Flow burst-induced Kelvin-Helmholtz waves in the terrestrial magnetotail

M. Volwerk, K.-H. Glassmeier, R. Nakamura, T. Takada, W. Baumjohann, B. Klecker, H. Réme, T. L. Zhang, E. Lucek, and C. M. Carr

Received 26 January 2007; revised 10 April 2007; accepted 20 April 2007; published 19 May 2007.

[1] The Kelvin-Helmholtz instability (KHI) on the boundary of a flow channel in the Earth’s plasma sheet is investigated using Cluster and Double Star TC1 data. It is shown that when Cluster moves into the flow channel the magnetometer measures strong oscillations of the magnetic field, that increase as the spacecraft moves further into the flow channel. These waves are identified as Kelvin-Helmholtz waves. DoubleStar TC1, closer to the Earth, also observes these waves when entering the flow channel but at larger amplitude and with only little flow. The increase in wave amplitude agrees with the KHI wave growth. It is argued that the development of the KHI can play a major role in flow braking in the magnetotail, which is an important aspect of magnetotail dynamics. The large amount of kinetic energy released by a reconnection event or bursty bulk flow gets converted to other kinds of energy such that in the near Earth region the flow is stopped.


1. Introduction

[2] The Kelvin-Helmholtz Instability (KHI) is well known in (magneto)hydrodynamic [see, e.g., Chandrasekhar, 1961] and in magnetospheric physics it is usually associated with the interaction of the solar wind with the magnetosphere at the dayside magnetopause and at the flanks of the magnetosphere [Southwood, 1968; Jungerman and Baumjohann, 1988; Fujita et al., 1996; Mills et al., 2000; Otto and Fairfield, 2000; Fairfield et al., 2000; Hasegawa et al., 2004; Nykyri et al., 2006]. However, in the Earth’s magnetosphere there are more locations where shear flows can occur. One prominent site is the magnetotail where, usually after reconnection, fast flows are observed [Baumjohann et al., 1990; Angelopoulos et al., 1992, 1994]. Yet only few numerical papers have been published on the possibility of KHI in the magnetotail: Yoon et al. [1996] discussed this instability for the cross-tail current and Takagi et al. [2006] discussed this instability in the magnetosheath at the magnetotail flanks. The existence of these waves on the boundary of a flow channel inside the plasmasheet has only been hinted at by Volwerk et al. [2005]. The KHI has also been proposed as a possible source for turbulence in the tail current sheet [Volwerk et al., 2003].

[3] There are various locations other than the Earth’s magnetotail where the KHI is observed at a flow channel, e.g. the interaction of the solar wind with the tail of a comet. The velocity shear between the tail and the solar wind is enough to trigger the KHI on the boundary [Ershkovich et al., 1972; Ershkovich and Heller, 1977; Ershkovich, 1978]. Naturally, compared with a flow channel in the Earth’s magnetotail the flows are reversed, i.e. for a cometary tail (and also at the Earth’s magnetotail flanks) the flow is in the external medium, whereas in the magnetotail the flow is in the internal medium. This is easily changed using a Galilean transformation. Another location for KHI on a flow channel is found in astrophysical jets [Ferrari et al., 1981, 1982; Cohn, 1983; Hardee and Norman, 1988; Norman and Hardee, 1988; Min, 1997].

[4] Fast flows, observed in the magnetotail [Baumjohann et al., 1990; Angelopoulos et al., 1992] seem to decrease in number the closer one comes to the Earth. As the flows usually have velocities well over a few hundred km/s it is reasonable to ask how these flows are braked before they reach the Earth [see also Baker et al., 1996]. Several models have been proposed for the flow braking. Shiokawa et al. [1997] proposed that the high speed flows are stopped by a clear boundary between the dipolar field region and the tail-like field region. Magnetic file up at this boundary will set up inertial currents that produce the braking of the flows. Birn et al. [1999] later showed from numerical simulations that not only these inertial currents but also strong pressure gradients play an important role in flow breaking. In this paper it is argued that KHI in the flow channel is also a player in the flow braking game.

