Kelvin–Helmholtz waves at Earth’s magnetopause
Shiva Kavosi, H. E. Spence, Jimmy Raeder

University of New Hampshire, Durham, NH

The research is supported from NASA (Grant no. 80NSSC18K0661), NASA Grant 80NSSC18K1365.

Observations of Kelvin-Helmholtz Waves in the Earth’s Magnetotail Near the Lunar Orbit, Ling, Y. et al.

Kelvin-Helmholtz Instability in Saturn’s outer magnetosphere observed by Cassini

Kelvin-Helmholtz Instability in coronal mass ejections observed by SDO/AIA

Kelvin Helmholtz clouds observed on Saturday, May 17, 2014 at Tupper Lake, New York
Kelvin–Helmholtz waves at Earth’s magnetopause

Overview

- Background and KH Identification
- KH THEMIS survey
- Plasma transport and KHI
- MMS electron microinjections associated with KHI
- Seasonal and diurnal variation of KHI and its dawn-dusk asymmetry: New hypotheses

\[
(k \cdot V_0)^2 > \frac{n_{01} + n_{02}}{n_{01}n_{02}} \left[ n_{01}(k \cdot V_{A1})^2 + n_{02}(k \cdot V_{A2})^2 \right]
\]
Kelvin–Helmholtz waves at Earth’s magnetopause

Dungey (1955) proposed the idea that Kelvin-Helmholtz instability might occur at the magnetopause boundary separating solar wind and magnetosphere plasma.

Soon after:  
\[
(k \cdot V_0)^2 > \frac{n_{01} + n_{02}}{n_{01}n_{02}} [n_{01}(k \cdot V_{A1})^2 + n_{02}(k \cdot V_{A2})^2]
\]

Many numerical and observational studies investigate how plasma transport be achieved in association with the KHV?.

1. Reconnection within a rolled-up KH vortex
   The KH Wave in its nonlinear stage can develop small-scale filamentary field and current structures resulting to magnetic reconnection.

2. Secondary Instabilities and Turbulence
   Due to the mass difference of the two regions and the centrifugal force exerted by the vortex motion, the boundary inside the rolled-up vortex becomes sensitive to the RT instability. This causes turbulence and a plasma transfer.

The first observation of KHI at the Earth MP reported by Otto and Fairfield, 2000 using Geotail data. Later, H. Hasegawa, et al, first Transport of solar wind into Earth’s magnetosphere through rolled-up Kelvin–Helmholtz vortices, using Cluster data. The growth of KHI at the magnetopause lead to the “rolled-up” vortices.

The existence of KH waves at the magnetopause has been established for a long time mostly by analyze of single event. And the KH events were considered to be relatively rare.

A recent statistical analysis [Kavosi and Raeder, 2015] has shown that KH waves at Earth’s magnetopause are ubiquitous, occurring ~19% of the time under all solar wind and IMF conditions.

Figure a shows: The occurrence rate is 35% for near northward IMF, near 20% if the IMF lies in the equatorial plane, and about 10% for southward IMF.

Figure b shows: The instability maximizes when the magnetic field on either side of the shear layer is close to collinear, which occurs for 90 cone angle. And minimized in 0,180 cone angles.
Detection of Kelvin-Helmholtz Vortices: Single spacecraft method

Occurrence rate of KHW as a function of solar wind plasma parameters!

- show the relative KHW occurrence rate
- show the number of 5-min KHW intervals in that bin

a) The KH occurrence rate increases with solar wind speed.

b) At low densities there is a positive correlation, which tapers out for densities larger than 10/cc.

c) There is a positive correlation with the solar wind Alfven Mach number, which also tapers out at high (>12) Mach numbers.

d) The IMF magnitude have only an effect for unusual high values (>16 nT).
Detection of Kelvin-Helmholtz Vortices

The vertical red dashed lines demonstrate the jumps from the magnetosphere to magnetosheath values coincide with maxima of the total pressure. These loci correspond to the hyperbolic points ‘H’.

The bipolar $B_n$ signatures are centered on the red lines, i.e. the ‘H’ points.

