Advances in Electronics and Electron Physics

VOLUME 54

EDITED BY
L. MARTON AND C. MARTON

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FOREWORD

The articles in this volume characterize the broad range of subjects that fall into the category of electron physics. In addition, electromagnetic phenomena are reviewed in P. J. Baum and A. Bratenahl's contribution on magnetic reconnection experiments. Lawrence E. Cram's review of solar physics, as pure physics, stands in contrast to the down-to-earth industry-oriented article on microfabrication by P. R. Thornton. Midway between these contributions are two articles that deal with both pure and applied physics, the first by A. T. Georges and P. Lambropoulos on multiphoton processes and the second by Paul H. Holloway on Auger spectroscopy.

We trust our readers will find this volume to be a valuable survey of five vital areas in current electron physics research and thank our authors for their splendid presentations.

As is our custom, we present a list of articles to appear in future volumes of *Advances in Electronics and Electron Physics.*

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As in the past, we have enjoyed the friendly cooperation and advice of many friends and colleagues. Our heartfelt thanks go to them, since without their help it would have been almost impossible to issue a volume such as the present one.

L. MARTON
C. MARTON

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Magnetic Reconnection Experiments

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I. PROLOG

This review is intended to give the general reader an overview of the present status of laboratory magnetic "reconnection" experiments while also providing the specialist with a unified critical picture in some detail. It is necessary to give some attention to the theory of the subject as well as its developmental history not just to clarify definitions and terminology, but more especially to explain the purpose and objectives of laboratory "reconnection" experiments, and perhaps show how results to date may influence the future development of the theory. We present many researchers' work, but it can be noticed that our own is accorded more space. That happens partly because we understand this to be the usual custom in this type of review and partly because we are most familiar with our own work. "Reconnection" theory began in 1953, and although laboratory experiments specifically designed to test the theory did not begin for another 10 years, this

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review covers the period 1953–1979, with emphasis on the late 1960s and the 1970s. Referencing ends in mid-1979.

The word "reconnection" appears here in quotation marks because much of the literature on the subject, especially the earlier literature, has treated the process as a "moving together" of oppositely directed field lines, leading to a new configuration through their "breaking" and "rejoining new partners" and, on occasion, even to their mutual "annihilation." This moving-field line concept, by aiding visualization, has provided the basis for many ideas concerning "reconnection," but its nonphysical nature can lead to misleading conclusions (Alfven, 1976), and block the way to the use of more powerful methodologies. We therefore restrict our attention to measurable physical quantities and concepts derivable from them. Our use here of the traditional term "reconnection" is merely to identify the general subject matter and is not intended to imply any connotation of "moving field lines" that "do" anything. The reader, however, will find the quotation marks deleted from now on.

II. INTRODUCTION

In this section we are concerned with what is meant by magnetic-field reconnection in a general sense and why there is interest in its study.

The magnetic vector field **B** is a local quantity, but the field possesses also a spatial structure expressed by its field lines, which are its integral characteristics (Morozov and Solov'ev, 1966). Both the local field vector and its spatial structure are uniquely determined by a second vector field, the current density and its spatial structure, although the inverse is not true. In general, the field line structure may be analyzed in terms of its topological elements, which may include: one or more separatrix surface distributions of field lines; separator lines where a separatrix appears to intersect itself; and null points of various kinds where the field vanishes. The general subject may be called magnetomorphology.

The separatrix partitions the magnetic flux into cells, each distinguished by the unique linkage of its field lines with respect to the currents. It is obvious that any change whatever in the currents, including the introduction of new currents, will result in changes in the allocation of magnetic flux between the cells, including the possible development of new cells. Faraday's law requires that any change of flux is accompanied by an inductive (rotational) electric field, and the Faraday electric field along a separator where three cells meet measures the rate of flux loss (gain) of two of the cells, and a corresponding gain (loss) of the third cell. Such flux changes among cells constitute reconnection in its broadest electrodynamic sense, and it will be appreciated that its topological basis requires an appropriate system-wide definition. The definition of "system" in this sense requires careful consideration in order that the electrodynamic and topological aspects of the reconnection problem can be properly expressed. We shall shortly return to this point.

