Real Properties of Electromagnetic Fields and Plasma in the Cosmos

Donald E. Scott

***Abstract*—A majority of baryons in the cosmos are in the plasma state. However, fundamental disagreements about the properties and behavior of electromagnetic fields in these plasmas exist between the science of modern astronomy/astrophysics and the experimentally verified laws of electrical engineering and plasma physics. Many helioastronomers claim that magnetic fields can be open ended. Astrophysicists have claimed that galactic magnetic fields begin and end on molecular clouds. Most electrical engineers, physicists, and pioneers in the electromagnetic field theory disagree, i.e., magnetic fields have no beginning or end. Many astrophysicists still claim that magnetic fields are "frozen into" electric plasma. The "magnetic merging" (reconnection) mechanism is also falsified by both theoretical and experimental investigations.**

***Index Terms*—Magnetic fields, Maxwell equations, merging, plasmas.**

I. Introduction

PLASMA cosmology was formally introduced more than 25 years ago by Alfvén [1]–[3]. This paper was based on his earlier experimental investigations and those of Birkeland and Langmuir. They, in turn, had been motivated by the concepts embodied in Maxwell's equations. This compact set of relations codifies the results of a long series of experiments that were performed by the founders of electrical science. Thus, plasma cosmology is not based simply on deductive reasoning and mathematical formalisms, but rather on verified laboratory evidence.

For example, an indication of the dominance of the magnetic force is demonstrated by a ball bearing on a table. All of Earth's baryonic mass exerts a gravitational pull on the bearing, preventing it from lifting off the table. Yet, the smallest horseshoe magnet easily snatches it away. On a cosmic scale, magnetic energy density can also exceed gravitational energy density. For example, in the local supercluster, the magnetic field energy density exceeds the gravitational energy density by at least an order of magnitude [4].

The local interstellar medium has an estimated ion–electron pair concentration in the range of 0.01–1/cm^3. Thus, the volume between the Sun and its nearest neighbor contains some 6×10^{54} ion–electron pairs. However, quantitative calculations based on simple electrostatic forces between such particles lead to erroneous conclusions. This is because double layers (DLs) separate cells of plasma in space (e.g., heliospheres) such that electrostatic forces between bodies that are each surrounded by such DL-bounded plasma cells are negligibly weak. Homogeneous models often are found to be misleading and should be replaced by inhomogeneous models, with the inhomogeneities being produced by filamentary currents and DLs that divide space into cells [5]. Space in general has a cellular structure.

Theoretical analyses based on the classical plasma theory often fail to correspond to real results that are obtained via direct observation. On the other hand, simulations on supercomputers and actual laboratory experiments provide accurate descriptions of the behavior of such cosmic plasmas. Rotation is an inherent result of interacting electric currents in plasma. Computer models of two current filaments interacting in a plasma have accurately reproduced details of spiral galaxy rotation profiles [6]. Plasma cosmology also offers [1] a model that predicted the existence of galactic jets and the behavior of double-radio-source galaxies prior to their observation.

It is clear that a rigorous understanding of the real physical properties of magnetic fields in plasmas is crucial for astrophysicists and cosmologists. Incorrect pronouncements about the properties of magnetic fields and currents in plasma will be counterproductive if these conceptual errors are propagated into publications and then used as the basis of new investigations. There are some popular misconceptions.

1) Magnetic "lines of force" really exist as extant entities in 3-D space and are involved in cosmic mechanisms when they move.
2) Magnetic fields can be open ended and can release energy by "merging" or "reconnecting."
3) Behavior of magnetic fields can be explained without any reference to the currents that produce them.
4) Cosmic plasma is infinitely conductive, so magnetic fields are "frozen into" it.

II. Magnetic Lines of Force

Since the 1950s, some solar astrophysicists have asserted that the interplanetary magnetic field (IMF) is really open ended [7], with one end "anchored" to the Sun and the other waving in the solar wind. Open field lines supposedly connect to the polar regions of the Sun and define the polar coronal holes that are prevalent at solar minima [8].