- (L) is the center of vortex.
- Total pressure minimizes at the center (L) of the vortices, while it maximizes at the hyperbolic point (H).
- The magnetosphere-to-magnetosheath transitions is characterized by rapid density increases coincide with maxima in the total pressure.

- Schematic of reconnection signatures at the trailing edge of a rolled-up vortex H hyperbolae point.

- Bipolar signature at H point
Comparison between the properties of FTEs and Kelvin-Helmholtz Vortices

<table>
<thead>
<tr>
<th>Signature</th>
<th>Kelvin-Helmholtz Vortex</th>
<th>FTE</th>
</tr>
</thead>
</table>
| Magnetic field | 1. Bipolar $B_n$  
2. Often has a maximum in magnetic field strength at the edge of the vortex, with less than 10 nT magnitude.  
3. Continuous bipolar $B_n$. | 1. Bipolar $B_n$  
2. Has a magnetic field strength maximum at the core of FTE, usually larger than 10 nT magnitude.  
3. Bipolar $B_n$ separated by a few minutes quiet. |
| Plasma | 1. Substantial pressure perturbations, minimum at the vortex center and maximum at the edge. A large and rapid density increase coincides approximately with a maximum in the total pressure at the edge of the vortex.  
2. Usually small perturbation in $V_n$.  
3. Low-density plasma flowing faster than sheath velocity. | 1. Total pressure maxima at the FTE center.  
2. Typically bipolar $V_n$. The $V_n$ perturbation is usually larger than those seen in KHW.  
3. No accelerated low-density plasma. |
| Duration and Period | 1. Continuous wave trains.  
2. 1-4 minute periods. | 1. Short (<2 min) bipolar $B_n$ signatures separated by quiet.  
2. Repetition period typically longer than 4 minutes. |

The red symbols show the first part of the event (11:20-11:50 UT), which were identified as FTEs during the FTE interval the tangential flows are mostly less than 100 km/s, which clearly separates the FTEs from KHW.

The black symbols show the second part of the event (11:55-12:10 UT), which were identified as KHW. There is some low-density plasma (circled in red) that flows faster than the magnetosheath plasma (~200 km/s), confirming that rolled-up vortices are present.
Why KH under southward IMF occurs only at one quarter of the rate compared to northward IMF?

- The occurrence rate is 35% for near northward IMF, and about 10% for southward IMF.

**Questions?**

- What are the differences between KHWs under Southward and Northward IMF conditions?
- Why KH under southward IMF occurs only at one quarter of the rate compared to northward IMF?

We study Kelvin-Helmholtz under southward IMF using THEMIS observations and Open GGCM simulation.
Our data set shows that the majority of the events during southward IMF are irregular, short and polychromatic in compared to regular, long lasting, and monochromatic waves under northward IMF condition.
To effectively isolate these differences, we performed OpenGGCM global simulations for constant idealized solar wind under both northward and southward.

- KH under Northward IMF is unstable for all velocity ranges, and there is no cut off velocity.
- KH under southward are unstable only for velocity >400 km/s.
THEMIS Survey: Southward IMF

The correlation of KH waves with the solar wind plasma parameters for southward IMF

- Themis survey shows KH under southward IMF occurs for velocity high enough to take over the FTEs, and majority of the events occurs for velocities higher than 400 km/s.

- Themis survey also shows KH under southward IMF occurs for only low $|B|$. And the occurrences rate decrease by increasing the magnetic field magnitude.
Our data set shows that the majority of the events during southward IMF are irregular, short and polychromatic in comparison to regular, long lasting, and monochromatic waves under northward IMF.

- This might explain a few in-situ observations of KH waves under southward IMF. One reason is that the signatures of KH under southward IMF are quite different than the signatures expected for KH waves under northward IMF. This means that even if the KH waves under southward IMF have been observed, they have not been suitable for reporting or publication.

