a large fraction of the energy released
during the flare into mass motion, as is required to explain some flares.

The Alfven-Carlqvist model involves only one phase of particle accel-
eration. They propose that both electrons and ions may be accelerated at
the same time in the same region. This does not fit with the current
concepts concerning "first phase acceleration" and "second phase acceler-
ation," but (as we have already discussed) it is not clear that these
concepts are well founded. If data indicate that acceleration typically
takes place in one phase only, this would be supportive of the general
ideas advanced by Alfven and Carlqvist. On the other hand, they consider
only closed field configurations so that there is nothing in the model,
as proposed, which permits easy escape of electrons or ions into inter-
planetary space. Hence their model, if valid, must be restricted to flares
which do not manifest "particle events."

Alfven and Carlqvist did not consider energy release at photospheric
levels, since it was not clear at that time that such release might occur.
Even at this time, it is not certain that a mechanism for released energy
at photospheric levels is definitely required.

9.4.3 Closed Current Sheet Models. One class of flare models involves
current sheets which form between two or more sets of closed magnetic

field lines. The most detailed analysis of this situation appears to be that of Syrovatskii, and we therefore begin by a discussion of his model. Syrovatskii has in recent years developed his model of solar flares in a series of articles (Syrovatskii, 1966, 1969; Somov and Syrovatskii, 1977). This model is based on the formation and decay of a current sheet near a magnetic null line or surface. In this respect, it is similar to the model proposed by Sweet (1958a,b) who proposed that flares occur as two distinct flux systems move into proximity. This leads to the development of a magnetic field configuration such as that shown in Figure 9.2. It is argued that the high electrical conductivity of the coronal plasma prevents the magnetic field from adopting the minimum-energy state (i.e., a potential field) and instead develops a thin boundary with a current sheet. Sweet argued, from a hydrodynamic analogy, that such a configuration can become unstable. It was argued that, when this occurs, a very thin layer (the "collision layer") forms sufficiently thin that rapid reconnection occurs in a quasi-steady state. Petschek (1964), in an important paper on the theory of solar flares, developed a model of the reconnection process indicating that reconnection could occur at a fraction of the Alfven speed. There have been extensive further studies of this possible quasi-steady reconnection process.

Syrovatskii emphasizes that the flare problem is basically an instability problem: one must consider a stationary plasma-field configuration, or one which is evolving very slowly in time, and understand how it can suddenly develop into a state of rapid energy release. Syrovatskii therefore considers the time-evolution of conditions in a current sheet rather than the steady-state reconnection process of Petschek.

Syrovatskii argues that, if reconnection occurs, the sheet becomes progressively wider and thinner, and the density of plasma in the sheet

becomes progressively lower. If the density becomes low enough, the electron velocity required to carry the current in the sheet may be high enough to excite the ion-acoustic instability. This would give rise to plasma heating and to the acceleration of some particles. If the density becomes lower still, the displacement current may become more important than the electron current. In this case, Syrovatskii argues that there would be a "rupture" of the current sheet with the development of a pulsed electric field and acceleration of particles to high energies, possibly ultrarelativistic energies. However, Syrovatskii envisages that at any instant these critical conditions are likely to be met only in a number of localized regions rather than throughout the current sheet. This concept has an important bearing also on Syrovatskii's views on acceleration. He points out that, if particles of very high energy are to be produced, it is essential that only a small fraction of particles in the flare region be subjected to the acceleration process. There are two ways in which this could occur: one possibility is that acceleration occurs throughout a large volume but there is a "selection mechanism" such that only a small fraction of particles are accelerated, due possibly to their mass, charge, or initial energy. Another possibility is that the acceleration is inhomogeneous in space: in this situation, a large fraction of the particles in a small part of the volume will be accelerated to high energies. Syrovatskii considers that both of these processes may occur within the context of his model, the latter process occurring near regions of current-sheet rupture, and the former process occurring in a larger volume due to the generation of plasma turbulence of some type.

We now compare Syrovatskii's model against the requirements set out in Section 9.2. As with all other models here considered, the energy released during a flare is ascribed to a current-carrying coronal magnetic

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field.  However, Syrovatskii's model can account for more than one stage
of energy release.  Syrovatskii interprets the slow onset phase as the
stage of energy release in which ion-acoustic instability develops in the
current sheet.  He interprets the rapid impulsive phase as one in which
current sheet "rupture" occurs leading to a much more rapid process and
stronger acceleration.  There is no analog to the "late phase" in his model.
Syrovatskii claims that the possible transition from one process to the
other meets the requirement that flares be explosive in nature.  Although
plasma flow occurs in the Syrovatskii model, it is not demonstrated that
a major fraction of the energy released during a flare can go into mass
motion.  He does however argue that a considerable fraction can go into
heat and into high-energy particles.

Syrovatskii's comments concerning acceleration seem to meet require-
ments as now indicated by gamma-ray data.  Syrovatskii envisages that there
are two acceleration processes which can, however, proceed substantially
in the same volume and presumably at the same time.  There is strong accel-
eration in small regions where current-sheet rupture is occurring which may
meet the needs of "first phase" acceleration.  In addition, the region may
be in a turbulent state so that stochastic acceleration can occur, meeting
the requirements of "second phase" acceleration.  There is no discussion of
escape of high-energy particles into the outer corona or into interplanetary
space.

Syrovatskii does not discuss mass ejection nor heating of the temperature-
minimum region.  It is quite possible that Syrovatskii's ideas, in the
context of appropriate more specific magnetic-field configurations, could
lead to mass ejection and/or to temperature minimum heating.

A recent development concerning a theory of closed-current-sheet
models of flares is discussed in Chapter 3.  Uchida and Sakurai (1977)

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have noted that a current-sheet configuration is likely to be unstable to the MHD interchange mode and point out that, if this occurs, it will have important effects in itself and will have a very strong influence on the reconnection rate.

In their picture, the slow reconnection which might occur without the interchange instability would correspond to the onset phase of a flare. If, at some stage, the interchange instability occurs, it will develop rapid bulk motion and the dissipation of this motion will lead to a sudden heating of the plasma. This process is identified with the impulsive phase of a flare. Subsequent to the interchange instability reconnection should continue at an enhanced rate due to the folded geometry of the current sheet, and this process is taken to be the explanation of what they term the "quiet thermal phase," which we have termed the "late phase."

In comparing the Uchida-Sakurai model with the primary requirement set out in Section 9.2, we see that energy storage is again attributed to a current-carrying coronal magnetic field. We also see that there are possible explanations for the three phases of a flare. It is not clear that the onset of instability will be explosive, but the nature of the interchange instability is such that a large fraction of the energy released should go into mass motion.

The main defect in the simple version of the theory is that it does not provide for particle acceleration--either of electrons or of ions. Since reconnection occurs in their model, one would expect on the basis of the work of Syrovatskii, for instance, that acceleration will occur. However, observational data indicates that much of the acceleration occurs during the impulsive phase, but the Uchida-Sakurai model does not involve a great release of energy by reconnection during this phase.

It is clearly important to determine whether the interchange instability

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will occur in the vicinity of a current sheet, such as that envisaged by Syrovatskii or by Uchida and Sakurai. If it does, one needs to know the dynamical effects of this instability but it would also be necessary to reconsider the model developed by Syrovatskii to take account of the change in the magnetic-field configuration of the current sheet due to the interchange instability.

9.4.4 Open-Field Models. Models which have been discussed so far involve only closed magnetic-field configurations. As we have noticed in discussing these models, it is difficult to understand particle events in such a context since particles, if accelerated in such a configuration, would find it difficult to escape into interplanetary space: they would tend to remain trapped in the closed-field configuration. It is possible that flares may occur in closed-field geometries in which acceleration takes place and the particles remain trapped for a certain length of time but, in the course of the flare, magnetic field lines expand and weaken in strength so that eventually particles may effectively escape from the system of field lines on which they were accelerated. It is known that there is a close correlation between the particle events on the one hand and Type IV bursts and moving Type II radio bursts, on the other hand. The latter may be attributed to an outward moving plasmoid and the shock which it generates, which may both develop by means of the expansion of a closed magnetic-field configuration. On the other hand, this plasmoid may arise from an initially open magnetic-field configuration. The most direct evidence that some flares involve initially open field configurations comes from the fact that many flares involve Type III radio bursts. These are attributed to electron streams propagating out through the corona-- necessarily on magnetic field lines. Since Type III bursts occur at the very beginning of a flare and have durations of seconds only, these bursts

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provide evidence that some flares, at least, occur in magnetic-field configurations which are partially open.

It appears that the first flare model involving an open-field configuration was that proposed by Carmichael in a paper submitted for presentation at the AAS-NASA Symposium on Solar Flares held at Goddard Space Flight Center in 1963 but not given because of shortage of time. However, the paper (Carmichael, 1964) was included in the published proceedings of the conference. Carmichael proposed that magnetic field lines extending high above the photosphere could be forced open by the solar wind (Figure 9.3). A similar configuration (Figure 9.4) was proposed by Sturrock (1966b, 1967, 1972, 1974b) who also proposed that the free energy of the open-field system is derived from the nonthermal energy source which heats the corona and drives the solar wind.