"The IMF originates in regions on the Sun where the magnetic field is 'open'—that is, where field lines emerging from one region *do not return to a conjugate region but extend virtually indefinitely into space* [9]."

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Although it is well understood among the space physics community that the divergence of magnetic fields in space is zero valued (B is "solenoidal"), some recent statements are equivocal on this point.

"Magnetic field lines can exist in two types: closed and open. A closed magnetic field line is anchored at two points in the photosphere and extends into the corona as a loop or arch. This explains the shape of solar prominences. Open field lines are only anchored at one point in the photosphere, and they extend out into interplanetary space; it is in these open field lines that the corona can expand outward in the form of the solar wind [10]."

"An 'open' field line is defined as being one upon which the solar wind flows. As Parker predicted, the solar wind flows faster than the critical speed, and hence *the field line does not return to the Sun* locally [11]."

If it is well understood that the "open" field lines are actually closed loops and eventually return to the Sun, how and at what location does the matter in the solar wind get off the closed path?

"Field lines intersecting the photospheric boundary are said to be anchored and the point of intersection is termed a foot-point. Field lines anchored at both ends to the photospheric boundary are said to be *closed*. Closed field lines appear to account for the majority of an active region's corona. *Open field lines,* such as in coronal holes, are those with one footpoint in the photosphere and the other end in the source surface or *extending to infinity* [12]."

Regarding the end that is supposedly anchored in the Sun, to what kind of entity does the magnetic field line attach itself? These questions are important in cosmology because the Sun is a typical star, and all stars in the cosmos must have at least somewhat analogous characteristics.

The notion that magnetic field lines can be open ended is impossible to reconcile with Maxwell's simple and universal equation, i.e.,

$$\nabla \cdot B = 0 \tag{1}$$

or in integral form (Gauss' law for magnetism) given by

$$\oint_A \vec{B} \cdot d\vec{A} = 0 \tag{2}$$

and the vast body of experiments that led to it. At any instant of time, the net sum of all magnetic flux entering any closed surface A is zero. The closed surface can be of any size or shape. Therefore, there can be no beginning or end to a magnetic field anywhere. Whatever magnetic flux enters the closed surface also leaves it. There is no way to store magnetic flux inside the volume that is defined by the closed surface. Every magnetic field is a continuum, i.e., a vector field. Each of the infinite and uncountable points in this continuum has a magnitude and a direction that is associated with it. This continuum is not composed of (does not contain) a set of discrete lines. Lines are sometimes drawn on paper to describe the magnetic field (its direction and magnitude). Where the field is strong, such as at the poles of an electromagnet, the lines come close together. However, the lines themselves do not actually exist in reality. They are simply a visualization device, i.e., a useful way to understand the properties of a vector field. The loci are always endless (closed) loops. There is only one "type of magnetic field line." They are useful abstractions and nothing more.

III. Double Helix Nebula

Another misleading statement surfaced regarding the properties of magnetic fields in the search for an explanation of a double-helix-shaped plasma near the center of the Milky Way galaxy [13]. Investigators have attempted to describe this object in terms of twisted magnetic flux tubes and Alfvénic magnetic waves. Yet, it is obviously a galactic Birkeland current. It can clearly be seen as a pair of helical current filaments in a plasma. One attempt with which the author is familiar is being made to model its twisted shape as being caused by the rigid connections of a magnetic field to a pair of counterrotating molecular clouds, with one at each of its "ends." A supercomputer study is being conducted using a magnetohydrodynamic (MHD) model to explain the "kinks" (plasma instabilities) in the object. This MHD model is based on a nonresistive plasma, which is a notion that Alfvén showed decades ago that is a purely mythical concept.

The point is that nothing can be explained by assuming that an open-ended magnetic field has rigid connections either to the Sun, which is a star, or a rotating molecular cloud at one or both of its ends. Magnetic fields do not have ends.

