Fire hose instability in the multiple reconnection

*Alexandra Alexandrova[1] , Alessandro Retinò[1], Andrey Divin[2,3], Olivier Le Contel[1], **Lorenzo Matteini**[4,5], Hugo Breuillard[1], Jan Deca[6,7], Filomena Catapano[1], Giulia Cozzani[1], Rumi Nakamura[8], Evgeny V. Panov[8] , and Zoltán Vörös[8]

[1]Laboratoire de Physique des Plasmas, UPMC/Ecole Polytechnique, Paris, France, [2]Saint Petersburg State University, Saint Petersburg, Russia, [3]Swedish Institute of Space Physics, Uppsala, Uppsala, Sweden, [4]Lesia, Observatoire de Paris, Paris, France,
[5]Imperial College London, London, UK, [6]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, USA, [7]Institute for Modeling Plasma, Atmospheres and Cosmic Dust, NASA/SSERVI, USA,[8]Space Research Institute, Austrian Academy of Sciences, Graz, Austria.

* please, feel free to write me if you like to discuss:
sasha.alexandrova@gmail.com
alexandra.alexandrova@lpp.polytechnique.fr

ABSTRACT

We present observations of multiple reconnection in the Earth's magnetotail. In particular, we observe an ion temperature anisotropy characterized by large temperature along the magnetic field, between the two active X-lines. The anisotropy is associated with right-hand polarized waves at frequencies lower than the ion cyclotron frequency and propagating obliquely to the background magnetic field. We show that the observed anisotropy and the wave properties are consistent with linear kinetic theory of fire hose instability. The observations are in agreement with the particle-in-cell simulations of multiple reconnection. The results suggest that the fire hose instability can develop during multiple reconnection as a consequence of the ion parallel anisotropy that is produced by counter-streaming ions trapped between the X-lines.

INTRODUCTION

Multiple reconnection is an important phase of energy conversion in the current sheets in plasma. During multiple reconnection, several reconnection sites, the X-lines, are present in the current sheet. Multiple reconnection has been extensively studied by numerical simulations. Between the X-lines, a looped magnetic field structures (magnetic islands/ plasmoids) tend to form [e.g., Markidis 2012, and ref. therein]. A chain of plasmoids alternating with X-lines may effectively accelerate particles, and at the same time, may be affected by the kinetic instabilities, like fire hose instability, related to the acceleration [Drake et al., 2010]. However, such mechanisms are yet poorly understood from the space plasma observations. Recent observations in the Earth's magnetotail showed the dynamical interaction of the reconnection jets between two X-lines [Alexandrova et al., 2016], indicating a complicated stage of the plasmoid formation. In the present study, we investigate the proton temperature anisotropy observed between the two X-lines in the magnetotail, in order to understand the kinetic effects on the plasmoid formation.