There are certain difficulties with the assumption that a pre-flare open-field configuration is formed either by the solar wind or by coronal heating. First, we note that the magnetic field would open only if the plasma stress were to exceed the magnetic stress. Since the plasma pressure in an active region does not rise much above 1 dyne $cm^{-2}$, the plasma pressure could not force open magnetic field of more than a few gauss in strength. This would make it impossible for the Y-type neutral point, which marks the transition from closed to open field lines, to be situated low in the sun's atmosphere where the field strength may be of order $10^2$ or $10^3$ gauss. On the other hand, some energetic flares are so compact that the Y-type point, if it exists, must be quite low in the atmosphere.

The second difficulty occurs in the context of "homologous" sequences of flares which are regularly spaced in time and quite similar in form (Ellison, 1963). The implication seems to be that the magnetic-field configuration which is disrupted during a flare is reformed by the time of

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the next flare. In consequence, the energy released during one flare must be replaced before the next flare occurs. The interval between flares in such sequences increases with importance of the flares, being approximately one day or $10^5$s for flares of importance 3. Since such flares are likely to cover an area of $10^{20}$cm$^2$ and release about $10^{32}$erg, we see there is an energy flux of $10^7$ erg cm$^{-2}$s$^{-1}$ is required to provide the flare energy. This requirement exceeds, by a factor of approximately 100, the energy flux required to heat the quiet corona and drive the solar wind (Athay, 1976). However, it is possible that the energy flux into the coronal volume of an active region may be f order $10^7$ erg cm$^{-2}$s$^{-1}$ (Withbroe and Noyes, 1977). If the flux is that high, the energy released during a flare may indeed be derived from the nonthermal energy flux which heats the corona. If it is not, some other energy source is required to provide the free energy released during a flare.

It was for these reasons that Barnes and Sturrock (1972) proposed an alternative process leading to the formation of open-field configurations. They considered the possible evolution of a closed force-free magnetic-field configuration as the field becomes more and more stressed due to photospheric motion. Their particular example was a simple case of cylindrical symmetry produced by a hypothetical disk of one magnetic polarity surrounded by a ring of opposite polarity. As the ring is rotated with respect to the disk, the field pattern expands and the total energy in the field increases. It was found that after a rotation of about half a complete revolution, the force-free field contains as much energy as the corresponding open-field configuration with the same distribution of magnetic flux at the photosphere. For larger rotations, the force-free field contains more energy than the corresponding open field. Hence, from these purely energetic considerations, it appears that the force-free field must at some point either be unstable or metastable since energy would be

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released if the field were to make a transition permitted within the context of MHD theory. If such an eruption were to occur, it would necessarily lead to an open field configuration. Since such configurations are believed to exist within coronal streamers (Sturrock and Smith, 1968), it seems clear that open current sheets can persist for some length of time. On the other hand, the open current sheet may reconnect by the tearing-mode process: if this were to occur at all, it seems most likely that it would occur as soon as the current sheet comes into existence, since it would then be thinnest and subject to fluctuations likely to trigger the instability.

These considerations therefore led to a rather more complex interpretation of the flare process. The preflare state comprises a magnetic-field configuration which is comprised mainly of closed magnetic flux, although some of the field-lines may already be open. Photospheric motions stress the field, which maintains a force-free state with steadily increasing energy. At some stage, the configuration is subject to an MHD instability (which may or may not need triggering) which leads to the eruption of some or all of the closed magnetic flux. This eruption leads to the formation of current sheets which are then subject to the tearing-mode instability leading to reconnection. Reconnection in such a configuration explains very naturally the formation of a detached plasmoid. Since the magnetic energy of both the plasmoid and the surrounding magnetic field decreases as the plasmoid moves out and expands, the plasmoid must be subject to a magnetic force driving it away from the sun. This is the "melon-seed" effect discussed some time ago by Schlüter (1957).

This model may now be compared against the primary flare requirements set out in Section 9.2. It is not yet clear whether or not the model can satisfactorily explain the three stages of energy release. In the event that eruption and reconnection occur almost contemporaneously, the onset phase may be associated with the MHD processes which occur between the

initiation of the MHD instability and the development of a current sheet. Then the rapid impulsive phase is due to the faster energy release by magnetic-field reconnection which occurs after the current sheet has formed.

It is possible, however, that these two phases both occur as stages of energy release after the current sheet is formed. The reconnection process may involve the development of a large number of localized regions in which anomalous processes occur [such as double layers (Goetz, 1978) or regions of ion-acoustic instability (Stix, 1962)]. Then the onset phase represents the development of larger and larger numbers of such regions by means of a cascade. When the number has reached the saturation value, the energy release rate is at a maximum, representing the impulsive phase. The latter interpretation is more easily reconciled with the high-temperature plasma formed during the onset phase, as is made evident by soft x-ray emission.

The slow late phase may possibly be due to continued reconnection occurring at the rate set by the MHD eruption process. On the other hand, it may be due to a change in coronal density. The reconnection rate is set by the Alfven speed which varies inversely as the square root of the density. It is believed that the coronal plasma density increases by a factor of $10^2$ to $10^4$. This leads to a reduction of the reconnection rate by a factor of 10 to $10^2$. This is sufficient to explain the reduction of energy release rate in going from the impulsive phase to the slow late phase.

However, it is not easy to understand how the density can be increased in the region of magnetic-field lines which have not yet reconnected. The most likely explanation seems to be that x-ray emission from the high-temperature plasma in shells which have already reconnected leads to heating of the nearby chromosphere. This x-ray heating can drive evaporation

along field lines which have not yet reconnected.

We have already noted that mass motion occurs quite naturally in this model. Furthermore when reconnection occurs, either contemporaneously with field-eruption or in a quiescent open-field configuration, there results a plasma-field configuration which will be driven away from the sun by magnetic pressure, magnetic tension, or a combination of the two [Figure 9.3(c)].

Since magnetic-field reconnection plays a key role in this model, one expects that acceleration will occur (possibly two stages of acceleration) as earlier discussed in the context of Syrovatskii's model. However, it should be noted that accelerated particles can escape into interplanetary space more easily in the context of the present model than in the context of a closed-field model. If the flare occurs in a magnetic-field configuration which is initially open, particles may stream out along the open field lines. If, on the other hand, acceleration occurs in a localized current sheet in an erupting magnetic-field configuration, particles may escape as the disconnected plasmoid moves out into interplanetary space.

We have already seen that the present model offers a natural explanation for the ejection of plasmoids into interplanetary space. However, one needs to understand why only a small fraction of flares produce such ejecta. There are two possibilities: (a) the majority of flares may produce ejecta which are too small (in terms of mass and energy) to be detected; or (b) only a small fraction of flares occur in an open field configuration. Since only a small fraction of flares give rise to particle events, interpretation (b) seems preferable to interpretation (a).

It is also easy to associate flares with filament eruptions in the context of this model. The eruption of a filament is almost certainly due to magnetic forces, the energy required to eject the gas in a filament

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being derived from the magnetic free energy associated with coronal currents. Hence the association of filament eruptions with flares fits neatly with the version of the model in which a closed magnetic-field configuration erupts and, in so doing, leads to the development of current sheets which then reconnect to produce the flare. The fact that some filament eruptions are not accompanied by flares may simply be interpreted as the case in which significant reconnection does not occur in the current sheet. If this interpretation is correct, such filament eruptions should typically lead to the formation of open current sheets which may be visible as coronal streamers.

Since a filament already contains a large amount of gas, the gas contained in the ejected plasmoid may simply be the gas originally present in the filament. However, in considering a possible interpretation of the transition from the rapid impulsive phase to the slow late phase, we noted the possibility that x-ray heating of the chromosphere leads to the evaporation of chromospheric gas into regions of the magnetic field which have not yet reconnected. If this process does indeed occur, it would provide the necessary transfer of mass from the chromosphere into the corona where, after reconnection, it would be trapped in a closed plasmoid which is then ejected into interplanetary space. When a flare "spray" occurs, one is observing gas of chromospheric temperature since it is emitting Hα light; it is therefore likely that this gas had its origin in a quiescent prominence. On the other hand, a coronal transient is seen by continuum radiation scattered by electrons, and typically shows little or no Hα emission so that the gas is probably at coronal temperatures (Poland and Munro, 1976); this case is more naturally interpreted in terms of the evaporation process.

One may understand temperature minimum heating in the context of the

present model, as in any other current-sheet model: if reconnection tends to develop a high current density in the corona, it will do the same at the top of the photosphere so that temperature minimum heating may be attributed to Joule heating.

