Identification of Magnetic Null on Reconnection 19 September 2015 Event using Magnetospheric Multiscale Mission

S. Ekawati* [(1,2)], and D. Cai[(1)]
(1) Graduate School of System and Information Engineering, University of Tsukuba, Japan, https://www.cs.tsukuba.ac.jp/english/index.html
(2) Space Science Center, National Institute of Aeronautics and Space (LAPAN), Indonesia

Abstract

Magnetic nulls referred to a region with vanishing magnetic fields play an essential role in energy conversion and particle acceleration during magnetic reconnections. Moreover, they are also useful tools to characterize the complex magnetic topologies and are essential in three-dimensional (3D) magnetic reconnection. In this paper, we apply the linear interpolation methods to derive the null positions of the dayside reconnection Electron Diffusion Region (EDR) on 19 September 2015 using Magnetospheric Multiscale (MMS) mission spacecraft. The number of the signs of the real part of eigenvalues determines the magnetic field topology nearby this null. The change of the topology can be related to the occurrence of bifurcation or magnetic reconnection. Here, we report the first in situ measurement that the field topology of magnetic nulls changes from B type to A type at around 07:43:30.4 associated with the reported EDR event.

1 Introduction

The magnetic nulls play an essential role in energy conversion and particle acceleration in space plasma [1, 2]. Observing this magnetic null is a useful tool to characterize 3D magnetic topology, turbulences, and magnetic reconnection [1, 3-5]. Magnetic reconnection is essential in astrophysical and solar-terrestrial plasma such as Sun and Magnetosphere[6, 7]. The magnetic reconnection has been frequently observed in the Earth magnetosphere [8, 9], near, the Earth magnetopause.

The magnetic reconnection is initiated and maintained in a small region called the electron dissipation/diffusion region (EDR), where electrons are demagnetized [10-12]. Inside this EDR, during magnetic reconnection, the magnetic field strength vanishes, disappears, and becomes zero. Therefore, nulls or magnetic nulls appear [5].

Several studies on magnetic nulls in the dayside EDR event using Magnetospheric Multiscale (MMS) Mission spacecraft have been reported. They report radial nulls and their associated X-line reconnection [5]. However, the in-depth study of the magnetic nulls topology on the EDR event on 19 September 2015 is not discussed. Moreover, the study of the bifurcation [13, 14] has not been discussed.

This study reports the “bifurcation” or magnetic reconnection by showing the change of magnetic field topology from B-type to A-type occurs from 07:43:30.39 to 07:43:30.42.

2 Methods

2.1 Identify Magnetic Null Type

Based on the three eigenvalues (λ_1, λ_2, λ_3), the 3D nulls can be classified into A, B, As and Bs type[15], as shown in Table 1. Therefore, the magnetic field structure near the magnetic nulls can be determined. This null type is derived from Jacobian ∇B around the magnetic null as follow:

$$\nabla B = \begin{pmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\ \frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & \frac{\partial B_z}{\partial z} \end{pmatrix} \tag{1}$$

Table 1. The magnetic null type based on the eigenvalues λ_1, λ_2, λ_3 derived from the tensor $\nabla \cdot \mathbf{B} = \mathbf{0} \equiv \boldsymbol{\lambda_1} + \boldsymbol{\lambda_2} + \boldsymbol{\lambda_3} = \mathbf{0}$.[15, 16]

λ_1	λ_2	λ_3	Type	Structure
λ_1	λ_2	0	X	2D
$+i\lambda_1$	$-i\lambda_1$	0	O	2D
$-\lambda_1$	$-\lambda_2$	$+(\lambda_1+\lambda_1)$	A	3D
$+\lambda_1$	$+\lambda_2$	$-(\lambda_1+\lambda_1)$	B	3D
$-\lambda_1/2+i\lambda_2$	$-\lambda_1/2-i\lambda_2$	$+\lambda_1$	A_s	3D
$+\lambda_1/2+i\lambda_2$	$+\lambda_1/2-i\lambda_2$	$-\lambda_1$	B_s	3D

These eigenvalues cannot be all positive nor negative due to the solenoidal condition $\nabla \cdot \mathbf{B} = \mathbf{0} \equiv \boldsymbol{\lambda_1} + \boldsymbol{\lambda_2} + \boldsymbol{\lambda_3} = \mathbf{0}$. Basically, the magnetic reconnection model is based on a nulls pair of A-B type [3, 15, 17]. Therefore, the 3D radial nulls, A type (negative null) or B type (positive null), is important to be identified. Moreover, identifying the separator line is also essential because the 3D reconnection occurs on a separator line analogous to a 2D

X-line. The separatrices, which are the legs of this line, correspond to fans (Σ-surfaces) bounded by spines (γ-lines) that emerge from the nulls[17, 18].

