SESSION III

LABORATORY EXPERIMENTS ON RECONNECTION IN CURRENT SHEETS

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ABSTRACT. Laboratory reconnection experiments dedicated to problems of space and astrophysics are briefly reviewed with the purpose of demonstrating that such experiments can provide important insights of considerable value to the development of reconnection theory. Moreover, many of these insights are of a kind not likely to be perceived either when working directly with space observations or while pursuing a course of pure theoretical reasoning without reference to laboratory results.

1. INTRODUCTION

1.1 History and Motivation

At the Jet Propulsion Laboratory in Pasadena in 1963, one of us (AB) became intensely interested in the pioneering theoretical work on reconnection of Dungey (1953) and the solar flare model of Sweet (1958a,b). A laboratory facility was developed in order to test the validity of some of the basic assumptions and approximations that were used.

Sweet (1958a), for example, assumed that a flat neutral current sheet would form where two bipolar sunspot field systems were pressed together. Note, a neutral current sheet implies, topologically, the complete absence of a weak transverse magnetic field crossing the field reversal plane. Until a possible tearing mode develops (Furth et al., 1963), there are no x-points and therefore no reconnection, only field annihilation via resistive diffusion. Sweet's hypothesis was based on the traditional MHD assumption that solutions at very high conductivity can be approximated by solutions at infinite conductivity to which is simply added the effect of resistive diffusion. However, based on the well known asymptotic paradoxes in ordinary hydrodynamics due to the effect of viscosity (Birkhoff, 1950), AB was suspicious that analogous asymptotic paradoxes might occur in MHD. Thus, just as ordinary viscosity can introduce wakes and boundary layers, so resistivity might

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introduce neutral points, shock waves, etc. In other words, Sweet's assumption might be invalidated.

1.2 Reconnection Experiments

The laboratory facility, designed to test these and other theoretical ideas related to reconnection became known as the Double Inverse Pinch Device (DIPD) (Fig. 1a). In simplest terms, two insulation-covered conducting rods carry parallel currents of increasing strength. The rod return currents, forced to flow through the preionized argon, develop expanding cylindrical sheets (inverse pinches). Upon colliding at the center of the device, the two cylinders merge into a single expanding oval. The resulting magnetic field line topology (Fig. 1b) has a figure eight-shaped separatrix surface which partitions the field lines into cells according to their linkage with the source current rods, i.e., with either one of the rods alone, the "parent" cells, or with both, the "daughter" cell. On the axis of the device, the separatrix intersects itself along a line called the separator, forming a locus of x-type neutral points in this 2-D magnetic field configuration.

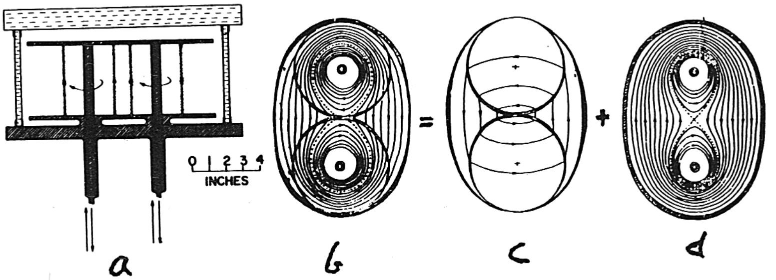

Figure 1. DIPD with its currents and magnetic fields: (a) the device producing a pair of inverse pinches; (b) the total field and current system; (c) the induced separator current system and its field; (d) the source current and field. (b), (c) and (d) were calculated using the coax approximation.

In the vicinity of the separator, a secondary current system is induced, which develops into a hyperbolic pinch with extensions trailing off downstream in the daughter cell. These extensions were later identified (Bratenahl and Yeates, 1970) as slow mode shocks in the Petschek (1964) configuration.

The significance of the separator current system is this: The field of this current system (Fig. 1c) when vectorially added to the field of the source current system (Fig. 1d) increases the flux in the parent cells and reduces the flux in the daughter cell. Thus, relative to the minimum energy potential field (Fig. 1d) of the source currents alone, the parent cells build up a store of excess magnetic flux, and the

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daughter cell is left deficient in flux. The induced separator current circuit is closed by a return current on the outer oval which flows in the opposite direction from that of the source current return. The total current flowing on the outer oval is thus reduced by an amount which is consistent with the reduced field in the daughter cell.

We may note further, that at least in the DIPD, it turned out that Sweet's neutral current sheet does not develop and there may well exist asymptotic paradoxes in MHD, as originally suspected.

We wish to emphasize the fact that in the basic DIPD design concept, the strategy was to set up conditions to investigate the interpenetration of two independent field systems that differed in the topological connectivity of their field lines as in Sweet's interaction between two bipolar sunspot fields. For reasons of experimental simplicity, however, the model actually used was based on the 2-D example of Dungey (1958, Fig. 4.2). Furthermore, in order to avoid unnecessary interference from wall effects, the design strategy mandated the inclusion of the entire field system and plasma dynamics within the test volume, i.e., no field lines should be permitted to intersect the chamber walls.

The first preliminary results of the DIPD program were reported in 1965 (Bratenahl and Hirsch, 1966). In 1969, the project was moved from JPL to UC Riverside and there the work continued until 1980.