Our THEMIS dataset and OpenGGCM simulations, show that KHW under northward IMF can occur for all solar wind IMF conditions, while KHW under southward IMF occurs only under specific conditions: High velocity and Low |B|. This might explain a few in-situ observations of KH waves under southward IMF.
Electron Microinjections Observed by MMS

Microinjections appear to be a distinctly different phenomenon from classic substorm injections and unrelated to nightside processes

Characteristics

- Energy range: ~50-400 keV
- Spatial distribution: ~8 - 12 Re on nightside (16 to 0 to 9 MLT)
- At dusk, energy dispersion suggests an origin at earlier MLT
- Occur in clusters in rapid succession (~10 per hour)
- Bidirectional field-aligned angular distributions
- Often accompanied by ULF perturbations
- Possibly observed in ions as well

Observed fairly regularly in the MMS/FEEPS duskside data

- First observed only at dusk, but that was largely related to MMS orbit/operation
- MMS orbit rearrangement and FEEPS operation change has permitted observation of microinjections in local morning MLT as well
Identifying the Source Region of Microinjections

There is some evidence (e.g., Kavosi+ [2018]) that duskside microinjections are related to dayside magnetopause boundary dynamics (KH waves/FTEs)

Particle tracing from the MMS location backwards in time

Impact/Importance: Microinjections could provide an additional source of seed electrons that has not yet been considered in radiation belt dynamics
Identifying the Source Region of Microinjections: OpenGGCM

We used Open Geospace General Circulation Model (OpenGGCM), a global MHD model of the Earth’s magnetosphere (Raeder et al., 1998) with upstream solar wind input parameters from OMNI data.
Comparison of Simulation and Observations

Back-tracer and forward-tracer during the time of KHWs

Back-tracing

The trajectories of a 100-keV electron with different pitch angles 15°-90° with colored circle points where they pass the simulated MP.

Back-tracing shows the field-lined electrons have drifted from the post-noon MP.

Forward –tracing

The positions of 100 keV electrons with different pitch angles ranging from 15°-90° when electrons are launched at the different points in the small box near the dusk magnetopause inner boundary layer.

Forward tracing result that the electrons with pitch angles <60° are injected into the magnetosphere and reach the location of MMS, while electrons with pitch angles ≥60° trace to locations much deeper in the tail or are lost further down the duskside magnetopause.
Direct observational evidence of source origins for the observed electron microinjections is needed to investigate the potential processes by which energetic electrons near the magnetopause are injected onto drift paths connected with the MMS/FEEPs in the dusk region of the magnetosphere.

Electron particle trajectories in the DMLR, as caused by the Kelvin-Helmholtz instability at the magnetopause will be studied in order to identify the acceleration mechanisms.

Kelvin–Helmholtz instability and Aurora beads
Auroral Vortex Observations

Field-Aligned Currents in Auroral Vortices
Jay R. Johnson1, Simon Wing1, Peter Delamere2, Steven Petrinec3, and Shiva Kavosi5

Abstract: Auroral bright spots have been observed at Earth, Jupiter, and Saturn in regions that map to the magnetopause boundary layer. It has been suggested that the bright spots are associated with the Kelvin-Helmholtz (KHI) instability. We utilize a quasistatic magnetosphere-ionosphere coupling model driven by a vortex in the boundary layer to determine how the field-aligned current structure depends on ionospheric and boundary layer parameters. We compare vortex induced currents with shear-flow driven currents. We find that the strength of the maximum currents are comparable, but the structure and development of Kelvin–Helmholtz (KH) vortex structures (H. Hasegawa et al., 2006, 2009) is also known to drive Kelvin–Helmholtz instabilities (Johnson et al., 1980). Free energy from the shear differences between vortex driven currents and shear flow driven currents.

RESEARCH ARTICLE

Ongoing project: We currently working on ionospheric signature of KHWS using Open GGCM simulation.
Seasonal and diurnal variation of Kelvin-Helmholtz Instability at the Earth’s Magnetopause

The results present a comprehensive statistical study to investigate KH occurrence and its distribution along the magnetosphere using THEMIS and MMS data during one solar cycle, 2007-2019.