2.2 Determining null positions

Using four MMS SCs, magnetic field data at a fixed time, we linearly interpolate the MMS tetrahedron's magnetic field. For example, fixing the origin to MMS1, the linear magnetic field can be expressed as:

$$\mathbf{B} = s\,(\mathbf{B}_2 - \mathbf{B}_1) + t(\mathbf{B}_3 - \mathbf{B}_1) + u(\mathbf{B}_4 - \mathbf{B}_1) + \mathbf{B}_1 \qquad (2)$$

where the subscript numbers 1, 2, 3, and 4 denote MMS1, 2, 3, and 4, respectively, and the parameters *s, t*, and *u* satisfy $0 \leq s,\ t,\ u,\ s+t+u \leq 1$. The magnetic null position can be found by setting **B**= 0. The null outside the MMS tetrahedron can also be identified by extending s, t, u, $s+t+u$ values larger than one and less than zero. However, this extension must be careful because the linear interpolation is only valid near the null.

3 MMS Data

We analyze the EDR event detected by the four-tetrahedral Magnetospheric Multiscale (MMS) Mission on 19 September 2015 with possible EDR time is at around 07:43:30.3 – 07:43:30.4 as reported by Chen et al. [19]. Figure 1(a-d) shows the magnetic field data B_x, B_y, B_z, and B_{total} from all MMS spacecraft on 19 September 2015 from 07:43:29.8 to 07:43:31.02. The magnitude of B_{total} from MMS3 is almost zero at around 07:43:30.4, as shown in fig.1(d).

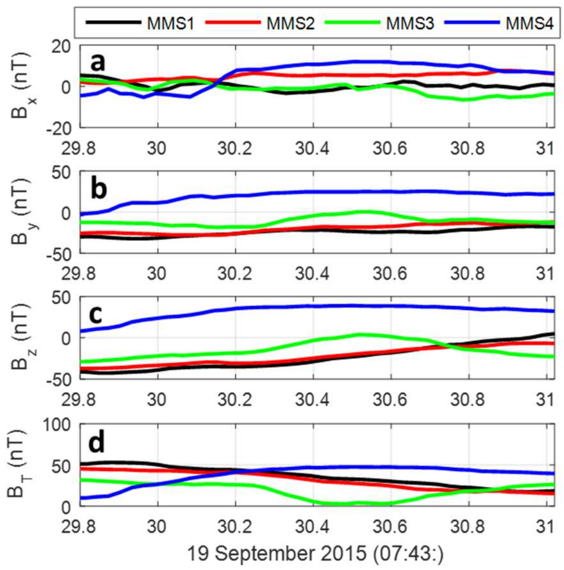

Figure 1. The magnetic field data components in GSM for all four MMS Spacecraft (DES with resolution 30 ms) on 19 September 2015 from 07:43:29.8 to 07:43:31.02. (a) B_x, (b) B_y, (c), B_z, and (d) B_{total}.

4 Result

Figure 2 shows the identified magnetic nulls on 19 September from 07:43:29.8 to 07:43:31.02 by linear interpolation in eq. (2) with setting $-0.95 \leq s,\ t,\ u,\ s+t+u \leq 0.95$ This setting is used to detect the null not only inside the tetrahedron but also outside the tetrahedron. We derived all magnetic null types: (1) B types at 07:43:29.85, (2) A types at 07:43:30.09, (3) B type from 07:43:30.27 to 07:43:30.36, (4) A type from 07:43:30.72 to 07:43:31.02. The blue bar is the possible time of the EDR event. In this study, we only focus on the radial null, especially, the bifurcation indicated by field topology change from B type to A type. It seems there is a gap where no null exists from 07:43:30.36 to 07:43:30.72 because we limit the distance of the magnetic nulls less than 50 km from the centre of MMS tetrahedron.

Using linear interpolation, we derive more magnetic nulls in the gap between identified B type to A type (blue bar) in Figure 2. The result is shown in Figure 3 (d). The field topology changes from B type to A type at 07:43:30.4. Some of these magnetic nulls have 2D structures from 07:43:30.15 to 07:43:30.63 since the value of one eigenvalue is smaller than the other two eigenvalues.