A variant of the above model has been proposed by Kopp and Pneuman (1976) as an explanation of loop prominence systems. They consider the hydrodynamic effects of the closing of a system of open field lines by field-line reconnection. Their assumption is that field lines are opened either by prominence eruption or by a flare, and that there is a high outward flux of energy and mass while the field lines are open due to an enhancement of the normal solar-wind mechanism. When lines close, there is a sudden stoppage of this outflow which leads to an increase in the temperature and density, each increasing by a factor of about two (Figure 9.5).

In its gross outline, this model is similar to the slow late phase of the open-field model discussed earlier in this section. However, there are the following differences:

(a) The energy supply in the Kopp-Pneuman model is the normal non-thermal input into the corona; energy is not derived from field-line reconnection.

(b) The mass supply is derived from the outflow of solar wind, not from chromospheric evaporation.

Since loop prominence systems show up in $H\alpha$ light, they involve lumps of gas at chromospheric temperature. This points towards a thermal insta-bility in a hot, dense gas at coronal heights. The analysis of Antiochos (1976) shows that such an instability can occur in the hot, dense flare plasma responsible for the long-lived soft x-ray emission from flares. The Kopp-Pneuman model would lead to temperature of only $4.10^6$K at a density of order $10^9 cm^{-3}$; the temperatures proposed by Kopp and Pneuman are certainly

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too low to account for the soft x-ray emission from flares.

The Kopp-Pneuman model requires a very large nonthermal energy flux into the corona of order $10^7$ erg cm$^{-2}$ s$^{-1}$. Even if only 10% of the sun's surface is coupled into interplanetary space through open field lines, this would give an energy flux at the earth much larger than is observed. Current estimates of the nonthermal energy flux into the corona are of order $10^5$- $10^6$ erg cm$^{-2}$ s$^{-1}$ (Athay, 1976). The Kopp-Pneuman model implies that there should be an association between high-mass-flux solar-wind streams and active regions. However, we have learned (Zirker, 1977), that such streams are in fact associated with coronal holes which are regions of low coronal density and weak magnetic field. It is also notable that there is a conflict between most flare theories and the Kopp-Pneuman model in that the former consider that magnetic-field reconnection leads to a release of magnetic energy, whereas the latter consider that such energy release is negligible.

9.4.5 Emerging Flux Model. In a series of papers (Priest and Heyvaerts, 1974; Canfield et al., 1974; Heyvaerts et al., 1977; Tur and Priest, 1978) Heyvaerts and Priest, with collaborators, have developed a model of solar flares which explicitly takes cognizance of the importance of emerging magnetic flux in flare activity. When new flux emerges in a quiet region, it produces x-ray faculae or "bright points," which sometimes suffer tiny flares; when new flux emerges near a sunspot, reversed-polarity elements called "satellites" appear which are the focus of surge and flare activity. The basic concept is that current sheets develop between the newly emerging flux and the pre-existing flux, and that mechanisms occur in the current sheets to produce various aspects of flare activity, as summarized in Figure 9.6. The discussion in this section follows most closely the article by Heyvaerts, Priest, and Rust (1977).

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If new magnetic flux emerges into a pre-existing magnetic-field configuration, one expects at least one current sheet to develop. The authors investigate the possible state of such a current sheet, assuming that steady reconnection is occurring and taking into account the energy equation which determines the temperature of the plasma in the current sheet. From this analysis, they determine an equilibrium temperature as a function of the height of the sheet (see Figure 9.7). This analysis indicates that, if the sheet rises to a certain height, there will be no neighboring equilibrium situation, implying that there will be a sudden increase in temperature, corresponding to the jump from boint B to point D in the diagram. This analysis indicates that the configuration is subject to a thermal instability, and that the onset of this instability is "explosive" (Sturrock, 1966a). Since the pressure of plasma in the current sheet balances the pressure of the adjacent magnetic field, the density of the plasma will decrease as the temperature increases. This leads to an increase in the drift-speed of the current-carrying electrons, which can eventually lead to a two-stream instability of the Buneman (1958a,b) type. For typical parameters, the authors find that this critical condition is passed as the current sheet makes a transition from B to D.

The development of turbulence due to micro-instabilities leads to a sudden increase in the magnetic diffusivity, as a result of which the current sheet rapidly expands. During this sudden expansion, strong electric fields develop which lead to the runaway acceleration of electrons. In this process, however, the scattering is due to the ion-acoustic turbulence rather than Coulomb collisions. The authors draw a distinction between the "impulsive" phase and the "flash" or "explosive" phase. The former is attributed to sudden electron acceleration leading to impulsive hard x-ray emission; the latter is due to the sudden expansion of the current sheet.

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In their model, these normally occur in close association, but the impulsive phase may precede the flash phase or vice versa.

Heyvaerts, Priest, and Rust consider that, after the sudden change in state of the current sheet, reconnection will proceed faster than in the preflare phase: this stage is interpreted as the "main phase" of a flare. In the case of a simple loop flare, energy released during the main phase is still attributed to the slow emergence of magnetic flux. However, in the case that the flare is a "two-ribbon" type, the authors propose that the activity described above "triggers" the release of energy of a non-potential sheared magnetic-field configuration, and that this release of pre-existing magnetic free energy constitutes the "main phase" of such a flare (see Figure 9.8).

In comparing this model with the primary requirements set out in Section 9.2, we first note that it differs notably from the normal viewpoint concerning energy supply. The normal view is that there is a pre-existing state containing magnetic free energy which is metastable. The view of Heyvaerts, Priest, and Rust is that the energy released in most solar flares is due to the sudden transport of magnetic energy from below the photosphere to above it. One needs a more detailed comparison of the change of the photospheric magnetic-field pattern in relation to flares to determine whether the rate of change of magnetic fields is sufficiently rapid to explain the rate of energy released during the preflare phase, and whether the rapid acceleration of energy release during the preflare phase is due to an acceleration in the rate of emergence of magnetic flux. As noted above, Heyvaerts, Priest, and Rust do attribute the main phase of a two-ribbon flare to the release of magnetic free energy; in addition, their attribution of the impulsive phase to a sudden expansion of the current sheet implies that, during this phase, energy is being released

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rapidly from the free energy of the magnetic field configuration comprising the preexisting flux and the newly emerging flux. On the other hand, they attribute the main phase of a simple flare again to the release of magnetic energy as new flux continues to emerge.

Another requirement was that the model should provide for two or three stages of energy release, corresponding to the preflare phase, the impulsive phase, and the late phase. The present model meets this requirement.

Another requirement is that the model should provide for acceleration and/or heating. The authors provide for heating during all three phases, and argue that electron acceleration would occur, specifically during the impulsive phase. However there is no discussion of ion acceleration so it is not clear whether or not this part of the requirement would be met. The model does provide for the possible access of particles to open magnetic field lines since some of the preexisting magnetic flux may be open and the eruption of a filament may lead to an open field configuration. In this respect, the model is similar to that discussed in the previous section.

There is no discussion of the ejection of mass, except to recognize that the eruption of a filament would lead to the ejection of mass originally supported by the filamentary magnetic field. As has been argued earlier in this chapter, it seems likely that the eruption of a filament can explain mass ejection events in which the gas is at chromospheric temperatures (such as flare sprays), but it does not seem likely that filament eruptions can explain ejecta in which the gas is at coronal temperature. However, if these events do require chromospheric evaporation, this evaporation could occur just as well in the context of the emerging flux model as in previous models.

Major questions concerning this model which need to be resolved are the following:

(a)  Does the preflare phase represent the dissipation of newly emerging magnetic energy, or does it represent an early phase in the development of instability in a possibly quiescent plasma-magnetic-field configuration?

(b)  Does the thermal instability discussed by Heyvaerts, Priest, and Rust (1977) occur and, if so, does it play a key role in the flare phenomenon?

9.4.6  Spicer and Colgate Models.  Spicer (1977a,b) has recently developed in great detail a model which has some similarities to that proposed by Alfven and Carlqvist (Section 9.4.2).  Both models are based on plasma processes which can occur in a twisted current-carrying flux tube.  The first primary requirement, that of energy storage by a current carrying coronal magnetic field, is therefore satisfied.

Spicer's model provides for various modes of energy release which can be related to the apparently distinct phases of solar flares.  For instance, Spicer points out that a "super heating" instability can occur in the presence of magnetic shear, and that this will tend not only to increase the temperature of the plasma but also to increase the current density. This process may be responsible for the onset phase of a solar flare in which the temperature of the coronal plasma apparently increases and conditions (such as an increase in current density) develop which lead eventually to a more rapid process for energy release.

It is possible that energy release can occur by mechanisms which will lead to a "thermal" flare.  In particular, the tearing-mode instability can occur under conditions where it is dominated by classical resistivity. There may also be an electrostatically unstable current occurring in some singular layers which also will give rise to heating of the coronal plasma. Such conditions need not occur along the whole length of an arch, but may

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exist only in well localized regions. Nevertheless, the heating would rapidly extend over the entire length of the flux tube.

