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Possible magnetospheric Kelvin-Helmholtz vortex signatures near the post-noon magnetopause

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Abstract. We report on magnetospheric Kelvin-Helmholtz (KH) vortex signatures detected by THEMIS probes located near the post-noon magnetopause in the magnetosphere side for northward magnetosheath magnetic field. Oscillations of the magnetic field and of the ion velocity are measured with a period around 300 seconds. Once we moved into a magnetopause boundary coordinate system, the magnetic field and ion velocity oscillations display vortex-like signatures. Yet ion spectrograms show no strong magnetosheath/magnetosphere plasma mixing and these vortices appear mostly as magnetospheric vortices. Numerical simulations of the KH instability are presented to support this possibility.

Key words. THEMIS– Kelvin-Helmholtz instability– magnetosphere– solar wind

1. Introduction

The Earth's magnetopause flanks with their nearly perpendicular magnetic field at the velocity shear generated by the solar wind, represent the most likely regions around the magnetosphere for the development of KH instability. This provides an efficient mechanism for the formation of a mixing layer between the ion population of solar wind and magnetospheric plasma (2000,?). Magnetosheath plasma with high density and magnetosphere plasma with lower density generally coexist in the KH vortex. In this paper we will discuss particular events observed by two of the five THEMIS spacecrafts on 19/05/2008 between 02:00 and 03:10 UT in post-noon flank of the magnetopause at low latitude. A sequence of magnetic and velocity fields oscillations was detected in the magnetosphere with an amplitude up to 20 nT and up to 200 km/s respectively and a time scale of 5 minutes. We show that these oscillations propagate flankward almost tangentially to the magnetopause. Moreover, oscillations shape validate the possibility of vortices formation due to KH instability. However, the typical mixing layer between the solar wind plasma and the magnetosphere plasma is not observed. Therefore, the vortex structures seem mostly magnetospheric vortices. Numerical simulations of the KH instability are presented to support this possibility.

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Table 1. Magnetosheath and magnetospheric parameters. In order we show: plasma density, ion and electron temperature, solar wind velocity, magnetic field, $\beta_T = 2\mu_0(P_e + P_i)/B_0^2$ parameter (defined as the ratio of the plasma pressure over the magnetic field pressure) and Alfven velocity.

Region	$(part/cm^3)$	$T_i(eV)$	$T_e(eV)$	$V_0(Km/s)$	$B_0(nT)$	β_T	$V_A(Km/s)$
Magnetosheath(THC)	15	100	20	230	15	2.9	86
Magnetosphere(THE)	0.4	4500	1000	0	15	3.7	530

2. Observations

The five THEMIS probes revolve around the Earth in a near-equatorial orbit. On May 19, 2008 during the 01:30-03:30 UT time period, the THEMIS constellation is located in the postnoon region. We focus on three THEMIS probes. At 01:30 UT, THC probe is at X=1.8, Y=18.4 and Z=-5.1 R_E in GSE coordinate system. At same time, THE and THD probes are very near and are at X=-0.6, Y=11.1, Z=-3.1 R_E and X=-1.6, Y=11.1, Z=-2.7 R_E respectively. The observations of THC in the 01:30-03:30 UT interval, when the probe is located in the magnetosheath, indicate that the interplanetary magnetic field turns from southward to northward around 02:17 UT and after, it remains northward with a value around 15 nT. Moreover, the data show that the density of plasma is about 15 $part/cm^3$. The ion and electron velocities show that the plasma bulk motion is directed antisunward and about 230 km/s typical of the magnetosheath plasma. The ion temperature is about 100 eV. Figure 1 displays the THE observations in the magnetospheric side. From top to bottom panel we show: ion temperature, ion density, magnetic field and velocity component oscillations in GSE coordinates and in a local boundary normal (tpn) coordinate system where the local vector t (ΔX=0.85,ΔY=-0.50,ΔZ=0.15) is tangent to the magnetopause and directed toward the subsolar point. The local normal n (0.52,0.81,-0.25) points outward from the magnetopause. Finally, p (0.,-0.29,-0.95) points in a southward direction almost along Z-GSE. Finally we show the ion spectrogram. The period of oscillations is about 5-6 minutes. We observe an amplitude of magnetic component oscillations between -10 and +10 nT. In association with the magnetic field oscillations, THE probe observes a series of velocity component oscillations between -50 and 50 km/s with some peaks between -100 and 100 km/s precisely at 02:13, 02:27, 02:35, 02:41, 02:49 UT. Ion density and ion temperature have values about 0.4 $part/cm^3$ and 4500 eV respectively. THD probe (not shown) detected a similar signature as the THE probe with same magnitude. From the observations of THC and THE we can estimate the typical plasma conditions in each side of the magnetopause. These conditions are summarized in Table 1. The full velocity measurements from THC show that the velocity in the magnetosheath is mainly directed along -t. It confirms a posteriori that (tpn) system is well suited for the interpretation of these data. Therefore if we exclude the vortex signature around 02:27 UT which seems to be consistent with an outward motion of the boundary, we can consider that most of the vortex signatures are consistent with a tailward motion as expected for KH vortices generated by the shear flow between the magnetosheath plasma and the static magnetospheric plasma.