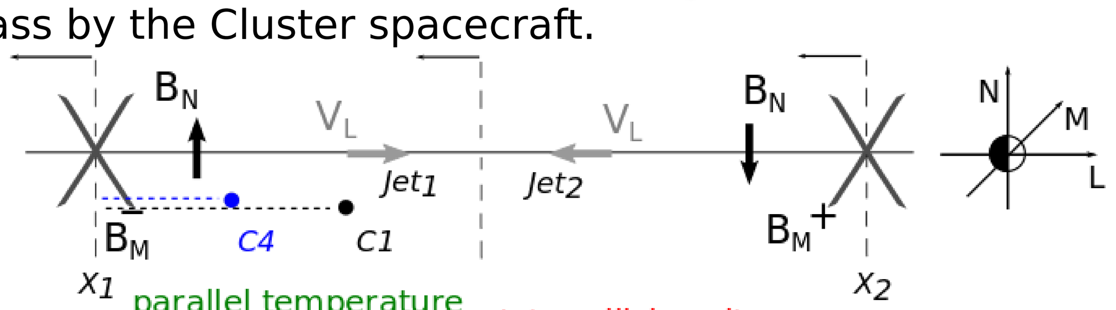
METHODOLOGY

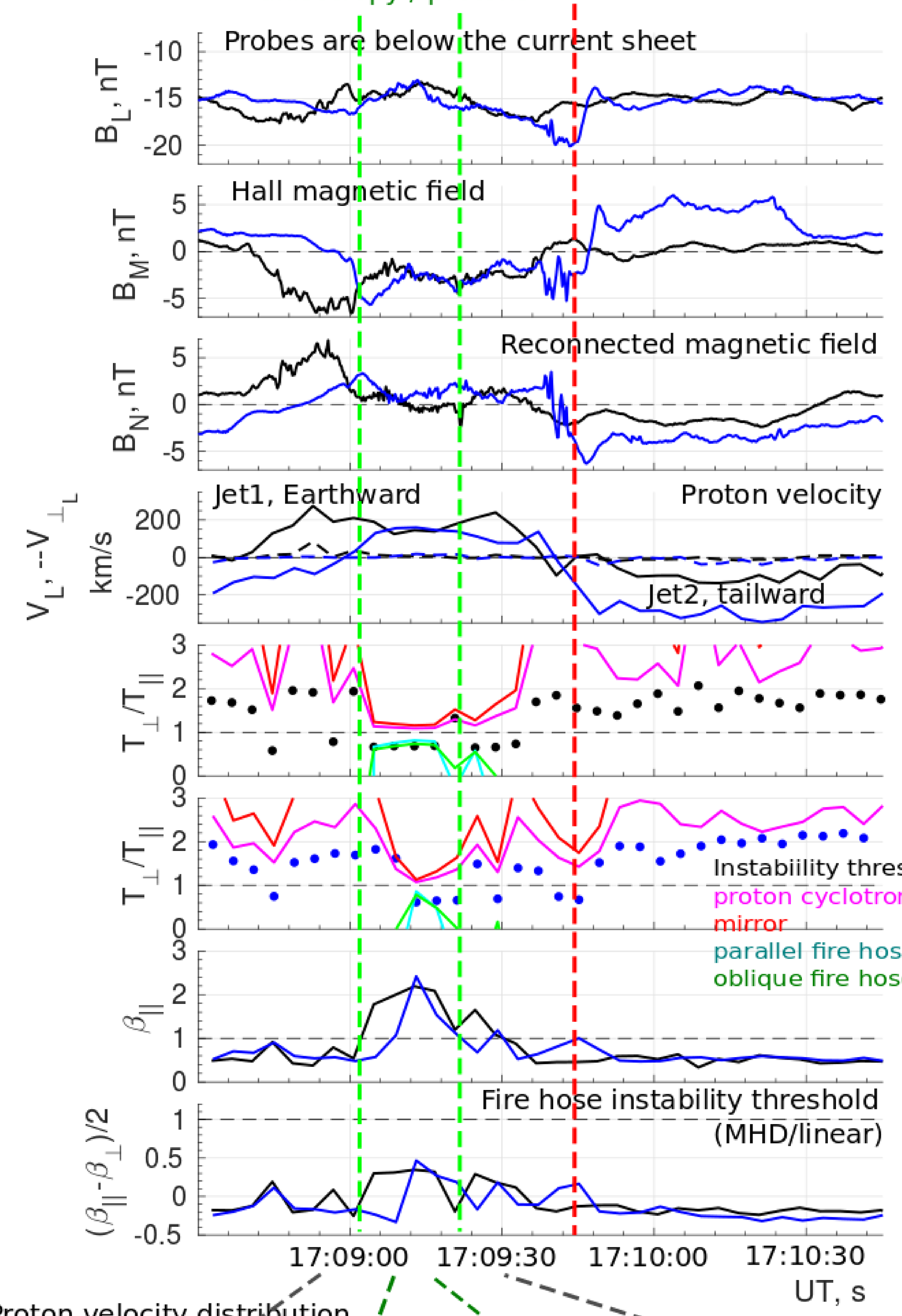
Cluster spacecraft is used for the magnetic field (FGM) and particles (CIS) observations in the Earth's magnetotail. A rough estimation of the fire hose instability threshold is done according to Hellinger et al., 2006. Magnetic field fluctuations during the temperature anisotropy observations are identified by using the wavelet analysis.
Minimum variance analysis is used to calculate the direction of propagation and the polarization of the fluctuations.
To investigate a growth rate of the possible fire hose instability, the Vlasov-Maxwell equations are solved by using WHAMP solver for the observed plasma parameters and for the presumable parameters with higher anisotropy (assuming the bi-Maxwellian gyrotropic proton distribution).
We compare observations with the PIC simulations, representing corresponding interaction of two X-lines and a plasmoid formation.

