Journal of Atmospheric and Solar-Terrestrial Physics 99 (2013) 32–40

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Multiscale studies of the three-dimensional dayside X-line

T.E. Moore [a,*], J.L. Burch [b], W.S. Daughton [c], S.A. Fuselier [b], H. Hasegawa [d], S.M. Petrinec [e], Zuyin Pu [f]

[a] NASA Goddard SFC, Heliophysics Science Div., Code 670, 8800 Greenbelt Rd., Greenbelt, MD 20771, USA
[b] Southwest Research Institute, San Antonio, TX 78238, USA
[c] Los Alamos National Labs, Los Alamos, NM 87545, USA
[d] Institute of Space and Astronautical Science, JAXA, Kanagawa 252-5210, Japan
[e] Lockheed Martin ATC, Palo Alto, CA 94304, USA
[f] Department of Geophysics, University of Beijing, Beijing 100871, China

ARTICLE INFO

Article history:
Received 19 March 2012
Received in revised form
11 September 2012
Accepted 1 October 2012
Available online 7 November 2012

Keywords:
Reconnection
Magnetosphere
Multiscale
Plasma
Magnetic

ABSTRACT

We review recent experience from the Cluster, Double Star, and THEMIS missions for lessons that apply to the upcoming Magnetospheric Multiscale Mission (MMS) being developed for launch in 2014. On global scales, simulation and statistical studies lead to mean configurations of dayside reconnection, implying specific relative alignments of the inflow magnetic fields and X-line, with implications for MMS operations designed to maximize the number of close encounters with the diffusion region. At intermediate MHD-to-ion scales, reconstruction of features created by one or two X-lines have developed to the point where data from a cluster of spacecraft can determine their temporal trends and the approximate three-dimensional X-line structure. Recent petascale particle-in-cell (PIC) simulations of reconnection encompass three spatial dimensions with excellent resolution, and make striking predictions of electron scale physics that creates complex interacting flux ropes under component reconnection. High time resolution measurements from MMS will determine the detailed electron scale kinetics embedded within the global and MHD–ion scale contexts. These developments will lead to the refinement of our three-dimensional multiscale picture of reconnection, yielding improved understanding of the global, MHD, and local physics controlling the onset or quenching, variability, and mean rate of reconnection. This in turn will enable improved predictability of the structural features created by transient reconnection, and their space weather consequences.

Published by Elsevier Ltd.

1. Introduction

From the perspective of the dayside magnetopause, reconnection is a process that disrupts the magnetopause current sheet, leading to direct coupling of solar wind energy into the magnetosphere along connected magnetic flux tubes. The magnetopause current sheet nominally separates the internal geomagnetic field and plasmas from the external shocked solar wind and magnetic field. The internal and external plasmas vary strongly and are in general highly dissimilar, leading to strong asymmetries in the current sheet. The current sheet can perhaps be thought of as an asymmetric version of the simple (Harris, 1962) current sheet, with a thickness on the order of the ion inertial length, though there is no formal solution for this of which we are aware (Pritchett, 2008). In such a current sheet, a local reduction of the magnetic field intensity is to zeroth order balanced by an increase in the plasma pressure, such that the sum of the two pressures is constant across the sheet. This is presumably valid when a guide field reduces the field shear and hence, the amount of plasma pressure needed to balance the field pressure reduction. Though complicated by the disparate properties of internal and external plasmas, an asymmetric sheet current can and does exist at the magnetopause.

Disruption of the current sheet allows the magnetic fields to connect locally across the sheet along an X-line, with reconnection rapidly convecting plasma from the solar wind and magnetosphere onto the newly created flux tubes connecting the two regions. On such flux tubes, the plasmas rapidly interpenetrate and mix, while energy is transported from the magnetosheath into the magnetosphere and along field lines to the conjugate ionosphere, as the flux tubes are dragged anti-sunward into the magnetotail.

In this paper, we focus mainly upon recent studies of the dayside magnetopause and the connection of interplanetary magnetized solar wind with the magnetospheric plasmas of Earth,

* Corresponding author. Tel.: +1 301 286 5236; fax: +1 240 205 2377.
E-mail addresses: t.e.moore@nasa.gov, thomas.e.moore@gsfc.nasa.gov (T.E. Moore), jburch@swri.org, sfuselier@swri.org (J.L. Burch), daughton@lanl.gov (W.S. Daughton), hase@stp.isas.jaxa.jp (H. Hasegawa), steven.m.petrinec@lmco.com (S.M. Petrinec), zypu@pku.edu.cn (Z. Pu).

1364-6826/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.jastp.2012.10.004

with an eye toward studies of this type of reconnection that will be made possible by the Magnetospheric Multiscale Mission (MMS), currently in development for a late 2014 launch. A more comprehensive review of diffusion region physics is given by Hesse et al. (2012). Here we summarize a number of recently published results across the range of scales, and then examine the capabilities that MMS will bring to our understanding of reconnection in this context. Though MMS will also study the nightside plasma sheet and reconnection there, we will limit our discussions to the dayside case.

2. Global scales

Q. What determines X-line configuration: characteristic curves, the locus of maximum shear, or?

At the largest scales for a magnetosphere, we are concerned mainly with the distribution of reconnection X-lines (curves, actually) on the dayside magnetopause, and within the magnetotail, and their integrated contribution to plasma circulation and the transpolar potential. Here we focus on the dayside magnetopause, where statistical studies have begun to bear on and in some cases, challenge our theoretical ideas. A decade ago, there was a debate about whether reconnection was highly localized in regions of nearly antiparallel internal and external magnetic fields (Crooker et al., 1979; Luhmann et al., 1984) or more distributed on the magnetopause, especially across the subsolar region, as "component" reconnection, that is with a "guide field" normal to the plane in which it looks two-dimensional. By now this debate has largely been resolved in favor of an important role for component reconnection (Chandler et al., 1999, 2008; Kim et al., 2002; Moore et al., 2002; Sonnerup et al. 2004; Pu et al., 2005; Trattner et al., 2004; Pu et al., 2007; Trattner et al., 2007).

