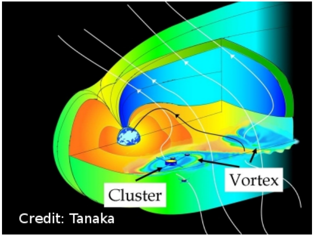
Space Weather
Lecture 4: Kelvin–Helmholtz Instability and Field Line Resonances



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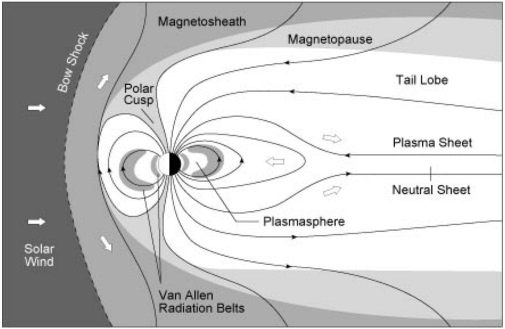
Magnetospheric boundary

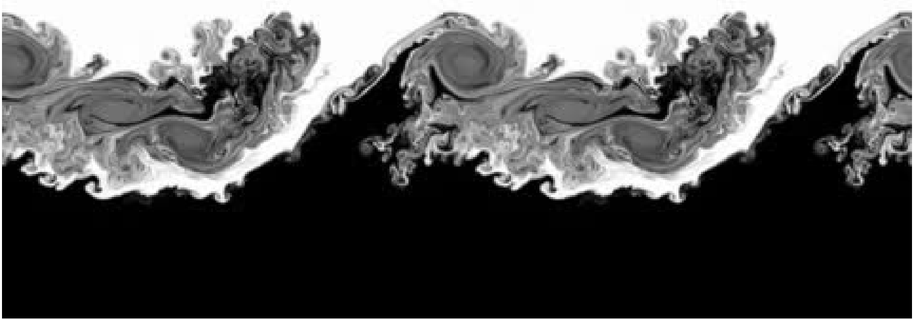
- Schematic diagram conveys the impression that the magnetosphere is a well ordered and stable system.
- The magnetosheath plasma is flowing along the magnetopause around the magnetosphere.
- However, contact between the flow and the magnetospheric field may cause ripples on the boundary.



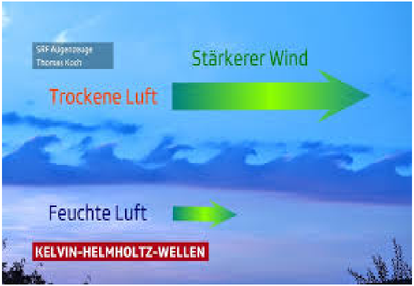
Magnetospheric boundary

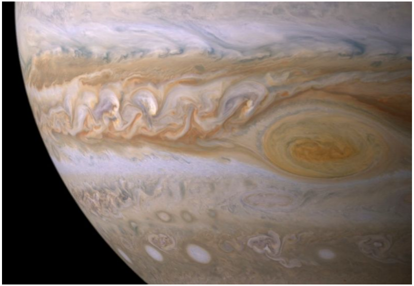
- This triggers Kelvin–Helmholtz Instability (KHI) – which occurs when there is velocity shear in a single continuous fluid, or where there is a velocity difference across the interface between two fluids.

Credit: Wikipedia



Examples of KHI





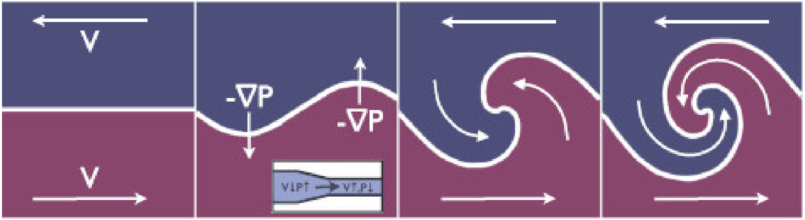
Own observations of KHI

Messeling, Tirol

Big Island

KHI formation

- Deformation of the boundary between two fluids modifies pressure.
- From the Bernoulli principle, the deformation into a flowing fluid leads to increased velocity and reduced pressure, while the expansion of the boundary leads to reduced flow and an increased pressure.
- The deformation leads to pressure gradient in the opposite direction.
- Fluid from one side of the interface will be carried by the flow on the other side of the interface leading to a rolling up of the interface.
- Vortex formation is a typical observational signature of the KHI.



From Johnson et al., 2014

The dispersion relation for KHI

From Johnson et al., 2014

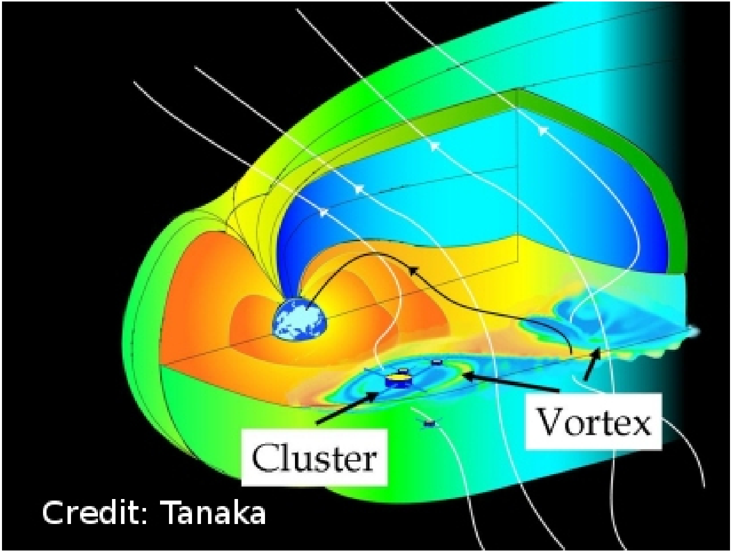
$$\omega_{\text{kh}} = \frac{\mathbf{k}(\rho_{\text{msh}}\mathbf{V}_{\text{msh}} + \rho_{\text{msp}}\mathbf{V}_{\text{msp}})}{\rho_{\text{msh}} + \rho_{\text{msp}}}$$

$$\pm i\sqrt{\left(\frac{\rho^*}{\rho_{\text{msh}} + \rho_{\text{msp}}}\right)\left(\left[\mathbf{k}\cdot(\mathbf{V}_{\text{msh}} - \mathbf{V}_{\text{msp}})\right]^2 - \frac{(\mathbf{k}\cdot\mathbf{B}_{\text{msh}})^2 + (\mathbf{k}\cdot\mathbf{B}_{\text{msp}})^2}{4\pi\rho^*}\right)}$$

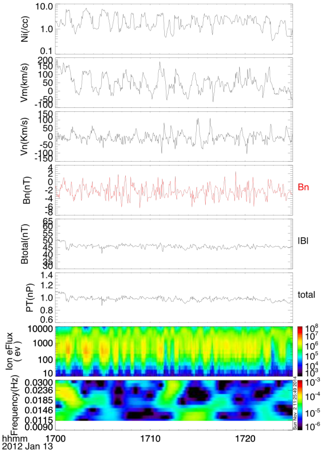
where $\rho^* = \rho_{\text{msh}}\rho_{\text{msp}}/(\rho_{\text{msh}} + \rho_{\text{msp}})$ is a mean mass, $\mathbf{k}$ wave vector, V is the plasma velocity and msh/msp is magnetosheath/magnetosphere.

- KH waves are unstable if $\left(\mathbf{k}\cdot(\mathbf{V}_{\text{msh}} - \mathbf{V}_{\text{msp}})\right)^2 > \left((\mathbf{k}\cdot\mathbf{B}_{\text{msh}})^2 + (\mathbf{k}\cdot\mathbf{B}_{\text{msp}})^2\right)/4\pi\rho^*$ (CGS)
- The KHI leads to formation of a surface wave on the interface.
- KH instability is driven by the velocity shear but can be stabilized by the magnetic tension force and is modulated by density difference.
- KH is generally favored at low latitudes when the IMF is predominantly northward.

KHI in the magnetosphere

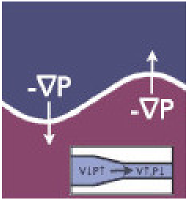


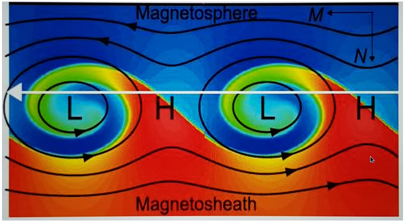
KH wave in linear stage



Supplementary Figure 1. THEMIS E observations of KHWs in linear stage on 13 Jan 2012. From top to bottom: (a) Ion density, (b) M component of the velocity V_M, (c) N components of the velocity V_N, (d) N component of magnetic field B_N, (e) Magnetic field magnitude |B|, (f) total (magnetic plus ion) pressure, (g) ion energy flux spectrogram, and (h) wavelet spectrum of the total pressure. The solar wind had a flow speed 450 km/s and density N = 13 cm^3. The IMF vector was (1,2,4) nT. There were no significant solar wind dynamic pressure variations before or during the event. Themis E was located at (8.3,-7.6,3.4) and was moving sunward. Themis E observed quasi-periodic fluctuations at the dawn flank magnetopause during the interval 1640 - 1720 UT, but no significant fluctuations in total pressure or magnetic field magnitude. We thus conclude that this wave train is a KHW in the linear stage and it has not developed to a vortex yet.

