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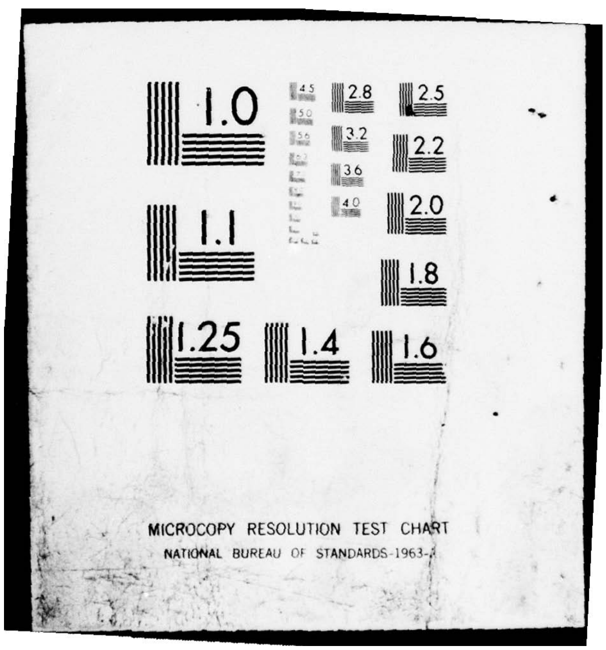
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The Primary Energy Release in Reconnection Flare Models

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E. O. Hulburt Center for Space Research

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A brief review is given on the primary energy release associated with reconnection flare models. In particular ~~we~~ will be examined how the most recent flare models of Spicer ~~(1974, 1975, 1976, 1977a)~~ and Uchida and Sakurai ~~(1977)~~ have attempted to overcome the standard difficulties with reconnection, i.e., the rate of reconnection and subsequent energy release. In addition ~~we~~ comments are made on whether the primary flare instability is explosive or non-explosive.

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CONTENTS

Introduction

It is generally accepted that the source of flare energy has its origins in the magnetic fields that exist about the photosphere. However, just what the mechanism is that converts the potential energy stored in the magnetic field into the dynamic effects associated with this energy conversion (i.e., the flare) is still a hotly debated question. Putting aside the question of how this potential energy is built up prior to the flare (if it is built up at all) we can begin our review by noting that there are basically three schools of thought presently advanced to explain how the magnetic energy is dissipated.

A. Collision Dominated Reconnection

B. Collisionless (Anomalous) Reconnection

C. Collisionless (Anomalous) Current Dissipation (sometimes referred to as current interruption).

The latter of these proposed mechanisms has been addressed rather critically and successfully by Smith and Priest (1972) and elsewhere in these proceedings. The main objection of Smith and Priest was that the current densities necessary for exciting the required anomalous processes far exceeded the known or even expected electric current densities in the solar atmosphere, that is to say the magnetic field gradients associated with the required currents exceeded $\sim$50 kilogauss/km.

Another objection to anomalous dissipation of current and also of reconnection flare models that require anomalous transport processes excited prior to field reconnection occurring is that reconnection at least in sheared magnetic fields has a much lower instability threshold than anomalous transport processes that various theorists have argued for

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occurring first. This perhaps subtle point is fundamental for our understanding of the preflare state as well as the flare state. This problem has arisen because the study of instabilities that leads to anomalous processes, e.g., the ion acoustic instability, makes use of homogeneous magnetic fields during the analysis of these instabilities. This of course is an excellent approximation for micro instabilities because the scale length of any magnetic field inhomogeneity far exceeds the characteristic scale lengths of any microinstability excited. However, by demanding homogeneity in the analysis of these microinstabilities, one has eliminated a source of free energy which can drive macroinstabilities some with instability thresholds which occur far earlier than the microinstabilities that flare theorists require to obtain anomalous reconnection or dissipated current. This is just the case for reconnection by the tearing mode. The tearing mode will occur long before any of the generally assumed microinstabilities which cause anomalous resistivity, etc. Thus, a current carrying sheared loop would have tearing modes occurring within it (Spicer, 1974, 1975, 1976, 1977a) long before current interruption would occur as was proposed by Alfven and Carlquist (1967). This argument is also applicable to any flare model which requires anomalous transport due to currents flowing parallel or perpendicular to a magnetic field. Thus while options two and three may appear attractive, they are theoretically inconsistent. However, one word of caution: there is no reason why that after reconnection has begun that anomalous processes cannot set in later (Spicer, 1977 a,b,c).

