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# Formation of current sheets in a highly conducting fluid

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**Abstract—Magnetic field embedded in a highly conducting fluid has an important property that magnetic field lines are frozen to the fluid elements. As any two fluid elements approach towards each other under the influence of some unbalanced forces then the magnetic field lines also move along with the fluid elements and whenever the two fluid elements come into direct contact with each other then at the surface of contact the magnetic field lines become discontinuous as the field lines associated with respective fluid elements do not mix with each other. This discontinuity in magnetic field led to a very high value of electric current density at the surface of contact of the two fluid elements. As the electric current density is confined to a two-dimensional plane so it is termed as current sheets. In the presence of electrical resistivity, current sheets decay through ohmic dissipation resulting in heat and kinetic energy along with change in magnetic field topology. This process of energy conversion is called magnetic reconnection. The formation of current sheets and their eventual decay in a highly conducting fluid reveals the mysteries of various phenomena like heating of solar corona at its million-degree Kelvin temperature, solar flares and coronal mass ejections. The theory of the formation of current sheets is also applicable to laboratory plasmas, interplanetary medium and astrophysical plasmas.**

**Index Terms— Current sheet, Magnetic topology, Magnetic discontinuity, Magnetic reconnection, Solar corona**

## I. INTRODUCTION

The dynamics of magnetic field embedded in a highly conducting fluid is governed by the magnetohydrodynamic (MHD) equations [1]. An important parameter in magnetohydrodynamics is the magnetic Reynolds number which is the ratio of diffusion time scale and the convective time scale [2]. The magnetic Reynolds number shows the relative dominance of the two scales. A high value of magnetic Reynolds number indicates that the convection is dominant whereas a low value of magnetic Reynolds number indicates that the diffusion is dominant. A fluid having infinite value of Reynolds number is governed by ideal magnetohydrodynamic equations. An important property of ideal magnetohydrodynamics is that magnetic field lines are frozen to the fluid elements/parcels--- called frozen-in or flux-freezing condition [2]. Under the frozen-in condition, any interlinking or connectivity of magnetic field lines--- called the magnetic topology--- is preserved. A highly conducting fluid containing magnetic field is termed as magnetofluid as the magnetic field lines and the fluid elements move together. Now consider the case when two fluid elements approach towards each other under the influence of some unbalanced forces like Lorentz force, pressure gradient, viscous drag, etc. As two such fluid elements come into a direct contact with each other then at the surface of contact the magnetic field lines associated with respective fluid elements will also come into a direct contact with each other. The magnetic field lines from the two fluid elements do not mix with each other because of the frozen-in condition and at the surface of contact the magnetic field lines will develop magnetic discontinuity (MD) [3]. Because of such discontinuity in magnetic field, a large gradient in magnetic field develops across the common surface of contact, resulting in a high value of electric current density. This current density is totally confined to a two-dimensional surface and hence also called a current sheet (CS). In case of ideal magnetohydrodynamics, a true discontinuity in magnetic field appears where the thickness of the current sheet is zero. However, in real magnetofluid, the electrical conductivity is not infinite and there is some finite electrical resistivity. In case of real magnetofluid, the magnetic field lines associated with the two fluid elements do not come into a direct contact with each other, but rather, the diffusion becomes dominant as soon as the separation between the two fluid elements becomes very small where the value of magnetic Reynolds number is low. In such a scenario, a current sheet of finite thickness is formed in between the two fluid elements. Such current sheet will decay by the presence of very small but finite electrical resistivity--- resulting in generation of heat and kinetic energy along with a change in magnetic field topology. This process of energy conversion along with a change in field topology is called magnetic reconnection (MR) [4]. Such a process of the formation of current sheets and their eventual decay by magnetic reconnection plays a major role in heating the outermost layer of the Sun, i.e. the solar corona, at its million degree Kelvin temperature [5].