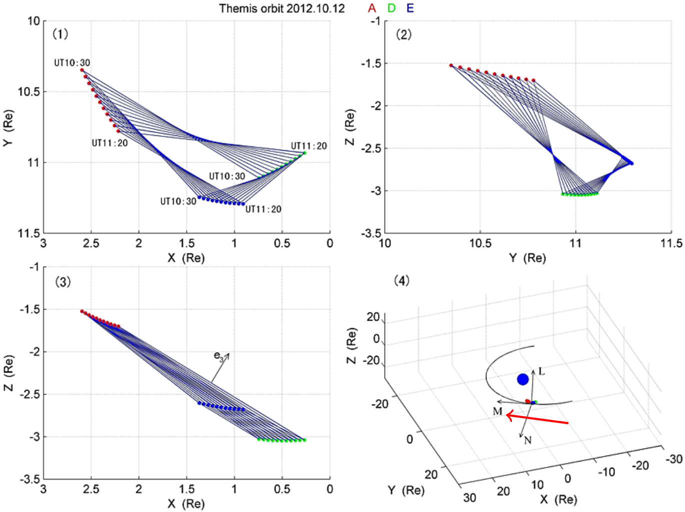
linear stage

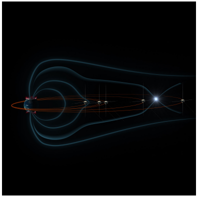




non-linear stage

Kavosi+15



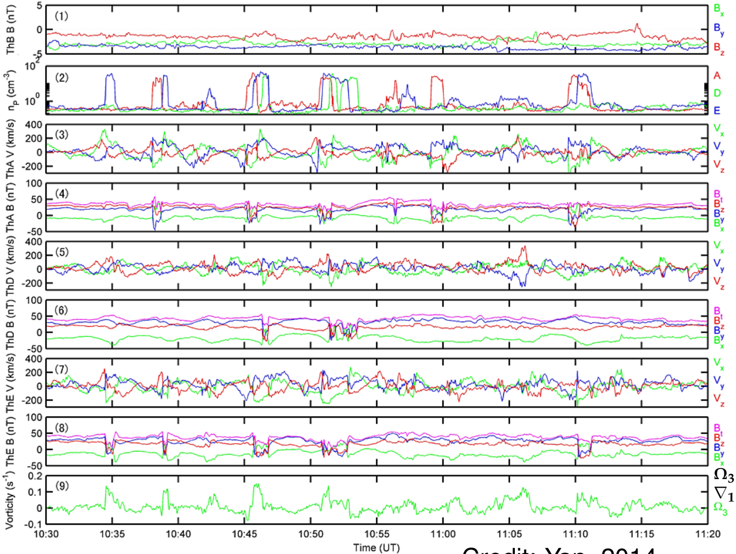


Credit: Yan+2014

Rolled-up vortices: observations by THEMIS

Upstream SW magnetic field →

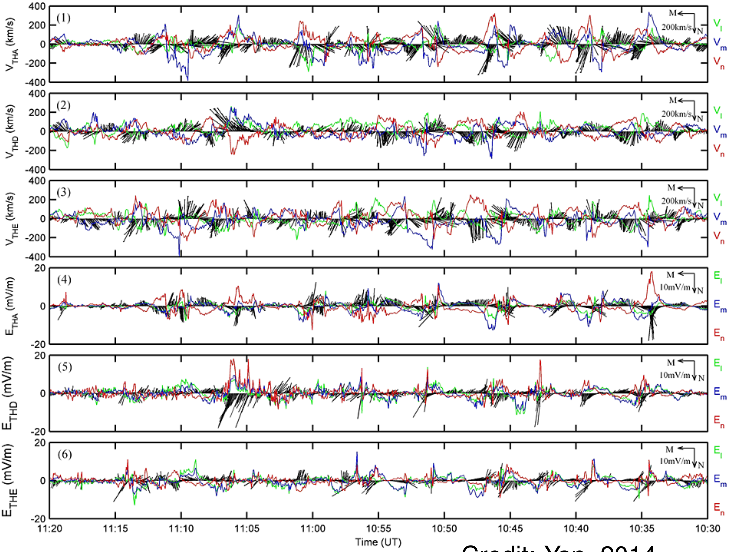
Vorticity normal →



$\Omega_3 = \nabla_1 V_2 - \nabla_2 V_1$

Credit: Yan+2014

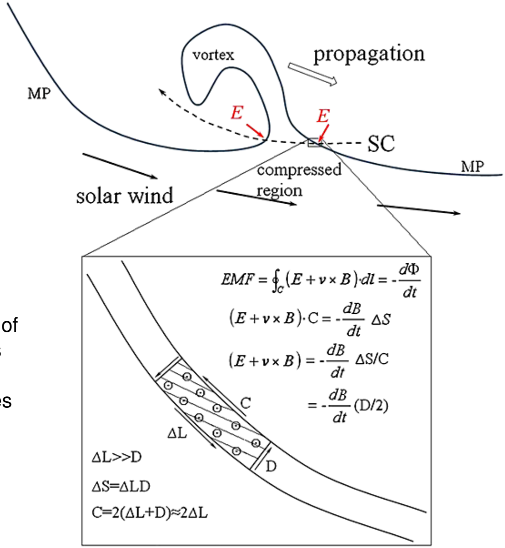
Rolled-up vortices: observations by THEMIS



Reversed time ⟵

Credit: Yan+2014

Rolled-up vortices: observations by THEMIS

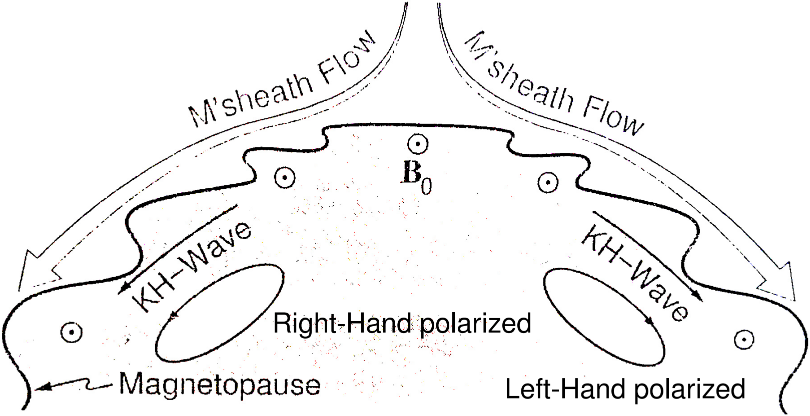


An induced electric field of about several mV/m was deduced at the both leading and trailing edges of vortices when the magnetic field compression occurred. This can accelerate charged particles.

Credit: Yan+2014

Convective growth of magnetopause KH waves

- KHI may excite surface waves



Credit: Treumann&Baumjohann

KHI growth

- The wave period is related to the scale thickness of the boundary:

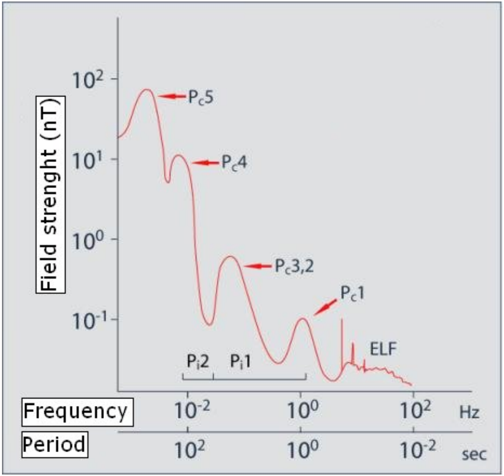
$$T = \frac{2\pi d}{0.6V_0} \simeq 10d/V_0$$

  where d is the scale thickness of the boundary, V_0 is half the solar wind speed in the magnetosheath.

- The waves are in frequency Pc3, Pc4, Pc5
- For d=6400 km (1 R_E) and V_0 = 200 km/s, T= 320 s – a typical Pc5 period
- For d=1200 km ($\simeq$0.2 R_E) and V_0 = 400 km/s, T= 32 s – a typical Pc3 period

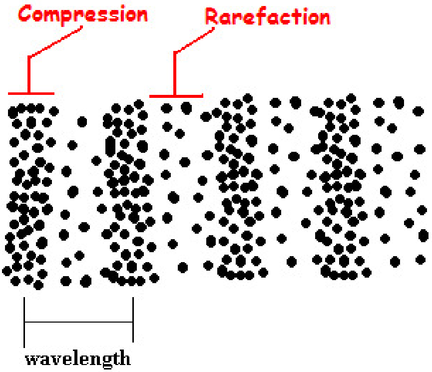
From Walker 1981

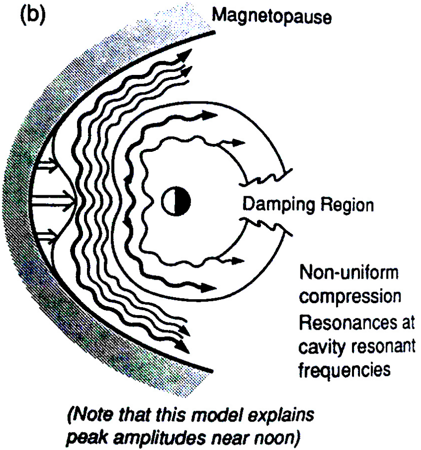
KH waves may excite Pc5-Pc3 geomagnetic pulsations at the Earth's ground



Magnetosheath's compressional waves

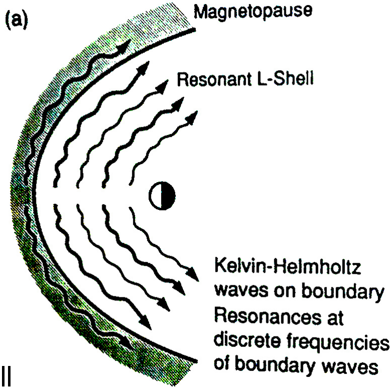
- Compressional waves enter the magnetosphere at its nose





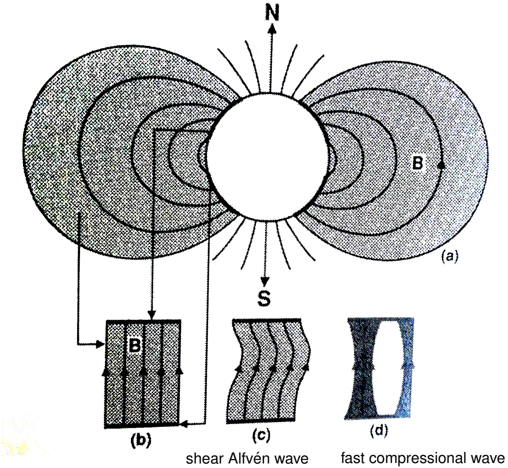
Effect of boundary instabilities

- Such waves at the boundary may trigger Field Line Resonances (FLR) within the magnetosphere
- FLR can be also excited by shocks and other large-scale solar wind discontinuities



Credit: Kivelson&Russell

Perturbations of field and plasma



Credit: Kivelson&Russell

- If the length of the field line between the two ionospheres is l, the allowed wavelength along the field direction $\lambda_{\parallel}$ are

$$\lambda_{\parallel} = 2l/n,$$

where n is integer.