THEMIS probes P3, P4, P5, and MMS orbit during 2016-2019 are in the dawn-dusk side of the magnetosphere when MMS is placed in a way that is in opposition to THEMIS, which makes the best data set to study KHWs dawn-dusk asymmetry.

As shown, the occurrence rate is maximizing during equinoxes, and the minimum occurs during solstices.

The KHI occurrence rate during equinoxes is twice greater than the solstices. The trends shown in figure 1 is in agreement with previously reported results by Boiler and Stolov [1970]. Their model falls into the equinoctial class of hypotheses. It proposes that the diurnal and annual variation of the earth's dipole angle causes a modulation of Kelvin-Helmholtz instability at the flank magnetopause. Boiler and Stolov suggested that the semiannual variation of geomagnetic activity is associated with Kelvin Helmholtz instability variation at the earth magnetopause. They showed that according to theory, KHI dispersion relation, the probability of KHI varies by the seasonal changes of the orientation of the earth’s magnetic dipole to the solar wind flow.
Seasonal and diurnal variation of Kelvin-Helmholtz Instability at the Earth’s Magnetopause

\[ U^2 > \frac{\rho_l + \rho_M}{4\pi \rho_l \rho_M} \left[ B_I^2 \cos^2 \psi_I + B_M^2 \cos^2 \psi_M \right] \]

The angle \( \psi_M \) between the local velocity shear and the magnetic fields.

If \( \psi_M = 90 \), the magnetosphere magnetic field lines cannot exert stabilizing influences on velocity shear, and the magnetospheric term is zero. In this case, the inequality becomes in favor of the KH instability, i.e., equinoxes.

Solstices \( \psi_M = 90^\circ \) and Magnetospheric field lines can exert maximum stabilizing influence on KHI.

Equinoxes \( \psi_M = 0 \) Magnetospheric field lines can not exert stabilizing influence on KHI.
Seasonal and diurnal variation of Kelvin-Helmholtz Instability at the Earth’s Magnetopause

\[ U^2 > \frac{\rho_I + \rho_M}{4\pi\rho_I\rho_M} [B_I^2 \cos^2 \psi_I + 0.0397B_M^2] \]

The most unstable configuration at solstices occurs when it is \( \Psi_M \) 78 and 102 degrees.

\[ U^2 > \frac{\rho_I + \rho_M}{4\pi\rho_I\rho_M} B_I^2 \cos^2 \psi_I \quad \text{Most unstable situation} \]

The least unstable during solstices when is 55 and 125.

\[ U^2 > \frac{\rho_I + \rho_M}{4\pi\rho_I\rho_M} [B_I^2 \cos^2 \psi_I + 0.329B_M^2] \]

least unstable situation at the flanks during the equinoxes occurs when \( \Psi_M \) at the maximum angle, which is 78.5- or 101.5-degree during the equinox.

Diurnal variations of KHI occurrences during (a) Winter solstice (b) summer solstice (c) Spring Equinox and (d) Fall Equinox. The red line shows the line plot of the variations and the gray dotted line shows the trend lines for comparison with theory.
How dipole tilt angle affect KHI distribution along the magnetosphere?

The percentage of KHI occurrence broken down by dipole tilt angle and dawn-dusk

This implies that most of the KHI events in our dataset are observed on the dawn flank during negative dipole tilt and on the dusk flank during positive

The dependence of KHWs locations on the geomagnetic dipole tilt angles for northern, and southern hemispheres.

- This scatterplot over the magnetopause serves to visualize the data distribution over the entire set for the south and north hemisphere.
- Normalized occurrence rates indicate that KHI in the northern hemisphere favors the dusk sector when the dipole tilt is negative and favor dawn when the dipole tilt is positive and vice versa for the southern hemisphere.
- Most events with negative dipole tilt occur in the dawn sector, and with positive dipole, tilt occur on dusk sector events in the southern hemisphere.
Seasonal and diurnal variation of Kelvin-Helmholtz Instability at the Earth’s Magnetopause

