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Wave Modes at Magnetic Reconnection Sites

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Abstract

The subject of transport and transfer of energy by magnetic reconnection and particles-waves energy interchange is the main focus today on earth magnetosphere. The magnetospheric multiscale spacecraft, MMS with its grate instruments performance on monitoring the magnetic reconnection signatures, has made a noticeable progress on the research and study of this new transfer of energy. Two main magnetic reconnection signatures are of great importance, the pressure tensor and the presence of KAW and EMIC waves modes.

Keywords: magnetic reconnection; wave modes; plasma; magnetosphere; energy transport.

1. Introduction

Establishment of generalized Ohm's law in earth magnetosphere has great importance in studying magnetic reconnection and electromagnetic wave modes in this important part protecting our planet. Electromagnetic waves propagate everywhere in the magnetosphere by contrast magnetic reconnection is a challenge for science astrophysics now days. Both subjects are the main means for energy interchange and transport in magnetosphere, which hide the mechanism of energy transfer behind it.

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An establishment of generalized Ohm's law from moment and Maxwell's equations is useful for the illustration of the expected modes at the location of study. Kinetic Alfven waves, KAW and electromagnetic ion cyclotron waves, EMIC deduced equations have been treated. Distinguishing the ambient magnetic reconnection field components and illustrating pressure term tensor at magnetic reconnection sites are the main ideas of this part.

Then a description of the methodology followed for recognizing the magnetic reconnections of the events and the expected and proved modes at the locations. An addition to the known signatures, two main indications of magnetic reconnection at the events candidates have been suggested, the presence of KAW and EMIC wave modes that are the result of the reconnection itself, and the electrons pressure term contribution which is necessary for plasma outflow jet.

Finally, a deep interpretation and explanation by curves from the different measurement of MMS instruments have been used to uncover the best technique for recognizing the magnetic reconnection. The nature of the wave modes and its contribution in magnetic reconnection and wave-particles energy interchange have been explained by curves in this discussion part.

2. Generalized Ohm's Law

The generalized Ohm's Law is as follows without showing the pressure term and distinguishing the magnetic reconnection field in the equation:

$$\frac{m^{+}m^{-}}{\rho c^{2}}\frac{\partial \vec{J}}{\partial t} = \vec{E} + \frac{\vec{u}\Lambda\vec{B}}{c} - \frac{m^{-}}{\rho e c}\vec{J}\Lambda\vec{B} \qquad (1)$$

Considering the approximation: $\frac{m^{-}}{m^{+}} \sim 0$ and $n^{+} = n^{-}$

The electrodynamic equation is as follows using plan waves method:

$$k^{2}\vec{E} - (\vec{k}.\vec{E})\vec{k} = \frac{\omega^{2}}{c^{2}}\vec{E} + i\frac{4\pi\omega}{c^{2}}\vec{J} \qquad (2)$$

From (1) and (2) we deduce the following equation:

$$\omega^{2}\vec{J} = \frac{i\omega\omega_{p}^{2}}{4\pi}\vec{E} + \Omega_{i}\Omega_{e}\left[(\vec{J}.\overrightarrow{b_{0}})\overrightarrow{b_{0}} - \vec{J}\right] + i\omega\Omega_{e}(\vec{J}\Lambda\overrightarrow{b_{0}}) \qquad (3)$$

With $\overrightarrow{b_{0}} = \frac{\overrightarrow{B_{0}}}{|B_{0}|}$, Ω_{i} *and* Ω_{e} are respectively the ion and electron cyclotron frequencies

Also, from (2) and (3) we get the following:

$$\left[\omega^{2} - \frac{\omega^{2}\omega_{p}^{2}}{\omega^{2}-k^{2}c^{2}} + \Omega_{i}\,\Omega_{e}\right]\vec{J} = i\omega\Omega_{e}\vec{J}\Lambda\overrightarrow{b_{0}} \qquad (4)$$

The precedent calculations are based on low frequencies, $\omega \ll \Omega_{i}$

As $\omega_p^2 = \frac{4\pi n^+ e^2}{m^-}$, $\Omega_i = \frac{eB_0}{m^+ c}$, $\Omega_e = \frac{-eB_0}{m^- c}$

Then from (4), $\frac{k^2c^2}{\omega^2} = 1 + \frac{c^2}{V_A^2}$ (5)

where $V_A^2 = \frac{B_0^2}{4\pi n^+ m^+}$

V_A is Alfven velocity which depends on proton density and local magnetic field intensity.

