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The location and rate of occurrence of near-Earth magnetotail reconnection as observed by Cluster and Geotail

K.J. Genestreti [a,b,*], S.A. Fuselier [b,a], J. Goldstein [b,a], T. Nagai [c], J.P. Eastwood [d]

[a] Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, Texas, USA
[b] Space Science and Engineering Division, Southwest Research Institute, San Antonio, TX, USA
[c] Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo, Japan
[d] The Blackett Laboratory, Imperial College London, London, UK

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ABSTRACT

A statistical characterization of the location and rate of occurrence of magnetic reconnection in the near-Earth magnetotail is performed by analyzing the set of ion diffusion region (DR) observations made by the Cluster and Geotail spacecraft during solar maximum and the declining phase. The occurrence rate is analyzed in terms of its dependence on both X_{GSM*} and Y_{GSM*} (where coordinates are in the solar wind aberrated geocentric solar magnetospheric system). Within the limits of the statistics available to this study, we find the purely X_{GSM*} – dependent occurrence rate to be roughly constant over a large portion of the near-Earth magnetotail. In contrast, we find the purely Y_{GSM*} – dependent occurrence rate to be biased towards dusk with a local maximum between $0\ R_E \le Y_{GSM*} \le 5\ R_E$. The Y_{GSM*} – dependent occurrence rate is then used to construct a quasi-2D formulation of the DR occurrence rate, which has explicit dependence on X_{GSM*} and implicit dependence on Y_{GSM*}. The quasi-2D occurrence rate is then used to examine the predicted ephemeris of the Magnetospheric MultiScale (MMS) spacecraft. We estimate that, during its near-Earth magnetotail survey phase, MMS will likely observe 11 ± 4 DR events.

1. Introduction

Magnetic reconnection in the terrestrial magnetosphere is a multi-scale phenomenon. While reconnection can substantially alter the global state of the magnetosphere, the process is enabled by physics that occurs within the micro-scale ion and electron diffusion regions. This multi-scale nature is evident in reconnection at the near-Earth magnetotail neutral sheet. Reconnection onset in the near-Earth magnetotail is thought to enable the rapid restructuring of the global magnetic field that occurs during substorms (Baker et al., 1996; Angelopoulos and et al., 2008; Runov et al., 2008; Gabrielse et al., 2009). Despite this global-scale influence, the near-Earth magnetotail ion diffusion region (hereafter referred to as the DR) is highly localized. The DR extends only several hundreds of km in the north–south (Z_{GSM*}) direction, and several hundreds of km in the X_{GSM*} direction, which is the direction that connects the Earth to the distant magnetotail (Nagai et al., 2011) (where GSM* denotes the solar wind aberrated geocentric solar magnetospheric coordinate system (Fairfield, 1980)). The near-Earth magnetotail DR also has a finite width in the dawn–dusk (Y_{GSM*}) direction, the extent of which is likely to be at least several tens of thousands of km (Nagai et al., 2013a, 2013b). The location of the micro-scale DR can feed back into the global-scale influence of near-Earth reconnection. The effectiveness with which reconnection generates geoactivity is likely determined in part by the X_{GSM*} location of the DR (Imber et al., 2011).

The position in the magnetotail where the DR forms is highly variable. Following formation, the position of the DR is time dependent. Observations of the reconnection site have been made over a wide range of locations along the 2D magnetotail neutral sheet, where observations are typically discussed in terms of their dependence on X_{GSM*} and Y_{GSM*}. Machida et al. (2009) analyzed several years worth of Geotail-observed substorm-related changes to the structure of the magnetotail magnetic field and plasma. They found that the average region where the reconnection site formed was ~20 R_E (Earth radii) down the magnetotail ($X_{GSM} = -20\ R_E$), though the actual region of formation was highly variable on an event-by-event basis. The X_{GSM*} position where the DR forms is likely governed by the strength of the solar wind energy input into the magnetosphere (Nagai et al., 2005). The DR forms closer to the Earth for higher energy input and farther from the Earth for lower energy input. During periods of enhanced solar activity, the DR can be observed as close to Earth as

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* Corresponding author.
E-mail address: kgenestreti@swri.edu (K.J. Genestreti).

