# 3D Outflow Jets Originated from Collisionless Magnetic Reconnection

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## 1. Introduction

Magnetic reconnection is an efficient energy converter, generating intense plasma jets by use of the magnetic field energy, so that it has a significant impact on large-scale dynamics of space and astrophysical phenomena. Satellite observations in the Earth's magnetotail have often detected fast and intermittent plasma flows called the bursty bulk flows (BBFs) [1] during magnetospheric substorms. The BBFs are composed of narrow channels with a width of 1-3Re (Re is the Earth radius) and are considered to originate from magnetic reconnection. However, the mechanism connecting such the 3D jets and reconnection has been poorly understood. Previous fluid (MHD and two-fluid) simulations have implied some relation between the waves around the x-line and 3D jet structure. However, the fluid models were unable to describe the wave generations in the self-consistent manner and full kinetic treatment is necessary to understand the relation.

## 2. Methodology

The present study performs a large-scale 3D particle-in-cell (PIC) simulation on the K computer. The simulation model employs the adaptive mesh refinement (AMR), which facilitates efficient computation of multiscale kinetic processes. The simulation is initiated with the 1D Harris current sheet without the guide field. The basic plasma parameters are $m_i/m_e=100$, $\omega_{pe}/\omega_{ce}=2.7$, and $T_i/T_e=5.0$. The system extends over $41c/\omega_{pi}$ in the cross-field direction, and is bounded by the periodic boundary in the cross-field and outflow directions, using the maximum particle number of $5\times10^{11}$ for each species. The simulation covers multiscale processes from the electron scales to MHD scale.

## 3. Results

After the onset of a fast reconnection, a laminar electron current layer is formed around the x-line. The electron layer is extended in the outflow direction, which results in the formation of flux ropes. At the same time, it is found that the laminar layer is unstable to two kinds of flow shear instabilities. They are excited mainly by the electron flow shear either in the inflow direction (mode I) or in the outflow direction (mode II). Since the flow shear scale is much larger in the outflow direction than in the inflow direction, the wavelength of the mode II reaches ~Re in the cross-field direction, regardless of the instability controlled by the electron dynamics. The mode II introduces a Re-scale fluctuation in the current density and limits the cross-field scale of the flux ropes generated intermittently in the current layer.

Since the flux ropes ejected from the electron layer contains high mass density plasma around the cores, their motion is much slower than that of the ambient electrons surrounding the flux ropes. As a result, the electrons tend to flow through between the 3D flux ropes and develop the flow channels with a cross-field scale of ~Re, consistent with the BBFs.

## 4. Conclusions

The present study proposes a new theoretical model connecting the BBFs with collisionless reconnection [2]. The key mechanism is the formation of 3D flux ropes arising in the turbulent current layer formed around the x-line. The cross-field scale of the flux ropes is determined by the wavelength of an electron flow shear mode which is a ~Re scale larger than the typical kinetic scales. The 3D flux ropes are intermittently ejected from the current layer and regulate the outflow jets into three dimensions.

## 4. References

1. V. Angelopoulos et al., "Bursty bulk flows in the inner central plasma sheet," *J. Geophys. Res.*, **97**, A4, April 1992, pp. 4027-4039, doi: 10.1029/91JA02701.

2. K. Fujimoto, "Three-dimensional outflow jets generated in collisionless magnetic reconnection," *Geophys. Res. Lett.*, **43**, 20, October 2016, pp. 10,557-10,564, doi: 10.1002/2016GL070810.