In the meanwhile several other laboratory experiments relating to magnetic reconnection joined the effort. The first of these, in about 1967 at the Lebedev Institute, Moscow, is the work of A. G. Frank and co-workers. Their TS device was designed for the specific purpose of investigating the collapse of a current system into a pinch sheet current at an x-type magnetic neutral line and the possibility of its subsequent disruptive breakup through dynamic instability (Frank, 1976). This pair of experimental objectives provide a direct test of a major part of the theoretical effort of Syrovatskii and theorist colleagues at the Lebedev Institute to determine if magnetic energy, gradually stored in the build-up of the pinch sheet, could be converted rapidly and efficiently into particle kinetic energy upon the disruption of the sheet (Syrovatskii, 1976; Somov and Syrovatskii, 1976; Gerlakh and Syrovatskii, 1976; Bulanov and Syrovatskii, 1976; Frank, 1976, and references in this valuable collection of papers published together as Volume 74 of Proc. P. N. Lebedev Physics Inst., N. G. Basov (ed.) entitled Neutral Current Sheets in Plasmas (see also the posthumous review: Syrovatskii, 1980)).

Note that the motion of dynamic collapse of a current system in the vicinity of an x-type neutral line into a pinch sheet "discharge" originated with Dungey (1953, 1958) and represents a local aspect of a problem which, as we shall see, is complementary to, in fact, coupled to its global aspect, the topological conversion of field line connectivity as depicted in Dungey (1958, Fig. 4.2). Since the latter aspect is the

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formal basis of the DIPD and the former is the basis for TS, one might suppose the two experiments represent investigations of complementary aspects of the same problem. The truth turns out to be otherwise, however, and, in fact, the intercomparison between DIPD and TS provides much more insight into the complexity of reconnection than might be expected. This is a classic case of "the whole can be much greater than the sum of its parts." It is our purpose here today to make just such a comparison.

Following a description of the basic design and operation of TS, we shall return to the history of reconnection experiments, making, however, only brief mention of the various other projects. More details will be found in a recent review (Baum and Bratenahl, 1980).

TS-1 (and its subsequent versions, TS-2 and TS-3) is basically quite simple in design concept (Fig. 2). An ordinary z-pinch system is fitted with two pairs of external conductors carrying D.C. current in opposite directions. The resulting transverse quadrupole field has an x-type neutral line on the axis of the pinch glass-lined tube. Instead of an induced pinch current as in the DIPD, in TS the rapidly increasing current is directly driven by means of an external capacitor bank. The various versions (TS-1, TS-2, and TS-3) represent different methods of producing the plasma, and variations in plasma and field parameters.

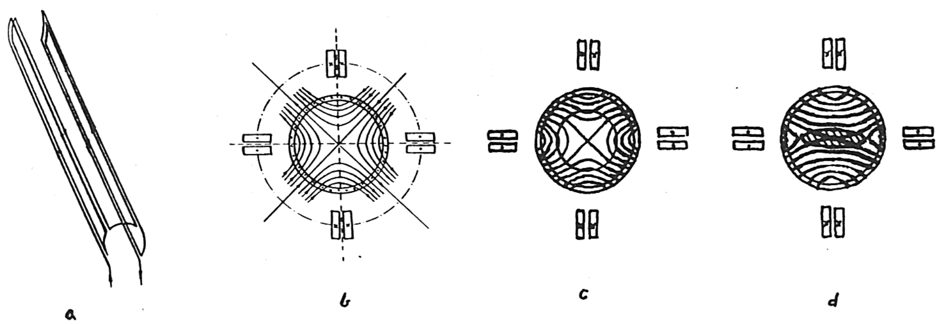

Figure 2. TS: (a) the D.C. quadrupole field conductors; (b) the quadrupole field; (c) converging cylindrical wave and its effect on (b); (d) the developing elliptical pinch current channel. Figs. 2a,b are from Frank (1976, Fig. 7a,b).

The resulting evolution and ultimate form of this directly driven current system is different in nearly all respects from the inductively driven system in the DIPD. Nevertheless, both devices eventually develop an instability leading to the violent tearing or rupturing of their pinch current sheets (Bratenahl and Yeates, 1970; Frank, 1976; Kirii, 1977). We shall return to this intercomparison and its interpretation in Section 3.2.

Continuing now with the historical development, the next to join the family of laboratory reconnection experiments, beginning in about

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1969 at the University of Tokyo, was a device somewhat similar in appearance to the DIPD in the sense that the magnetic field is completely contained within the test chamber but operationally the same as the TS concept of a D.C. background field defining a separator line, and a directly driven separator current system (Ohyabu and Kawashima, 1972; Ohyabu et al., 1974). This device also produces the current sheet rupture phenomenon.

Another directly driven reconnection experiment was carried out at MIT (Overskei, 1976; Overskei and Politzer, 1976), while in the meantime, the only other inductively driven device was the "pancake pinch" reported by Dailey (1972).

At the present time, by far the largest and most sophisticated reconnection experiment is that of Stenzel and co-workers at the University of California, Los Angeles, as reported here yesterday (Stenzel, 1985, see also references therein). The UCLA device (we shall call it UCLAD) has an inductively driven separator current system, similar to the DIPD. However, the device is about 10 times larger; it operates in the low density collisionless regime, requiring a hot cathode source to furnish current carriers; the source current rods are replaced by a pair of flat plate conductors; a D.C. axial bias field is needed to confine the plasma more or less to within the space between the plates. As might be expected, UCLAD performs in a way similar to DIPD although there are some noticeable differences, possibly related to the D.C. axial bias field (see Sec. 3 regarding singular lines). In the DIPD, flow is essentially laminar, in UCLAD it is somewhat turbulent. Spontaneous current rupture does not seem to occur (Bratenahl and Baum, 1983; Stenzel, Gekelman and Wild, 1983).