- For the shear Alfvén wave along the background magnetic field is

$$\omega = v_A k_{\parallel} = v_A 2\pi/\lambda_{\parallel}$$

Perturbations of field and plasma

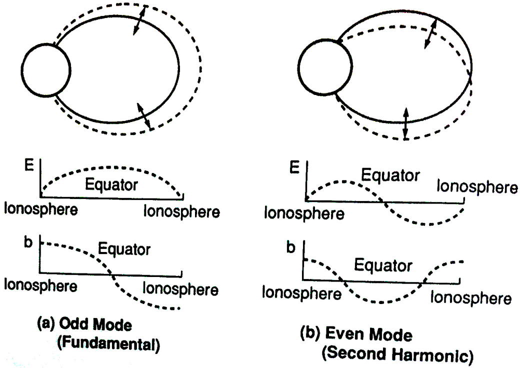
- The allowed frequencies of these waves standing on field lines are

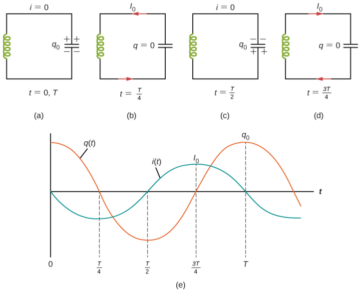
$$\omega_R = nv_A/(2l) = nB/(2l\sqrt{\mu_0\rho})$$

- Only certain resonance frequencies can be established.
- If the field geometry is known, it is possible to infer the plasma density by measuring the frequencies of shear Alfvén waves present in a magnetospheric cavity bounded by the northern and southern ionospheres.

Credit: Kivelson&Russell

Standing oscillations in the dipole field





Credit: Kivelson&Russell

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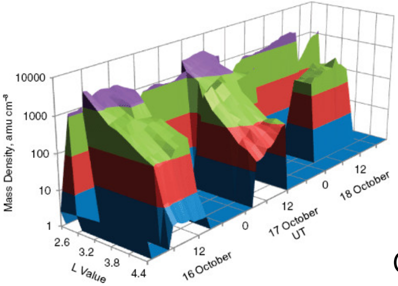
Plasma mass density derived from FLR

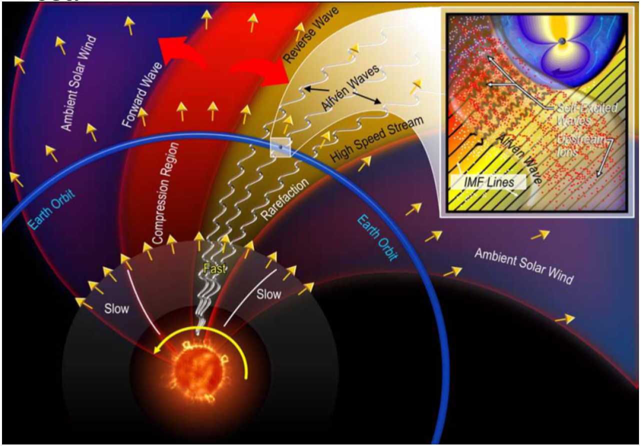
- The equatorial mass density is derived from FLR frequency across 2.4$< L <$4.5 in the Northern Hemisphere at 78°–106° magnetic longitude and centered on L=2.8 in the Southern Hemisphere at 226° magnetic longitude, for several days in October and November 1990.
- Stations used for this study are YOR, GML, FAR, KVI, NUR, and OUL.
- The density is derived from the relation
  $\omega_R^{-1} \simeq \frac{1}{\pi} \int \frac{ds}{v_A(s)}, \; v_A(s) = B/\sqrt{\mu_0 \rho}$



Credit: Menk+99

KHI in other space objects: High Speed Streams

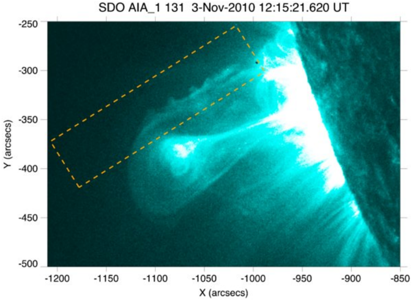
Credit: M. Desai

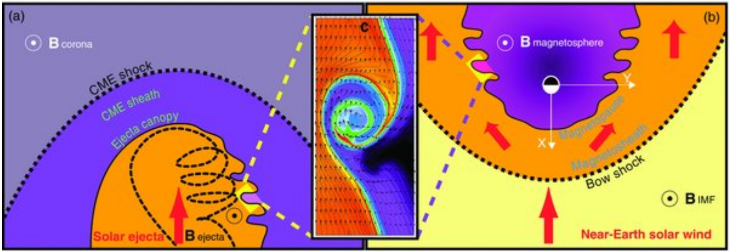


- Occures between interface of streams in the compression region
- Leads to generation of Alfvén waves

KHI in other space objects: CME

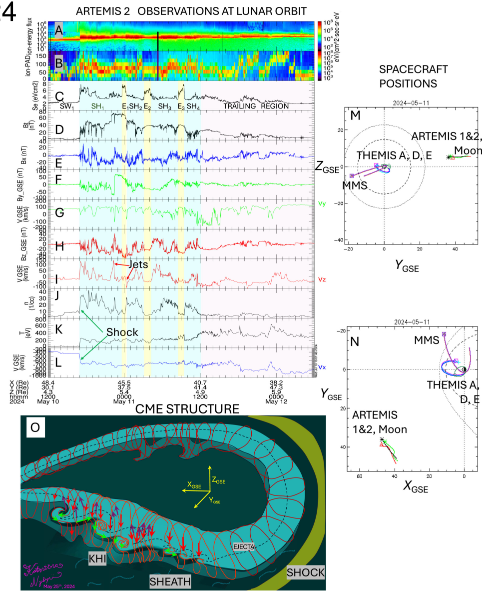
Credit: Foullon+11





KHI in other space objects: CME

Credit: Nykyri+2024



KHI in other space objects: Aurora

Credit: Asamura+09

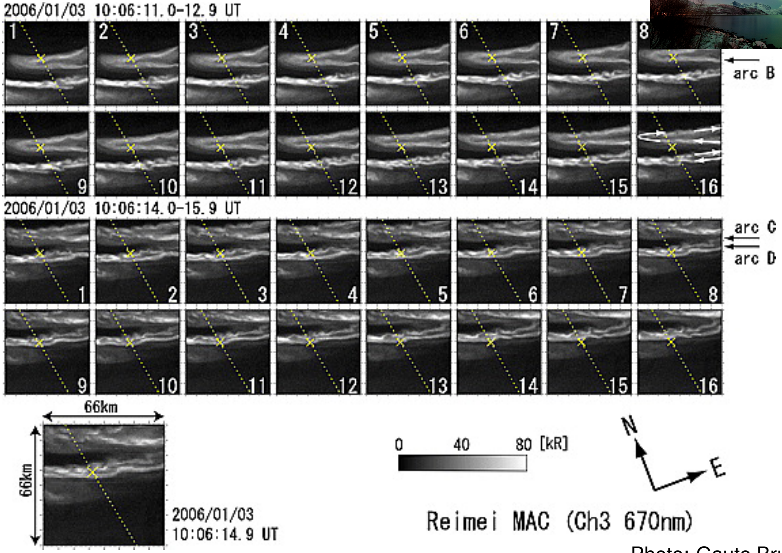


Photo: Gaute Bruvik

KHI in other space objects: Auroral spiral

ORIGINAL RESEARCH article

Front. Astron. Space Sci., 13 October 2023
Sec. Space Physics
Volume 10 - 2023 | https://doi.org/10.3389/fspas.2023.1240081

This article is part of the Research Topic
Vertical Coupling in the Atmosphere-Ionosphere-Magnetosphere System
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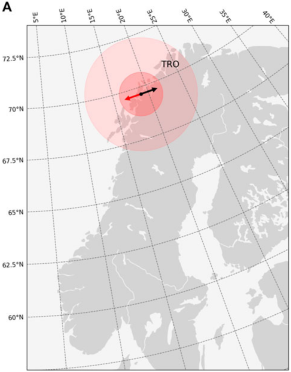
A possible mechanism for the formation of an eastward moving auroral spiral

Katharina N. Maetschke[1] Elena A. Kronberg[1]* Noora Partamies[2] Elena E. Grigorenko[3,4]