Given that component reconnection is relatively widespread over the magnetopause, the next issue is the distribution of X-line or lines on the magnetopause, as a function of solar wind magnetic field orientation. While the requirement for two magnetic fields to be antiparallel has softened, there is agreement that the amount of shear between the two fields strongly influences the curvature of newly reconnected field lines, and a strong suspicion that the rate of reconnection is greater when the magnetic tension force "pumping" plasma out the exhaust flow regions is greatest, that is, when the magnetic shear between the two fields is greatest. Fig. 1 illustrates some ideas concerning this question.

Moore et al. (2002) discussed this while arguing that the shape of the X-line is determined by the requirement that it locally constrained to bisect the angle between the two fields, and everywhere continuous. The authors computed a family of possible X-lines determined by the overall field geometry, and argued that the active X-line is selected by virtue of its passage at some point along its length through a region of maximal shear or current sheet density. 3D PIC simulations of reconnection (Shay et al., 2003) have lent plausibility to this picture, in that reconnection begins in those simulations in a location of maximal shear, and subsequently spreads along an X-line extending in both directions away from that starting point. Moore et al. (2002) found that the family of X-lines that intercepts the point of maximum shear has an S or Z shape, depending on the sign of IMF By, which is centered on the subsolar equatorial region, and loops poleward around each cusp. A necessary corollary of this approach is that the X-line must cross the ridges of antiparallel fields at a right angle, thus meeting them at a pair of single points, one in each hemisphere, which are usually points of maximal shear along the X-line. As the IMF clock angle varies from southward to northward, these points rotate from the equator

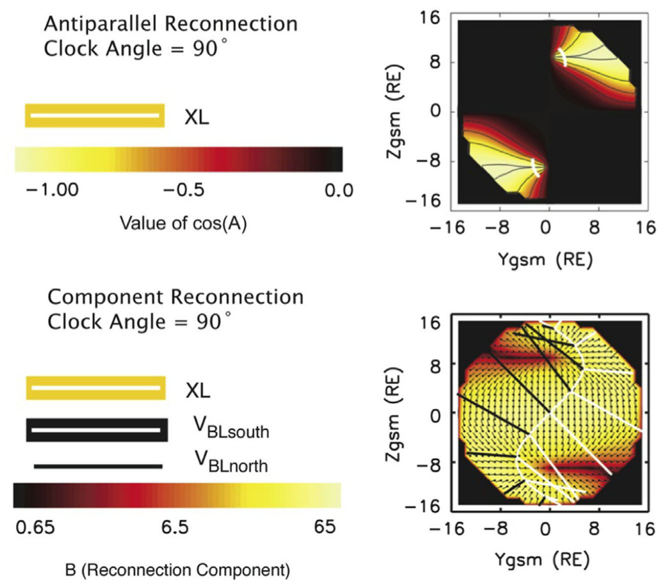

Fig. 1. Dayside magnetopause reconnection, from Moore et al. (2002), illustrating (top) reconnection with short X-line (white) segments limited to regions of antiparallel fields, (bottom) component reconnection distributed along a Z shaped X-line defined by local fields.

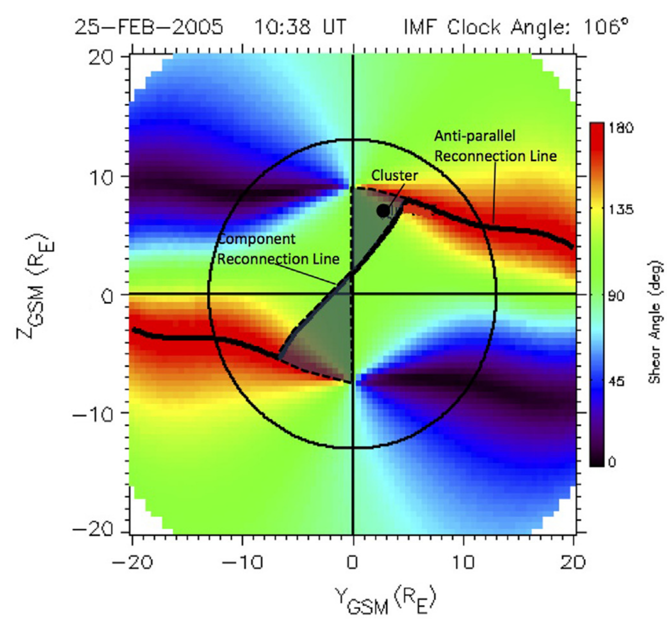

Fig. 2. Dayside magnetopause reconnection, from Fuselier et al. (2011) illustrating the X-line as a black trace following the locus of maximum shear, then the locus of antiparallel reconnecting fields.

to the flanks and then poleward of the cusps for northward IMF. Thus, the highest shear regions with antiparallel fields move from the equator at southward Bz, to the opposite flanks for zero Bz, to the lobes above each cusp for northward IMF.

In a contrasting approach, Fuselier et al. (2011) ascribed a primary importance to maximum field shear and argue that the X-line orientation follows the locus of maximum shear across the magnetopause. This approach is also consistent with a persistent X-line lying across the (tilted) near-subsolar region, connecting the two ridges of antiparallel fields emanating in opposite directions from the two cusps, as shown in Fig. 2. An S or Z shape similar to that derived by Moore et al. (2002) is found from this approach in the near-subsolar region, but when the X-line reaches