The phrase "magnetic lines of force," as coined by Faraday, is misleading. The only force that is uniquely associated with a magnetic field is the one that is applied to a compass needle to force it to align with the field's direction. If and when electrical charges pass through a magnetic field, other types of forces result, but these are due to the interaction between these moving charges and the field, as described by the equation of motion of Lorentz, i.e.,

$$\frac{d}{dt}(mv) = q(E + v \times B). \tag{3}$$

This relationship accurately describes the cause of synchrotron radiation and the spiral paths that are taken by currents in magnetized plasma.

Many astrophysicists, when presented with these ideas, will acknowledge that magnetic lines of force are only abstractions and not real-world extant objects. However, there is no justification for statements such as "For many years [these lines] were viewed as merely a way to visualize magnetic fields, and electrical engineers usually preferred other ways, mathematically more convenient. Not so in space, however, where magnetic field lines are fundamental to the way free electrons and ions move. These electrically charged *particles tend to become attached to the field lines* on which they reside, spiralling [sic] around them while sliding along them, like beads on a wire [14]." This erroneous concept becomes doubly dangerous when the magnetic field lines themselves are also thought to be able to move, as in magnetic reconnection.

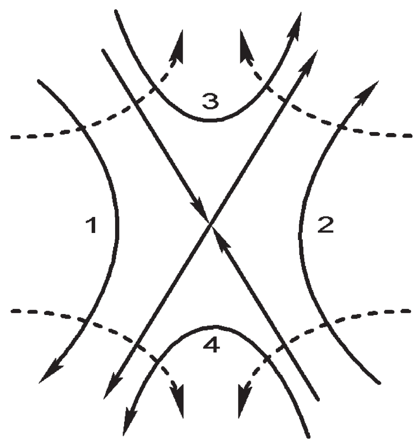

Fig. 1. Concept of magnetic reconnection: magnetic merging at an X-type neutral line. The solid lines are the magnetic field lines, whereas the dashed lines are the plasma flow lines.

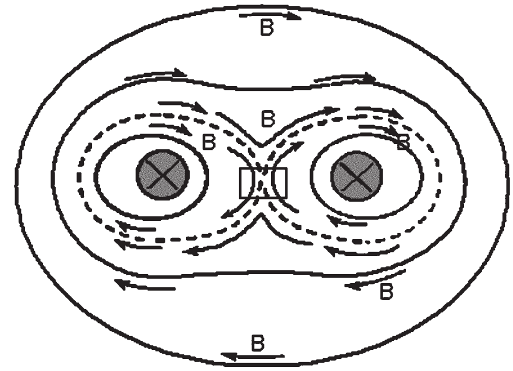

Fig. 2. Two parallel electric currents that are directed away from the viewer showing the resulting magnetic field. The central box in this figure is shown in Fig. 1. The dashed lines are "separatrix loci" that come into contact along a line central to and parallel with the currents.

IV. Magnetic Reconnection

In 1961, Dungey proposed magnetic reconnection, an idea that Giovanelli conceived in 1946 to explain solar flaring. It has become widely accepted among astronomers that when more or less oppositely pointing field lines approach each other, they can abruptly "short circuit," "merge," or "reconnect." In this reconnected configuration, the field lines are bent tightly like the elastic strings of a catapult. When the field lines suddenly straighten, they supposedly fling out plasma in opposite directions. The reason that they suddenly straighten is assumed to be the second term in the MHD pressure equation, i.e.,

$$\nabla(p + B^2/2\mu_o) - (B\nabla)B/\mu_0 = 0. \tag{4}$$

Alfvén addressed this point [5] by noting that the second term in (4) is equivalent to the pinch effect that is caused by electric currents.

The standard explanation of reconnection (Fig. 1) is that magnetic field lines 1 and 2 *move* in from the left and from the right, and eventually come together (short circuit) at the central point. There they change their structure: The two top halves join (reconnect) and *move* up, ultimately reaching the position of line 3, while the two bottom halves join and form the line that later moves to position 4.

However, lines 1, 2, 3, and 4 are magnetic field lines and, as such, cannot move or "reach the neutral line." In addition, there must be currents or current sheets that are not shown in Fig. 1 since curved magnetic fields cannot exist without them (see Section V). An additional error is made in assuming that plasma is "attached" to those lines and will be bulk transported, as shown by the dashed paths in Fig. 1, by this movement of the magnetic lines.