2. THE PROBLEM OF INTEGRATING EXPERIMENT WITH THEORY.

The purpose of the experiments under discussion here is to provide assistance in the development of theory. Unfortunately, there has been widespread skepticism concerning applicability or relevance of laboratory experiments to space and astrophysical problems: the impossibility of accurate scaling; the so-called "wall-effects"; plasma regimes, etc., etc. This basic prejudice persists today, though rapidly diminishing, thanks in large measure to the efforts of Bengt Sonnerup (1979; 1983) who has been actively stirring up interest in a much stronger integrative interaction between theorists and experimentalists. But, the problem of achieving this goal, is also further complicated by some of the concepts and disciplinary approaches that experimentalists must employ and which seem out of place to theorists. The experimentalist is bound to think very often as an electrical engineer: with circuits (albeit plasma conductor circuits which, obviously, behave quite differently from ordinary wires, Sec. 3.1); with inductances and inductive coupling between circuits; with nonlinear resistive impedances; with modes of energy input from outside the global system; with EMF's; with loads; with Faraday's law in integral form, etc., etc.

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The experimentalist must also deal with real plasma behavior: for example, plasma reacts to inductive (rotational) electric fields by attempting to cancel them out with their own self-generated space charge (irrotational) fields. This latter process has an extremely important consequence as we shall see in Sec. 3.

It might be helpful here to remind ourselves of the very different relationship, on the one hand, between observations and the development of theories to explain them, and on the other hand, the relationship between the theories and laboratory experiments for the purpose of testing and perhaps even guiding their development. An adequate reconnection theory should be consistent with both space as well as laboratory reconnection phenomena, differences in scaling and wall effects notwithstanding.

2.1 Scaling, Wall Effects, and Global Boundary Conditions.

As to scaling, the best that can be done follows Podgorny's "principle of limited simulation" (Podgorny and Sagdeev, 1970): compared to unity, dimensionless parameter ratios that are large or small in space should be made, correspondingly as large or small as possible in the laboratory, ratios of order one in space should be of order one in the laboratory.

As to wall effects, it turns out that if due consideration is given them, they need not be as detrimental as is generally believed. The study of wall effects, in actuality, is the study of the influence of global boundary conditions (GBC). Contrary to widespread belief, such conditions are always present in the astrophysical context although in theoretical development they are nearly always ignored, inadequately accounted for or for mathematical convenience, replaced by arbitrarily chosen boundaries. This tradition, which even includes much of Syrovatskii's work goes back to Dungey and Sweet not withstanding both of these pioneers in the subject realized that reconnection "is in principle a global process within a topologically complex structure" to quote Vasyliunas (1975) in his thorough going review of this so-called "restricted problem" mode of analysis.

Perhaps the most important of all insights we have been able to glean from our experience with laboratory reconnection experiments is that the restricted problem, despite quite logical reasoning, is incompletely posed (Forbes and Speiser, 1979) and can not furnish unambiguous answers to some of the more important questions raised, for example, by Sonnerup (1979) in his excellent summary of the present status of reconnection theory. The reason behind this, as we shall shortly see, has to do with the strong coupling between, on the one hand, the overall field topology and its time-dependence which introduces an essential nonlocal character to reconnection processes (Sec. 3), and on the other hand, the local conditions prevailing on the separator line which play a role of comparable importance.

A prime example of GBC is that which is determined by the solar photosphere and lower chromosphere: the permanent boundary separating the very high mean beta regime below from the low mean beta regime above (Dubov, 1971). Observational evidence suggests that down below, the high density plasma confines the magnetic field to very high field fibers, leaving most of the space occupied by essentially field-free plasma (Zwaan, 1978). In contrast, up above, strong currents must satisfy the force-free condition $\nabla \times B = \alpha B$ or else be confined to sheet current pinches, leaving most of the space occupied by nearly curl-free (potential) magnetic field. There is some strong observational evidence (Pneuman et al., 1978) for this latter condition.

Crossing the boundary from below, the tiny but intense field fibers fan out (Gabriel, 1976; Kopp and Kuperus, 1968; Dubov, 1971) to produce a continuous field above. The fibers, however, define the footpoints of field lines making up topologically distinct tubular flux cells. As these are shuffled about by the powerful convective motion below, EMF's are generated (Baum, et al., 1978, 1979; Bratenahl andd Baum, 1982) which drive the lively solar activity above, as Ionson (1985) mentioned yesterday. On this basis, we expect reconnection in pinch current sheets to be by far the dominant dynamic dissipation mode in the solar atmosphere. Indeed, we have been lead to propose, following Babcock (1961), a two-level solar dynamo model in which this ubiquitous reconnection dynamics becomes the essential factor in the alpha-process (Bratenahl et al., 1980).

3. THE NONLOCAL ASPECT OF RECONNECTION

If, under any of the following conditions, a nonzero line integral of an electric field exists: (i) around a closed magnetic field line, (ii) along the length a field line, both ends of which pass through a rigid conductor; (iii) along the length of a null line of either x- or o-type; or (iv) along the length of a separator as defined in a reconnection geometry, then such a line possesses singular properties (Syrovatskii, 1977). For instance, in infinite conductivity (ideal) MHD there would be "jump-like singularities in the magnetic field and correspondingly infinite current density" (Syrovatskii, 1978a), and a complete breakdown in the frozen-in flow condition. At such lines, conditions at arbitrarily high conductivity do not connect asymptotically to conditions at infinite conductivity. Here, at last, is theoretical support for one of our suspicions that lead to the DIPD program.