2. Observations

[5] On 14 August 2004 the Cluster spacecraft, located near (–14, –6, 4) RE in GSM coordinates (which will be used throughout the paper), entered from the magnetotail lobe into a flow channel at ~1955 UT [see also Volwerk et al., 2005]. The magnetic field data from the Flux Gate Magnetometer [FGM Balogh et al., 2001] and plasma data from Composition Ion Spectrometer (CIS) [Rème et al., 2001] are shown in Figure 1, left panel. Just before Cluster enters into the flow channel (between vertical line 1 and 2 in Figure 1) there is a strong decrease in density (and temperature). This could be an indication that the current sheet is...
thinning near the location of Cluster. During the interval of very low density, the calculation of the plasma moments may be incorrect. Therefore, the temperature and velocity are plotted in grey for \( n/C_0 \). Then the Cluster spacecraft enter a region of fast Earthward flow (between vertical line 2 and 3 in Figure 1), \( v_x \approx 500 \text{ km/s} \), and move closer to the center of the current sheet, from \( B_x \approx 23 \text{ nT} \) to \( B_x \approx 10 \text{ nT} \), accompanied by a slight increase in \( B_y \) from 5 to 15 nT and an even smaller variation in \( B_z \). This could be seen as a dipolarization in the magnetotail, with the tail severely twisted in the \( yz \)-plane, which is not uncommon [see, e.g., Zhang et al., 2002].

The motion of the spacecraft into the flow channel is accompanied by large scale oscillations of the magnetic field, with a quasi-period of \( \sim 5 \text{ min} \). The more the spacecraft enter into the flow channel, the larger the oscillation becomes, until the Earthward flow stops and the oscillation seems to ebb away. The spacecraft then start moving out of the central current sheet and \( B_x \) returns slowly to almost pre-event values.

The DoubleStar spacecraft TC1 is located in the southern hemisphere of the magnetotail near \((-11, -6, 2) R_E\) in GSM. The magnetic field FGM data [Carr et al., 2005] and Hot Ion Analyzer plasma data (HIA) [Rème et al., 2005] are shown in Figure 1 (right panel). Just before 1925 UT TC1 enters the central current sheet, with \( B_x \) increasing from \(-20\) to \(-5 \text{ nT} \). Note that this coincides with the interval during which Cluster observes the decrease in density. Although noisy, \( B_y \) does not change significantly and \( B_z \) increases slightly from 10 to 15 nT. This indicates that at the location of TC1 the magnetotail is less twisted in the \( yz \)-plane, which could be related to the fact that TC1 is near the hinging point of the magnetotail [Fairfield et al., 1981]. Also, it should be noted that TC1 enters the central current sheet approximately 29 min before Cluster. There are small variations in the plasma flow velocity, a few peaks
up to $\sim 250$ km/s with small tailward flows in between. Remarkably, there is only a short-lived peak of Earthward flow during the second interval reflecting fast flow observed by Cluster in the DoubleStar data.

3. Kelvin-Helmholtz Waves at Cluster

The large scale oscillations of the magnetic field start with the commencement of the fast flows (see Figure 1), which indicates that the process is flow driven. Timing analysis of all 4 spacecraft oscillations [cf. Harvey, 1998] shows that they are propagating mainly Earthward with a phase velocity $v_{ph} \approx 250$ km/s Earthward. This is approximately half of the plasma flow velocity, which indicates the possibility of Kelvin-Helmholtz waves on the boundary of the flow channel, as this instability requires that the shear velocity between the two media is approximately twice the Alfvén velocity. In the case of Cluster we find that the waves occur in a plasma which flows with $v_x \gtrsim 500$ km/s, the Alfvén velocity in the flow channel is $v_A \approx 350$ km/s and the sound velocity $v_s \approx 400$ km/s. This means that the plasma flow in the channel (using these estimates) is super-magnetosonic. Ferrari et al. [1981] show that the phase velocity is smaller than the Alfvén velocity.

As in the previous paper [Volwerk et al., 2005] it is assumed that the spacecraft (Cluster and TC1) are entering into the same flow channel in the Earth’s magnetotail. Indeed, only when the z-separation between Cluster and DoubleStar is sufficiently small ($\leq 2.5$ $R_E$ at 1955 UT) are all spacecraft in the flow channel. This agrees with the statistical vertical size of tail flow channels obtained by Nakamura et al. [2004]. This situation is distinctly different from the generally discussed KHI on the flanks of the Earth as there is a finite size to the flow channel perpendicular to the flow.