As we have seen if one accepts magnetic field dissipation as the source of flare energy one is forced to accept collision dominated reconnection for sheared fields with the anomalous processes typically proposed (ion acoustic, Buneman, Lower Hybrid, etc., instabilities) occurring at a somewhat later time during the flare (Spicer, 1977 a,b,c).

Recent Reconnection Theories

Up until recently the standard model of a flare due to the reconnection process has been the classical neutral sheet model. This model suffers from a number of problems which are briefly elucidated by Dr. Uchida in these proceedings. However, there have been two new theoretical models put forward which attempt to solve the problems associated with the classical neutral sheet model. The first due to Spicer (1974, 1975, 1976, 1977a) abandons completely the simple neutral sheet and examines the effects gained by going to more complex sheared magnetic field geometries (loops, prominences, etc.) in which tearing modes occur. Spicer in particular stresses a sheared magnetic loop (a simple twisted loop is not enough since reconnection cannot occur without shear) because of the recent Skylab data which indicates such a geometry although as he has pointed out any sheared field geometry will be workable (Spicer 1976, 1977a). Spicer shows that by going to the more complex sheared geometry that a number of non-linear phenomena can occur which greatly enhances the rate of reconnection and rate of particle energization. These mechanisms we will briefly describe later, but the basic result is that these non-linear phenomena lead to a far greater reconnecting surface to volume ratio than a single neutral sheet provides thereby increasing the field dissipation rate considerably.

On the other hand Uchida and Sakurai (1977) keep the neutral sheet model and argue that the neutral sheet be unstable to the interchange instability. This instability they claim also results in greatly increasing the reconnecting surface to volume ratio although in a manner completely different from the mechanisms proposed by Spicer. Below we will examine some of the ideas advanced in both these models.

Reconnection in Sheared Geometries: Non-Linear Effects

There are basically four important effects that occur in sheared magnetic fields that alter the rates of reconnection (Spicer, 1976, 1977a). They are:

(1) a spectrum of tearing modes can exist;

(2) mode coupling between modes of different perturbation vectors $\underline{k}$;

(3) multiple tearing modes (modes with the same $\underline{k}$ drive one another);

(4) driven tearing modes.

These four possible effects can occur because in sheared magnetic fields reconnection occurs by the tearing mode which has essentially three conditions for occurrence. They are:

$$\underline{k} \cdot \underline{B}_o = 0 \qquad (1)$$

$$|\underline{k}|\delta a < 0 \qquad (2)$$

and

$$\Delta' > 0 \quad , \qquad (3)$$

where $\underline{B}_o$ is the equilibrium magnetic field and δa the field gradient scale. Conditions (1) and (2) state that if a perturbation with a wave number vector $\underline{k}$ exists such that $\underline{k} \cdot \underline{B}_o = 0$ and $|\underline{k}|\delta a < 1$ then the tearing of the equilibrium magnetic field configuration can occur, lowering the energy state of the field provided that $\Delta' > 0$ which measures the free magnetic energy available to drive the tearing mode, this free energy eventually appearing as kinetic energy in some form. Since $\Delta' > 0$ is related to the free energy available to drive the tearing mode it explicitly determines the growth rates and non-linear evolution of a given tearing mode with a given $\underline{k}$. Δ' can differ for different sheared field geometries and for this reason different field geometries result in different rates of energy release.