However, the most important aspect of singular separator lines, enters the picture under realistic conditions of finite conductivity. The fact is, the line integral of E in question is the Faraday integral satisfying

$$\int \vec{E} \cdot d\vec{\ell} = -\frac{d\phi}{dt} \qquad (1)$$

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in which ϕ is the magnetic flux encircled by the closed circuit path of the separator current (for example, the daughter cell in the DIPD). In the Coulomb gauge (Cragin and Heikkila, 1981),

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \vec{\nabla}\phi, \tag{2}$$

the first term on the R.H.S. is the induction (rotational) electric field, E^i and the second term is the electrostatic (space charge) electric field E^s. Along a singular line, although the condition

$$\vec{E} = \vec{E}^s + \vec{E}^i \simeq o \tag{3}$$

may hold locally due to cancellation of E^i by an equal but opposite E^s, the nonlocal conditions:

$$\int \vec{E} \cdot d\vec{\ell} = \int \vec{E}^i \cdot d\vec{\ell} \neq o \tag{4}$$

$$\int \vec{E}^s \cdot d\vec{\ell} \equiv o \tag{5}$$

must prevail for integrals extended over the whole length of such lines whenever $d\phi/dt \neq o$ as in eq. (1) (Heikkila et al., 1979). This obviously implies that if eq. (3) holds over most of a singular line, then over the remaining portion, E^s must be reversed in direction, i.e., must be in the same direction as E^i and be large enough to satisfy eq. (5) (Baum and Bratenahl, 1980b). If this situation should occur in actuality, then we must be dealing either with a double layer or, equivalently with a large electrode sheath drop. The latter situation was clearly observed in the DIPD by Beeler (1979), in association with a sudden, explosively fast reconnection event we had previously, but quite erroneously, attributed (Bratenahl and Yeates, 1970; Baum et al., 1973) to the sudden development of anomalous (turbulent) resistivity (more about this in Sec. 3.3).

Since the nonlocal aspect of reconnection is related to inductive electric fields E^i, $= -\partial A/\partial t$, its importance arises in time-dependent processes. Unfortunately, time-dependent reconnection has been a very much neglected subject in theoretical work. In truth, however, steady state reconnection may be said to be a special (perhaps degenerate) case of the general problem in which, not only must the process compress, heat and accelerate plasma, but it must also produce a measurable redistribution of magnetic flux between the distinct field line mapping cells defined by the separatrix. The latter process known as flux transfer, does not occur in steady state reconnection (Alfven, 1976). Flux transfer involves Faraday's law in integral form and cannot be properly handled without taking into account the overall field line topology and the form of the current circuits as well.

Flux transfer is caused by changes in the strengths or geometrical arrangement of the various externally driven source currents. These changes on the global boundary produce an EMF along the separator which, in magnitude and direction is, to a good approximation, the line integral of $\vec{E}^1$ that would have been induced there in the total absence of any plasma.

In effect, the system acts like a transformer (Kaburaki, 1975; Bratenahl and Baum, 1982). Consider the DIPD (Fig. 3). The primary consists of the two source currents acting together, and the secondary is the induced pinch sheet current circuit. The EMF driving the secondary is the rate of change of flux coupling primary to secondary, expressed as the product of the primary current and the mutual inductance, between primary and secondary: $\dot{I}_p M_{ps}$.

The line integral of E on the separator is now the effective "IR" drop or load. It is also, by equation 3, the flux transfer rate. However, the effective "R" need not be a resistance in the usual sense, since, as already noted, it may include a double layer or sheath drop ϕ. This may be expressed as $\int \vec{E} \cdot d\vec{\ell} = I_s R_s + \phi$. Actually, the problem is somewhat more complicated because we are not dealing here with ordinary wire conductors threading a nonconducting medium but current flow in a continuous conducting medium. A special process of development of build-up of the sheet current pinch in this situation will shortly be considered.

Nevertheless, the field of this secondary current circuit as noted in Section 1.2, adds to the primary or source field in the parent cells and subtracts from that field in the daughter cell. In effect, some flux is withheld from the transfer process and stored. The amount of this stored flux is the product of separator current and the self inductance of the current path, $I_s L_s$.

On the basis of the preceding, we can write

$$\dot{I}_s L_s + (I_s R + \phi_s) = \dot{I}_p M_{ps} \tag{6}$$

$$\dot{I}_p L_p + I_p R_p = \Sigma - \dot{I}_s M_{ps}, \tag{7}$$

in which Σ is the externally applied EMF driving the primary circuit. Important facts to note are these: (i) the flux storage rate $\dot{I}_s L_s$ is the difference between the EMF, $(\dot{I}_p M_{ps})$ which drives the secondary (separator circuit) and the flux transfer rate, $(IR + \phi_s)$, so that a flux storage reservoir capacity is defined by the asymptotic state, $\dot{I}_p M_{ps} - (I_s R_s + \phi_s) = o$. Thus the integrity of the reservoir, as it is filled, depends on the ability of the conduction mechanism to support the required current without failure, i.e., either a sudden increase in R_s (anomalous resistivity) or a sudden increase in ϕ_s (double layer or sheath) or both. But if the conduction mechanism can support the required saturation current, the flux transfer rate from a completely filled reservoir is identical to that which would occur in the total absence of a conducting plasma medium. This might appropriately be called the Yeh-Axford theorem (Yeh and Axford, 1970). Note carefully, this concept could hardly have been rigorously derived from the restricted problem approach.