Although the proposed reconnection mechanism changes the topology of the magnetic field, it does not explicitly *reduce the strength* of any part of the magnetic field. Thus, it cannot liberate magnetic energy that is stored in that field.

One source explains reconnection as being caused by the breaking of magnetic field lines. "Magnetic reconnection is a fundamental physical process occurring in a magnetized plasma, whereby magnetic field lines are effectively *broken* and reconnected, resulting in a change of magnetic topology, conversion of magnetic field energy into bulk kinetic energy and particle heating [15]."

Proposing that magnetic field lines move around, break, merge, reconnect, or recombine is an error based on the false assumption that the lines are real entities in the first place. This is an example of reifying an abstract theoretical concept. Field lines are not real-world 3-D entities and thus cannot do anything. Like mathematical singularities, field lines are pure abstractions and cannot be reified into being real 3-D material objects.

The central point in Fig. 1 from which energy is supposedly released by magnetic reconnection (merging) is a neutral point, one at which the magnetic field strength is zero valued.

Fig. 2 provides a simple example that demonstrates how such a neutral point can be created. The field structure that is shown in Fig. 1 lies within the small rectangle at the center of Fig. 2. The two dark circles with central Xs in Fig. 2 represent two straight equal-amplitude electric currents I flowing away from the viewer (into the page). A clockwise-directed magnetic flux will therefore encircle these currents. Each of the dashed lines in this figure is a "separatrix." Inside these dashed lines, the magnetic field links only one current. Outside the separatrix, the magnetic field links both currents. The two separatrix loci intersect at the neutral point, which, in this 3-D case, is actually a neutral line.

The magnetic field strength vector at any point in the plane of the figure is the vector sum of all component fields that are produced by all differential current segments in the vicinity. At the neutral point (or line), the current on the right produces a magnetic field strength vector that is vertically upward. Similarly, the current on the left produces a magnetic field vector that is vertically downward at that point. Therefore, these two field strength vectors sum to zero at the center of the figure, and the strength of the B field at such a neutral point is identically zero. Additional currents AND/OR current sheets can be added to this diagram. Doing so will alter the topology of the magnetic field, possibly introducing additional neutral points or lines and separatrices.

Note that no electric currents exist near or at the neutral point. If they did, the point would no longer be magnetically neutral.

The energy that is stored at any point in a magnetic field is proportional to the square of the magnitude of the magnetic flux density at that point, i.e.,

$$W_B = \frac{1}{2\mu_o} \int B_I^2 dv \tag{5}$$

where B_I is the magnitude of the magnetic field, and dv is a small volume element. Thus, if $B_I = 0$ at any given point, then the stored energy there would be $W_B = 0$. No energy is stored at a neutral point; this is why it is called a neutral or null point.

No energy release can occur from any point at which no energy is stored.

However, a large amount of energy can be stored in and released from the surrounding field structure but *only* if either or both currents I take on lower values. This is easily demonstrated in the example in Fig. 2, which is given in the following.

The total energy that has been delivered to an electrical element (e.g., a unit length of the conductors that are shown in Fig. 2) by time t_0 is given by [16]

$$W(t_0) = \int_{-\infty}^{t_0} v(t)i(t)dt. \tag{6}$$

For the case of the flux-linked conductors in the example, $i(t) = 2I$, and $v(t)$ is the voltage drop across a unit length of the conductor in the direction of $i(t)$. Faraday's law indicates that

$$v(t) = \frac{d\phi(t)}{dt} \tag{7}$$

where ϕ is the total magnetic flux that links the conductors. Thus, the energy that is stored in the magnetic field that surrounds the conductors at time t_0 is given by

$$W(t_0) = \int_{-\infty}^{t_0} \frac{d\phi}{dt} i(t)dt = \int_{\phi(-\infty)}^{\phi(t_0)} i d\phi \tag{8}$$

where the total magnetic flux depends on the current's amplitude, i.e.,

$$\phi(t) = Li(t). \tag{9}$$

The constant of proportionality L is called the inductance, which may be a constant or a function of ϕ. When a current flows in large regions, this single inductance element L should be replaced by a transmission line, and the situation is then more accurately (but less intuitively) described by partial differential equations [1]. Equations (6)–(9) demonstrate the basic principle that the total energy that is stored magnetically in the infinite volume surrounding the conductors completely depends on the current. That is, using (9), (8) may be written as an integral in terms of only the current. The total energy that will be released from this volume over any time interval is thus clearly a function of the change in current amplitude over that interval.