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$X_{GSM*} = -15\ R_E$ (Miyashita et al., 2009; Eastwood et al., 2010). During periods of low solar activity, the DR is typically observed farther from the Earth at $X_{GSM*} \leq -20\ R_E$ (Nagai et al., 1998; Nagai and Machida, 1998).

Empirical evidence suggests that after formation, the DR is typically expelled tailward (Baumjohann et al., 2000; Nagai et al., 2005; Miyashita et al., 2009; Eastwood et al., 2010; Oka et al., 2011). Petrukovich et al. (2009) analyzed Cluster observations of fast flow onsets in the vicinity of a thinned current sheet and showed that shortly after their onset, fast flows within the region $-19.5\ R_E \leq X_{GSM*} \leq -17\ R_E$ are typically directed tailward. This result suggests that during the time period studied by Petrukovich et al., which corresponded to the solar maximum and declining phases (2001–2007), the DR typically formed within $X_{GSM*} \geq -19.5\ R_E$. Nakamura et al. (2004) analyzed Cluster observations of fast flows from July–October 2001 and showed that the ratio of tailward-oriented to earthward-oriented flows within $X_{GSM*} \geq -19.5\ R_E$ was approximately 1:4. This result suggests that, during the time period surveyed by Nakamura et al., the sources of the fast flows (post-onset) were typically tailward of $X_{GSM*} = -19.5\ R_E$. Conclusions drawn from the results of the Nakamura et al. and Petrukovich et al. studies are consistent with the hypothesis that the DR typically forms close to Earth (i.e. within $X_{GSM*} \geq -20\ R_E$) and is then subsequently expelled tailward. Nagai et al. (2005) used Geotail observations of fast tailward flows and DR events to characterize the spatial dependence of DR observations. Nagai et al. noted that, although Geotail did not directly observe any DR events earthward of $X_{GSM*} = -19\ R_E$, fast tailward flows coupled with large negative B_Z were observed as close to Earth as $X_{GSM*} = -11\ R_E$. Since reconnection outflow regions lie downstream of a DR, each of these fast tailward flow events must lie tailward of a DR. As such, the observations of these flows indicated that, during the time period surveyed by Nagai et al., the DR could have been observed as close to Earth as $X_{GSM*} = -11\ R_E$.

In comparison with the X_{GSM*} dependence of DR observations, the Y_{GSM*} (dawn–dusk) dependence has been less thoroughly studied. Observations of bursty bulk flows (BBFs) in the magnetotail have for some time been known to have a duskward bias (i.e. they occur more frequently for $Y_{GSM*} \geq 0$) [e.g. Raj et al., 2002]. A similar duskward bias has also been observed in optical observations of the locations of substorm onsets (Frey et al., 2004). Imber et al. (2011) studied the Y_{GSM*} dependence of observations of flux ropes and traveling compression regions made by the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission. They found that observations of reconnection-related magnetic field structures typically have a duskward bias as well, where the peak in the rate of occurrence of observations was near $Y_{GSM*} = 5\ R_E$. Imber et al. also noted that this peak in the event occurrence rate coincided with the Y_{GSM*} location where THEMIS spent most of its time. Nagai et al. (2013a) analyzed 16 years of single-point observations from Geotail and identified direct Geotail observations of the DR. Nagai et al. noted that out of the 30 events they identified, 18 were observed duskward of the midnight meridian. The DR events identified by Nagai et al. were observed over a wide range of Y_{GSM*}, where the dawn–dusk extent of the set of DR observations was $-12\ R_E \leq Y_{GSM*} \leq 15\ R_E$. They also noted that of the events that were located dawnward of the midnight meridian, almost all were observed during times of elevated Kp (i.e. elevated magnetospheric activity). The set of Cluster-observed DR encounters identified by Eastwood et al. (2010) fell within the range $-5\ R_E \leq Y_{GSM*} \leq 12\ R_E$ (though the duskward extent of their observations may have been limited by the geometry of the orbit of Cluster). Imber et al. (2011) used observations of flux ropes and traveling compression regions to show that such reconnection-related events were observed as far dawnward as $Y_{GSM*} = -8\ R_E$ and as far duskward as $Y_{GSM*} = 20\ R_E$.