For a given $\dot{I}_p M_{ps}$ (neglecting ϕ_s), the flux storage capacity increases with conductivity and the stored energy capacity $I_s^2 L_s/2$, as the squares of the conductivity. Thus, at high conductivity and significant EMF's we can expect catastrophic flux tranfer events due to one or another form of conduction mode instability.

3.1 Build-up of Pinch Current Sheets.

As electromagnetic energy (Poynting flux) enters a plasma system through some portion of its global boundary, current is initially induced to flow over the path of least inductance, which is the layer of plasma adjacent to that energy-entrance portion of the boundary. Then, as the Lorentz force accelerates the plasma layer to the local drift velocity $V_d = E/B$ and becomes thereby electrostatically polarized, the current path advances into the interior as an elementary hydromagnetic wave, accelerating the successive layers of plasma through which it propagates. Each subsequent increment of current propagates into the plasma in a similar fashion, the ensemble of all such waves constituting a system.

In a laboratory device, the nature of the rigid (non-plasma) boundaries impose conditions on $E_\parallel$ which must be considered. Where the boundary is a time-varying current-carrying conductor, $E_\parallel = E^i + E^s = 0$. An exposed conductor boundary therefore cannot serve as an entrance window for electromagnetic energy. Only if the conductor is completely covered with a solid dielectric (insulator) can that portion of the boundary permit the entrance of electromagnetic energy. In this case, the surface of the dielectric, easily and quickly acquires charge from the plasma sufficient to cancel the "E^s-effect" of induced surface charge on the conductor, and the necessary condition $E_\parallel = E^i \neq o$ for energy entrance is established.

If the field topology is such as to lead to the development of a (singular) separator line, or if one is already present in the system, the elementary current carrying waves gradually build up, through a nonlinear process, a current channel structure whose cross-sectional form depends significantly on the amplitude of the waves coming in from each direction. It also depends on the somewhat lower amplitude outgoing waves, if present, moving toward portions of the global boundary that act as energy sinks. All this, of course, depends on details of the initial structure of the magnetic field, and the changes in it that are taking place consistent with the changing source currents. In other words, it depends intimately on the initial conditions and global boundary conditions.

3.2 Intercomparison between DIPD and TS.

The development of Petschek shocks evidently must depend in a very sensitive way upon the details of the plasma flow field that is developed by the passage of the small amplitude wave system (Sec. 3.1). In the DIPD, this wave system diverges from the two glass-insulated source current rods and where they run into each other at points other than precisely at the separator, the Lorentz forces from both wave systems cooperate to accelerate the plasma into a pair of strong outflow structures. With no adverse interference of incoming waves in the outflow sectors, standing waves can develop nonlinearly into slow mode shocks (much like the bow waves of two speed boats about to collide head-on). For this to occur, however, the outflow velocity must develop selfconsistently to a value greater than the slow mode wave speed. The overall flow, development in the DIPD is laminar.

In contrast to the foregoing, the TS experiments produce radially inward propagating current-carrying waves (Gerlakh and Syrovatskii, 1976) which are uniformly induced over the inner surface of the cylindrical glass-insulated outer boundary. As these waves converge upon the central axis (as in a z-pinch), the interaction term in the Lorentz force (that which depends on the D.C. quadrupole field) increases the compressive pinch from the inflow sectors and weakens that force in the outflow sectors so that the current channel takes on the forms of a flattening ellipse. In this case the outflows are essentially blocked by net inward pinch forces. No Petschek shocks are possible under these circumstances. It should be noted, however, that this collapse of the current system into a pinch current sheet met precisely one of the stated objective of the TS experiments. The second objective, namely the instability of the sheet pinch was met in TS-3 through reduced initial density and increased field. In TS-3 the pinch sheet ruptures impulsively into two magnetic islands through some form of tearing mode. The rupture occurring at the separator line (Frank, 1976).

It is an important fact, however, that the qualitatively different pinch structure that develops in the DIPD also ruptures in an impulsive event, as we shall now describe in greater detail.

3.3 Impulsive Flux Transfer Events.

One of the earliest observations in the DIPD was the occurrence of a sudden and major change in the magnetic field and current. On the basis of detailed investigation, the phenomenon was given the descriptive identification: impulsive flux transfer event. IFTE is analogous to the bursting of a dam (Figs. 3b, 4a,b). The induced separator current system, consisting of the central hyperbolic pinch together with the attached Petschek shocks is observed to break up and fly away in all directions with little or no change in the total current flow. Large amplitude compressive blast waves propagate downstream in the daughter cell while large amplitude expansive fast mode waves propagate upstream toward the source current rods in the two parent cells (Fig. 4a).