Projecting the vectorial equation (4) yields:

$\frac{ij_x}{j_y} = \frac{iE_x}{E_y} = -\frac{\Omega_i}{\omega}\left[1 - \frac{\omega^2}{k^2c^2}\frac{c^2}{V_A^2}\right] \sim -\frac{\Omega_i}{\omega}$ for ω near Ω_i

The polarization is circularly left-hand (ion cyclotron resonance).

At magnetic reconnection sites there will be a new ambient magnetic reconnection field, B_R and non-negligible electrons pressure tensor, $\boldsymbol{P}_e$:

$$\frac{m^+m^-}{\rho c^2}\frac{\partial \vec{J}}{\partial t} = \vec{E} + \frac{\vec{u}\Lambda\vec{B}}{c} - \frac{m^-}{\rho e c}\vec{J}\Lambda\vec{B} + \frac{\vec{\nabla}.\vec{P_e}}{e n_e} \quad (6)$$

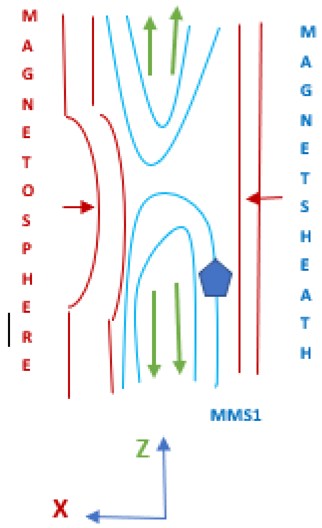

Figure 1: MMS1 location in Geocentric Solar Ecliptic, GSE coordinates of the dayside on 10 October 2015 at 06:47:15, is represented by the Cartesian coordinates by taking ox from earth to sun. Oz is of the direction north to earth poles and oy completes the third direction coordinates. Its location is in the lower part of magnetopause in its path from magnetosheath.

3. Events wave modes

This tentative study is based on two events measured in dayside and nightside magnetosphere regions by the Magnetospheric Multiscale spacecraft, MMS respectively on 10 October 2015 and 08 August 2020. We have classified these two events as magnetic reconnections candidates in first sight by the change in sign of the local ambient magnetic fields. The idea in our methodology of this study is to follow the others magnetic reconnection signatures from the other monitoring spacecraft instruments, for example EDP, FPI besides FGM. The location of these two events are places for the propagation of known electromagnetic waves in the magnetosphere. The ultra-low frequencies, electromagnetic ion cyclotron, EMIC and Alfvén kinetic waves, KAW are expected in both locations the dayside of 8 Re and the far 20 Re nightside events. The position of the 4 MMS spacecrafts in tetrahedron form and their ability of precise resolution in electron scale, have made a great progress in magnetospheric energy-particles interchange research. Today there is a focus essentially on the transport and transfer of energy by waves to particles and magnetic reconnection. Li and his colleagues have classified the known magnetic reconnection sites in 2015 and 2017 by their famous indication of magnetic flux transport, MFT [1]. In laboratory experiment, Hall effect plays a great role in identifying the magnetic reconnection [2].

Generalized ohm's law derived from Maxwell and moment equations could be applied everywhere especially on the anisotropic case where the local magnetic field playing the role of guiding plasma particles which represent the purpose of energy-particles interchange. This magnetic field would be different at magnetic reconnection sites, and another term of electron pressure would arise. In my opinion both, the magnetic reconnection field components and electrons pressure, would compensate the magnetic field before the magnetic connecting and disconnecting (reconnection) takes place. Pressure tensor is really a great magnetic reconnection signature. An enhancement of electrons temperature and ion temperature anisotropy, have been coincided in dayside event at 06:48:10 to 06:48:35 with a rise of this pressure. **Figure.2. e and 2.i**. Yamada and his colleagues quantified the energy converted from magnetic lines [3]. Heat and kinetic energy are the main forms of converted magnetic energy of magnetic lines. Kinetic energy driven by Alfven waves that accelerates particles and heat driven by EMIC waves that heats particles by resonance should be studied in place as first sign or in fact as a result of the magnetic reconnection that transfers the magnetic field lines potential energy to heat and kinetic energy by these modes.

