Particle-to-field energy conversion inside a magnetotail flux rope

Chenxi Du[1,2], Huishan Fu[1,2†], Jinbin Cao[1,2], Elena Grigorenko[3], Zuzhen Chen[1,2], Zhe Wang[1,2]

[1]*School of Space and Earth Sciences , Beihang University, Beijing, 100191, China*

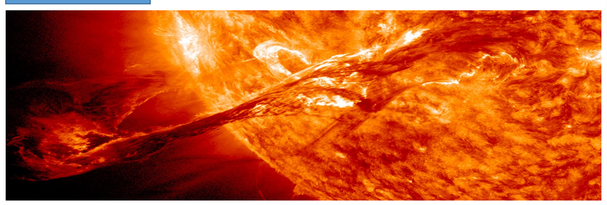
[2]*Key Laboratory of Space Environment Monitoring and Information Processing, Ministry of Industry and Information Technology, Beijing, 100191, China*

[3]*Space Research Institute of Russian Academy of Sciences, Moscow, Russia*

Abstract

Magnetic flux ropes (FRs) are commonly observed in the universal plasmas, in which various dynamic processes can be embedded and thus become important places for energy conversion. Previous observations generally suggested that the energy conversion inside FRs is from the field to particles. Interestingly, taking advantage of the Magnetospheric Multiscale (MMS) mission, we present here a newly observed magnetotail FR with strong particle-to-field energy conversion ($|E\cdot J| > 1.5$ nW/m^3). Meanwhile, we have revealed that such energy conversion is driven by an intense electron-carried field-aligned current (FAC) and parallel electric field. Continually, based on the analysis of the electron velocity distribution functions (VDFs) and the power spectral density (PSD) of the parallel electric field, we further discuss that the energy conversion probably results in the enhancement of the parallel electric field due to the anti-parallel electron nonthermal population.

Introduction



Magnetic flux ropes (FRs), which are typically characterized by bipolar variations of the poloidal magnetic field component and the enhancement of the axial magnetic field component, are 3-D helical magnetic structures commonly observed in universal plasmas such as solar corona, planetary magnetosphere, and laboratory.

The FRs are believed can play crucial roles in mediating reconnection, trapping particles, and accelerating electrons, and thus, they are usually considered as important channels for the energy conversion.

Since the previous observations generally suggest a field-to-particle energy conversion inside the FRs, and the particle-to-field energy conversion inside FRs has only been found in previous simulations, one may be very curious about whether such situations can be directly observed and how it can be achieved.

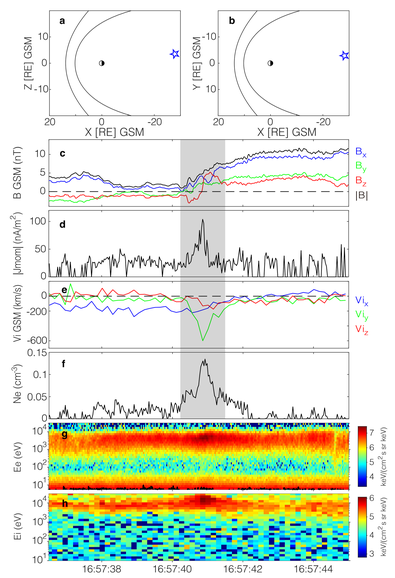


Figure 1 Overview of the magnetotail flux rope.

Figure 1 presents an overview of the FR within a dawnward high-speed flow observed by MMS1, when the four satellites were located at [-28.1 -2.71 3.51] Earth's radius (R_E) in GSM coordinates, and with a separation of ~ 36 km (about 2 d_e).

A clear bipolar signal from negative to positive appears on the Bz component, indicating a magnetic FR structure.

Interestingly, such a magnetic structure is accompanied by an intense current with a magnitude of 100 nA/m^2 and is embedded in a dawnward high-speed ion flow with ion velocity larger than 600 km/s.

Considering the flow velocity and crossing time of the structure, the scale of the flux rope is about 0.9 d_i.

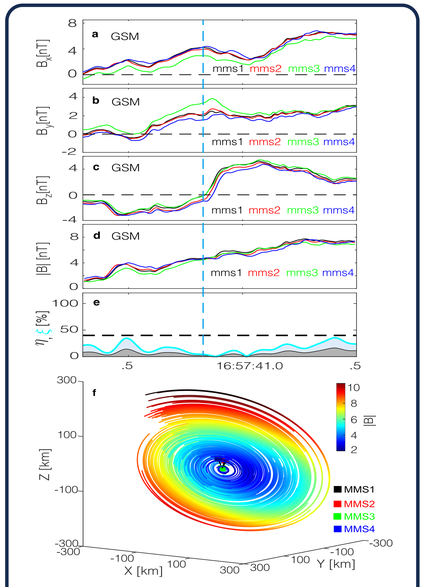


Figure 3 Magnetic topology reconstruction by using the First-Order Taylor Expansion method.