A



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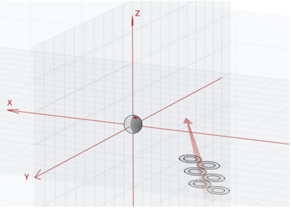
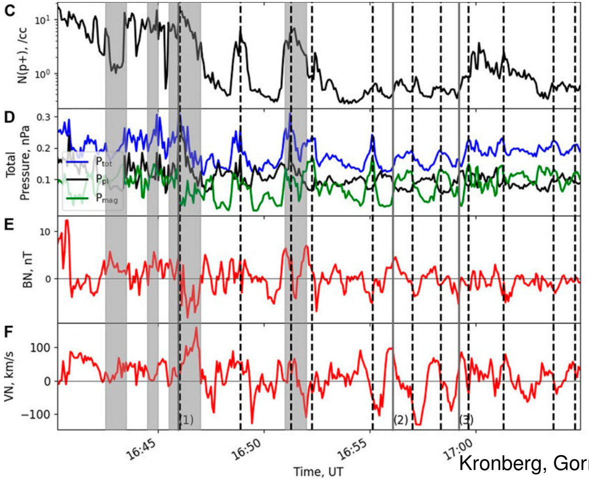
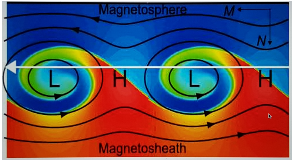


Cluster observations: southward IMF and high latitude

- Plasma velocity and density were fluctuating
- Maxima of the pressure and of the magnetic field normal component were aligned, indicating KH vortices



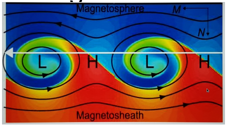


Kavosi et al., 2015

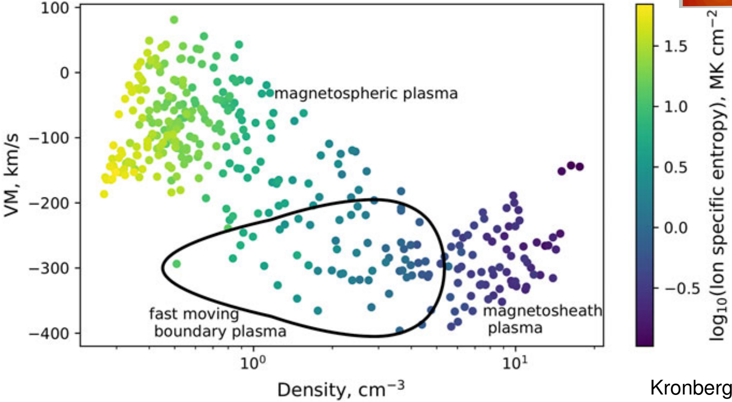
Kronberg, Gorman et al., 2021

Further evidence of KHI

- We expect to observe mixed plasma crossing the KHI region
- Entropy $S \sim \ln(T_p/n^{\gamma-1})$



Kavosi et al., 2015

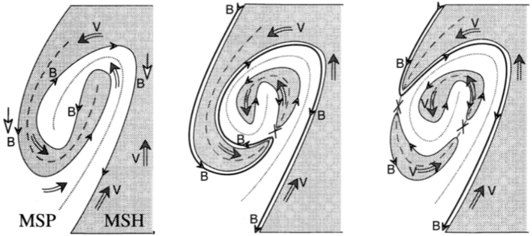


Kronberg, Gorman et al., 2021

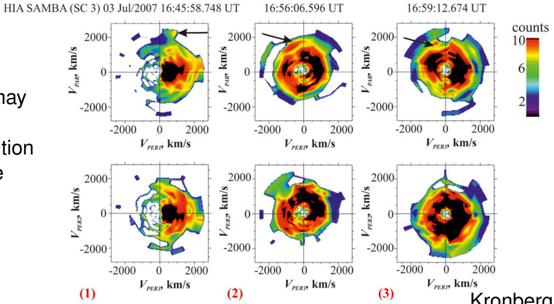
KHI is associated with reconnection

Nykyri&Otto, 2001

Reconnection is indicated by field-aligned beams

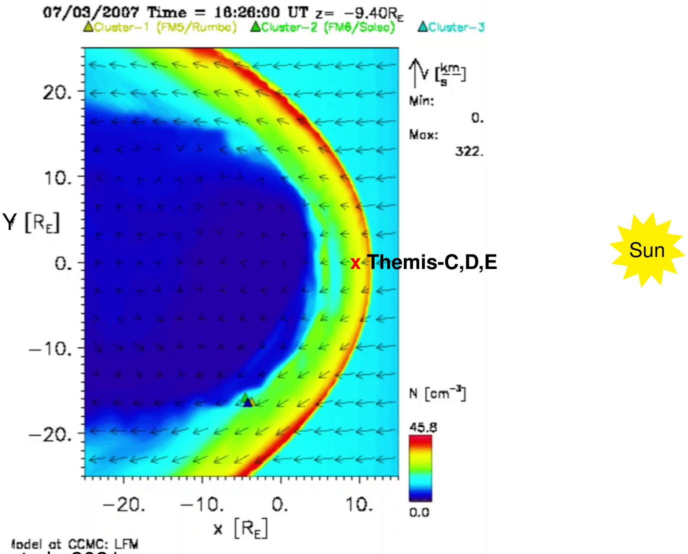


Field-aligned beams may imply separatrix & the crescent distribution indicates vicinity of the diffusion region



Kronberg, Gorman et al., 2021

Model: NASA Community Coordinated Modeling Center (CCMC) – Lyon-Fedder-Mobarry (LFM) global magnetosphere



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Modeling of this event

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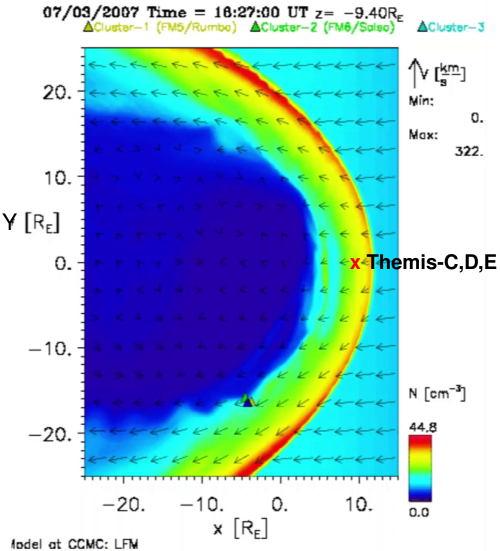

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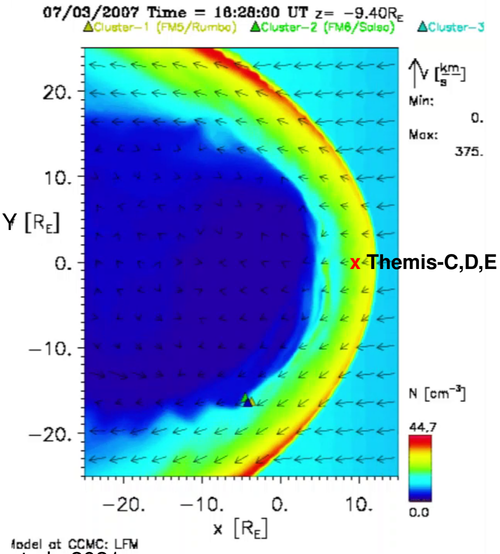

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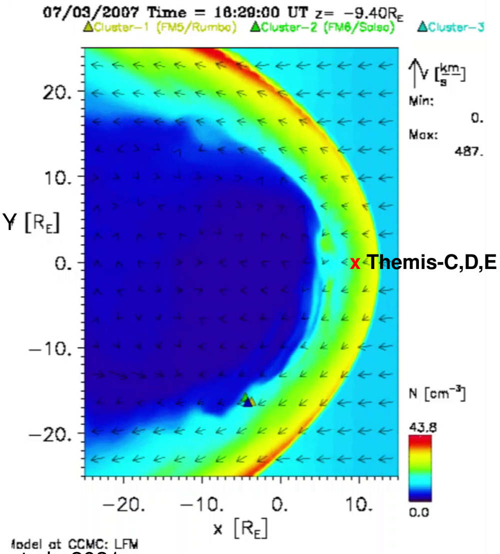

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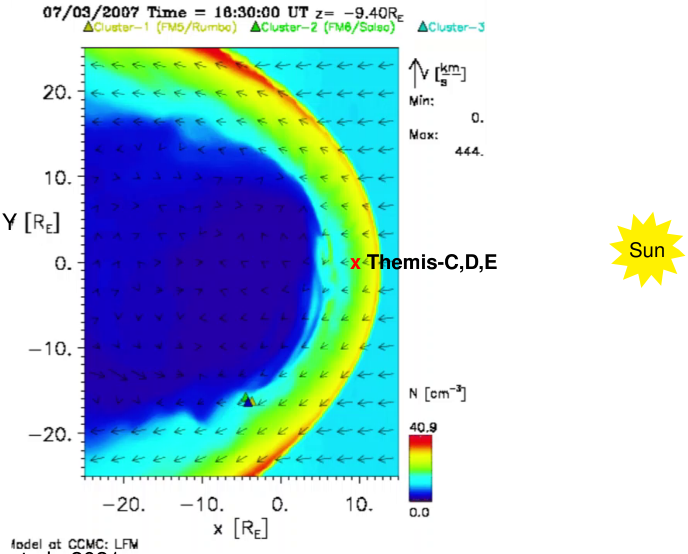