In addition to Alfven Kinetic, AKW and Electromagnetic Ion Cyclotron, EMIC waves modes, the ultra-low frequency, ULF waves are really expected at the sites. In fact, EMIC waves enter in the ULF frequencies range.

4. Discussion

The Electromagnetic Ion Cyclotron (EMIC) waves propagate parallelly on the direction of electromagnetic field or with oblique angle. The electric field is in the perpendicular plan to magnetic field. These waves are generally generated by ions instability driven by energy between 10 -100 keV. EMIC waves frequencies include in the ultra-low frequency waves, ULF that ranges in general from 1 mHz to 5 Hz [4]. FPI instruments measurements exhibit ions temperature anisotropy Tiper>Tipar and energy of order 10 keV**. Figure.2 f and k.**

Macek and his colleagues have supposed the quasi neutrality and the equality of the velocity of the ions and electrons of the plasma in the generalized Ohm's Law. He has illustrated the pressure tensor of the electrons in the equation [5]. Liu and his colleagues distinguishes the reconnection magnetic field B_R (the component B_{xo} in X line) in his calculation of the reconnection rate and has used this component in estimating Alfven velocity [6]. Gershman and his colleagues has used plan waves and wave number to estimate Alfven speed at the reconnection exhaust [7].

Kinetic Alfven Waves propagate along the ambient magnetic field lines and are responsible for the acceleration of electrons and ions respectively along and perpendicular to lines. There is enhancement of about 40 and 500 eV for the electrons and ions temperature respectively at this interval. Usanova and his colleagues has mentioned an enhancement of electrons and ions temperatures at inner magnetosphere based on some measurements on Kinetic Alfven waves, KAW waves.

We start discussing the possible and expected wave modes in the events regions to distinguish and know the source of energy either in heat or kinetic form. Both wave modes found KAW and EMIC play the role of the energy transport and interchange with particles at electron scale. Kinetic Alfven Waves accelerate electron in the direction of local magnetic lines and perpendicularly accelerate the ions to the direction of this field. In its turn, Electromagnetic Ions Cyclotron Waves, EMIC heat these particles as in resonance energy interchange.