It is also possible that the flux tube may be subject to a combination of MHD and resistive instabilities, such as appear to occur in Tokamak laboratory plasma experiments. It appears that the development of an MHD instability, specifically the kink instability, may promote conditions for a resistive instability, specifically the resistive kink instability, and vice versa. When this situation arises, the energy release rate may display periodic fluctuations. This may be related to periodicity in x-ray and microwave bursts produced by flares. The nonlinear interaction between various modes of instability leads to much more rapid growth rates, and therefore to more rapid energy release. Hence the impulsive phase of a flare may be understood, within the context of Spicer's theory, as a stage in which such nonlinear interaction occurs, leading both to rapid energy release and also possibly to periodicity.

There is apparently no discussion of a slow late phase in Spicer's theory, but it is possible that conditions for the nonlinear interaction of modes occurs only for a limited length of time, and the flare then reverts to the simpler mode of energy release which leads to a "thermal" flare.

Since the impulsive phase of flares is attributed to nonlinear processes, it can quite naturally explain the fact that this stage is "explosive."

Since the instabilities discussed by Spicer will naturally lead to the development of regions in which electric field is parallel to the magnetic field, it can give rise to particle acceleration. Spicer discusses primarily electron acceleration, and it is not clear whether or not appreciable ion acceleration would occur. Since Spicer's model basically involves closed magnetic field lines, it does not provide for the rapid escape of particles, as would be required to explain Type III radio bursts or prompt particle

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events. On the other hand, as we see from Figure 9.9, Spicer imagines that some of the closed magnetic field may expand as a result of the plasma-field reorganization due to the MHD kink instability. If this occurs, it would permit delayed escape of accelerated particles. In addition, it would lead to mass motions and the formation of a shock front; it might also lead to the ejection of a plasmoid from the flare region.

It appears that Spicer's model is sufficiently complex and sufficiently flexible to explain many of the phenomena which are characteristic of solar flares. Since one class of flares appears in fact to involve closed flux tubes, it seems very likely that a model such as that foreseen by Alfven and Carlqvist, and developed in more detail by Spicer, might meet the primary requirements of this category of flare.

Colgate (1978) has developed ideas which, as he points out, are very similar to those advanced by Spicer. He also considers that energy may be stored in a single twisted magnetic flux tube and that dissipation may occur throughout the volume of the tube. As seen in Figure 9.10, Colgate envisages that, in the course of the flare, an initially closed flux tube may become open allowing the ejection of particles and plasma into inter-planetary space. He cites laboratory experiments (Birdsall et al., 1962) which show that such a field-current distribution may break up into a number of current filaments. Hence the dissipation may at any one time be proceeding in a number of discrete filaments. Colgate points out that this is similar to the processes which would occur within the context of the Spicer model.

Colgate compares the implications of this model with observational data, especially data for the flare of 1972 August 4. He argues that this model can explain not only the soft x-ray emission, as a result of evapora-tion from the chromosphere to coronal heights, but also the impulsive hard

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x-ray bursts which he attributes to the superposition of bremsstrahlung

from a number of small flare filaments. He also argues that gamma-ray

data on this flare indicates that most of the current must have been carried

by high-energy ions rather than electrons. He suggests that in some flares

high-energy ions are accelerated by direct acceleration (in the presence

of ion-acoustic turbulence) or by later acceleration of an initially trapped

plasma by unspecified mechanisms.

Comparison of Colgate's model with the primary flare requirements is

substantially the same as that for Spicer's model. Although the models use

the same basic magnetic-field topology, Spicer concentrates on the primary

processes whereas Colgate concentrates on the secondary processes leading

to various estimates for radiation which can then be compared with observa-

tional data.

## 9.5 Closing Comments

It is clear that we have not yet arrived at the final stage at which

one theory or one model comes to be accepted as providing the "answer" to

the problem of understanding solar flares. We are instead engaged in a

vigorous process in which a large and somewhat unmanageable problem is

being broken down into simpler and more manageable parts. One can at this

time only speculate what the end of this process will be.

It is possible that in the end--one or two decades or more away-- one

model or one theory will synthesize components which meet all of the require-

ments emerging from observational data. We may in the process find that

there are two or more fundamentally different types of flares, and that

a separate model or theory must be devised for each type. One must also

be alert to the possibility that an enterprising group of theorists will

redefine the term "flare" in theoretical terms and then proceed to claim

that the problem of the nature of solar flares has been solved! This would

be like retreating from a real enemy, constructing his likeness in effigy, and then proceeding to destroy the effigy!

The contents of this Monograph certainly do not lead the reader to the final answer in our search for the nature of solar flares.  However, if the reader can use the contents as a tentative map  which will help him choose the most profitable direction for his own future research, then our efforts will not have been in vain.

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FIGURE CAPTIONS

Figure 9.1 Gold-Hoyle model. Two bundles of lines of force, both twisted up. The initial longitudinal field is in opposite directions, and the twisting has occurred in the opposite sense. The arrows indicate the two components of the field. The electric current responsible for the circumferential component is in the same direction in each one.

Figure 9.2 Sweet model. Movement towards each other of magnetic dipoles A and B produces a current sheet with "neutral line" N in atmosphere assumed to be perfectly conducting.

Figure 9.3 Carmichael model. Magnetic field lines are caught up in the solar wind and extended into interplanetary space to leave a pair of "open" tubes of magnetic flux.

Figure 9.4 Sturrock model. Schematic representation of (a) pre-flare open magnetic field configuration; (b) reconnection leading to acceleration, chromospheric heating and evaporation; and (c) ejection of plasma on open field and decay of plasma on closed field.

Figure 9.5 Kopp-Pneuman model. (a) Initially open field configuration; (b) reconnection produces rising-loop configuration.

Figure 9.6    Emerging-flux model.  (a) During the "preflare phase" ("onset phase"), the emerging flux begins to reconnect with the overlying field.  (b)  During the impulsive phase, the onset of turbulence in the current sheet causes a rapid expansion with rapid energy release.  (c) During the "main phase" ("late phase") current sheet reaches a new steady state with reconnection based on a marginally turbulent resistivity.

Figure 9.7    Emerging-flux model.  The thermal equilibrium temperature $T_c$ in the current sheet is shown schematically as a function of height h in the solar atmosphere.  As the sheet gains in height, the equilibrium solution moves along AB.  When the critical height $h_{crit}$ is attained, there are no neighboring equilibria and the sheet heats up dramatically along the path BD.  At this point, the temperature will typically have exceeded the critical value $T_{turb}$ for turbulence to develop.

Figure 9.8    Emerging-flux model in context of a two-ribbon flare.  (a) Preflare phase during which new flux emerges close to filament.  (b) Impulsive phase.  (c) "Flash phase" and "main phase" ("late phase").

Figure 9.9    Spicer model.  Development of flare, according to Spicer theory, when an emerging current-carrying arch interacts with a pre-existing magnetic structure.