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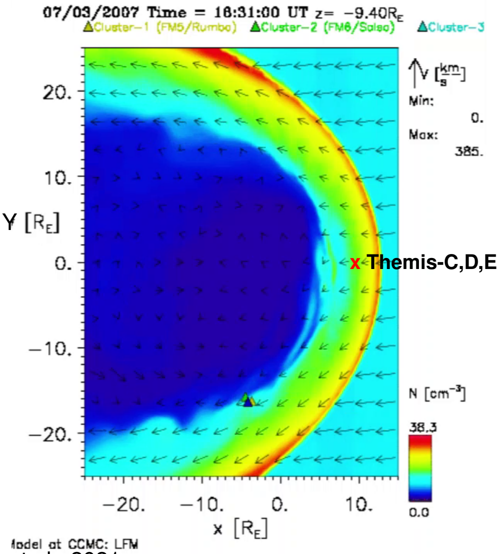

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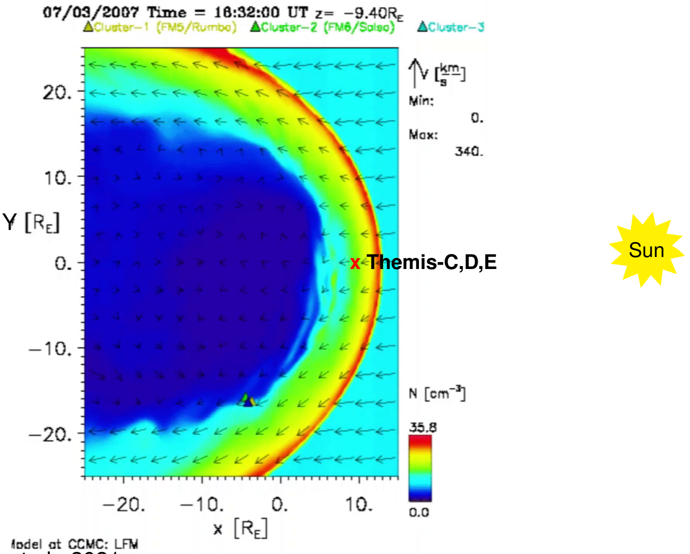

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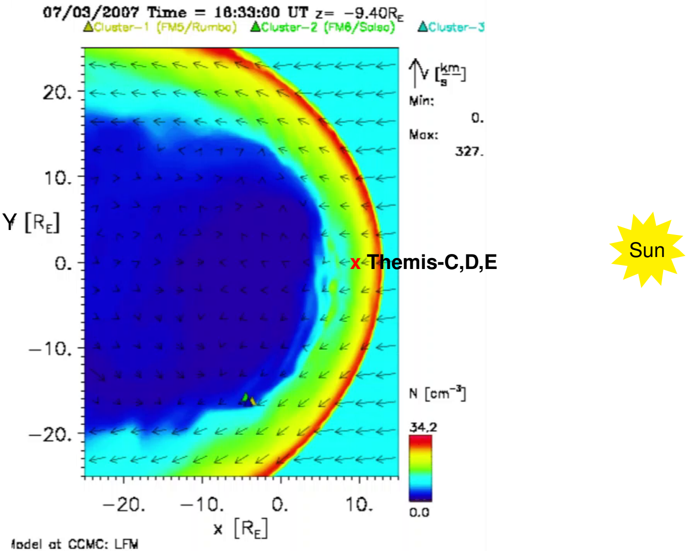

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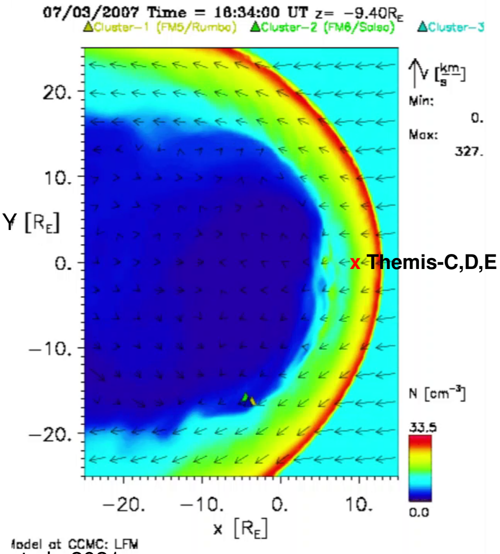

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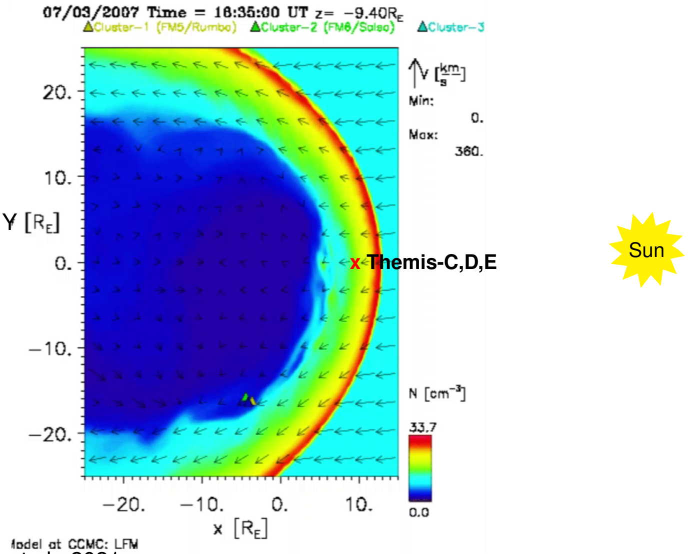

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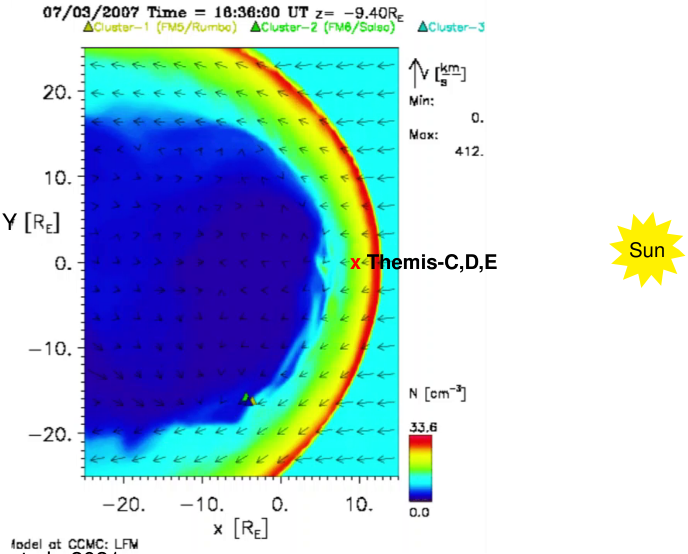

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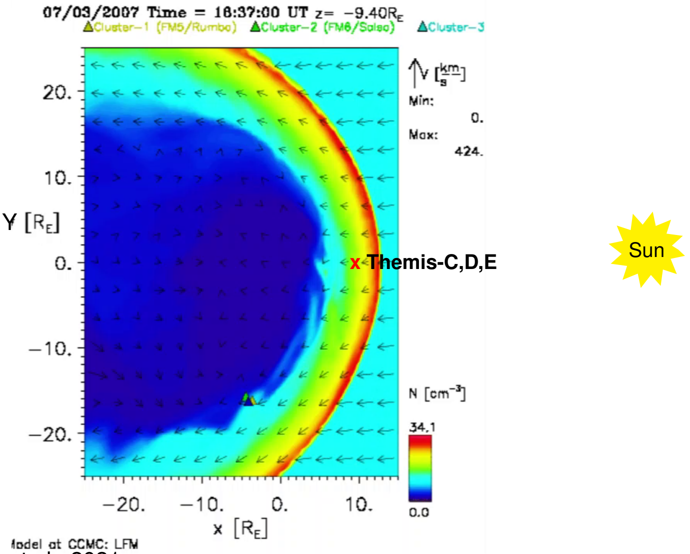

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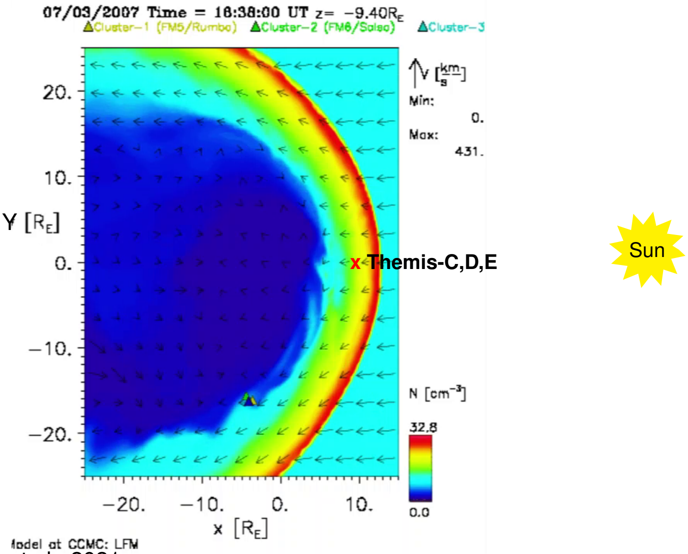