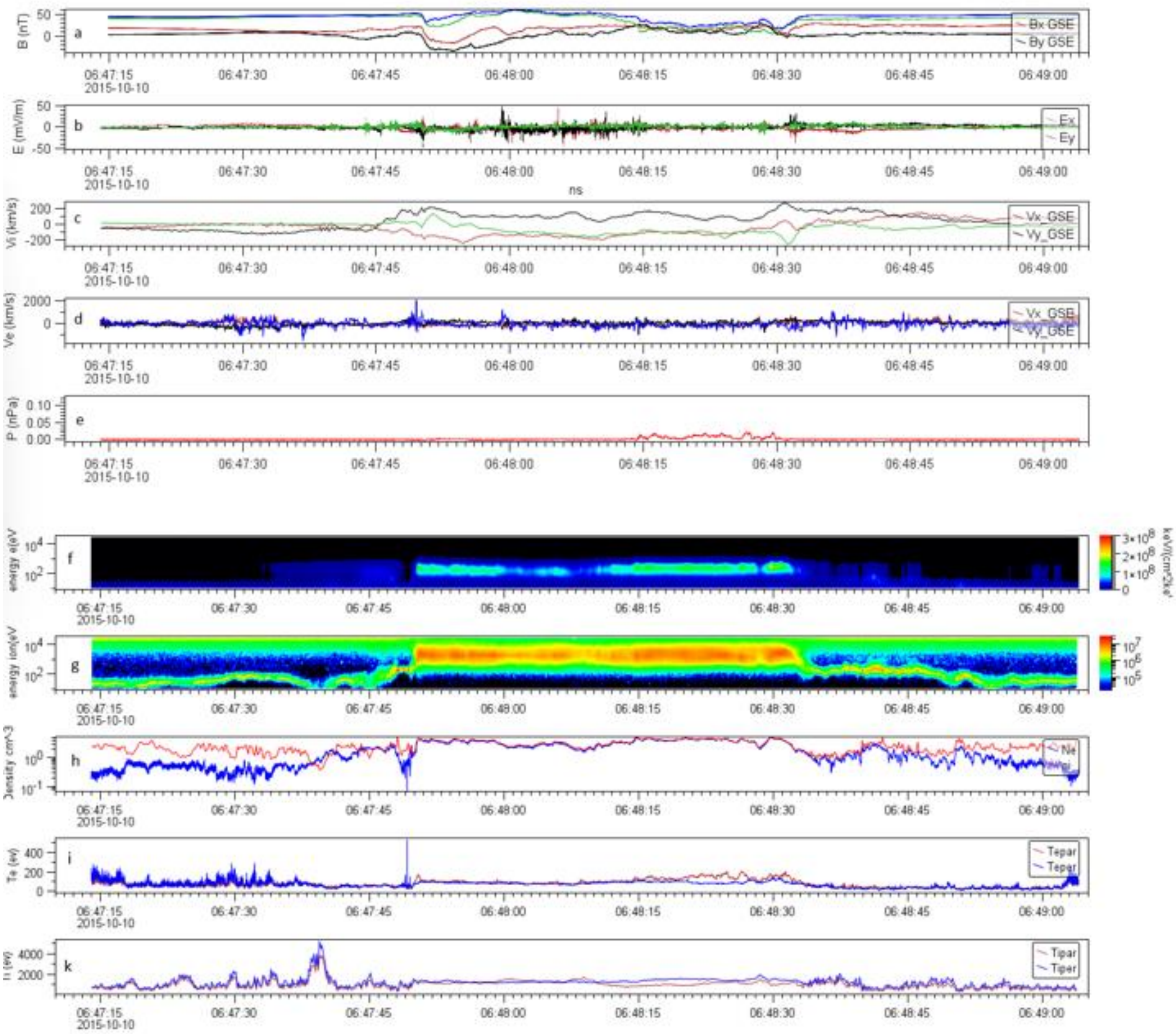

Figure 2: MMS1 measurements of dayside event, (a) total and magnetic components, (b) electric field, (c) ions velocity, (e) electrons pressure, (f) electrons energization, (h) ions and electrons density.

Interpreting the dayside event, a clear change in sign of the electromagnetic field sourced from Fluxgate Magnetic instruments of MMS1 spacecraft at 06:47:51 on 10 October 2015 through its path in the magnetopause. **Figure.2. a**. A corresponding important electric field monitored by EDP instrument may support these first signatures of magnetic reconnection. **Figure.2. b**. An ions jet, -Vz of 220 km/s that follows the magnetic reconnection is another main signature from FPI instrument. **Figure.2. c**. Energization of electrons at the sign change of magnetic field would be considered another indication of the magnetic reconnection. **Figure.2. f**. Burch and his colleagues have used this indication among the main signature [8]. A clear quasi neutrality of charges particles has been noticed. **Figure.2 h**. Both wave modes, KAW and EMIC have been seen in the interval after the reconnection in the magnetopause. They are perhaps a form of transfer of magnetic energy of the magnetic reconnection to kinetic and heat energy. That is to say the magnetic reconnection in this case would be considered as a drive for these modes.