The diagram in Fig. 2 approximates a cross section of a cosmic Birkeland current pair. If these twin currents are disrupted (e.g., by an exploding DL in their path), the field will quickly collapse and liberate all of the stored magnetic energy that is given by (8).

Investigators [15], [17]–[20] who prefer to avoid explicit mention of electric current as a primary cause of cosmic energy releases fall back on magnetic reconnection as an explanation. In certain situations, magnetic reconnection supposedly directly converts magnetic energy into kinetic energy in the form of bidirectional plasma jets. The process is initiated in a narrow source region that is called the "diffusion region." According to the theory, both resistive and collisionless processes can initiate reconnection. One of the key predicted signatures of collisionless reconnection is the separation between ions and electrons (plasma) in the diffusion region. This separation is said to create a quadrupolar system of Hall *currents* and, thus, an associated set of Hall magnetic fields. Even here however, it is understood that any released energy comes not from neutral points, lines, or surfaces, where no energy is stored, or bulk movement of plasma but from the surrounding magnetic field structure that depends on those Hall currents for its existence.

The crucial difference between the two explanations is the question of which quantity (time-varying electric current or moving magnetic "lines") causes energy release from the magnetized plasma.

Alfvén [1] was explicit in his condemnation of the reconnecting concept: "Of course there can be no magnetic merging energy transfer. The most important criticism of the merging mechanism is that by Heikkila [21], who, with increasing strength, has demonstrated that it is wrong. In spite of all this, we have witnessed, at the same time, an enormously voluminous formalism building up based on this obviously erroneous concept.

I was naïve enough to believe that [magnetic recombination] would die by itself in the scientific community, and I concentrated my work on more pleasant problems. To my great surprise the opposite has occurred: 'merging' ... seems to be increasingly powerful. Magnetospheric physics and solar wind physics today are no doubt in a chaotic state, and a major reason for this is that part of the published papers are science and part pseudoscience, perhaps even with a majority in the latter group."

V. Role of Electric Currents in the Cosmos

No real magnetic field can exist anywhere without an associated moving charge (electric current). Conversely, any electric current will create a magnetic field. The applicable Maxwell equation describes this inherent interrelationship, i.e.,

$$\nabla \times H = j + \varepsilon \frac{dE}{dt} \tag{10}$$

where j is the current density, and the second term on the right is the displacement current, which is often neglected. However, it is sometimes convenient to account for the kinetic energy of a magnetized plasma by introducing the effective permittivity, i.e.,

$$\varepsilon \Rightarrow \varepsilon \left[1 + (c/V_{\mathrm{MH}})^2\right] \tag{11}$$

where c and V_{MH} are the velocities of light and of hydrodynamic waves. If this is done, the displacement current can be large [1]. In any event, all terms in the equation are expressed in amperes per square meter. Magnetic flux density $B = \mu H$ (where μ is the magnetic permeability of the medium). Equation (10) defines the inherent coupling of magnetic fields and electric currents. The classroom interpretation of this relationship is called the "right-hand rule." Point your right thumb in the direction of the current density vector; your fingers show the direction of the magnetic field (and vice versa). Although magnetic fields are often included in astronomical hypotheses, the inherently associated electric currents are rarely mentioned. In addition, as is true in the proposed reconnection mechanism, the behavior of cosmic magnetic fields and the release of energy from those fields can only be understood by referencing the behavior of their causative electric currents.