Figure 9.10 Colgate model. In this model, (a) a twisted flux tube is
convected to the surface; (b) as the field dissipates due
to current instabilities, the helix partly unwinds; and
(c) depending on the development of stresses in this tube
and in the ambient magnetic field, part of the magnetic
flux may expand into the corona.
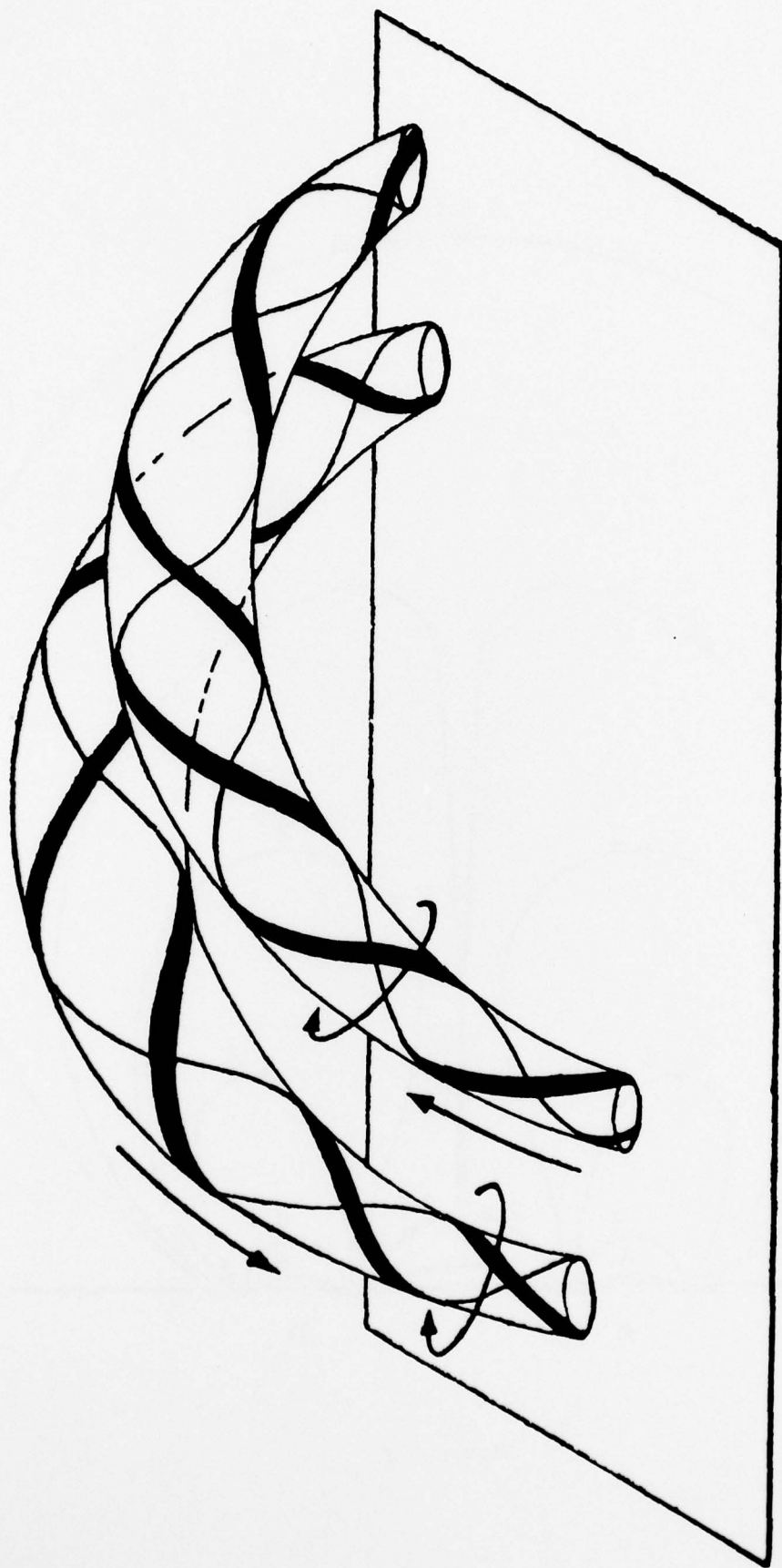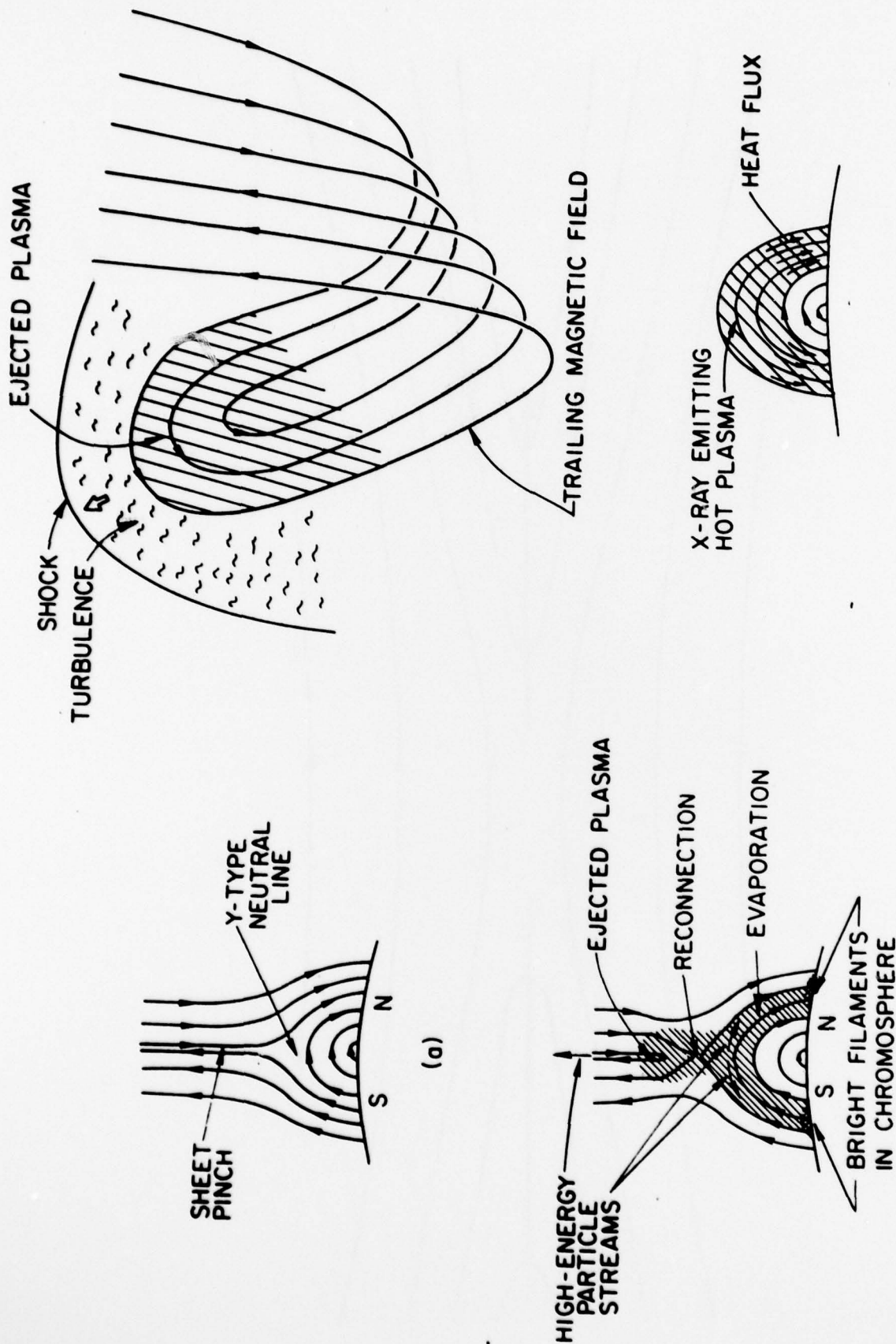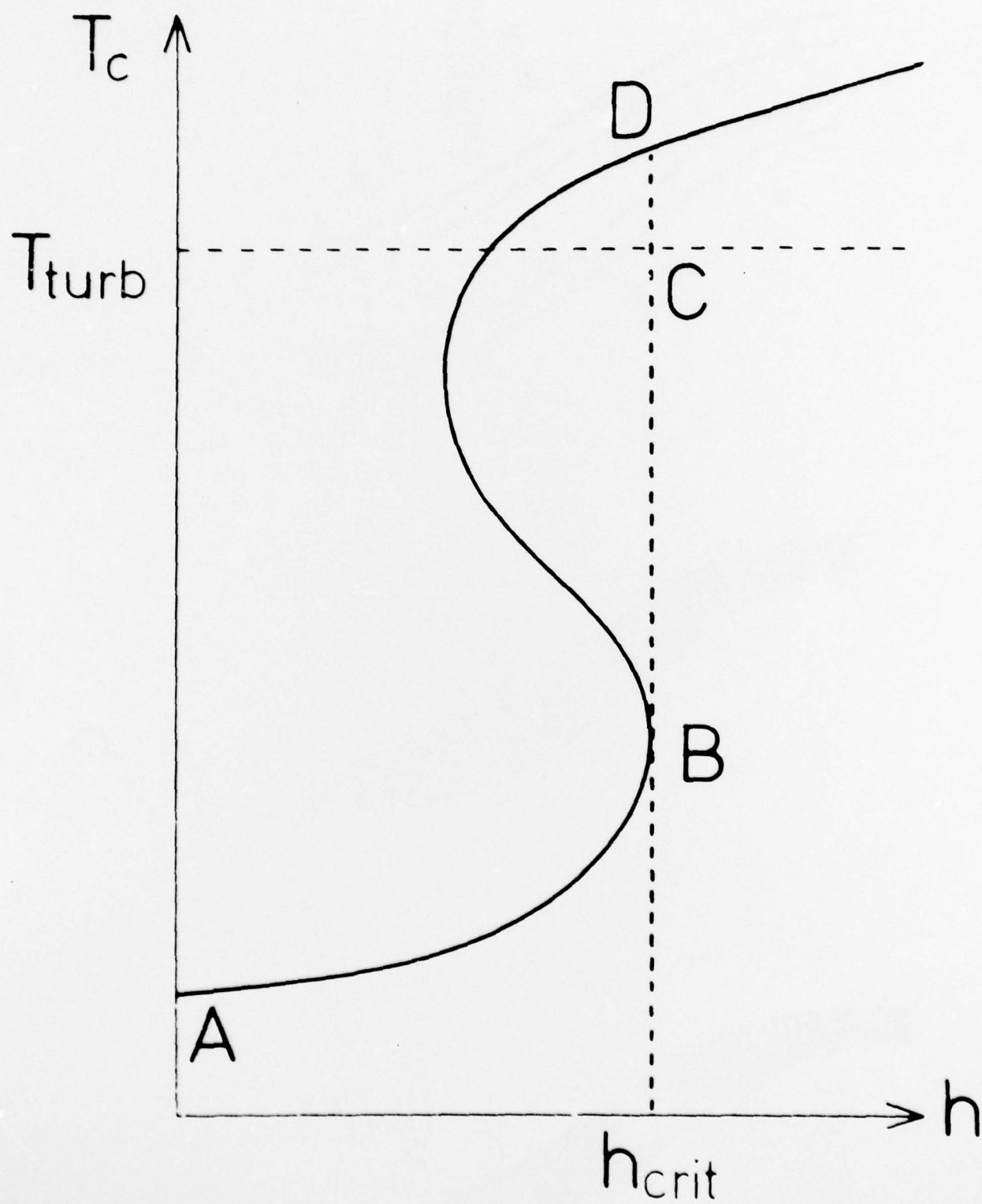
Figure 9.1