References:
Alexandrova, A. et al., GRL, 43, 7795–7803, 2016
Drake, J.F. et al., APJ, 709:963-974, 2010
Hellinger, P. et al., GRL, 33, L09101, 2006
Markidis, S., et al., Nonlin.Proc.Geophys., 19, 145-153, 2012

OBSERVATIONS

18 August 2002, 17:07:00-17:13:00, in the magnetotail, -18 RE from the Earth
two X-lines pass by the Cluster spacecraft.





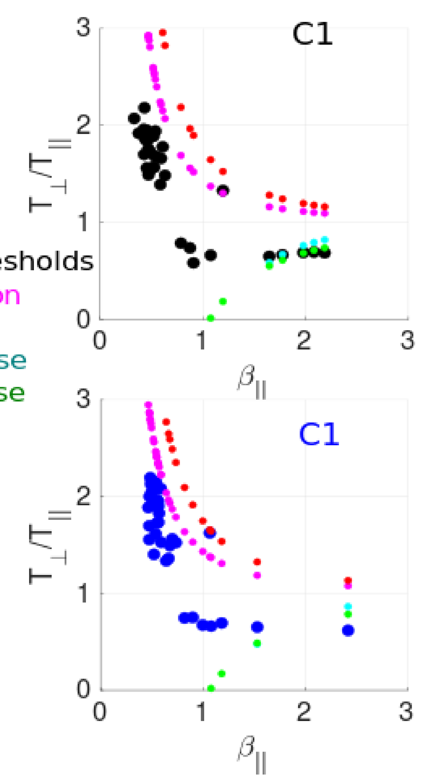
Coordinates LMN ~ GSM

C1 and C4 probes observe the passage of the X-lines with the time shift of ~5-15s.

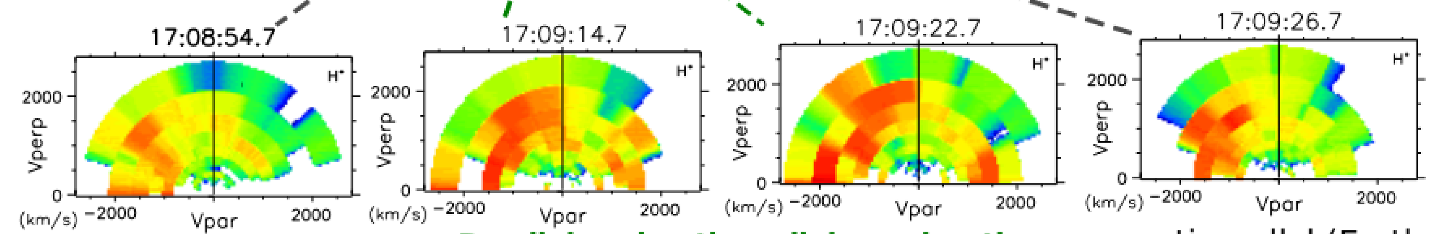
Distance between the X-lines ~2 RE ~ 20 di