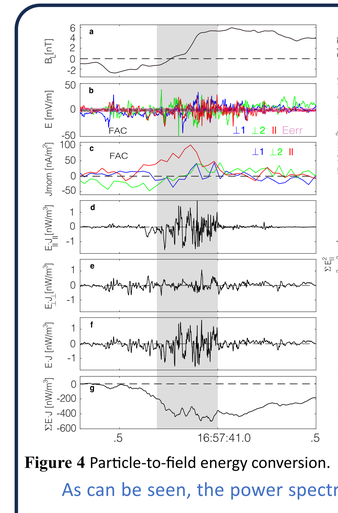


Figure 4 Particle-to-field energy conversion.

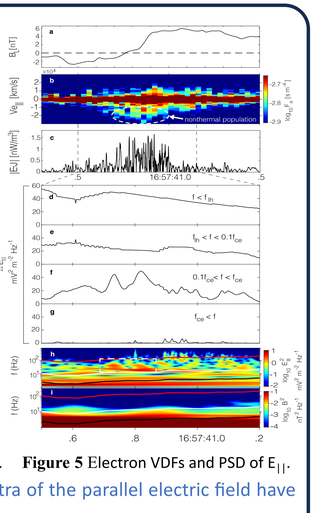


Figure 5 Electron VDFs and PSD of $E_{||}$.

As can be seen, the power spectra of the parallel electric field have been enhanced within the frequency range of $0.1f_{ce} < f < f_{ce}$ (as marked by the white square), indicating that such electron nonthermal population can trigger the localized electrostatic disturbance, and thus converts the particle's energy into the field's energy.

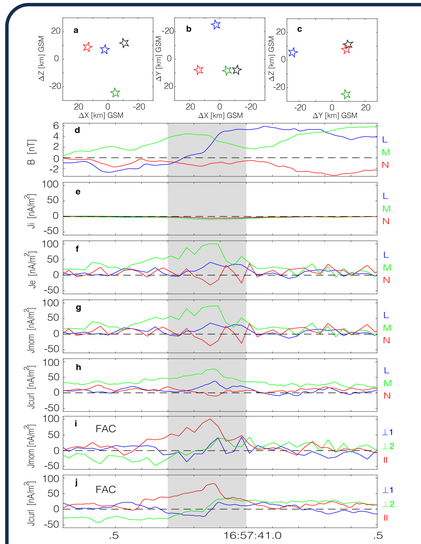


Figure 2 Intense current measured by MMS1.

The vectors are transformed into a local LMN coordinate system, which is given by L = [0.14 0.21 0.97], M = [0.69 0.68 -0.25], and N = [-0.71 0.71 -0.05]. B_L component presents a reversal variation, the B_M component reaches a peak value at the reversal point of B_L, while the normal component B_N does not show obvious variation.

It can be noticed that the electron current is the primary contributor to such an intense current, indicating the current is primarily carried by electrons. To further check the credibility of moments data, the Curlometer technique is utilized to calculate current density J_{curl} based on the magnetic field measurements from the four MMS satellites, as shown in Figure 2h. As can be seen, J_{curl} and J_{mom} are roughly consistent, which means the moment data are credible.

As can be seen in Figure 3, the reconstruction result presents an O-line style topology, suggesting a magnetic flux rope structure with the axis along the oblique axis in the X-Y plane, which is consistent with the axis direction in LMN coordinates.

Also, it can be noticed that the MMS tetrahedron is near the center of the flux rope, which is well-consistent with the MMS observations.

Summary

Contrary to the previous studies which suggest the energy conversion inside FR is generally from field to particles, in our observation, the strong energy conversion is from particles to field.

In particular, such a FR is embedded within a dawnward high-speed flow in the magnetotail and accompanied with an intense FAC with a magnitude larger than 100 nA/m2.

Based on the analysis of the parallel electron VDFs and the PSD of the parallel electric field, we continually discuss that such particle-to-field energy conversion probably manifests as an enhancement of the parallel electric field due to the electron nonthermal population appears in the anti-parallel direction.

Reference

Wang, S., Wang, R., Lu, Q. et al. Direct evidence of secondary reconnection inside filamentary currents of magnetic flux ropes during magnetic reconnection. Nat Commun 11, 3964 (2020).

Fu, H. S., Vaivads, A., Khotyaintsev, Y. V., André, M., Cao, J. B., Olshevsky, V., et al. (2017). Intermittent energy dissipation by turbulent reconnection. Geophysical Research Letters, 44, 37–43.