Ershkovich and Heller [1977] discussed the KHI for the case of cometary tails in the solar wind. The cometary tail was assumed to be a cylindrical channel. A schematic sketch of the situation (for the case of the magnetotail) is shown in Figure 2. They found that for incompressional plasmas the dispersion relation is given by (where we have corrected sign errors):

$$\omega = v_i + L_m \frac{N_e}{N_i} v_e \pm \sqrt{\frac{B_i^2 + L_m B_e^2}{4 \pi N_i} - L_m \frac{N_e}{N_i} (v_e - v_i)^2}$$

where the subscripts “i” and “e” stand for internal and external variables (with respect to the flow channel), $v$ is the velocity, $N$ is the density and $B$ is the magnetic field and

$$L_m(ka) = \frac{I''_m(ka) K_m(ka)}{I'_m(ka) K'_m(ka)}$$

where $I$ and $K$ are modified Bessel functions and the prime means the derivative [note that $(U/K)_m = (U/K)_{m+1}$, Abramowitz and Stegun, 1972, chap. 9.6] and $a = 2R_E$ is the radius of the flow channel [Nakamura et al., 2004]. From the data the following values are found $B_i = 10^{-8}$ T, $N_i = 4.0 \times 10^6$ m$^{-3}$, $v_i = 500 \times 10^3$ m/s, $B_e = 24 \times 10^{-9}$ T, $N_e = 0.03 \times 10^6$ m$^{-3}$, $v_e = 0$ m/s.

Usually, for KHI, being a convective instability, the frequency $\omega$ is taken to be real, whereas the wave vector $k$ is taken to be complex. Due to the form of the dispersion relation, equation (1), one finds a complex frequency. The imaginary component of the wave vector can then be found by [Ershkovich and Heller, 1977]: $\text{Im}(\omega) = v_g \text{Im}(k)$, where $v_g = \partial \omega / \partial k$ is the group velocity of the waves: $v_g \approx 500$ km/s. To get an estimate of the wave vector $k$ one can write: $\omega / k \approx v_g$, from which it is found that $k \approx 0.42$ $R_E^{-1}$, for 5 min oscillations and $v_g \approx 500$ km/s. For this $k$-value one finds from equation (1) that $\text{Im}(\omega) \approx 0.01$ and thus $\text{Im}(k) \approx 0.01/500 = 2 \times 10^{-5}$ km$^{-1}$.

KHI is a convective instability, which means that when one makes observations at one location in the system, there will not be wave growth. However, Cluster remains basically at the same x-location in the flow (moving only vertically with respect to the current sheet), but still observes an increase in the amplitude of the 5 min oscillations (see Figure 1). This increase is caused by the fact that the flow channel is limited in size perpendicular to the flow.
flow. Indeed, Ferrari et al. [1981] have shown through numerical simulations of the KHI on flow channels of finite width, that inside the flow channel reflection modes will occur. These reflection modes will increase the amplitude of the KHI waves towards the centre of the flow channel.

4. Comparison With Waves at DoubleStar

[13] The DoubleStar data show a dipolarization during the interval that Cluster is inferred to observe a current sheet thinning while in the lobe. During this interval there is erratic Earthward flow up to 150 km/s and sporadically a small tailward burst. The band-passed filtered data (4.5 min < T < 5.5 min) shown in Figure 1 indicate that the wave power is much stronger than for Cluster during the interval 1925–1955 UT.

[14] The fact that DoubleStar observes strong wave power before Cluster observes fast Earthward flow is not problematic. The flow most likely started before Cluster entered the flow channel. Indeed, conjugate ground based observations by the AARI magnetometers show that the 5 minutes oscillation is already present in the BS component of DIK, just before 1930 UT as can be seen in Figure 4 of Volwerk et al. [2005].