Obviously a spectrum of $\underline{k}$ can exist in the magnetic field geometries observed on the sun since there are a host of perturbers generating such $\underline{k}$'s (e.g., convective motion in the convection zone perturbs the field and the perturbation propagates upward into the solar atmosphere). For a given $\underline{B}_o$ one can find numerous $\underline{k}$, such that, $\underline{k} \cdot \underline{B}_o = 0$. Thus, if $\Delta' > 0$ and $|\underline{k}|\delta a < 0$ for a number of $\underline{k}$'s one can expect more than one tearing mode developing from the initial equilibrium field geometry.

Now the existence of more than one tearing mode permits two very important effects to occur. They are mode coupling and multiple tearing modes (Spicer, 1976, 1977a). Obviously if more than one tearing mode is occurring in a given volume the rate of energy release goes up proportionately. However, what occurs when two or more couple?

The simplest case of coupling to consider is when $\underline{k} \cdot \underline{B}_o = 0$ occurs in many places in the reconnecting volume for the same $\underline{k}$. If conditions (2) and (3) are satisfied the phenomenon called multiple tearing modes occurs. If $\underline{k} \cdot \underline{B}_o = 0$ occurs in only two places it is called a double tearing mode. The Lunquist field (force free Bessel function model $B_\phi = B_o J_1(\alpha r)$ and $B_z = B_o J_o(\alpha r)$) can result in multiple tearing modes (Spicer, 1976, 1977a) and the force free skin current model (Spicer, 1977d)

$$B_z = \frac{B_o}{(1 + x^6)^{2/3}}$$

$$B_\phi = \frac{B_o x^3}{(1 + x^6)^{2/3}} ,$$

where $r = xr_o$ and r_o measures the current channel thickness.

Let us illustrate how multiple tearing modes can help explain the rapid energy release of flares. It has been found numerically that for the $m = 1$ double tearing mode that the growth rate γ goes like $.26S^{-.254}/T_A$, where $S = T_R/T_A$, $T_R = 4\pi C^2/\eta(\delta a)^2$ and $T_A = \delta a/V_A$, where V_A is the Alfven velocity. Further it is found that approximately 5% of the total magnetic energy is dissipated after approximately 14 Alfven transit times (Schnack and Killeen, 1977) and of this 5%, 90% went into internal energy and 10% went into kinetic flow. Approximating the power density as

$$\frac{d\varepsilon}{dt} \quad \epsilon \frac{\gamma B_o^2}{4\pi} ,$$

where ϵ is the fraction of field energy dissipated we find taking $B_o \sim 1000g$, $n_o \sim 10^{11}cm^{-3}$, $\delta a \sim 10^6$ cm and $T_o \sim 10^6$ K that

$$\frac{d\varepsilon}{dt} \approx 3.25 \times 10^3 \text{ ergs/cm}^3\text{/sec} \quad .$$

A power density more than enough to heat the plasma in a loop and thus overwhelm energy sinks.

Taking

$$\frac{1}{2} \rho v^2 \approx .1 \times (.05 \frac{B^2}{4\pi})$$

and

$$nkT \approx .9 \times (.05 B^2/4\pi)$$

we find

$$v \approx 500 \text{ km/sec}$$

and

$$T \approx 26 \text{ keV} \quad .$$

for the flare fluid velocities and bulk thermal temperature of the flare plasma during the early heating phase of the flare.

The basic reason why multiple tearing modes result in such faster reconnection rates is that the convective flow pattern set up by the reconnecting magnetic field surfaces is such that the vortex plasma flow from each set of neighboring reconnecting surfaces convects new field surfaces into the neutral points of the surrounding reconnecting surface. (Fig. (1) illustrates this; Schnack and Killeen, 1977.)