- The seasonal dependence of KHWs locations (KHI unstable regions) along the magnetopause at dawn-dusk and southern and northern hemispheres.
- It is shown how the location of KHWs is distributed along magnetopause in dawn-dusk and south and north direction during fiscal quarters.
- KHWs are observed in the southern hemisphere on the dawn flank during Q3 and Q4 (July-December) and on the dusk flank during Q1, Q2, and vice versa for the northern hemisphere.
- In the northern hemisphere, most of the events occur on the dawn flank during Q1 and Q2 and dusk flank during Q3.
- The dawn-dusk asymmetry is opposite in the southern and northern hemispheres. It is also reverse during the second half of the year.
- The simple explanation is that during the first six months (Winter Solstice-Spring equinox), the sun is on the right side of the earth, and the second 6 months is on the left side of the earth.

As Earth orbit around the Sun and its axis, the angle between the Z-axis in (GSM) coordinate system and the Y-axis in, $\theta$, and the angle $\Psi$ between the Earth-Sun line and the dipole axis of the Earth changes. The semiannual and diurnal variation of these two angles plays a vital role in geomagnetic activities.
Equinoctial hypothesis:
The equinoctial hypothesis is based on the angle between the Earth-Sun line and the Earth’s dipole axis, $(\phi), \cos(\phi)$.

R-M effect:
The angle between Z-axis in (GSM) coordinate system and Y-axis in the (GSEQ) coordinate system plays an important role in the controlling factor of geomagnetic activity.
Seasonal Variation of KHI occurrence with different different IMF polarities

The IMF polarity is one of the most important parameters when investigating the seasonal and diurnal variation of geomagnetic activity. Seasonal and Diurnal Variation of Kelvin-Helmholtz instability varies during different IMF polarities.
Seasonal Variation of KHI occurrence/dawn-dusk asymmetry with different IMF polarities:

The KHI occurrence rate is maximum at Dawn southern hemisphere and dusk northern hemisphere with its preference for the dawn-side flank in the southern hemisphere when IMF By is negative and for By positive is reversed.

KHI dawn-dusk asymmetry solar minimum, and solar maximum. The asymmetry of KHI and its preference for dawn-side during solar minimum, 2007-2012, when average IMF By<0. and its preference for the dusk-side flank during solar maximum, 2013-2019, when average IMF By is positive, By>0.
KHI occurrence and spatial distribution along the magnetopause is controlled by IMF $B_y$ polarity, Angle $\varphi$ and $\theta$.

$B_{y_{gsm}} = B_{y_{gseq}} \cos(\varphi + \theta) + B_{z_{gseq}} \sin(\varphi + \theta)$

$B_{z_{gsm}} = -B_{y_{gseq}} \sin(\varphi + \theta) + B_{z_{gseq}} \cos(\varphi + \theta)$
Seasonal and diurnal variation of Kelvin-Helmholtz Instability at the Earth’s Magnetopause: OpenGGCM
Seasonal and diurnal variation of Kelvin-Helmholtz Instability at the Earth’s Magnetopause: OpenGGCM
KHWs are observed in the dawn flank northern hemisphere and dusk flank southern hemisphere during Q1 and Q2 (Feb-June) and vise versa during Q3 and Q4 (July-December) and on the dusk flank during Q3, Q4, and vice versa for the northern hemisphere.
Seasonal and diurnal variation of Kelvin-Helmholtz Instability at the Earth’s Magnetopause: OpenGGCM
Conclusions

• KHI strongly depend on the dipole tilt angle.

• Kelvin–Helmholtz waves (KHWs) occurrence rates and locations exhibit a semiannual variation; the rate maximizes at the equinoxes and minimizes at the solstices.

• The dawn-side-northern hemisphere preference at the equinoxes and dusk-side-southern hemisphere preference at the solstices is controlled by both the dipole tilt angle and the polarity of Interplanetary magnetic fields (IMF) By.

• KHW occurrence and dawn-dusk asymmetry can be attributed to the equinoctial and R-M effect hypothesis, respectively.

• Our results are consistent with the prediction, derived with MHD simulation.
Thank you