Figure 9.2

Figure 9.3

EJECTED PLASMA

TRAILING MAGNETIC FIELD

SHOCK

TURBULENCE

HEAT FLUX

X-RAY EMITTING
HOT PLASMA

(c)

SHEET
PINCH

Y-TYPE
NEUTRAL
LINE

N

S

(a)

EJECTED PLASMA

RECONNECTION

EVAPORATION

HIGH-ENERGY
PARTICLE
STREAMS

S    N

BRIGHT FILAMENTS
IN CHROMOSPHERE

(b)
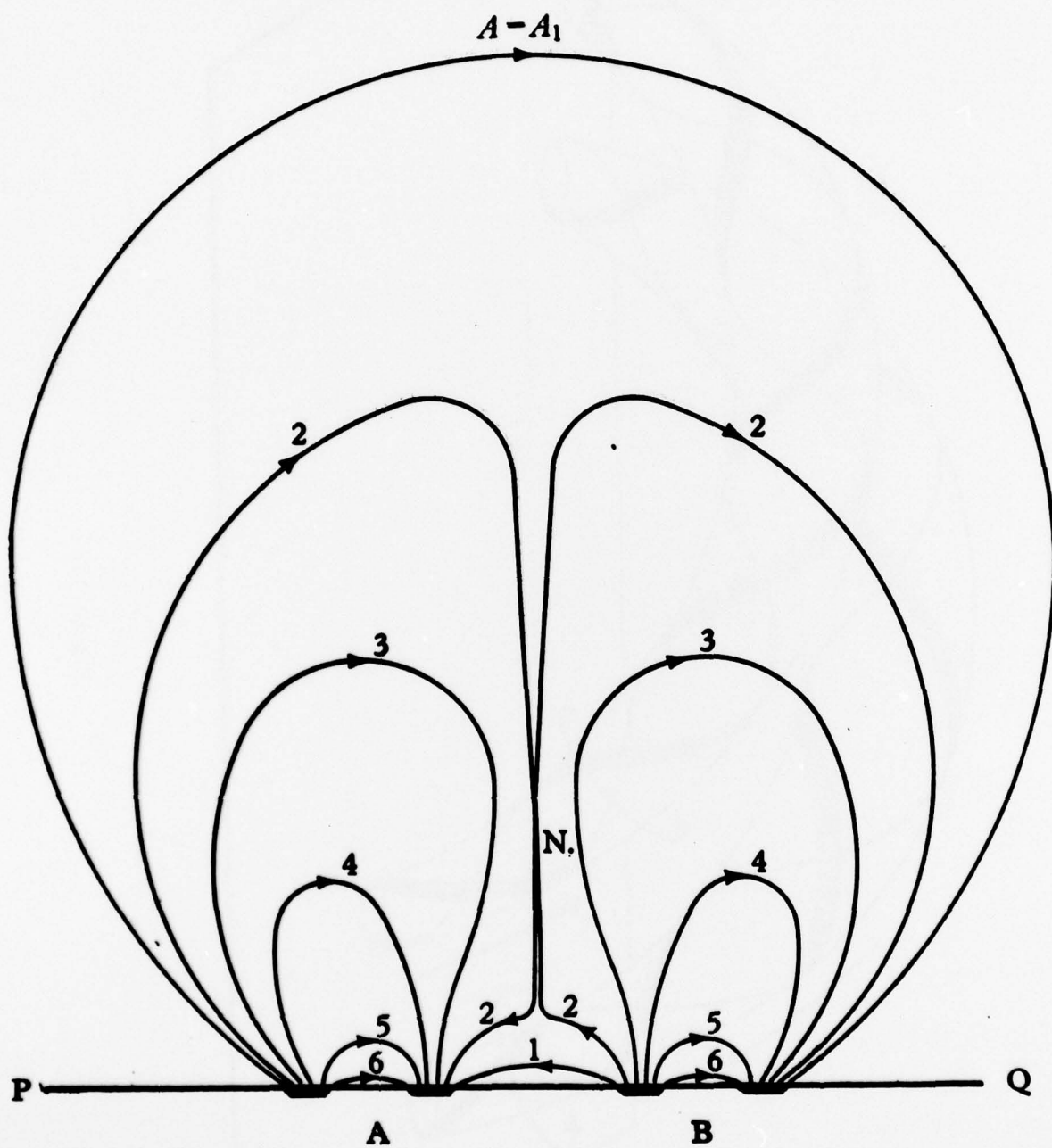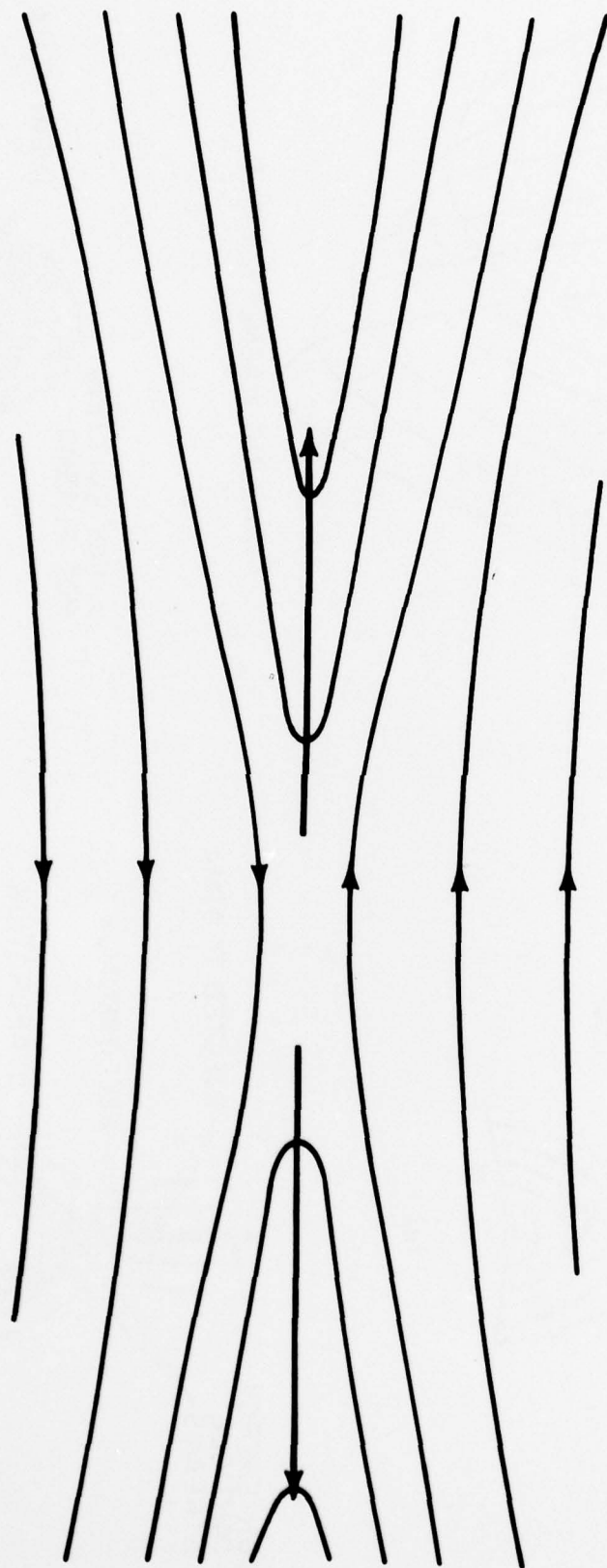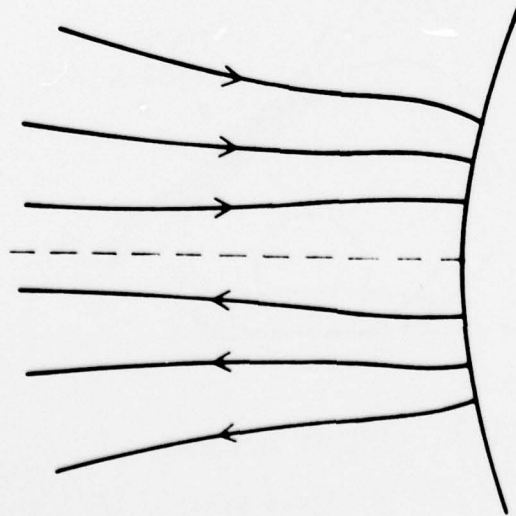
Figure 9.4