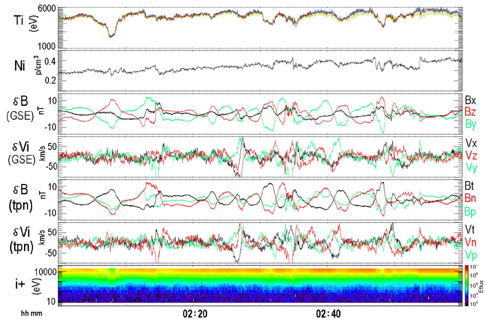

Fig. 1. Data of THE probe. From top to bottom: ion temperature, ion density, three components of the magnetic and velocity fields less the field average done on 600s, in GSE and (tpn) coordinate system respectively, ion spectrogram.

3. Simulations

We performed a series of KH instability simulations based on characteristic values of parameters detected by THEMIS probes reported in the previous section. We use a 2D two-fluid code in which all quantities are normalized to ion inertial length, ion cyclotron frequency and Alfven velocity. The set of equations in dimensionless conservative form is:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{U}) = 0 \quad (1)$$

$$\frac{\partial (n\mathbf{U})}{\partial t} = -\nabla \cdot \Big[\frac{n}{1+d_e^2}(\mathbf{u}_i\mathbf{u}_i + d_e^2\mathbf{u}_e\mathbf{u}_e) + \frac{1}{1+d_e^2}(P_{TOT}\bar{\bar{\mathbf{I}}} - \mathbf{BB})\Big] \quad (2)$$

We indicate with subscript i, e the ions and the electrons species. The plasma is assumed as quasineutral with density $n = n_i \approx n_e$. The fluid velocity is $\mathbf{U} = \mathbf{u}_i + d_e^2\mathbf{u}_e$ where $d_e^2 = m_e/m_i$ is the mass ratio corresponding in our units to the squared electron inertial length. We adopt an adiabatic closure equation:

$$\frac{\partial (nS_{e,i})}{\partial t} + \nabla \cdot (nS_{e,i}\mathbf{u}_{e,i}) = 0 \quad (3)$$

where $S_{e,i} = P_{e,i}n^{-\gamma}$ with $\gamma = 5/3$. The electric field is calculated by means of the generalized Ohm's law:

$$\mathbf{E} = -\mathbf{u}_e\times\mathbf{B} - d_e^2\Big\{\mathbf{u}_i\times\mathbf{B} + \frac{1}{n}\nabla\cdot[n(\mathbf{u}_i\mathbf{u}_i - \mathbf{u}_e\mathbf{u}_e)]\Big\} \quad (4)$$

in which electron inertia is considered, while pressure terms are omitted, because assuming a polytropic equation of state. We model the system by means of a xy box with the inhomogeneity direction along x axis and we assume the y axis where we impose periodic boundary conditions, as the solar wind direction. The box has dimension $L_x = 120$ and $L_y = 30\,2\pi$. In our model all the mean fields (velocity, magnetic field, etc..) vary following a tangent hyperbolic profile being homogenous on both the magnetosphere and magnetosheath sides (left and right, respectively). We use the observed typical values of the fields on the magnetosheath side as characteristic values. In our simulations

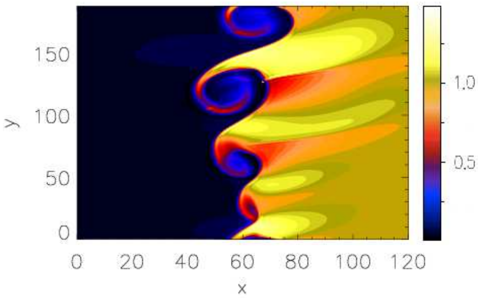

Fig. 2. Isocontour of the plasma density for the simulation with $V_0 = 2.5$ at time $t = 140$.