## II. FORMATION OF CURRENT SHEETS: THEORETICAL BACKGROUND

An arbitrary interlaced continuous magnetic field embedded in a highly conducting fluid develops current sheets while relaxing towards the static equilibrium [3]. An important property of static equilibrium is that the twist per unit length is constant along the magnetic field line. For an arbitrary magnetic field the twist per unit length may not have constant value along the field lines. Consequently, an arbitrary field topology will develop magnetic discontinuity or current sheets in the static equilibrium in order to accommodate the constant value of twist per unit length along the field lines. The formation of current sheets in a highly conducting fluid can also be understood mathematically by studying the nonlinear character of the magnetostatic equilibrium equation. The solution of the magnetostatic equation has real characteristics along with two families of imaginary characteristics [3]. The real characteristic of the magnetostatic equilibrium equation is nothing but the magnetic field line. Because of the inherent nonlinear character of this equilibrium equation, any two real characteristic curve may intersect at any point and the magnetic field will become discontinuous at that point. The discontinuous magnetic field then generates a high value of electric current density or current sheet.
The above idea of the formation of current sheet in a fluid with high electrical conductivity was first proposed by E.N. Parker [3]. In order to demonstrate the formation of current sheet Parker considers magnetic field embedded in an infinitely conducting fluid in between two conducting plates [3, 6]. All the magnetic field lines anchored at one conducting plate are held fixed while at the other conducting plate fluid motion is generated. Because of the motion of the fluid, the field lines will also move with the fluid following the frozen-in condition. As time passes the magnetic field lines wrap around each other and form a complex magnetic topology. The fluid motion is stopped when the field lines achieve such a complex topological configuration. The two ends of each magnetic field lines are tied and the whole system is allowed to relax towards the static equilibrium. Under the action of Maxwell stresses, the field lines achieve the terminal state of static equilibrium. In this equilibrium state the arbitrary topology of magnetic field lines is not the same as the topology of static equilibrium. The contradiction between the two sets of field topologies will result in the formation of magnetic discontinuity or current sheet. In this way by the formation of current sheets, the arbitrary field topology gets accommodated in the terminal state of static equilibrium.

## III. FORMATION OF CURRENT SHEETS IN SOME REAL PHYSICAL SYSTEMS

X-ray observation of the Sun reveals that the temperature of outermost layer of the Sun, called the solar corona, is of the order of million degree Kelvin [7]. The temperature of the surface of the Sun, called the photosphere, is of the order of few thousand Kelvin. The relatively high temperature of the solar corona is in general contradiction to the second law of thermodynamics that heat must flow from high temperature to a low temperature region. In solar atmosphere, the heat flows from the corona to the photosphere. It indicates that there must be some heat input to the solar corona in order to balance the corresponding heat loss from the corona. It is believed that the formation of magnetic discontinuity or the current sheet is responsible to to generate heat via joule dissipation in order to maintain the corona at its million degree Kelvin temperature. The Sun has its own magnetic field which is generated in the interior of the Sun through the dynamo mechanism. Because of the very high temperature of the solar corona, the gaseous medium of corona becomes ionized and is in plasma state. Thus, coronal medium has a high value of electrical conductivity. Therefore the coronal medium can be modeled as a magnetofluid which is well described by the magnetohydrodynamic equations. The coronal magnetic field lines are rooted to the photosphere. These field lines are shuffled by the convective motion of the fluid and the field lines become interlaced to generate complex structure of magnetic field lines in the solar corona. Thus, energy from the photosphere to the solar corona is transferred through the magnetic field lines. Under the action of unbalanced forces, any two portions of the magnetofluid may come into a direct contact with each other and form magnetic discontinuity wherever they meet. Following the Ampere's law, at the site of magnetic discontinuity, intense value of electric current density is generated in the form of current sheet. This high value of current density is then dissipated through the otherwise small but finite electrical resistivity of the coronal medium. In this process huge amount of energy is liberated in the form of heat and energetic particles along with the change in field topology. This is the mechanism which delivers enough heat to the solar corona to keep its temperature hovering in the range of million degree Kelvin. Also, topological changes in the coronal magnetic field lines lead to the various eruptive phenomena in the solar corona such as solar flares, coronal mass ejections, etc.

The interaction between Earth's magnetic field and the solar wind leads to the formation of current sheets in the magneto-tail region of the Earth [8]. Because of the impact of solar wind, the magnetic field lines associated with two distinct topological domains approach towards each other and current sheet is formed at the locations where the two topologically distinct magnetic field lines come into a direct contact with each other. In this process, high energetic particles are produced due to magnetic reconnection which lead to various atmospheric phenomena in the polar region of the Earth.

## V. CONCLUSION

The magnetic field embedded in a highly conducting fluid has a large value of magnetic Reynold's number. Because of this high value of Reynold's number, the magnetic field lines are frozen to the fluid elements at large length scales. As any two fluid elements containing the magnetic field lines approach toward each other under the action of unbalanced forces and come into a direct contact with each other then at the common surface of contact the magnetic field lines become discontinuous since the frozen-in condition prohibits the two sets of fluid elements to mix with each other. Because of the large value of magnetic field gradient across the common surface of contact, an intense electric current density or current sheet is generated at the points of contact. This current sheet is further dissipated by the electrical resistivity of the magnetofluid resulting in heat and kinetic energy along with the change in magnetic topology--- a process termed as magnetic reconnection. The formation of current sheets and their dissipation by electrical resistivity helps to understand the various phenomena like heating of the solar corona at its million-degree Kelvin temperature, solar flares, coronal mass ejections, etc. Also, current sheets form in the Earth's magneto-tail region and laboratory plasmas.

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