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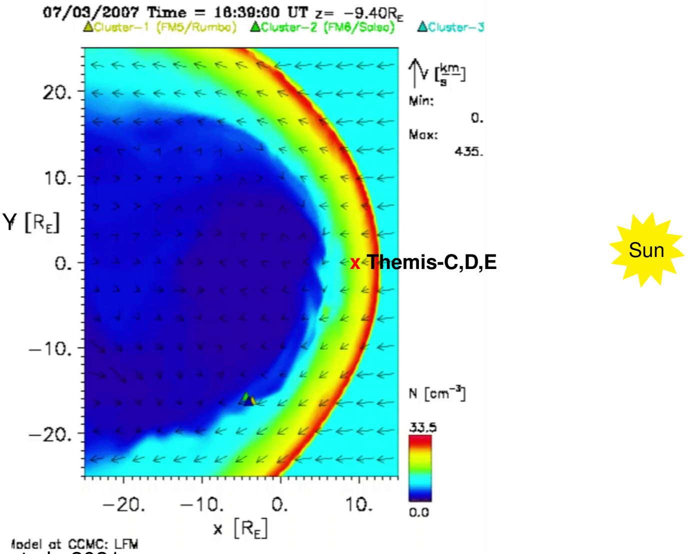

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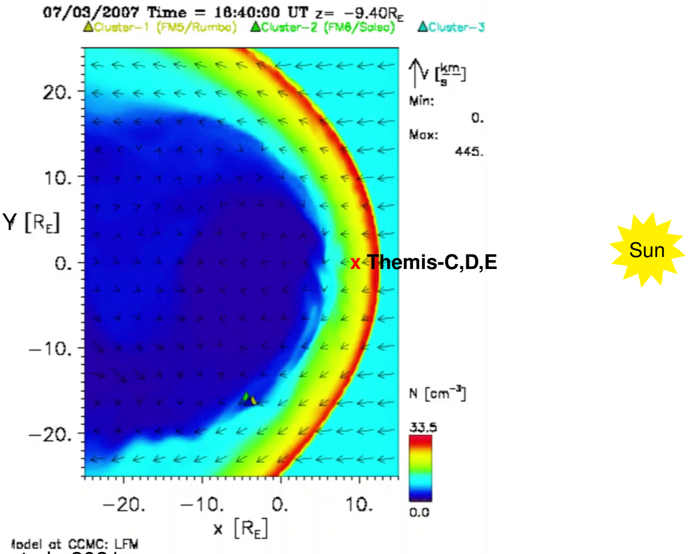

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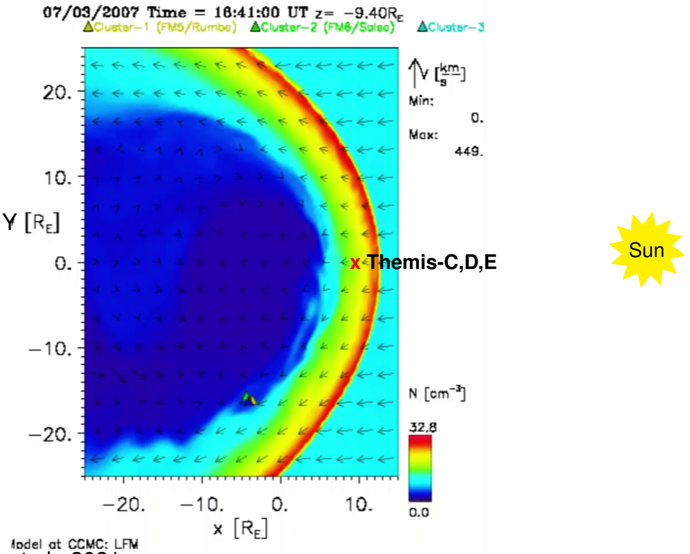

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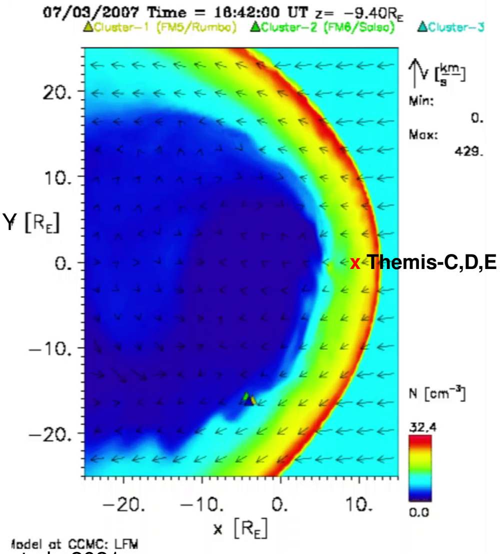

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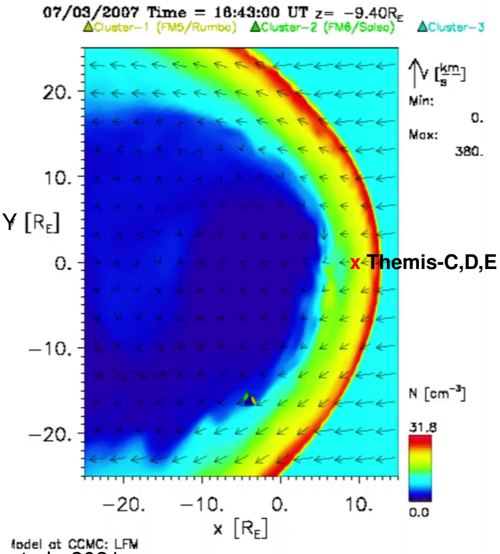

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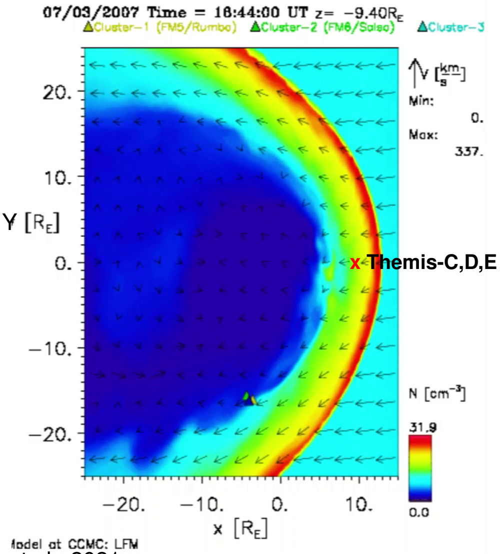

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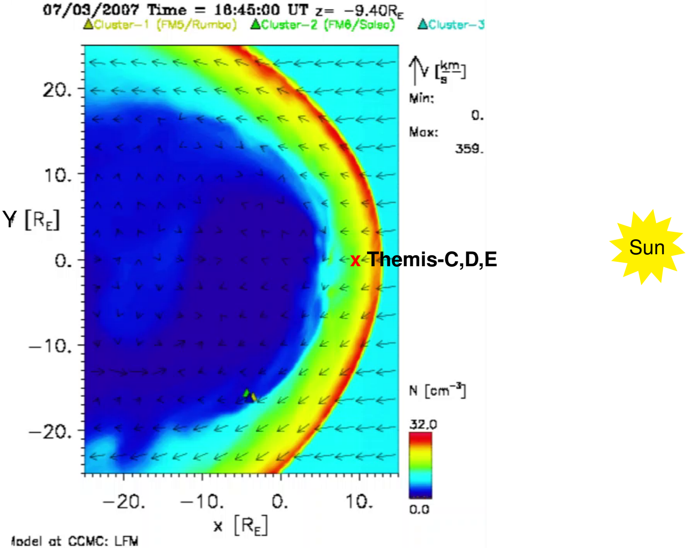

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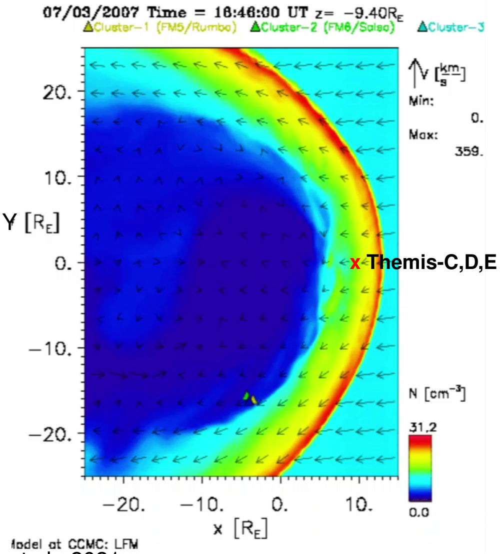

Sun

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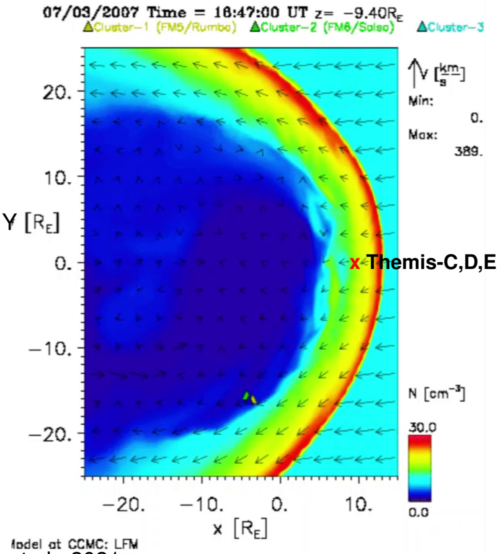

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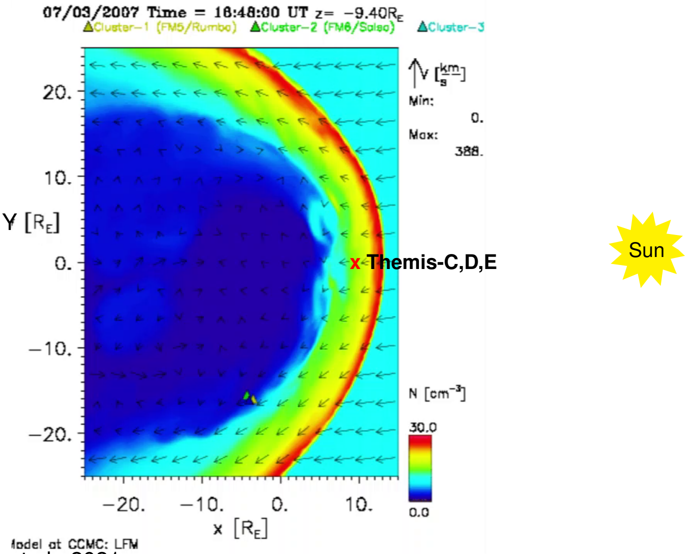