However, little interest would be generated in the problem of reconnection on the basis of the electrodynamic and topological aspects alone and in the absence of a plasma medium. It is, of course, the rich variety of plasma dynamic effects associated with reconnection that commands interest in the whole subject. Plasma dynamics enters the problem in several distinct ways. First, as the medium of conveyance of electromagnetic energy throughout the system from sources to sinks. In this way plasma can act as a partner with changes in the sources, thus contributing to the cause for which reconnection is the response or effect. Second, the plasma within an inner portion of the system may be in a higher potential energy (pressure) state than that outside it, being confined in equilibrium by a particular topological structure of the magnetic field defined by a combination of internal plasma currents and fixed external currents. The plasma may then find a means to escape this confinement through a rearrangement of the internal currents and corresponding changes in the topological structure of the magnetic field through reconnection (formation of magnetic islands through the tearing mode instability). Third, and of greatest interest here, the plasma can interfere strongly with the detailed process of reconnection itself, making it necessary for the expenditure of electromagnetic energy to compress, accelerate, and otherwise energize any plasma that gets in its way (Bratenahl *et al.*, 1979). In this interference process, compressed-plasma sheets and currents are built up along and in the neighborhood of separator lines, and this buildup of new structures constitutes the temporary storage of potential energy. Under appropriate conditions, and with significant amounts of magnetic and plasma energy thus stored, instabilities can develop, releasing this energy impulsively. This release mechanism or impulsive flux transfer event (IFTE) then offers itself as a prime candidate to explain solar flares and magnetospheric substorms (Russell and McPherron, 1973). Reconnection is also an essential ingredient in a self-excited dynamo that can maintain a magnetic field against ohmic losses.

Thus, it turns out that interest in the problem of reconnection is multidisciplinary: not only is it an important issue in cosmic plasma physics, but it also presents one of the more important plasma containment problems that must be overcome in the practical achievement of controlled fusion as an energy source.

The simplest manifestation of reconnection arises in the interpenetration of the magnetic fields of two independent current systems. By "independent" we mean that these current systems are sufficiently immune to back-reactions from the reconnection system defined by their fields that cause and effect chains can be isolated so that the reconnection problem is well-posed and determinate. Examples of two-current systems are easy to visualize (Figs. 1 and 2). In each case, the separatrix has been accented by a heavy line, and its point of self-intersection marks the location of the separator. The separatrix defines three flux cells: cells whose field lines link one or the other of the two currents, called parent cells; the cell whose field lines link both; and the daughter cell (Bratenahl and Baum, 1976a). Stenzel and Gekelman (1979a) refer to these as the private and the public flux regions, but we prefer to emphasize the cellular structure defined by the separatrix and its separator. In general, the separator connects between a pair of magnetic null points of semidivergence type (McDonald, 1954), but in cases of degenerate axial or translational symmetry, the separator will be a locus of x-type neutral points. A simple example of this latter type is discussed in Appendix I. (Most toroidal fusion devices, such as the tokamak, involve at least three independent current systems, and the topology is more complicated.)

Figure 1a represents the impingement of solar-wind-driven southward interplanetary field on the earth's dipole field. Figure 1b illustrates the inter-