If we now permit $\underline{k} \cdot \underline{B}_o = 0$ to occur for different $\underline{k}$'s, then the possibility of mode coupling between neighboring reconnecting surfaces becomes possible. Mode coupling results in shorter wavelength $\underline{k}^{-1}$ being generated which in turn causes additional reconnection. The initial $\underline{k}$'s caused reconnection that generated what are called primary magnetic islands and the mode coupling between these islands caused the larger $\underline{k}$'s which generated the so called secondary islands (Fig. (2)). If the amplitudes of the perturbations between reconnecting surfaces becomes large enough so that the distance between reconnecting surfaces becomes small enough the phenomenon called overlapping of resonances or magnetic braiding can occur (Stix, 1974; Spicer, 1976, 1977a).

Mode coupling is desirable because there is an enormous increase in magnetic neutral points and therefore the particle acceleration efficiency is increased. There is also the accompanying increase in rate of magnetic field dissipation. Up to now only analytical arguments have suggested this behavior, while numerical simulations are just now beginning at various institutions. However, the unpublished results support the above arguments.

Spicer has also emphasized that reconnection in flares may be a driven form of reconnection rather than simply a relaxation from some equilibrium. To illustrate this point suppose the magnetic field gradients in an active region are growing in strength and that the threshold for development of a tearing mode had been reached. The excitation of this tearing mode for a given $\underline{k}$ will tend to flatten the magnetic field gradients in an attempt to lower the free magnetic energy of the system. However, if the system is driven hard enough then despite the reconnection processes attempts to flatten the field gradient the gradients will continue to steepen causing the tearing mode to continue and not saturate. This phase of the flare can be identified with the rise phase. However, if the rate of field gradient steepening by the external driver decreases or matches the rates of field gradient flattening by the tearing mode, then the system will evolve to marginal stability and the tearing mode will be stabilized and destabilized by the competing processes. This state of the flare can be identified with the gradual phase of the flare so that a gradual but continuous release of magnetic energy will be occurring.

Another aspect of reconnection that has been overlooked but also helps explain various types of spikey behavior in electromagnetic bursts occurring during a flare are relaxation processes by the tearing mode. Suppose a given tearing mode $\underline{k}$ is unstable corresponding to

$$\underline{k} \cdot \underline{B}_o = 0$$

$$|\underline{k}|\delta a < 1$$

$$\text{and} \qquad \Delta' > 0 \ .$$

If a spectrum of $\underline{k}$ exists then a sequence of tearing modes will occur with different $\underline{k}$. This follows because the tearing mode saturates when $\Delta' \approx 0$ and $|\underline{k}|\delta a \approx 1$. Hence, we find for a given $\underline{k}$ the field gradients δa will flatten until $|\underline{k}|\delta a \approx 1$. Since $\underline{k}$ is fixed $\delta a \to \delta a'$ and

$B_o \to B_o'$, that is, the field and its attendent field gradients are weaker. Since we have a spectrum of $\underline{k}$ we can find a new $\underline{\tilde{k}}$, such that, $\underline{\tilde{k}} \cdot \underline{B}_o' = 0$, $|\underline{\tilde{k}}|\delta a' < 1$ and $(\Delta')' > 0$. This process can repeat itself in a quasi-periodic way leading to quasi-periodic electromagnetic bursts as is illustrated in Fig. (3).

The Interchange Instability and Neutral Sheet Reconnection

As we have noted above Uchida and Sakurai (1977) have suggested that if the neutral sheet were interchange unstable, then the resulting convoluted or fluted sheet would increase the rate of reconnection by increasing the reconnecting surface to volume ratio. Hence the Uchida-Sakurai proposal is strictly a geometrical effect unlike that due to Spicer which is both dynamic and geometric. This follows because even though the interchange instability is a dynamic process it of itself does not involve itself in the reconnection process.

While the Uchida-Sakurai proposal of an interchange unstable neutral sheet is attractive at first glance, there are serious theoretical flaws associated with it as pointed out by Spicer (1978a). To understand this, one has to appreciate the basic mechanism utilized by Uchida and Sakurai to achieve their increase in reconnection rates, that is the interchange instability.