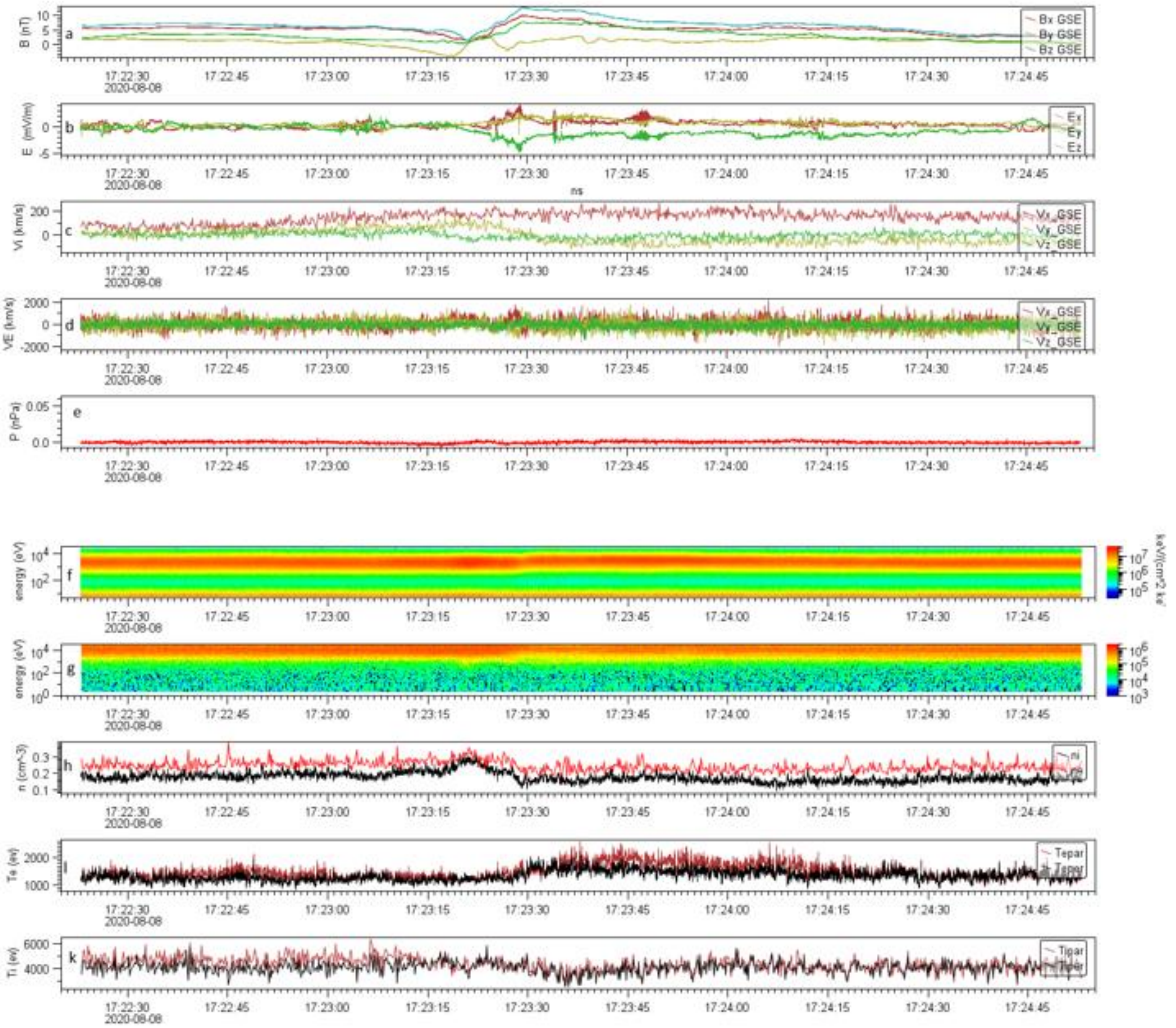

Figure 3: MMS1 nightside event measurements, (a) total and magnetic field components, (b) electric field, (c) ions and electrons velocity, (e) electrons pressure, electrons energy, (l) electrons temperatures.

In the nightside event on 08 08 2020 at 17:23:20, the ambient magnetic field monitored from FGM instrument of MMS1 through its path in lower magnetosphere, has changed its sign as a first known magnetic reconnection signature**. Figure.3. a**. This change in sign coincides with a distinguished electric field from EDP instrument. **Figure.3. b.** The important ion jet, - Vz of about 100 km/s is another induction from FPI instrument. **Figure.3. c**. The energization of electrons is an additional main signature of the possible magnetic reconnection of this nightside event candidate**. Figure.3. f**. There is an enhancement of electrons temperature that follows this magnetic reconnection which would be a sign of kinetic Alfven waves besides the heat energy. This is as we expect a result from the transfer of magnetic reconnection to kinetic and heat energy.

The pressure tensor from FPI instrument has a clear contribution to the ohm's law that supports the first magnetic reconnection at the dayside location candidate and confirm the enhancement of temperature of electrons predicting the kinetic Alfven waves mode mentioned before. **Figure. 2. e**. In contrast there is no clear contribution of this term in the nightside event candidate. **Figure. 3 e**. In fact, plasma density in this region of magnetosphere is too low so that there is no sufficient plasma inflow to have an important plasma outflow jet as it happens in EDR at X-lines regions at bow shock and plasmasheet where the places of complete magnetic reconnection with all signatures and electrons pressure real contribution.

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