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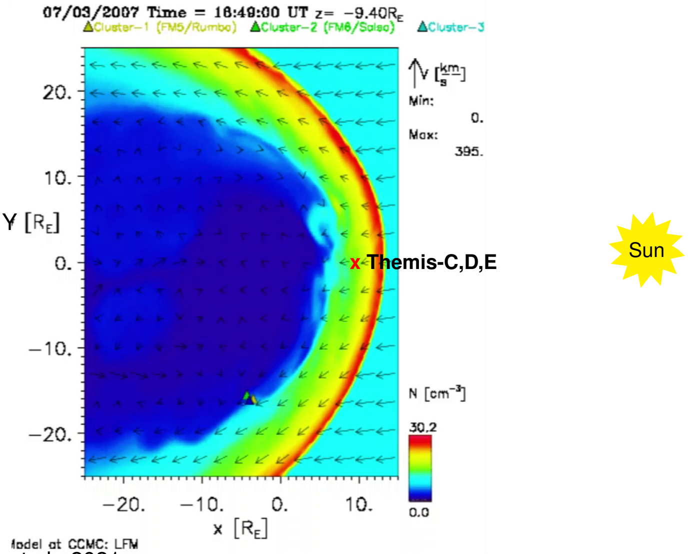

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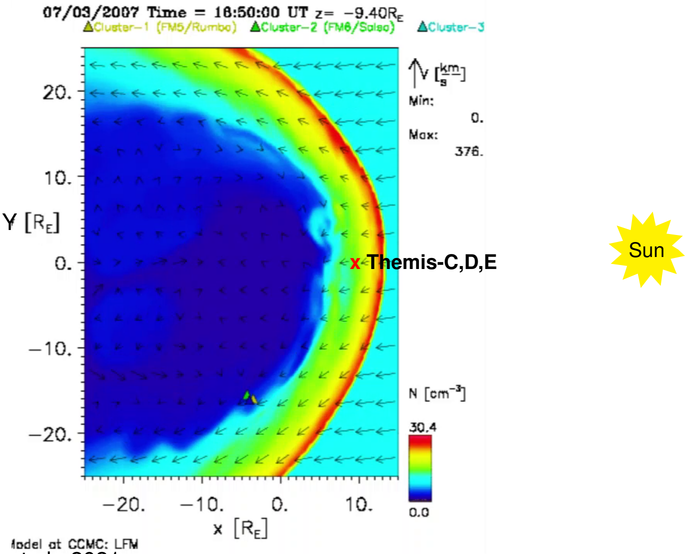

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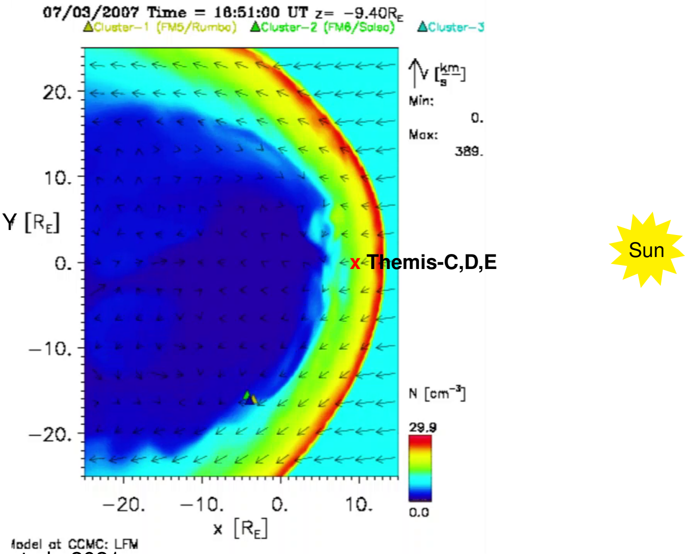

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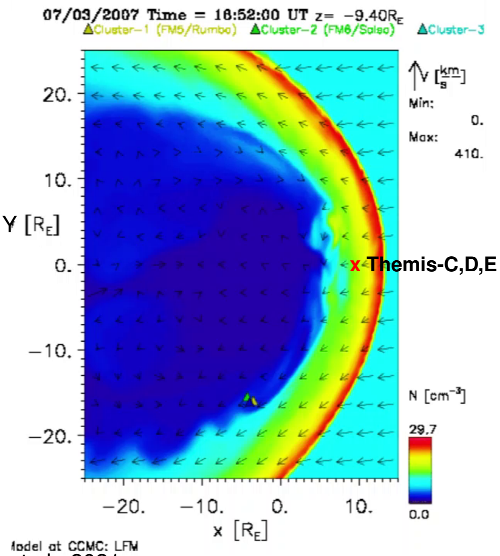

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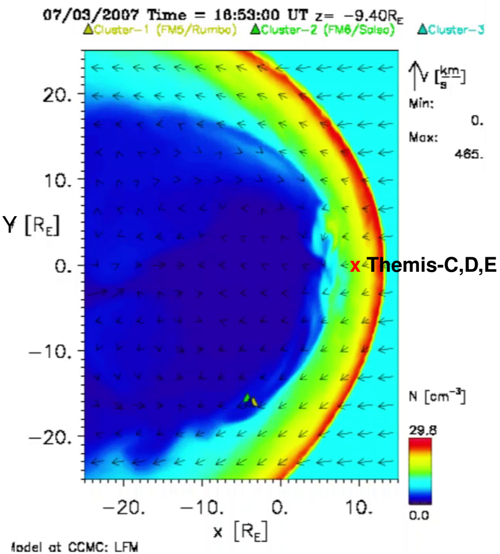

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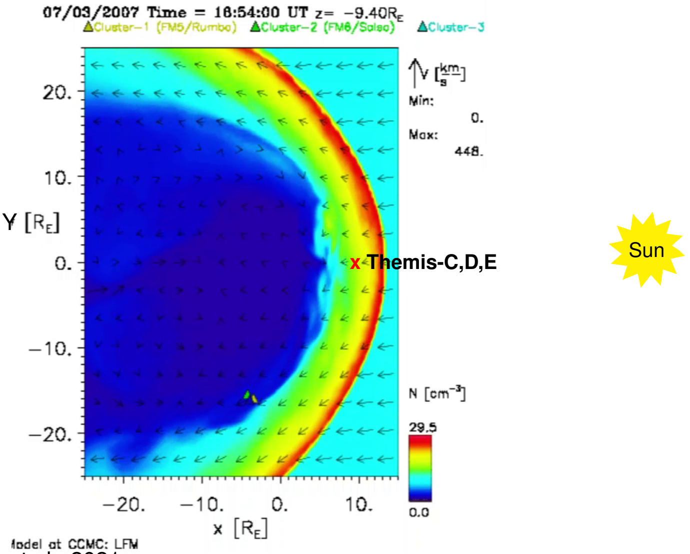

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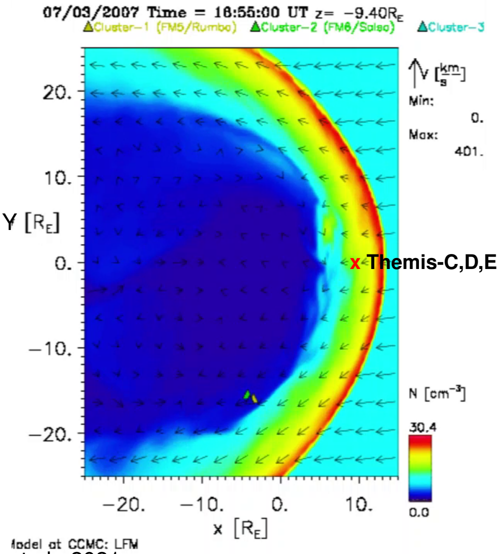

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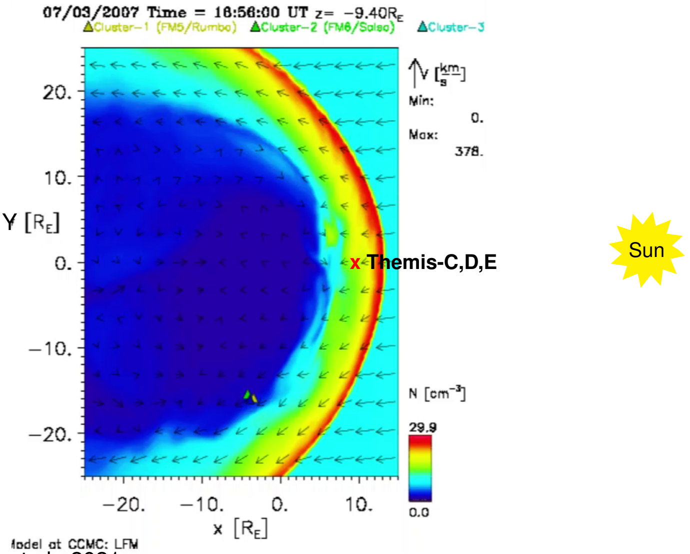