The interchange instability despite its name is a very primitive and well understood instability both in the linear and non-linear regimes. It was first studied by Lord Rayleigh and later by Taylor (1950). In the context of fluids it is called the Rayleigh-Taylor instability and in the context of plasmas and magnetic fields it is called the Kruskal-Schwarzschild instability. The instability also goes under the name flute instability but in general the name interchange instability is appropriate because the source of free energy that drives the instability is basically the same, some effective acceleration, e.g., gravity or curvature effects, for all the variations in its name.

The basic problem with the Uchida-Sakurai model is that they neglect to examine the well known non-linear behavior of the interchange instability. Below we summarize this behavior.

In the linear regime the fastest growing wavelengths of the interchange instability are the shorter wavelengths while the slower growing modes are the long wavelength modes. This can be seen from the linear dispersion relation

$$\omega^2 = |\underline{k}| g_{eff} \quad .$$

However, while large $\underline{k}$'s grow faster, they saturate faster and are also easier to stabilize. On the other hand, the long wavelength modes grow slower but are difficult to stabilize, if at all. Indeed non-linearly it is well known that the amplitude A of an interchange mode is given by

$$A \sim 1/k \quad .$$

Hence, the longer the wavelength, the larger the amplitude while the smaller the wavelength the smaller the amplitude. One can visualize this behavior by considering the classic Rayleigh-Taylor instability using a glass of water. If one takes a glass of water with a plate of glass on its open end, turns it over and slowly pulls away the glass plate, he would observe that initially many small short wavelength flutes or ripples occur first (the flutes result from the interchange in position between the water and air). Later, as time progresses, these ripples coalesce into fewer longer wavelength ripples which have larger amplitudes. This process continues until one or two large amplitude ripples exist which continue to grow at the free fall rate due to gravity. This is the classic non-linear behavior of an interchange instability and similar behavior occurs with a plasma and magnetic field configuration.

The fundamental problem then with the Uchida-Sakurai model should now be clear. They require a geometric increase in surface area. They can only achieve a significant increase in surface area if they can have many interchanges or ripples with large amplitude forming in the neutral sheet surface. However, many ripples require a short wavelength and short wavelengths do not result in large amplitudes but small amplitudes. Hence the increase in surface area is negligible, perhaps at best a factor of 10.

There is no escape from these arguments since they are based on the well known non-linear behavior of the interchange instability. For this reason the Uchida-Sakurai model has serious if not insurmountable difficulties just on theoretical grounds.

Is the Flare Instability Explosive?

A question that generally arises concerning the primary energy release of the flare is whether the instability that releases the flare energy is explosive or not explosive. This is not to say that the instability is like an explosion in the sense of a bomb, but rather does the instability grow exponentially (non-explosive) or faster than exponential (explosive). From the point of view of observations this question cannot at present be answered since the time scale of most non-explosive instabilities, like the tearing mode, are far shorter than present instrumentation can resolve ($\lesssim$ 1 sec). Hence, there is no experimental justification for demanding the flare instability be explosive or non-explosive. In a like manner theory cannot answer this question because there is no theoretical reason for supporting either choice except a matter of theoretical preference.