see Alexandrova et al., 2016 for the details about the jets collision

Proton temperature anisotropy



Proton velocity distribution

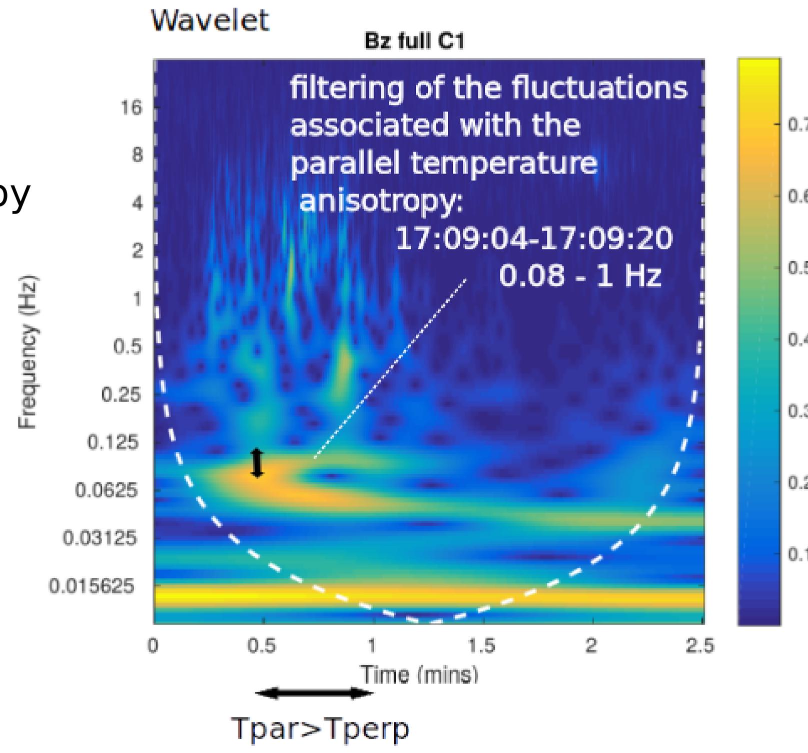


antiparallel (Earthward) acceleration

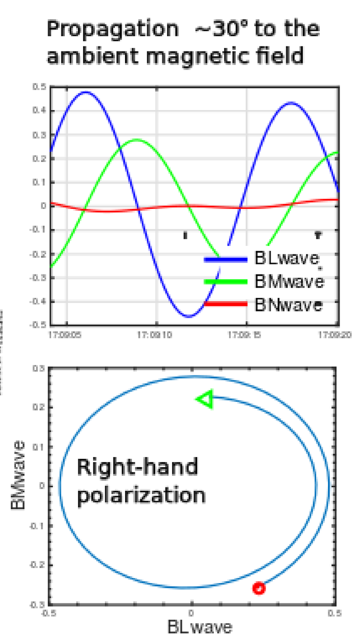
Parallel and antiparallel acceleration

antiparallel (Earthward) acceleration

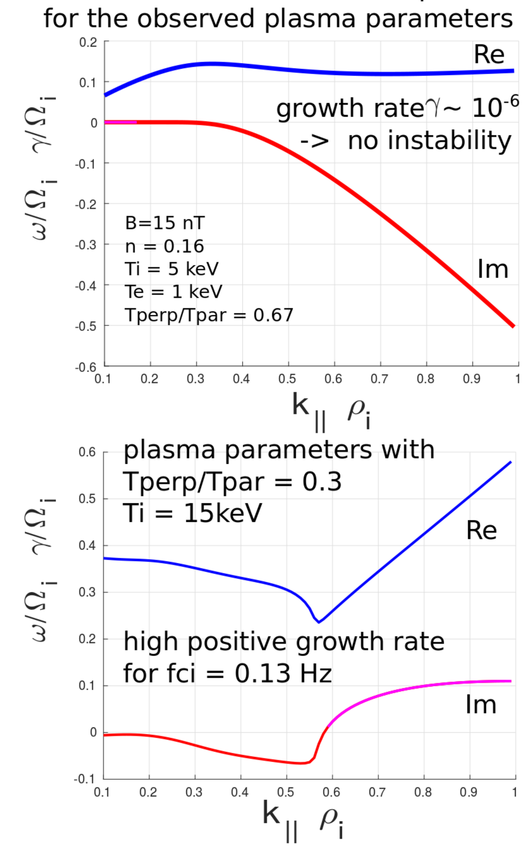
17:08:30 - 17:11:00
