THEORETICAL APPROACHES TO THE DESCRIPTION OF MAGNETIC MERGING: THE NEED FOR FINITE $\beta_\infty$ ANISOTROPIC AMBIPOLAR HALL MHD

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Abstract. Theoretical models of magnetic reconnection are reviewed with a critical view of their suitability for astrophysical plasmas, with a focus on those sampled plasmas near the magnetopause. Frequently the approximations are more those of convenience than physically justified. It is concluded that magnetic reconnection cannot be qualitatively or quantitatively addressed with any one fluid MHD picture unless the Hall, ambipolar and inertial emfs are included in the Generalized Ohm's Law. The observed size of electron pressure anisotropies ensures that the thawing of magnetic flux is almost always determined by the often neglected ambipolar term of the Generalized Ohm's Law. Thus resistive MHD or even resistive Hall MHD cannot possibly give a correct structural picture of the reconnection current carrying layer at the magnetopause. In the magnetotail the ion inertial "resistivity" is much larger than coulomb resistivity with a similar structural form as the coulomb emf. However, until recently the ambipolar contributions there have not been considered. This change in viewpoint of the controlling factors for thawing of magnetic flux parallels the recent evolution of understanding of collisionless shocks, where initially stochastic wave-resistivities were thought to substitute for the coulomb dissipation of high density shock waves. Now these shocks are known to be controlled by coherent agents that can modify emf's such as the ambipolar electric field, the Hall contributions or the gyrating ions, and the electric electron emf in the shock layer to support the current without thawing flux and without any requirement of ohmic dissipation per se. The observational tests that reconnection is a viable process for plasma entry in the magnetosphere are briefly reviewed. Sites where these conservation laws are said to be approximately fulfilled are discussed with an eye toward systematic experimental issues of these tests. That magnetic shear poorly indexes "good" Walén testing layers may be an indication that the resistive dissipation is either not uniformly important across the data set or resistive emf's are not the appropriate agent for the thawing of flux. The ambipolar scale length clearly exceeds the resistive or electron skin depth regime with layers that pass the "good" Walén test layers which have $\beta < 5$; this may indicate the importance of the ambipolar violations to the frozen field description.

1. Introduction

Based on circumstantial evidence the space physics community is convinced that $\mathbf{B}$ field line topologies change about the Earth. Were this not the case the solar wind magnetic field hung up over the magnetopause would intensify indefinitely. The substorm activity on the ground and witnessed in space are indicators of the reality of this scenario. Nevertheless, we do not "know" what process or processes mediate the topology changes whereby flux is shed from the dayside magnetosphere and recycled to the lobes in the magnetotail. In large scale plasmas these changes in topology are accompanied by specific rearrangements of the plasma. The effects of field line interconnection that accompany these topology changes have been modeled most simply with fluid-like equations of MHD by adding lumped parameters.

such as localized (anomalous) enhancements of resistivity. While this approach may be the simplest, there remains the problem of defining the agent for this resistivity. There are, however, many other possible ways that the reconnection can be permitted that this paper will summarize. At least two of the known alternative agents for enabling reconnection are present even in the collisionless limit and have a wholly different structure than that mocked up by a collisional or enhanced ad hoc resistivity.

A number of excellent reviews on the description of merging already exist from the fluid picture (cf. Asford 1984; Vasyliunas, 1975; Sonnerup, 1984; Lee, 1995), and the collisionless picture (Hill, 1975; Cowley, 1982), so a brief statement of purpose for the present paper is appropriate. The present situation in the reconnection arena is much like the situation a few years ago with collisionless shocks. Then, observers told theoreticians shocks were present; theoreticians gave an explanation in terms of anomalous resistivity driven by micro-instabilities in the collisionless shock current layers. In this way a one for one substitution between two body resistivity and collective resistivity yielded a theory to "explain" the existence of the shock with insufficient empirical corroboration for the assumptions of their theory. However, with further experimental scrutiny it became clear, contrary to this explanation, that a rather diverse set of neglected coherent effects in the shock layer could explain their existence and the reformation of the shock layers themselves without this substitution of waves for binary collisions. Further, careful determinations of scales and sources of free energy found that the picture of linear growth, followed by non-linear reaction thought to facilitate anomalous resistivity, was a cycle that had insufficient time to take place before the fluid was swept through the layer and no longer able to tap the free energy. In the present view of shocks the collective wave particle effects "round the corners" of otherwise coherent processes in the DC electromagnetic fields of the shock structure. The self-consistent, post MHD, electromagnetic field including $E_\parallel$ was crucial to that paradigm shift.

The physics of reconnection is almost totally determined theoretically by an acceptably accurate description for the parallel electric field. Resistivity is just one of several ways to support parallel electric fields. Because reconnection involves moving plasmas in the presence of magnetic fields at current sheets with gradients, this parallel electric field will certainly have a coherent ambipolar component; whether a sufficiently vigorous stochastic $E_\parallel$ can be found to substitute for the almost negligible classical coulomb resistivity and dominate the coherent ambipolar parallel electric field (which has usually been neglected) remains to be seen in the problem of astrophysical reconnection. It is clear for $\beta \approx 1$ plasmas that there are significant coherent sources of the parallel electric field that may routinely be more important in understanding the factors that control the onset of reconnection than surmised anomalous resistivities from yet to be defined wave particle instabilities.

This review will attempt to organize all the effects that could possibly be involved in describing magnetic reconnection at the level of the conservation laws of magneto-