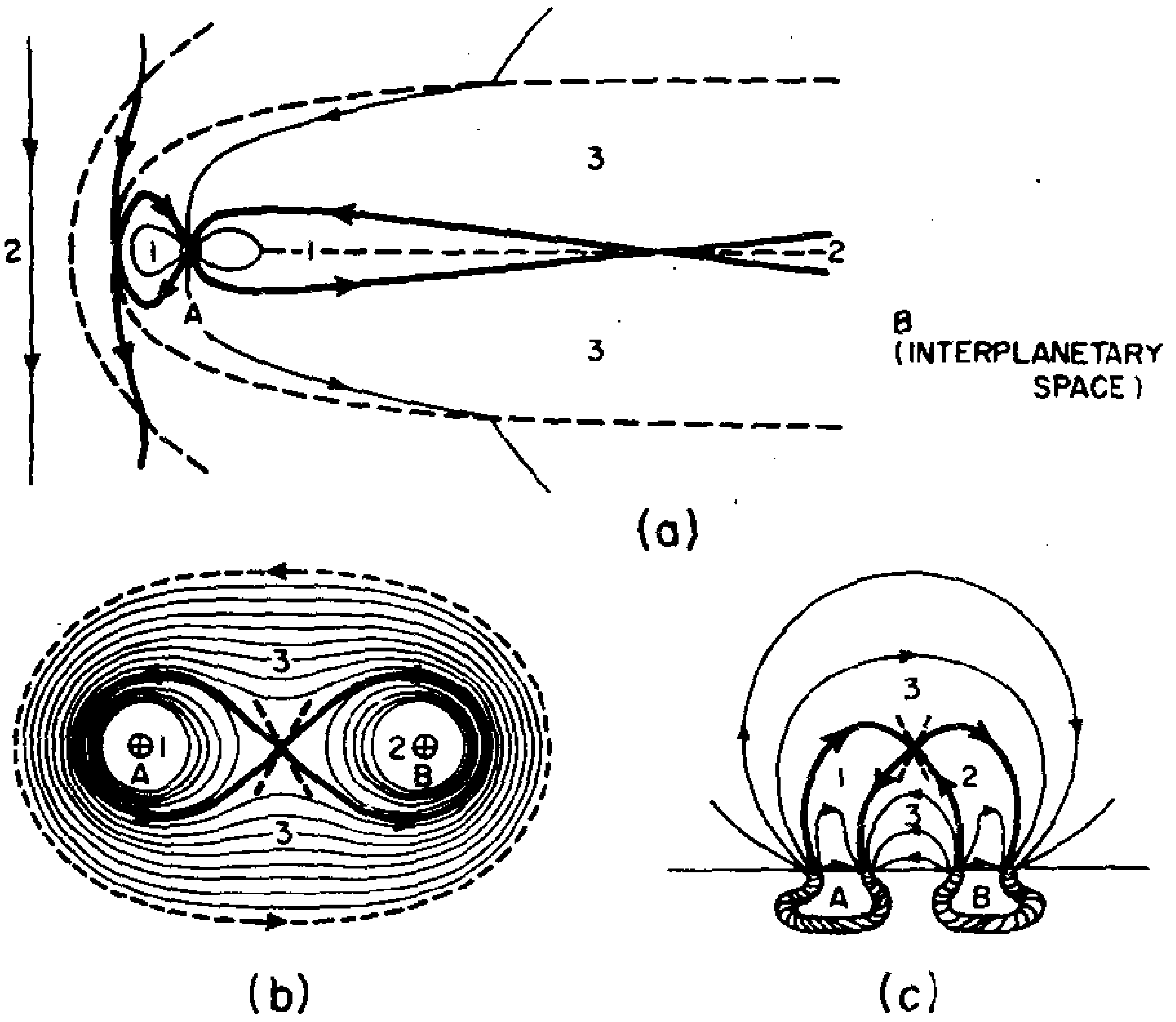

FIG. 1. Three expressions of the three-celled field topology of two primary current sources A and B. (a) Magnetosphere, source A in earth, B in interplanetary space. (b) The double inverse pinch device (DIPD); sources A and B are conductors on which externally driven currents increase with time. (c) Field of two bipolar sunspot groups. Current sources A and B are schematically represented by subphotospheric solenoids. [From Bratenahl and Baum (1976a).]