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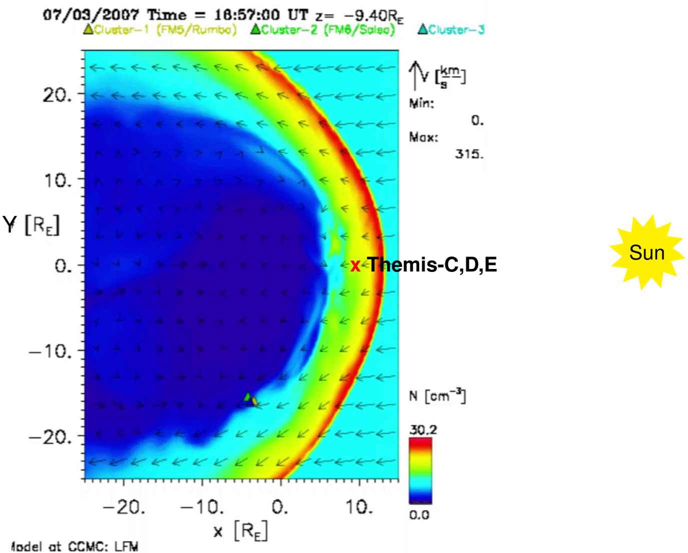

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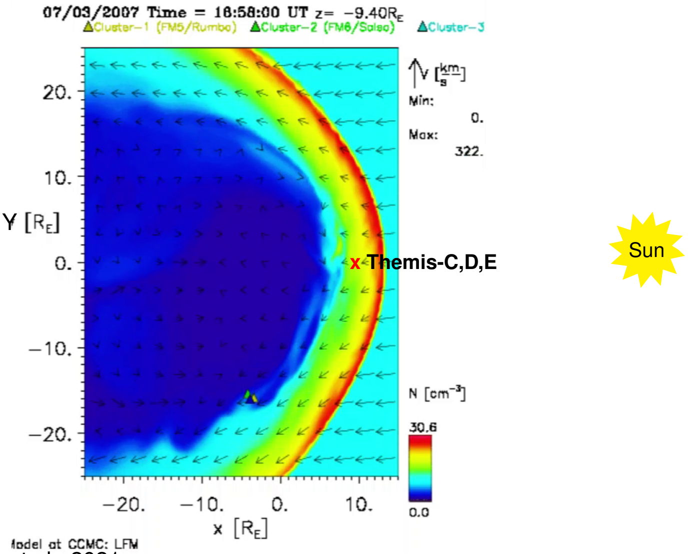

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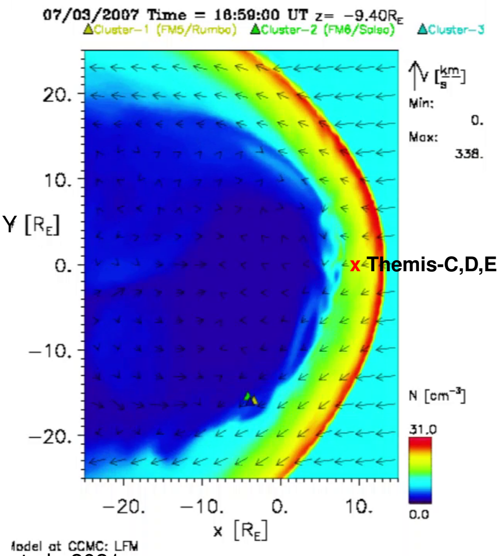

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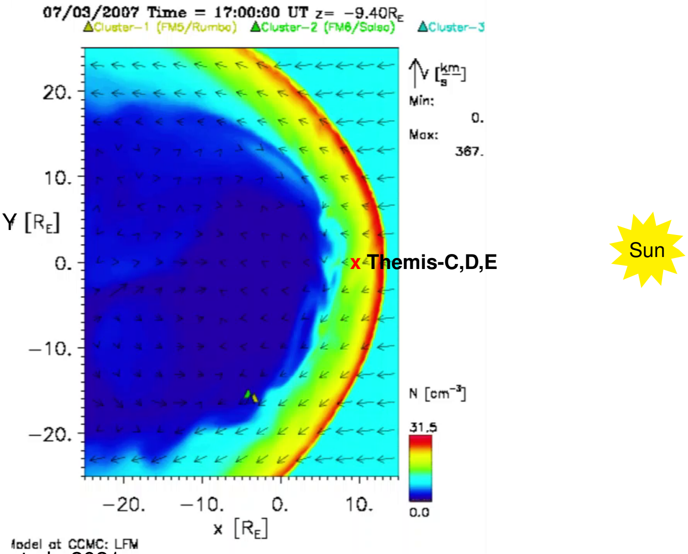

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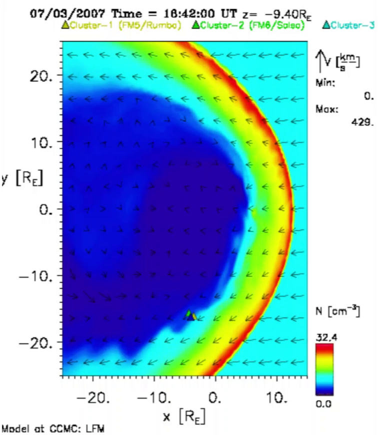
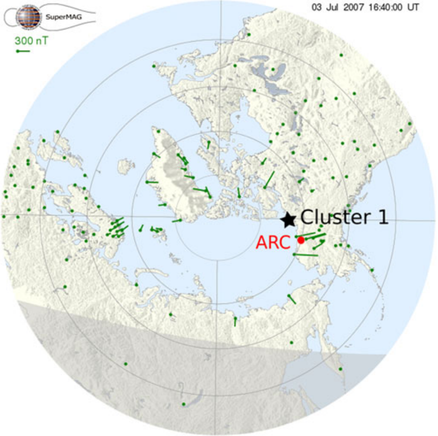
Mapping of the Kelvin–Helmholtz instability to the ground





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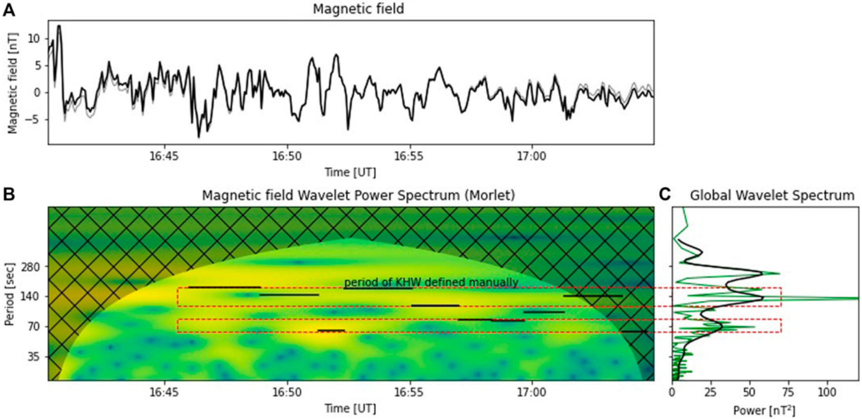
Wavelet analysis of the magnetic field fluctuations at Cluster

- Pc4 fluctuations are observed



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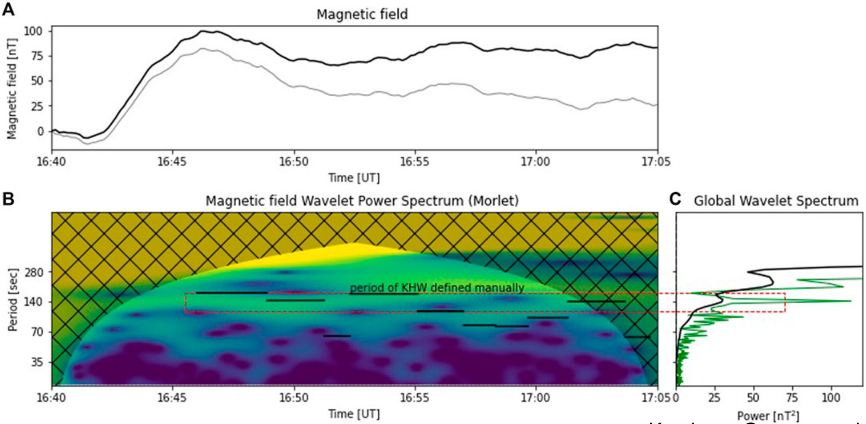
Wavelet analysis of the fluctuations at the ground (ARC)

- Pc4 fluctuations are also observed
- Solar wind energy is transformed by Kelvin–Helmholtz instabilities to electromagnetic energy at the Earth's surface.



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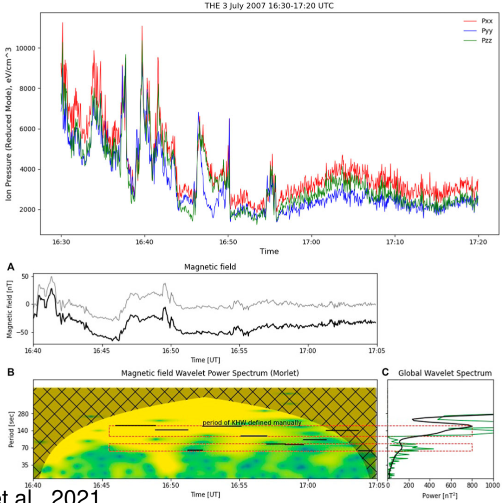
- Pressure pulsations at subsolar point acted as seed perturbations
- B_z fluctuations provided further modulation via reconnection



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Summary

- Kelvin–Helmholtz Instability is a universal process observed in many regions of space and on the ground.
- KHI may lead to excitation of waves.
- Waves triggered by KHI may couple with FLR in the magnetosphere.
- FLR observed at the ground may be used to infer the space weather characteristics in the magnetosphere, e.g., the density of the plasmasphere.
- KH waves can be observed at the ground

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