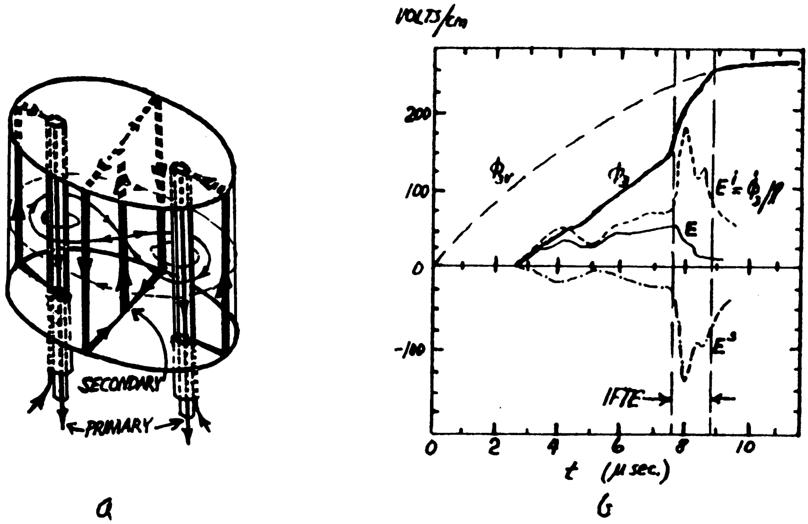

Figure 3. Flux and electric field relationships in the DIPD: (a) schematic view of the transformer basis of Eqs. (6) and (7); (b) long dash; $M_{ps} \int I_s dt$, Eq. (7), heavy solid line, daughter cell flux, $I_s L_s$, short dash $E^{is}(t)$; dash dot, $E^s(t)$; thin solid, $E(t)$.

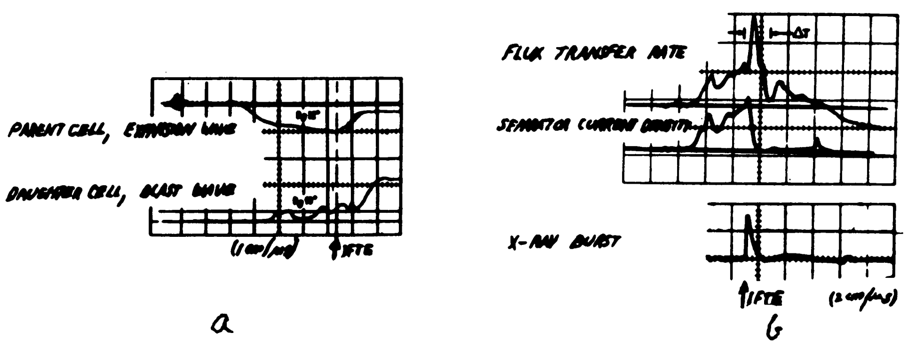

Figure 4. IFTE: (a) magnetic field behavior showing upstream expansion waves and downstream blast waves; (b) $E^i(t)$, $j_s(t)$, and x-ray burst.

The constancy of the total current during IFTE means that the growth of current in the propagating waves is at the expense of the current in the original pinch current system. By Ampere's law, this precisely identifies the rapid intrusion of transferred flux into the daughter cell and the corresponding rapid withdrawal of flux from the parent cells.

IFTE is caused by a conduction mode instability. Until quite recently, all the evidence seemed to indicate a sudden transition to anomalous resistivity: first, the initiation of runaway carriers, evidenced by observation of x-rays produced at the anode end of the separator; and then followed by ion-acoustic noise, accompanying the impulsive event. However, Beeler (1979) discovered that anomalous

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resistivity was not the principal factor at all. By an ingenious method of separately measuring E^i, E^s, and E at points distributed over 80% of the separator (Fig. 5), he was able to show that: (1) there is no measurable change in resistivity, $\eta = E/j$; (2) that E^s and E^i are large but nearly cancel each other out over the region of measurement. Now recalling eqs. (3), (4) and (5), and the comments following in Sec. 3, it becomes quite clear that the conduction mode instability must result in, or take the form of, the sudden development of a large space charge sheath at one of the electrodes. This is analogous to a double layer in its effects (eq. 6), including the x-ray production through energization in the large potential drop ϕ_s. (Energetic ions have also been observed).

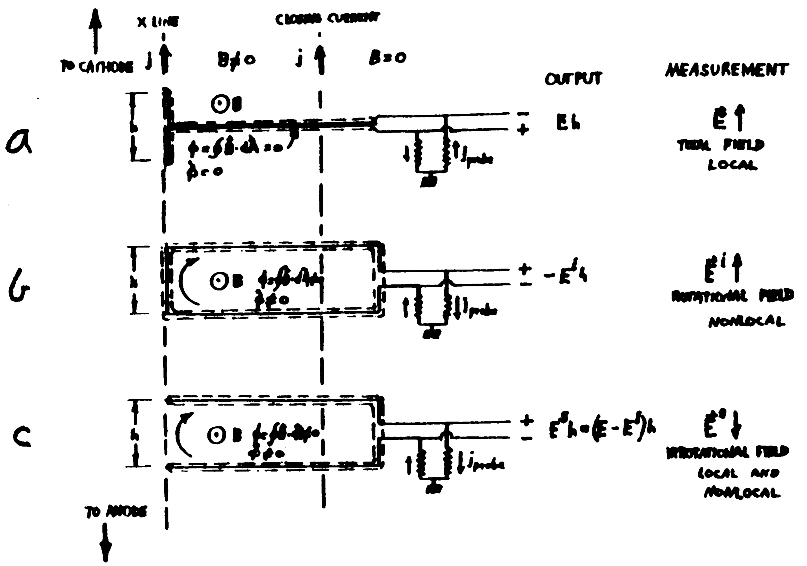

Figure 5. Beeler (1979) method of separately measuring E, E^i and E^s: (a) double probe with close-spaced leads; (b) flux look probe; (c) double probe with separated leads. This system works only for B-fields with 2-D translational symmetry.