VI. Frozen-in Magnetic Fields

Astrophysicists often assume that plasmas are perfect conductors, and as such, any magnetic field in any plasma must be "frozen" inside it. (This rigid attachment is assumed in the magnetic reconnection mechanism that is discussed in Section IV.) Indeed, it was plasma pioneer Alfvén who first proposed this idea. It was based on the observation that, since plasmas were thought to be perfect conductors, they cannot sustain electric fields.

Alfvén's original motivation for proposing "frozen-in" fields stemmed from another one of Maxwell's equations, i.e.,

$$\nabla \times E = -\frac{dB}{dt}. \tag{12}$$

This implies that if the electric field in a region of plasma is identically zero valued (as it would have to be if the medium had zero resistance—perfect conductivity), then any magnetic field within that region must be time invariant (must be frozen). Thus, if all plasmas are ideal conductors (and thus cannot support electric fields), then any magnetic fields inside such plasmas must be frozen in, i.e., cannot move or change in any way with time.

The electrical conductivity of any material, including plasma, is determined by two main factors, namely: 1) the *density* of the population of available charge carriers (free ions and electrons) in the medium and 2) the *mobility* of these carriers. Most, if not all, cosmic plasmas are magnetized (contain large and long internal magnetic fields). In any such plasma, the transverse (perpendicular to this field) mobility of charge carriers is severely restricted because of the spinning motion that is imposed on their momentum by Lorentz force (3). Mobility in the parallel (and antiparallel) direction, being unaffected by this transverse force, is extremely high because electrons and ions have long mean-free paths in such plasmas. However, the density (the number per unit volume) of these charge carriers may not be at all high, particularly, if the plasma is a very low pressure (diffused) one. Therefore, conductivity is less than ideal, even in the longitudinal direction, in cosmic plasma.

Laboratory measurements demonstrate that a nonzero-valued electric field in the direction of the current ($E_{\mathrm{parallel}} > 0$) is required to produce a nonzero current density within any plasma no matter what mode of operation the plasma is in. Negative-slope regions of the volt-ampere characteristic (negative dynamic resistance) of a plasma column reveal the cause of the filamentary properties of plasma, but all static resistance values are measured to be > 0.

Thus, although plasmas are excellent conductors, they are not perfect conductors. Weak longitudinal electric fields can and do exist inside plasmas. Therefore, magnetic fields are not frozen inside them.

When, in his acceptance speech of the 1970 Nobel Prize in physics, Alfvén pointed out that this frozen-in idea, which he had earlier endorsed, was false, many astrophysicists chose not to listen. In reality, magnetic fields do move with respect to cosmic plasma cells and, in doing so, induce electric currents. This mechanism (which generates electric current) is one cause of the phenomena that is described by what is now called plasma cosmology.

Alfvén said, "I thought that the frozen-in concept was very good from a pedagogical point of view, and indeed it became very popular. In reality, however, it was not a good pedagogical concept but a dangerous 'pseudo pedagogical concept.' By 'pseudo pedagogical' I mean a concept which makes you believe that you understand a phenomenon whereas in reality you have drastically misunderstood it."

Now, we know that there are slight voltage differences between different points in plasmas. Many astrophysicists are still unaware of this property of plasmas, and so, we often still read unqualified assertions such as "Once a plasma contains magnetic fields, they move with the plasma as if the magnetic field lines were *frozen in* [18]."

In addition, "... plasmas and magnetic fields interact; they behave, approximately, as if they are '*frozen*' together [19]."

"... fields that are 'stuck' inside conductors take a long time to diffuse out (i.e., the magnetic flux is *frozen* into the moving plasma) [20]."

VII. Conclusion

Maxwell showed that magnetic fields are the inseparable handmaidens of electric currents and vice versa. This is as true in the cosmos as it is here on Earth. Those investigators who, for whatever reason, have not been exposed to the now well-known properties of real plasmas and electromagnetic field theory must refrain from inventing "new" mechanisms in efforts to support current-free cosmic models. "New science" should not be invoked until all of what is now known about electromagnetic fields and electric currents in space plasma has been considered. Pronouncements that are in contradiction to Maxwell's equations ought to be openly challenged by responsible scientists and engineers.

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