As shown in Figure 3, this change of field topology at 07:43:30.4 (Fig.3 (d)) is related to the EDR event. This event is indicated by a very high electron velocity V_x (MMS) at around 700 km/s and the reversal of B_x (MMS3) from negative to positive (Fig. 3 (a)). The electron density is low at around 20 cm^{-3} (Fig.3 (b)). The parallel temperature is around 50 eV, and the perpendicular one is around 60 eV (fig.3.c).

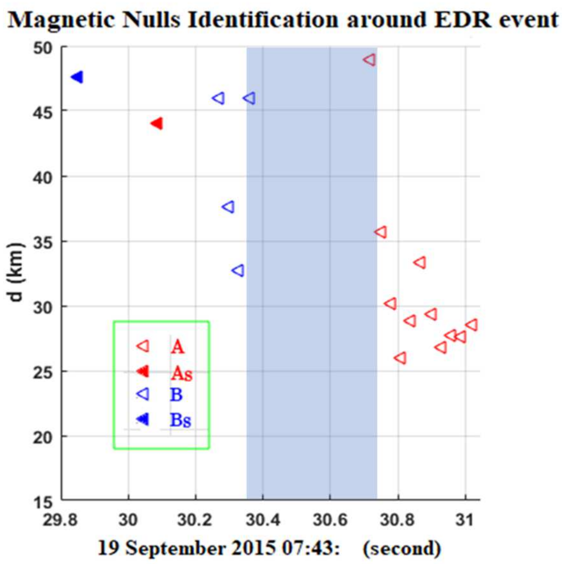

Figure 2. The identified magnetic nulls on 19 September 2015 from 07:43:29.8 to 07:43:31.02. The blue bar is the possible EDR event.

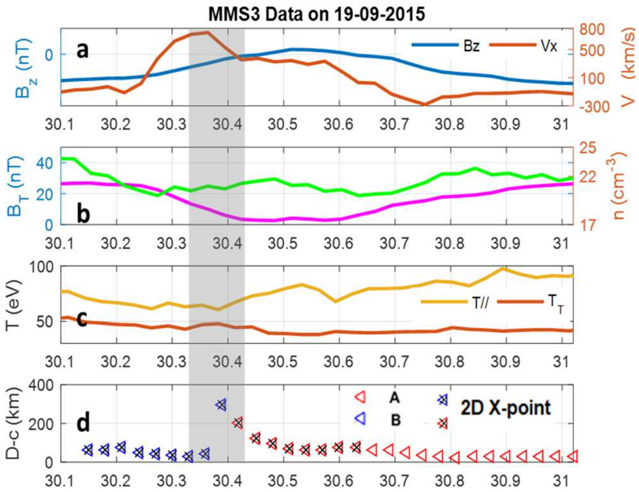

Figure 3. The change of magnetic field topology from B type to A type occurs at 07:43:30.39 to 07:43:30.42. Near the EDR event, the 3D magnetic nulls are degenerated and become 2D X-point nulls as one of their three eigenvalues is almost zero.

5 Conclusion

The change Magnetic Field topology from B type to A type occurs between 07:43:30.39 and 07:43:30.42. At 07:43:30.39 the magnetic null is B-type with the eigenvalues are 0.55893, -0.28168, and 0.0074051. At 07:43:30.42 the magnetic null is A-type with the eigenvalues are 0.56412, -0.2787, and -0.014435. Both the third component of eigenvalues is almost zero, and the null is degenerated, which means the topology generated by these two nulls is two-dimensional. The identified magnetic nulls are simultaneously B type and then change to A type between 07:43:30.39 and 07:43:30.42. This field topology change is associated with the EDR event and can be related to the bifurcation or magnetic reconnection.

Data availability

The observation data are derived from the MMS data available at https://lasp.colorado.edu/mms/sdc/public/). The magnetic field data are available at https://lasp.colorado.edu/mms/sdc/public/datasets/fields/, and the ion and electron velocity data are available at https://lasp.colorado.edu/mms/sdc/public/datasets/fpi/.

Acknowledgements

The authors would like to show the greatest appreciation to the instrumental teams of MMS Science Data for providing magnetic field and plasma data. This research is sponsored by the *Riset-Pro* (Scholarship) Program, *Kemenristek-Dikti* (the Ministry of Research and Technology – Higher Education of Indonesia), and it is supported by the Indonesian National Institute of Aeronautics and Space (LAPAN).