Note that an impulsive increase in resistive impedance ($I_sR + \phi_s$) on the separator current channel due to either R or ϕ_s produces an impulsive increase in E^i (Figs. 3b,) and by eq. (4), the flux transfer rate. The resulting large amplitude wave system is the (nonlinear) inverse of the build-up mechanism of Sec. 3.1. Note further, this process provides a very plausible setting for the current interruption solar flare model (Baum et al., 1978; Baum and Bratenahl, 1982) of Alfven and Carlquist (1962) and Carlquist (1982).

Obviously, during the preceding current buildup, rapid Petschek-type reconnection, including flux transfer, was taking place. Evidently also, this proces was not fast enough to compete with the simultaneous flux and energy storage buildup as represented by the

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ever-increasing pinch current system, I_p. Then, bang! Could this be a more realistic version of Sweet's solar flare model? We certainly can believe it is. It goes "bang" because the demand for current carriers inevitably grows faster than the rate of supply. Considering the inhomogeneous structure of the solar atmosphere: higher density plasma in thin current sheets increasing in strength with time and which are separated by large spaces consisting of lower density plasma in nearly curl-free field, the DIPD process simulation may not be so far off base.

In contrast to the DIPD, it should be noted that in TS, because the quadrupole background field circuit (constant in time) is not inductively coupled to the pinch current circuit, no flux transfer takes place during the process of current build-up. Indeed, parent and daughter cells are not even completely defined within the test volume. However, current rupture into a pair of magnetic islands may certainly be identified as an IFTE, and, as in the case of the DIPD, it too is caused by some form of conduction mode instability. (The precise cause is not known to us at this writing).

This raises an important issue: the resolution of a total B-field into the contributions of the major current circuits, some of which change while others remain constant, may provide a much more advantageous strategy for analysis of reconnection than the not so reliable but traditional strategy of "moving field lines, frozen into the flow." This is especially true because of the presence of singular lines (e.g., separator lines) where the freezing-in concept breaks down anyway.

4. TOWARD A BETTER UNDERSTANDING OF SOLAR ACTIVITY

Why, might you ask, this preoccupation with Sweet's interaction between simple bipolar structure rather than the popular notion among theorists of twisted force-free fields? We would answer simply as follows: There appears to be no reasonable mechanism, either observationally suggested or theoretically proposed within constraints imposed by observations, capable of systematically twisting high field flux fibers or bundles of them to the extent required by the force-free field concept beyond occasional occurrences. On the other hand, based on both topological arguments involving flux conservation as well as overwhelming abundance of direct observational evidence, all new flux erupts upward through the photospheric boundary as bipolar structures (Sheely et al., 1975). The low mean beta condition above does not restrict large currents to flow only in force-free field structures satisfying $\nabla \times B = \alpha B$. The concept that all strong currents in the solar atmosphere must be of this force-free type is merely an assumption which seems to overlook the other possibility. In fact, pinch current sheets, in otherwise very nearly curl free field, are also entirely compatible with the low mean beta regime, and on the basis of evidence are much more likely to be the dominant currrent structure in the solar atmosphere, and yet, we know almost nothing about the structural transformation of a 3-D separator-separatrix system (Sweet, 1978; Baum and Bratenahl, 1980) in the presence of a sheet current pinch. Note, the current on such a separator is strictly field aligned, nevertheless, is not a force-free structure in the traditional sense.

A recent paper in Solar Physics (Fig. 18) (Machado et al., 1983), is quite relevant here. We believe this is the first time the 3-D separator-separatrix structure, originally proposed by Sweet (1958), has been explicitly considered other than in several papers by our colleagues and ourselves (Bratenahl and Baum, 1976b; Baum et al, 1978a, 1979; Baum and Bratenahl, 1980, 1982).

5. SUMMARY

Among the numerous insights derived from laboratory reconnection experiments, we believe the following to be the most significant: (i) "Reconnection," as the term ought to imply, but unfortunately through long usage in a different sense, does not seem to, is fundamentally the time-dependent process of topological conversion of field line connectivity or flux transfer which, however, must draw upon electromagnetic energy to compress, heat, accelerate, and otherwise energize any plasma that gets in its way. Steady state reconnection might more properly be called "merging," as in the "confluence of two streams of plasma:" it is a special limiting case of the more general one, in as much as topological conversion through flux transfer is entirely missing. (ii) Topological conversion necessarily involves a nonzero line integral of E^I along the separator, and this introduces a nonlocal aspect into the problem which tightly couples the global boundary conditions to the local condition in the neighborhood of the separator. Since steady state reconnection must be regarded as an asymptotic state, derivable from the general case, it must surely contain information uniquely determined by GBC and initial conditions. The restricted problem approach is therefore incompletely posed. (iii) The failure of the assumption of a neutral sheet formation by Sweet (1958a) illustrates the dangers of deriving finite conductivity solutions by simply adding resistive diffusion effects to solutions based on ideal MHD. (iv) The hydromagnetic wave process by which pinch current sheets are built up (or destroyed, as in IFTE) depends intimately on the way energy enters the system on its global boundaries, as well as the presence of any preexisting magnetic fields. Therefore, analysis in terms of the superposition of fields belonging to the individual current circuits provides a more powerful approach than the unreliable methods of "moving field lines, frozen into the flow." (v) The unquenchability of E^I along singular field lines and the difference in plasma response to E^I vs E^S, provides an obvious mechanism to produce double layers, and thereby hoists a cautionary flag against the customary and unqualified assumption that anomalous (turbulent) resistivity is the only form or even the most important form of over-current instability.