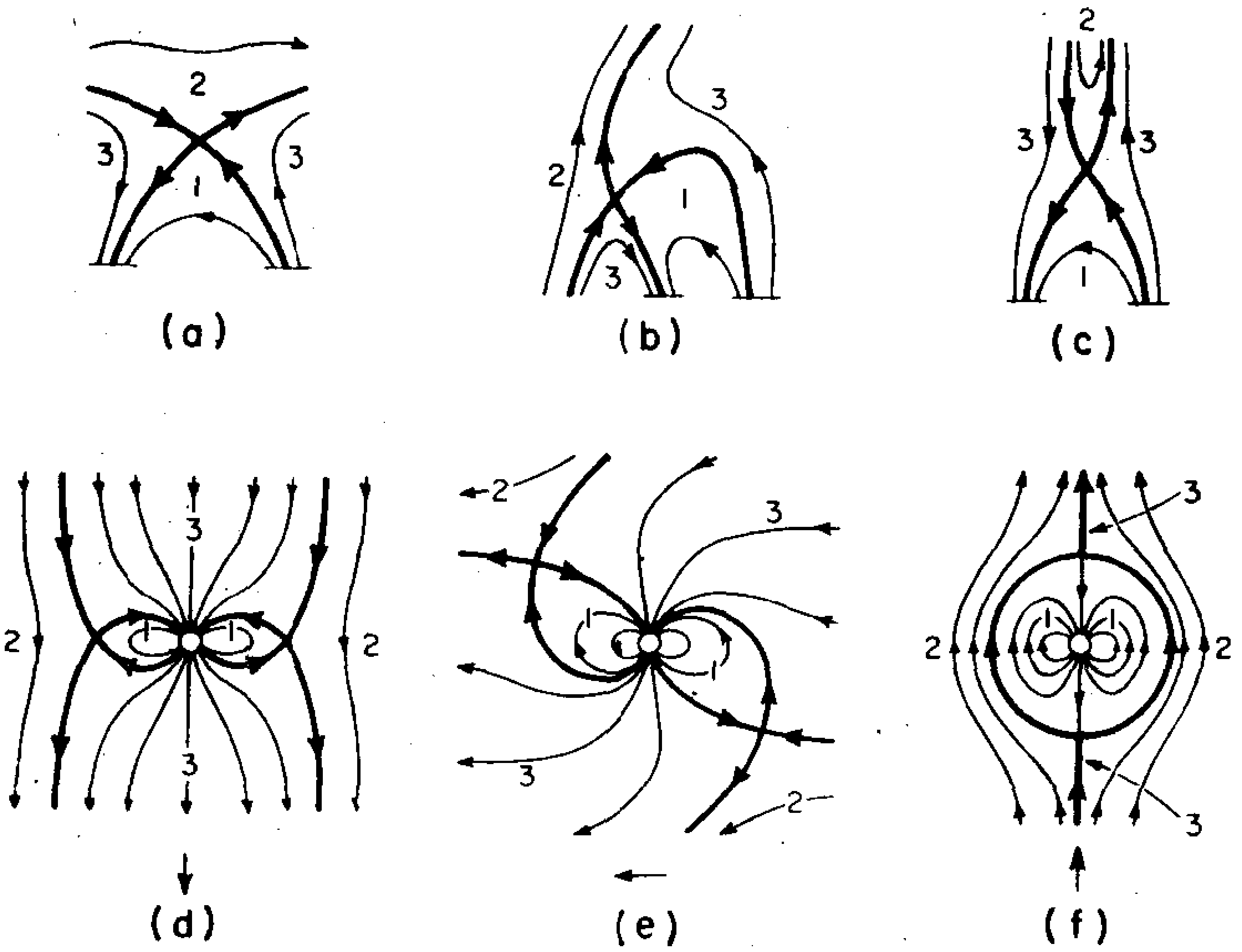

FIG. 2. Other three-celled field topologies. (a) Bipolar sunspot interacting with horizontal field. (b) Bipolar sunspot interacting with vertical field. (c) Field at border of plage regions of opposite polarity. (d)–(f) A dipole immersed in a uniform field showing how the flux content of the three cells changes with field orientation. [From Bratenahl and Baum (1976a).]

action of the fields of two conducting rods carrying parallel currents. Figure 1c depicts the field of four sunspots, assumed to represent the erupted portions of two subphotospheric flux bundles defined by solenoidal current systems. In Fig. 2 we see other ways of generating what we call the characteristic three-cell topology of two current systems. Also demonstrated is the dependence of the allocation of flux among the three cells upon the angle between a uniform field and the axis of a dipole field.