[15] Just before Cluster enters the current sheet (i.e., line 2 in Figure 1) the spacecraft observe approximately 1-nT oscillations at the lobe side of the boundary of the flow channel. If indeed a convective instability is present in the flow channel, the wave amplitude at DoubleStar should be calculable:

\[ B_{DS} = B_C \times \exp(\text{Im}(k) \times \Delta x_{DS,C}). \]  

With \( \Delta x_{DS,C} \approx 4 R_E \) one finds that \( B_{DS} \approx 1.7 B_C \). This only slightly underestimates what is observed by DoubleStar while entering the flow channel: \( B_{DS} \approx 2\text{nT} \). This will be discussed further in section 5. The conversion of flow energy into magnetic energy can be described by:

\[ W_k = \frac{1}{2} \frac{N_i m_p v_{flow}^2}{\mu_0} = \frac{\Delta(b^2)}{2\mu_0} = W_b, \]  

with \( W_k \) and \( W_b \) the kinetic and magnetic energy densities, \( m_p \) the proton mass (assuming a proton plasma), \( \Delta(b^2) \) is the difference in the wave amplitude squared between the two measurement points and \( \mu_0 \) the permeability of vacuum. The corresponding magnetic energy for these waves is \( W_b \approx 1.19 \times 10^{-12} \text{J/m}^3 \) or a \( \Delta v_{flow} \approx 60 \text{km/s} \).

5. Discussion

[16] Cluster and DoubleStar data have been investigated for the entrance into a flow channel in the Earth’s magnetotail. The spacecraft data showed quasi-periodic oscillations in the magnetic field on the boundary and inside of the flow channel. These waves were identified as Kelvin-Helmholtz waves, driven by the fast flow in the central plasma sheet. The fact that the waves are driven by the flow reduces the probability of other instabilities like the Rayleigh-Talor or ballooning.

[17] Although KHI is a convective instability, Cluster observes an increasing amplitude of the waves even though the spacecraft remain at approximately the same location during the event. This is caused by the finite width of the flow channel. In the case of a super-sonic flow reflection modes are created in the flow channel which add to the amplitude of the waves [Ferrari et al., 1981]. These extra modes increase the amplitude of the waves as the spacecraft move further into the flow channel. A schematic view is shown in Figure 2.

[18] DoubleStar TC1 also observed these waves at entering the flow channel, albeit with a larger amplitude than Cluster. This is explained by wave growth over the distance between Cluster and DoubleStar. (At later times, when Cluster moves further into the flow channel, this does no longer hold.) Earlier it was estimated that the wave growth between Cluster and DoubleStar should be \( \sim 1.7 \). Comparing the magnetic field magnitude using the band-pass filtered data from Cluster and DoubleStar and respective flow braking should be performed to investigate the role of the KHI on flow braking. The KHI can be a significant player in the plasma flow braking, in addition to the mechanisms described by Shiokawa et al. [1997] and Birn et al. [1999].

6. Conclusions

[20] The KHI has for the first time been observed on a flow channel in the Earth’s magnetotail by Cluster and DoubleStar TC1. The waves from the convective instability are shown to grow along the flow from Cluster towards TCI. Also the Cluster data show that the amplitude of the waves grows when the spacecraft enter deeper into the flow channel, as expected from numerical models. The KHI might play a significant role in the braking of the fast flows in the Earth’s magnetotail.

[21] Acknowledgments. We would like to acknowledge the Cluster Science Data System (CSDS). The work by M. V. and K. H. G. was financially supported by the German Bundesministerium für Bildung und Forschung and the Zentrum für Luft- und Raumfahrt under contract 50 OC 0104 and 50 OC 0105 respectively.
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W. Baumjohann, R. Nakamura, T. Takada, M. Volwerk, and T. L. Zhang, Space Research Institute, Austrian Academy of Sciences, A-8042 Graz, Austria. (martin.volwerk@oeaw.ac.at)

C. M. Carr and E. Lucek, Department of Physics, Imperial College, London SW7 2BZ, UK.

H.-H. Glassmeier, Institute for Geophysics and Extraterrestrial Physics, TU Braunschweig, D-38106 Braunschweig, Germany.

B. Klecker, Max Planck Institute for Extraterrestrial Physics, D-85741 Garching, Germany.

H. Réme, Centre d’Etude Spatiale des Rayonnements, CNRS, F-31028 Toulouse, France.