Wavelet



MVA 17:09:04-17:09:20



Solution of Vlasov-Maxwell equations for the observed plasma parameters



NUMERICAL SIMULATIONS

3D Particle-in-Cell, Implicit time discretization
Open source: https://github.com/CmPA/iPic3D
Markidis et al., 2010

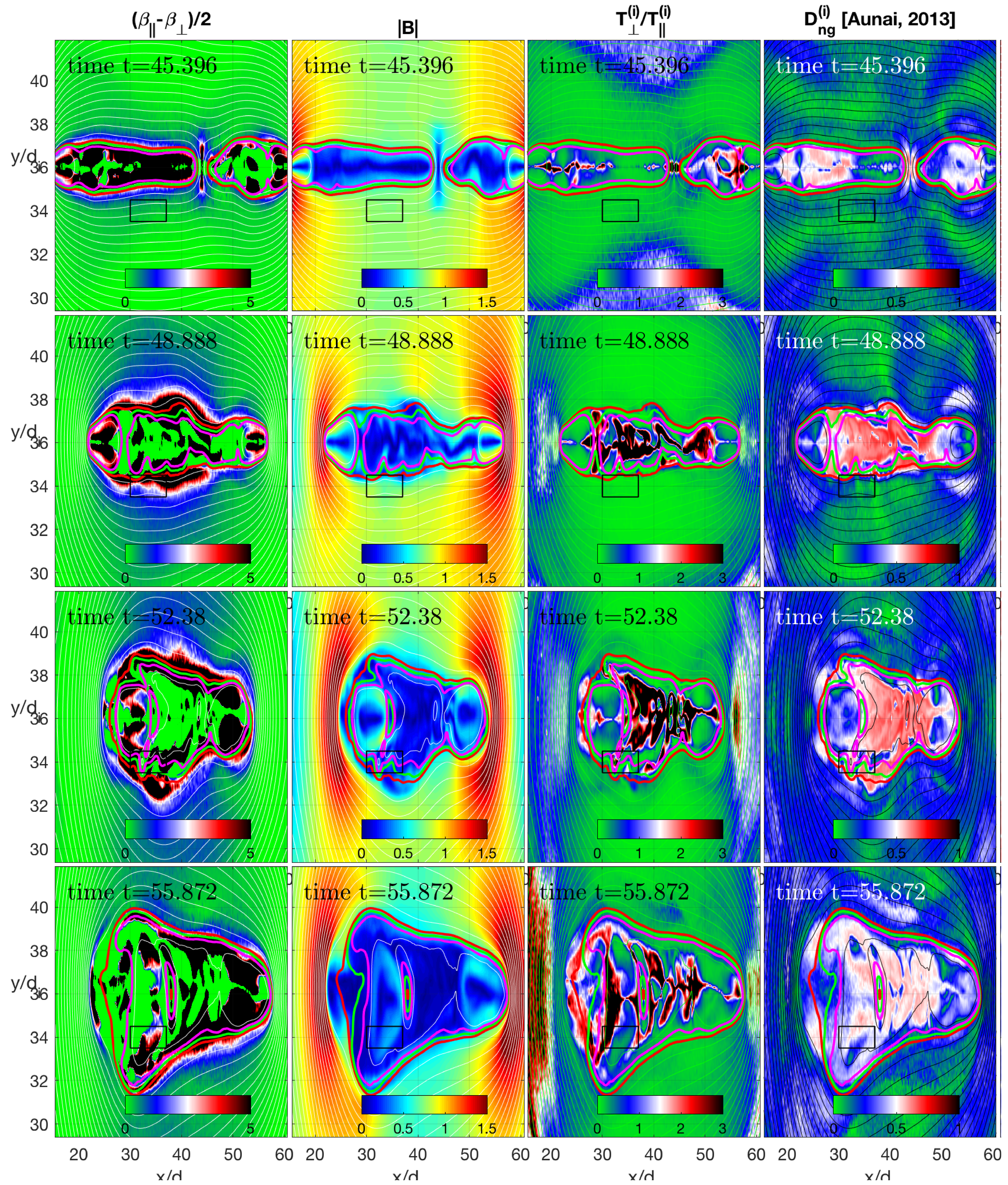
Initial condition: double periodic Harris current sheet, half-width 0.5 of the ion inertial length, di