References

[1] E. Priest and T. Forbes, "Magnetic Reconnection: MHD Theory and Applications, Cambridge Univ," *Prees, Cambridge,* 2000.

[2] V. Olshevsky, A. Divin, E. Eriksson, S. Markidis, and G. Lapenta, "Energy dissipation in magnetic null points at kinetic scales," *The Astrophysical Journal,* vol. 807, no. 2, p. 155, 2015.

[3] D. Cai, Y. Li, T. Ichikawai, C. Xiao, and K.-i. Nishikawa, "Visualization and criticality of magnetotail field topology in a three-dimensional particle simulation," *Earth, planets and space,* vol. 53, no. 10, pp. 1011-1019, 2001.

[4] E. Eriksson, A. Vaivads, Y. V. Khotyaintsev, V. Khotyayintsev, and M. Andre, "Statistics and accuracy of magnetic null identification in multispacecraft data," *Geophysical Research Letters,* vol. 42, no. 17, pp. 6883-6889, 2015.

[5] H. Fu *et al.*, "Evidence of magnetic nulls in electron diffusion region," *Geophysical Research Letters,* vol. 46, no. 1, pp. 48-54, 2019.

[6] T. Nagai *et al.*, "Structure and dynamics of magnetic reconnection for substorm onsets with Geotail observations," *Journal of Geophysical Research: Space Physics,* vol. 103, no. A3, pp. 4419-4440, 1998.

[7] H. Hasegawa *et al.*, "Evidence for a flux transfer event generated by multiple X - line reconnection at the magnetopause," *Geophysical Research Letters,* vol. 37, no. 16, 2010.

[8] M. Øieroset, T. Phan, M. Fujimoto, R. Lin, and R. Lepping, "In situ detection of collisionless reconnection in the Earth's magnetotail," *Nature,* vol. 412, no. 6845, pp. 414-417, 2001.

[9] J. Eastwood, T. Phan, M. Øieroset, and M. Shay, "Average properties of the magnetic reconnection ion diffusion region in the Earth's magnetotail: The 2001–2005 Cluster observations and comparison with simulations," *Journal of Geophysical Research: Space Physics,* vol. 115, no. A8, 2010.

[10] J. Burch *et al.*, "Electron-scale measurements of magnetic reconnection in space," *Science,* vol. 352, no. 6290, p. aaf2939, 2016.

[11] S. Fuselier *et al.*, "Large - scale characteristics of reconnection diffusion regions and associated magnetopause crossings observed by MMS," *Journal of Geophysical Research: Space Physics,* vol. 122, no. 5, pp. 5466-5486, 2017.

[12] T. Phan *et al.*, "Electron magnetic reconnection without ion coupling in Earth's turbulent magnetosheath," *Nature,* vol. 557, no. 7704, pp. 202-206, 2018.

[13] D. Cai, K.-i. Nishikawa, and B. Lembege, "Magnetotail field topology in a three-dimensional global particle simulation," *Plasma physics and controlled fusion,* vol. 48, no. 12B, p. B123, 2006.

[14] D. Cai, B. Lembège, H. Hasegawa, and K. I. Nishikawa, "Identifying 3 - D Vortex Structures At/Around the Magnetopause Using a Tetrahedral Satellite Configuration," *Journal of Geophysical Research: Space Physics,* vol. 123, no. 12, pp. 10,158-10,176, 2018.

[15] Y.-T. Lau and J. M. Finn, "Three-dimensional kinematic reconnection in the presence of field nulls and closed field lines," *The Astrophysical Journal,* vol. 350, pp. 672-691, 1990.

[16] H. Fu *et al.*, "How to find magnetic nulls and reconstruct field topology with MMS data?," *Journal of Geophysical Research: Space Physics,* vol. 120, no. 5, pp. 3758-3782, 2015.

[17] C. Xiao *et al.*, "Satellite observations of separator-line geometry of three-dimensional magnetic reconnection," *Nature Physics,* vol. 3, no. 9, pp. 609-613, 2007.

[18] C. Xiao *et al.*, "In situ evidence for the structure of the magnetic null in a 3D reconnection event in the Earth's magnetotail," *Nature Physics,* vol. 2, no. 7, pp. 478-483, 2006.

[19] L. J. Chen *et al.*, "Electron energization and mixing observed by MMS in the vicinity of an electron diffusion region during magnetopause reconnection," *Geophysical Research Letters,* vol. 43, no. 12, pp. 6036-6043, 2016.