The occurrence rate of DR and fast tailward flow events was calculated in Genestreti et al. (2013) (hereafter referred to as $G13$). To perform this calculation, they used the set of Geotail DR and fast tailward flow encounters that were identified in Nagai et al. (2005) from the solar maximum period 1998–2003. $G13$ calculated the occurrence rate ($f(X_{GSM*})$) by arranging these events by their X_{GSM*} location ($n_{events}(X_{GSM*})$) and normalizing the number of events by the number of hours ($t_{NS}(X_{GSM*})$) that Geotail spent near the modeled neutral sheet (e.g. $f(X_{GSM*}) = n_{events}(X_{GSM*})/t_{NS}(X_{GSM*})$). To locate the neutral sheet, they used the empirical model of Fairfield (1980). They defined the region 'near' the neutral sheet to be the region within a distance d from its surface. Values of d were deduced empirically by examining the distances between the Geotail-observed neutral sheet locations and the locations predicted by the Fairfield model. $G13$ calculated the occurrence rate solely in terms of its X_{GSM*} dependence, neglecting any dependence on Y_{GSM*}. The DR occurrence rate calculated in their study may have been limited by the geometry of the orbit of Geotail; because the apogee of the spacecraft occurred at a large (31 R_E) geocentric distance, no DR events were identified within $X_{GSM*} \geq -20\ R_E$, despite the fact that fast tailward flows with large negative B_Z were identified by $G13$ as close to Earth as $X_{GSM*} = -11\ R_E$. $G13$ noted the need to expand their calculation of the occurrence rate by considering the Y_{GSM*} dependence of the occurrence rate and by including observations from a spacecraft mission with an orbital configuration better suited to study the region $X_{GSM*} \geq -20\ R_E$.

The purpose of this study is to build upon the work of $G13$ by calculating the occurrence rate of DR events from a larger data set than was used in $G13$. Specifically, this expanded data set consists of DR observations from both Geotail and Cluster, where the set of Geotail DR events is from Nagai et al. (2005) and the set of Cluster DR events is from Eastwood et al. (2010). As the Cluster mission is better suited than Geotail to study the region $X_{GSM*} \geq -20\ R_E$, we find that this study is able to calculate the occurrence rate in this region with much greater certainty than in $G13$. This study also builds upon the work of $G13$ by taking into account the effect that a non-uniform probability of observing a DR event in Y_{GSM*} has on the X_{GSM*} – dependent occurrence rate.

The following section provides a review of the Geotail and Cluster missions, the methodologies used by Nagai et al. (2005) and Eastwood et al. (2010) to identify DR events, and introduces the methodology with which we calculate the occurrence rate. In Section 3.1, two X_{GSM} – dependent occurrence rates are calculated separately from Geotail and Cluster observations and are compared with one another, with favorable agreement. After showing that the Geotail-based and Cluster-based calculations of the occurrence rate are similar, the Geotail and Cluster data sets are combined and studied as one. In Section 3.2 the fully 2D occurrence rate is calculated using this combined data set. In Section 3.3 the Y_{GSM*} dependence of the occurrence rate is investigated and is shown to be nonuniform with a bias towards dusk. The deduced profile of the occurrence rate in Y_{GSM*} is then used in Section 3.4 to remove the Y_{GSM*} dependence from the X_{GSM*} – dependent occurrence rate. This revisited X_{GSM*} – dependent occurrence rate is referred to as the quasi-2D occurrence rate, as it has explicit dependence on X_{GSM*} and implicit dependence on Y_{GSM*}. This quasi-2D occurrence rate is compared with similar calculations performed in the existing literature. Finally, the quasi-2D occurrence rate is used in Section 4 to analyze the predicted orbit of the upcoming Magnetospheric MultiScale (MMS) mission in order to estimate the number of DR events it will observe during its nightside survey phase. Note that it is only because of the simplicity of the Fairfield neutral sheet model, which is used to calculate the occurrence rate and is only dependent on the dipole tilt angle, that the calculated occurrence rate can be used to examine the predicted ephemeris for MMS.