(a) OPEN FIELD LINES AFTER TRANSIENT

(b) Rising Neutral Point
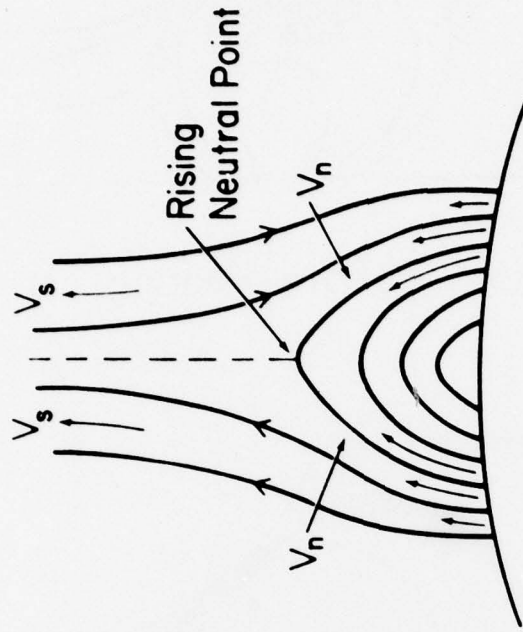
SUBSEQUENT RECONNECTION WITH CAPTURE OF MATERIAL ON CLOSED FIELD LINES

Figure 9.5
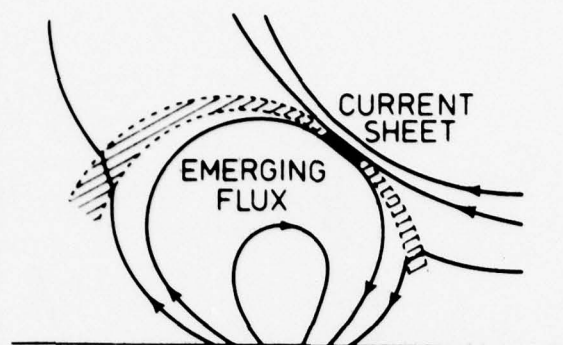
(a)   Preflare Heating
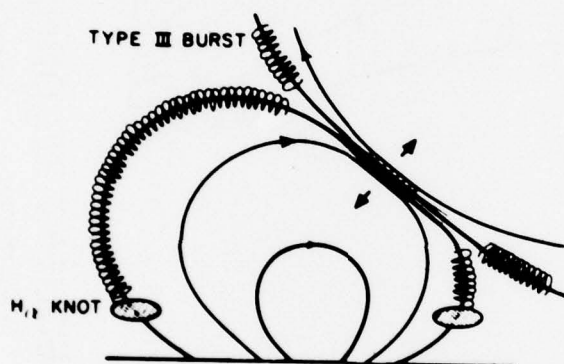
(b)   Impulsive Phase
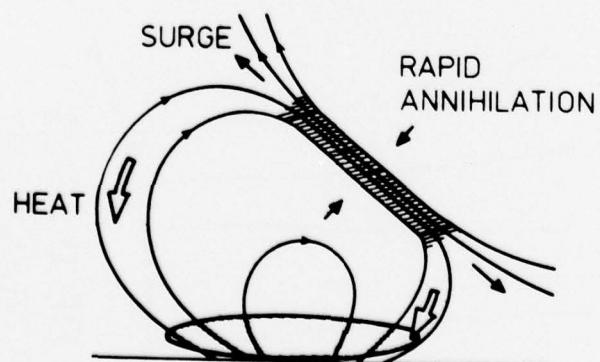
(c)   Main Phase

Figure 9.6

Figure 9.7

FILAMENT

SLIGHT MOTIONS

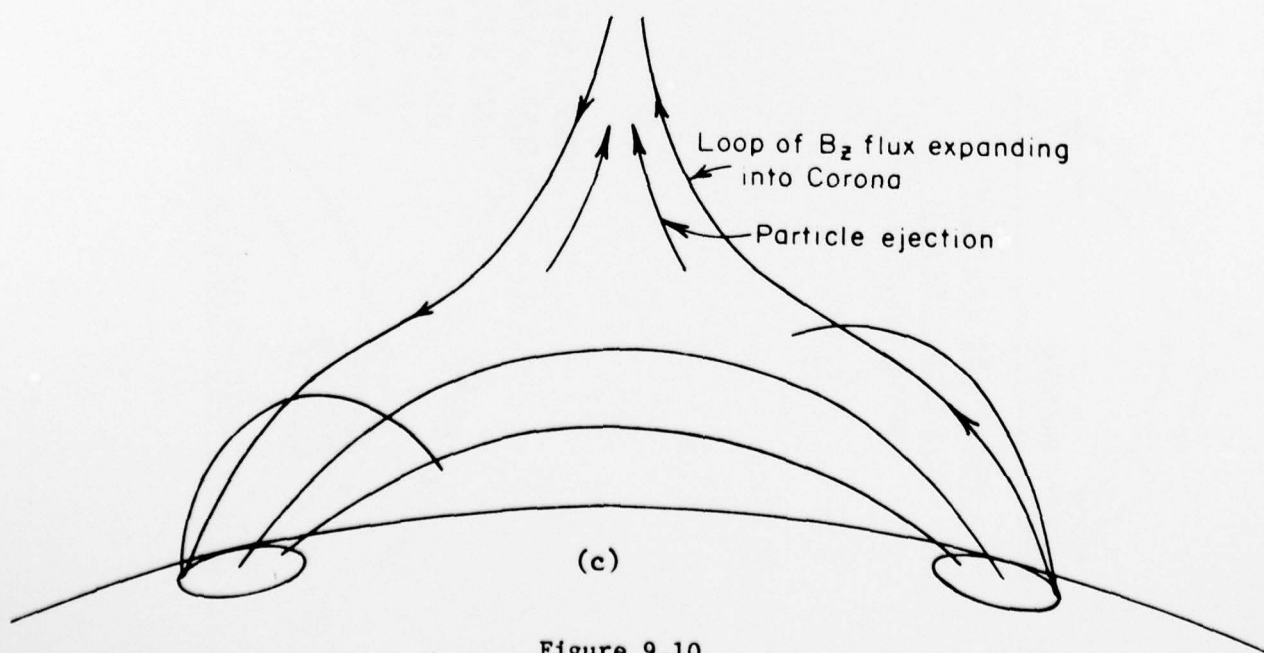EMERGING FLUX
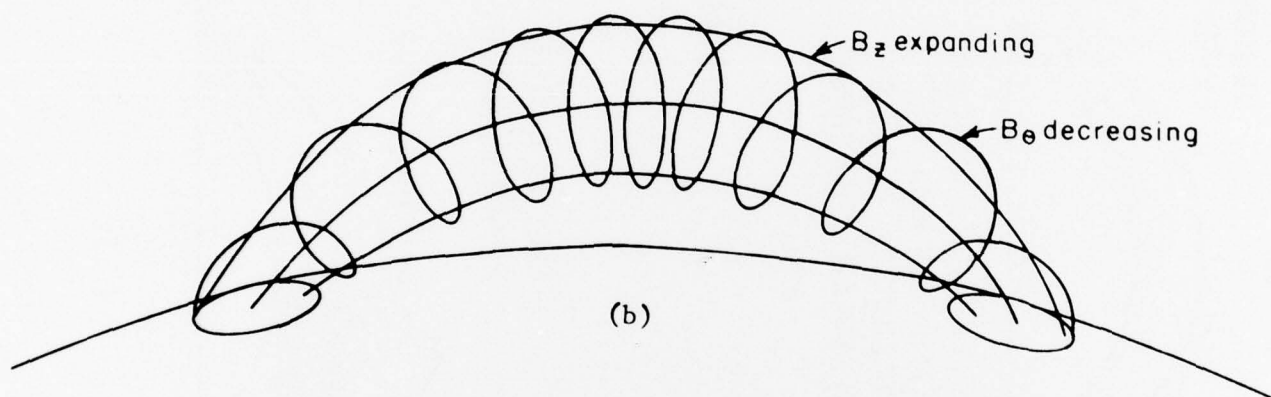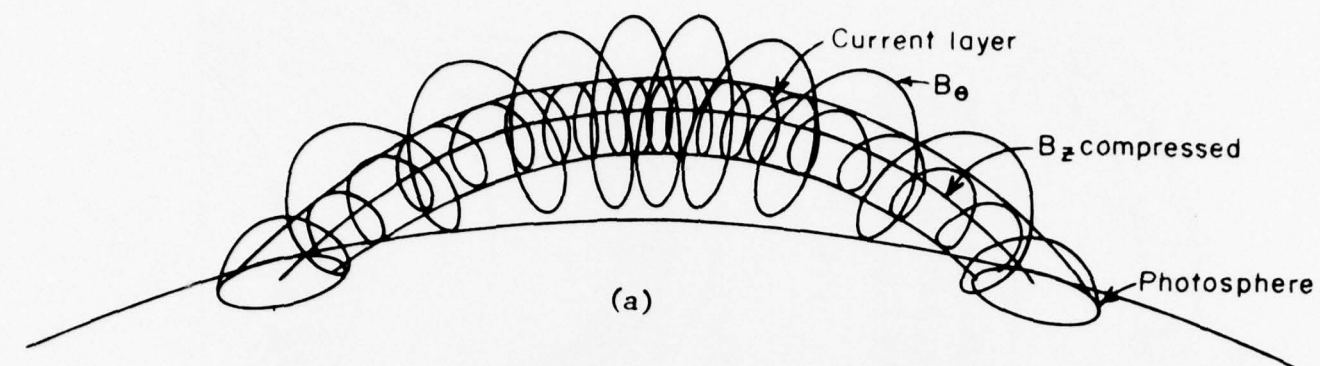
a