Although at the outset of theoretical work on the reconnection problem Dungey (1958b) and also Sweet (1958a,b) clearly recognized its system-wide topological aspects, these were quickly put aside in favor of investigating the local plasma dynamics in the neighborhood of magnetic null points, particularly x-type neutral points. This concentration on local effects with insufficient attention paid to distant causes and distant effects was, perhaps, the very natural consequence of pursuing a new line of theoretical investigations on a purely deductive basis without a parallel interactive effort in the laboratory. In addition to the unfortunate introduction of the notion of moving magnetic field lines, which excludes the physically valid and more powerful method of superposition, an orthodoxy soon developed that expressed itself by saying that because of the huge difference of scale, obtainable plasma regimes and "wall effects," laboratory reconnection experiments can bear little or no relevance to the problem of reconnection on the cosmic scale. This viewpoint has some merit if the experimental objective is to produce a scale model of cosmic processes, but it quite misses the mark if the objective is directed at testing the assumptions and approximations in the corpus of the theory. The essential point is this: the study of reconnection in the laboratory forces upon the investigator an awareness of the system-wide aspects of the problem, much as an electrical engineer must consider the functioning of a whole system, and the cause–effect chains within it due to the interactive couplings between its component parts or subsystems. For instance, although the detailed nature of an instability that might develop may be quite different in the laboratory and cosmic contexts, nevertheless, the ultimate cause leading inevitably to some kind of instability and the ultimate consequence of that instability may, in fact, be very similar. This can be of great assistance in learning how to pose the right questions, fundamental questions that can lead to a proper definition of the nature of the problem. Moreover, an adequate theory should be equally capable of explaining reconnection phenomena whether it be in the laboratory or in space.

We conclude from the above that in order to pose the electrodynamic and topological aspects of the reconnection problem as a determinate problem, the system under consideration must include the entire domain of the flux cells that engage in the exchanges and transfers of flux. In the discipline of fusion energy research, this has become the *modus operandi* for the obvious reason that laboratory experiment is the *raison d'etre* of theory, so that theory and laboratory experiments have, of necessity, become closely integrated. In cosmic physics, on the contrary, the "orthodoxy" referred to above has interfered with such an integration. The result at the present time is that reconnection theory in the cosmic physics context has largely ignored laboratory evidence and has concerned itself almost exclusively with the so-called restricted problems (Vasyliunas, 1975): the plasma dynamics in a neighborhood of x-type neutral points, neutral line, or neutral sheet, a neighborhood that has been excised out of the three-cell system topology with the assignment of an arbitrarily but conveniently chosen boundary.

Theoretical work on the restricted problem has been mostly confined to steady plasma flows despite the fact that a principal objective, the understanding of flares and substorms, involves impulsive phenomena. Moreover, Cowley (1975) seems to have demonstrated that the steady restricted problem is not well posed. Inductive (rotational) electric fields are not considered, nor could they be introduced in a self-consistent way since this would require keeping track of the changes in flux content of the various cells, and these are not defined in the excised system. On the other hand, such time-dependent studies of the restricted problem as have been made do not seem to lead to steady solutions (Sweet, 1969). This presents one of several paradoxes that have arisen, and it is the resolution of such paradoxes that provides a strong motivation for laboratory reconnection experiments designed to test theory. More will be said of these paradoxes in what follows.