$B_x(y) = [B_0 \tanh(y/\lambda), 0, B_{0z}]$

$n(z) = N_0 \cosh^{-2}(z/L) + N_b$, $N_b = 0.03$

Reference frame: 'X' is directed parallel to the reconnecting B field, 'Y' is normal to the current sheet at t=0, 'Z' is parallel to the current.

Parameters: m_i/m_e=256, c/V_A=276, T_i/T_e=5 (similar to the averaged magnetotail conditions), total box size
(Lx,Ly)=(96 di,48 di),
(Nx, Ny) = (1024, 512)



We compare the observations with the simulations of similar system: two active X-lines on a large scales of ~20di, a corresponding to the observational case region: a periphery of the plasmoid forming during the interaction of two colliding jets between the X-lines (see black rectangle on the simulation plot). Magnetic field evolution is seen on the highlighted field lines.

Simulations represent well the observed parameters: similar values of the temperature anisotropy, parallel beta, magnetic field fluctuations on the proper scales (see time 52.38).

Simulation illustrate the mixing of plasma Inside the plasmoid (the region, which is missed by the Cluster probes in the observations).

RESULTS

Between two interacting X-lines, on the periphery of the forming plasmoid, the observations show

1. Parallel temperature anisotropy of protons Tperp/Tpar ~ 0.7
2. Magnetic field fluctuations on the scales 0.08-1 Hz lower than the ion cyclotron scale ~0.24 Hz, right-hand polarized, oblique propagation, which correspond to the linear MHD fire hose instability.
3. Growth rate for the fire hose instability is negligibly small, indicating no instability development.
4. For the 'presumable' plasma parameters with the increased anisotropy and parallel temperature, high positive growth rate for the fire hose instability, corresponding to the magnetic field fluctuations on 0.13 Hz, similar to the observed waves.

The results indicate that the spacecraft might observe the system after the development of the instability, on a stage when the plasma energy is transferred from the anisotropy to the magnetic field fluctuations, and the anisotropy decreases.

CONCLUSIONS

We studied the dynamics of the plasmoid formation between to X-lines. According to the observational results and comparison with simulations, when two X-lines are present in the current sheet, the counter-streaming reconnection jets collide and tend to form a plasmoid structure. Tracking stages of the plasmoid formation, we see that closer to the center of the activity/current sheet, plasma is mixing, smaller internal X-lines disappear, providing closure of the field lines. As long as the dominating X-lines produce the reconnected magnetic flux, the forming plasmoid tends to contract. The contraction leads to the field line bending. At the same time, at the periphery of the forming plasmoid, protons are accelerated parallel to the field following the recently closed filed line. Parallel acceleration together with the field line bending may give rise to the fire hose instability, which facilitate further bending and initiate the magnetic field fluctuations. Further compression of magnetic field by ongoing reconnection may lead to the transformation of the fluctuations to a bent field line in a way of a thin boundary formation, as it was observed in Alexandrova et al., 2016.

A.A. research was supported by the Plas@Par

A.D. research was supported by Russian Science Foundation (RNF Number 14-17-00072). Simulations were conducted using resources provided by the Swedish National Infrastructure for Computing (SNIC) at KTH, Stockholm, Sweden, grants m.2016-1-457 and m.2016-1-401