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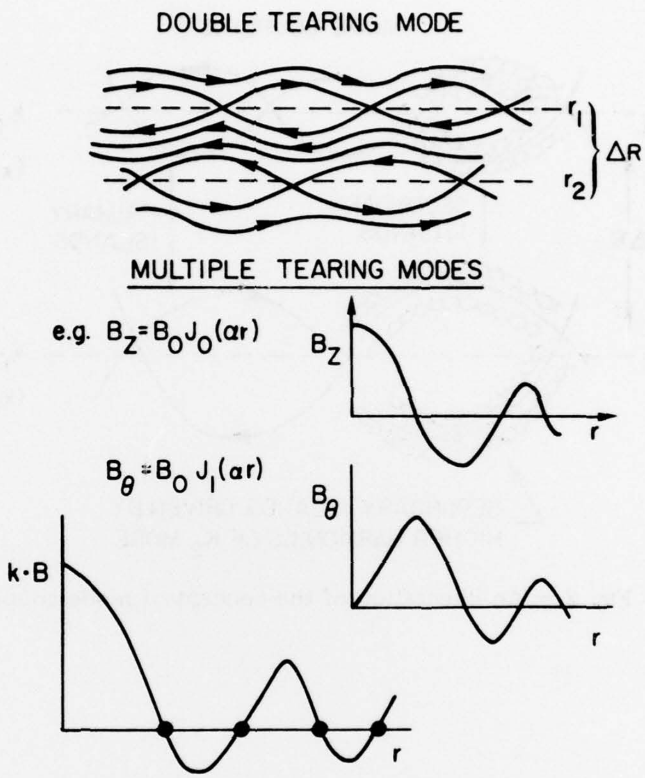

Fig. 1 — An illustration of the concept of multiple tearing modes

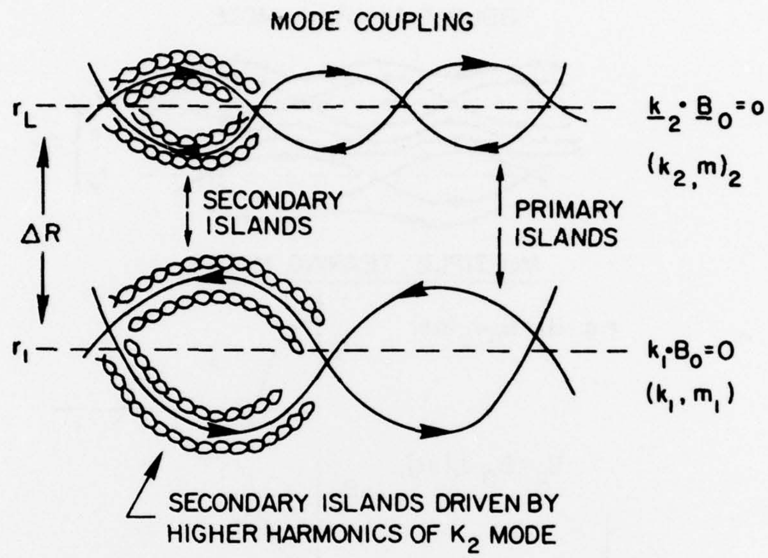

Fig. 2 — An illustration of the concept of mode coupling

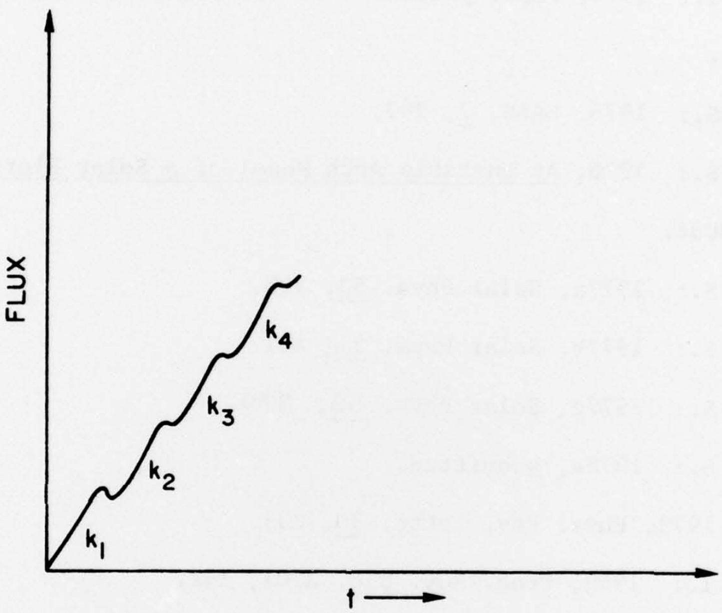

Fig. 3 — An illustration of the effects of driven tearing modes on flare radiative flux

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