Hα KNOTS

b

Hα RIBBONS

c
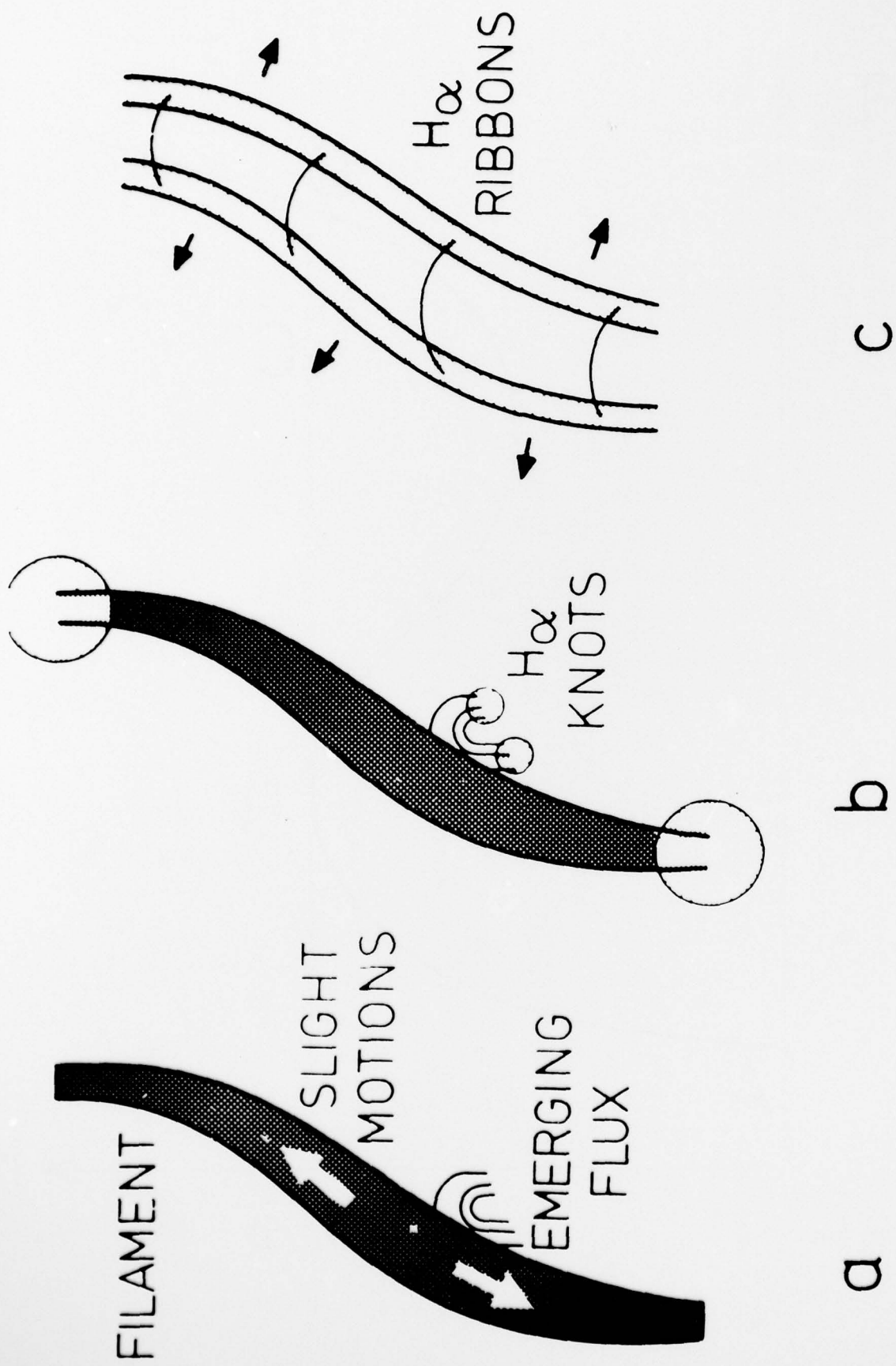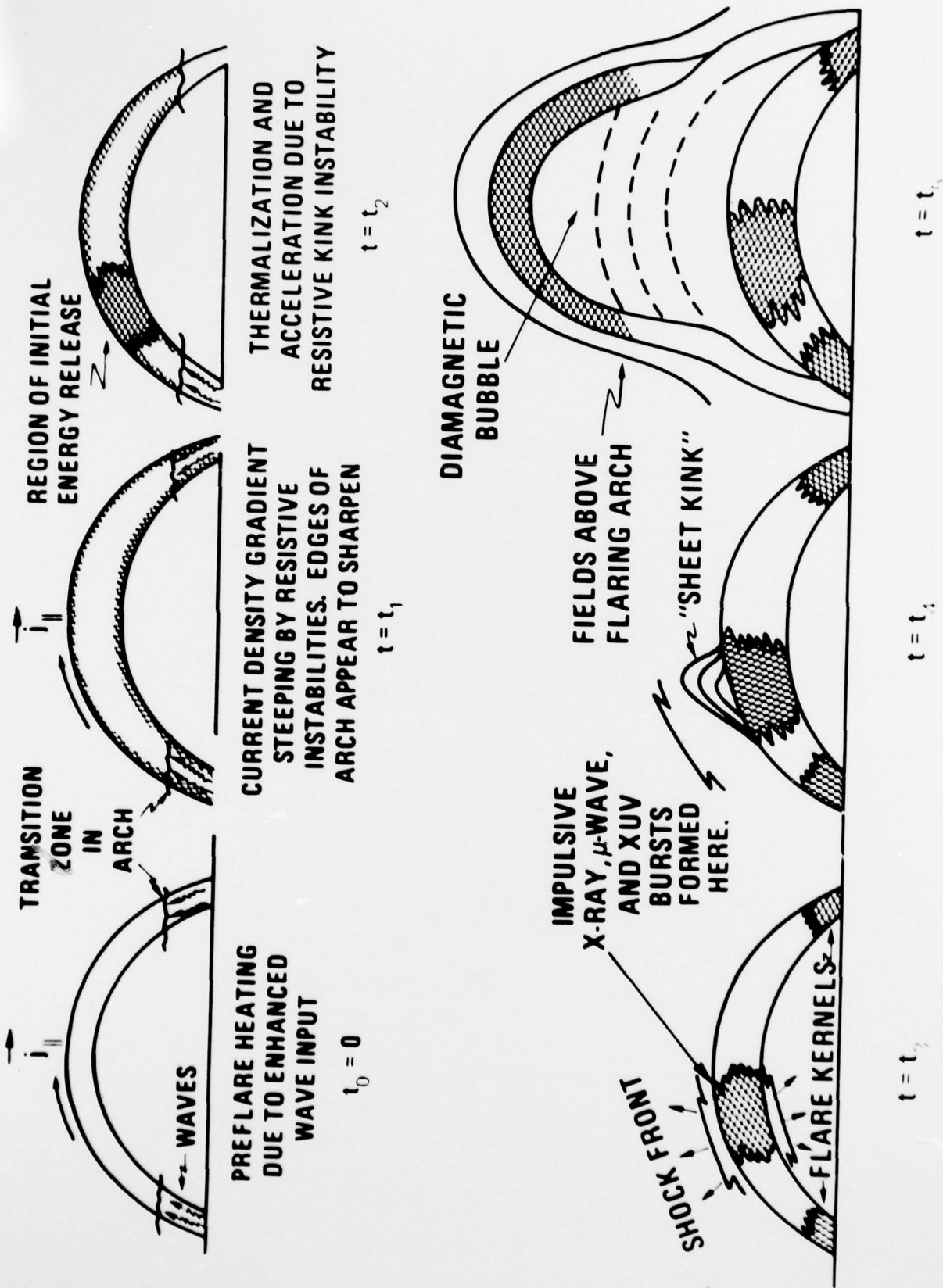
Figure 9.8

Figure 9.9

Figure 9.10

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    By reviewing the properties of solar flares analyzed by each of the seven teams of the Skylab Workshop, a set of "primary" and "secondary" requirements of flare models are derived.  A number of flare models are described briefly and their properties compared with the primary requirements.  It appears that, at this time, each flare model has some strong points and some weak points.  It has not yet been demonstrated that any one flare model meets all the proposed requirements.

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