therefore the magnetic field, the density, the Alfven velocity at the right boundary ($x = L_x$) are equal to unity. In the magnetosheath side we have $\beta_{T(THC)} \approx 2.9$ and we consider here $T_i(L_x) = 0.6$ and $T_e(L_x) = 0.4$ in order to have $\beta_T(L_x) \approx \beta_{T(THC)}$. We consider an initial density jump $\Delta n = 1-\alpha$ varying on the scale length L_{eq}:

$$n(x) = \frac{1}{2}\Big\{(1+\alpha)+(1-\alpha)\tanh[(x-L_x/2)/L_{eq}]\Big\} \quad (5)$$

and the following temperature profile with $\Delta T_{e,i} = T_{e,i}(L_x)(\xi_{e,i} - 1)$:

$$T_{e,i}(x) = \frac{1}{2}T_{e,i}(L_x)\Big\{(1+\xi_{e,i}) + (1-\xi_{e,i})\tanh[(x - L_x/2)/L_{eq}]\Big\} \quad (6)$$

where $\alpha = 0.1$, $\xi_i = 6$, $\xi_e = 4$ respectively for the ion and electron. We take $L_{eq} = 3$ of the order of the magnetopause thickness. Shape function of the mean magnetic field B is determined by the relation $P_T = Pe + Pi + B^2/2 = cst$. We assume a magnetic field compatible with observations nearly perpendicular to the xy plane with $B_z = B\cos\theta$ and $B_y = B\sin\theta$ where $\theta = 0.02$. We suppose an initial sheared velocity field given by:

$$V_{eq} = V_0 \tanh[(x - L_x/2)/L_{eq}]\hat{\mathbf{y}} \quad (7)$$

We performed several simulations varying the shear velocity V_0 between 1 and 3.5. In particular the simulations with V_0 between 1 and 1.5 show the formation of KH vortices constituted of filaments with different densities in agreement with the results of (2000). In Figure 2,

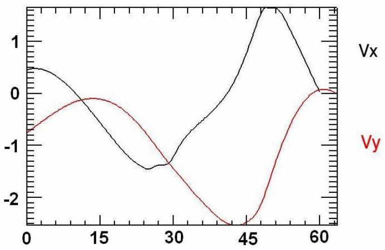

Fig. 3. Profile of velocity components for the simulations with V_0 = 2.5 along a trajectory that through the central vortex of Figure 2 .

we show the isocontour of the density for simulation with $V_0 = 2.5$ at the time $t = 140$. We define L and R the left and right side of the box corresponding to magnetospheric low density plasma and to magnetosheath higher density plasma, respectively. The magnetosonic Mach number values, defined as $M_f = |V_y - V_{ph}|/[(\gamma(Pe + Pi) + B_\perp^2)/n]^{1/2}$, correspond to a sub/super-magnetosonic regime on the two sides, namely $M_f^L = 0.4$ and $M_f^R = 1.6$. Here V_y and V_{ph} indicates the velocity of the plasma along the y direction and the phase velocity of the KH generated vortices. Here instead, the plasma density inside each vortex is nearly uniform and of "low-density"of the order of the magnetospheric initial value. The vortices also show the presence of a thin external ring of density $n_{ring} \approx 0.6$. By looking at the dynamics of passive tracers (not shown), we found that the plasma vortices are a mixing in equal share of both magnetospheric and magnetosheath plasma. As a results, during the vortex formation process, a strong rarefaction of the magnetosheath plasma occurred together with the formation of shock like structures inside the magnetosheath super-magnetosonic $M_f^R > 1$ region. These shock structures will be discussed in a forthcoming paper. In Figure 3 we show, for the simulations with $V_0 = 2.5$, the profiles of the velocity components V_x, V_y along an ideal straight trajectory that across a vortex of Figure 2 from (x=35, y=150) to (x=50, y=90). By comparing Figure 1 and Figure 3 we see a good qualitative correspondence between the simulations and the observations concerning the correlation of the velocity components inside the vortex observed by the probes (in particular, V_x changes sign when V_y assumes a maximum value). However, the observations show a V_{ph} of vortices in the anti-sunward direction lower than that one observed in the simulation. This and other aspects will be discussed in a forthcoming paper.

4. Conclusions

Through the data of the THD and THE probes we observe strong fluctuations of the magnetic and velocity fields of the plasma. The ion spectrogram, the temperature and the density indicate that these probes are mostly in the magnetosphere side. At the same time, THC probe in the magnetosheath at around the same latitude of other spacecrafts has permits the reconstruction of the boundaries layer useful to plan KH simulations. So,we realized a super-magnetosonic regime in the side with higher density (magnetosheath) and a submagnetosonic regime in the side with lower density (magnetosphere) and we observe an unexplored regime of KH instability in the planetary conditions. We found a good qualitatively agreement between the simulations and observations and we interpret the observed perturbations as vortices formed by low plasma density with same value of magnetospheric plasma generated by KH instability.

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