This introduction would not be complete without an attempt at a formal definition of reconnection. This is not as easy as it might seem because of the wide variety of situations in which it can arise. Within the context of the restricted problem, Vasyliunas (1975) defines reconnection as (1) the plasma dynamic process in which there is a plasma flow across a separatrix. In the same context, reconnection might alternatively be defined as (2) the plasma dynamic process in which there is an electric field along a separator. These local definitions address complementary features concerning just one aspect of the problem. The local region behaves like a nonlinear circuit element, and its reponse in any particular situation depends on the overall system structure and what is taking place throughout. In general, the electric field is the sum of rotational and irrotational contributions:

$$\mathbf{E} = -(\partial \mathbf{A}/\partial t) - \nabla\psi$$

These two component fields are coupled to the plasma dynamics in completely different ways. Under certain circumstances they can be separately measured in the laboratory through integral measurement techniques. In fact the first, relating to Faraday's law governing changes in the flux and its distribution among the cells, can redistribute space charges, even producing double layers, whereas the second, deriving from these space charges, local or distant, can be severely modified by the first. The restricted problem cannot address these issues. Accordingly, a system-wide definition has been proposed (Bratenahl and Baum, 1976a amended). (3) Reconnection is the transfer of flux from parent to daughter cells or vice versa, accompanied by the compression, acceleration, and energization of any plasma that gets in its way, and this work is performed at the expense of the electromagnetic field. This is closely related to Sweet's original definition (Sweet, 1958a): (4) Reconnection is the interpenetration of two flux tubes that differ in the connectivity of their field lines. (3) and (4) are related also to a definition within the fusion descipline: (5) Reconnection is a change in the magnetic topology involving the development of a new separatrix structure defining one or more magnetic islands enclosing additional magnetic axes in a system initially containing just one such axis. (A magnetic axis is a field line in a toroidal geometry that closes on itself after a finite number of turns around the toroidal direction.)

The experiments to be discussed herein are mainly those relating to reconnection theory within the discipline of cosmic plasma physics. However, there have been outstanding important instances of transfers of new concepts from the fusion discipline. One example is the tearing-mode instability of the sheet pinch and its experimental evidence must be included. We shall see some of the effects of this interweaving of the two disciplines in Section III.

III. HISTORICAL PERSPECTIVE PRIOR TO 1970

Reconnection had its roots in the early attempts to explain solar flares. Thus Giovanelli (1946, 1947, 1948, 1949) associated flares with electrical discharges at x-type neutral points. The dynamics of this x-point process was first considered by Dungey (1953, 1958a,b). Many others have followed his lead. A partial list of researchers who have worked in this field appears in Appendix II, which lists some of the technical jargon of the subject along with the earliest referenced use that we have been able to discover.

Dungey (1953) immediately noticed that once a current is started along the separator, there is a remarkable tendency for the x-point structure to collapse into a neutral current sheet, like a pair of scissors, accompanied by a spontaneous increase in the current. He interpreted this to be an instability, and thus we have Dungey's Paradox and Sweet's Paradox.

A. Dungey's Paradox

The Lorentz force of a current at an x point distorts the field in such a way that the current is increased, and with the increased current, distortion is increased still further, in violation of Lenz's law. (Dungey believed that this obvious violation of Lenz's law could be discounted by saying that Lenz's law only applies to rigid conductors.)

(1) *Resolution.* Lenz's law cannot be applied to an open system as Dungey did. The entire current circuit must be taken into account in order to apply Poynting's theorem. Dungey's instability interpretation was generally believed to be correct until Imshennik and Syrovatskii (1967), using Poynting's theorem, showed it to be a cumulation or storage of electromagnetic energy from external sources. In other words, the current increase is not spontaneous but is related to an influx of electromagnetic energy from sources outside the system under consideration.

(2) *Comment.* Consideration of the whole current circuit is almost never done by workers in this field, and numerous errors have resulted therefrom Appendix I shows the relation between Dungey's increasing current and external EMFs to drive it. The collapse of the x point led Sweet and almost everyone else since to believe that the end result was the formation of a single current sheet, which experiment now clearly shows is not necessarily