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6. CONCLUSIONS

We have tried to make it clear that laboratory experiments can provide valid testing and guidance in the development of reconnection theory even when that theory is directed toward understanding phenomena in astrophysics. A valuable resource already exists which theorists should now take greater advantage of. We are convinced that important ideas have been presented. For instance, the time has come to seriously challenge the unqualified assumption that the force-free field structure obeying $\nabla \times B = \alpha B$ is mandated for strong currents in the solar atmosphere. An alternative structure, the pinch current sheet is not only permissable, but on the basis of observations seems much more likely.

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DISCUSSION

Priest: What are the values of the magnetic Reynolds number and plasma beta in your experiment and A. Frank's experiment?

Bratenahl: In the DIPD the magnetic Reynolds number is $\sim$16 when based on the distance from the source current rods to the separator line. This being greater than one, the principle of limited simulation is satisfied. In the TS series of A. Frank the Reynolds number is probably larger. The beta in both experiments is much less than unity when averaged over the system.

Kundu: I believe in one of your viewgraphs, you showed an X-ray burst in time coincidence with inductive flux. My question is, what is the energy range of the X-ray burst and what is the time scale?

Bratenahl: The X-ray burst is thick target bremsstrahlung due to the impact on the copper anode of $\sim 2(10)^3$ electrons in the energy range 1 - 2.5 keV. The burst duration $\Delta t \sim 0.25$ μsec is estimated from the observed pulse width of 0.4 μsec and the instrumental width of $\sim$0.3 μsec. The burst occurs at the onset of the IFTE which has a duration of $\sim$1 μsec (Baum et al., 1973).

Smith: What is the role of ion-acoustic turbulence in impulsive flux transfer events?

Bratenahl: Evidence developed by Beeler (1979) makes it now quite certain that ion-acoustic turbulence is not sufficiently intense to cause a measurable increase in resistivity anywhere over 80% of the length of the separator. On the contrary, the evidence indicates the sudden development of a large electrode sheath drop (similar to a double layer). On the basis of X-ray data (Baum et al., 1973), we can be pretty sure it is an anode sheath. However, the sudden appearance of the turbulence may be related to the sudden development of the sheath.

Mullan: Under what conditions do Petschek shocks form?

Bratenahl: This is a very important question, and at present there is no definitive answer. However, we do know that the presence of shocks of any kind in a quasi-steady flow requires special conditions both upstream and downstream in order to satisfy the jump conditions. The flow must be able, self-consistently, to evolve asymptotically into such a state from some initial state via a transient process. Boundary and initial conditions hold the key. To develop Petschek shocks, a sufficiently large outflow velocity must be able to develop, unimpeded by adverse pressure or Lorentz stresses (to avoid choking as in nozzle flow). In the DIPD, at low enough initial pressure, Petschek shocks are observed (Bratenahl and Yeates, 1970) but not at higher pressures (Beeler, 1979). In the TS experiments of Frank et al., the boundary conditions impose adverse stresses on the outflow and Petschek shocks do not form.

Sonnerup: Is the transition from a compressed flat current sheet to a potential field in an IFTE accomplished by a wave front (a double layer) traveling from the anode along the separator?

Bratenahl: The answer is both yes and no: The sheath remains attached to the anode, but, as I have already explained, IFTE is like the bursting of a dam. Large amplitude blast waves propagate downstream forming the front of transferred flux previously stored upstream, and large amplitude fast mode expansive waves travel upstream as the stored flux is withdrawn in the transfer process. The corresponding changes in field strength must also propagate as wave structures along the separator and away from the sheath region, but this three-dimensional aspect remains to be explored.

Stenzel: Do you have any direct experimental evidence for the existence of a double layer during IFTE's?

Bratenahl: No, on the contrary, the evidence (Beeler, 1979) points to the sudden development of an electrode sheath. But let us not forget that such a sheath produces effects similar to a double layer, especially when in the presence of a strong inductive electric field.

Vasyliunas: The principle of gauge invariance implies that electrostatic and induced electric fields cannot be separately measured as physical quantities; they are mathematical constructs, possibly convenient, but not physically significant.

Bratenahl: I am most grateful that you raise this very fundamental issue. My last figure shows how Beeler (1979), with three different probes did, in fact, separately measure the electrostatic and induced electric fields and their vector sum, the total field. All three, of course, are local quantities, but separate resolution of the electrostatic and induction contributions to the total field requires non-local path integral measurements of appropriate paths that require prior knowledge of the magnetic field line structure together with the assumption of negligible displacement current. However, this fact in no way can be taken to imply that the local quantities, thus obtained, are mere mathematical constructs that cannot be separately measured as valid physical quantities. These quantities, of course, correspond to the Coulomb gauge, but for mathematical convenience, the two contributions to the total field may be transformed, say into the Lorentz gauge (Cragin and Heikkila, 1981).

I would strongly urge those of you here who doubt that the vector potential A has physical significance to consult Konopinski (1981, p. 158).