Kelvin-Helmholtz instability: lessons learned and ways forward

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Outline

1. K-H instability: quick reminder
2. Lessons learned from Cluster and Themis so far
3. Recent and future observational opportunities in 2018-2020
4. Conclusion

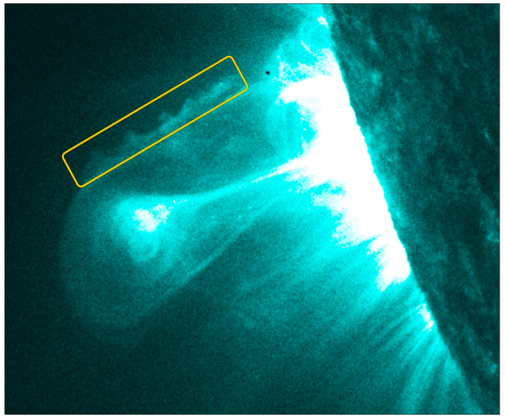
1. K-H instability: quick reminder

The Kelvin-Helmholtz instability (KHI) develops in a fluid flow when velocity shear occurs and exceeds a certain threshold [Chandrasekhar, 1961].

KHI is an ubiquitous physical phenomenon observed in various media including:

- **at the edge of clouds in the Earth's atmosphere (e.g. Houze, 2014)**

1. K-H instability: quick reminder



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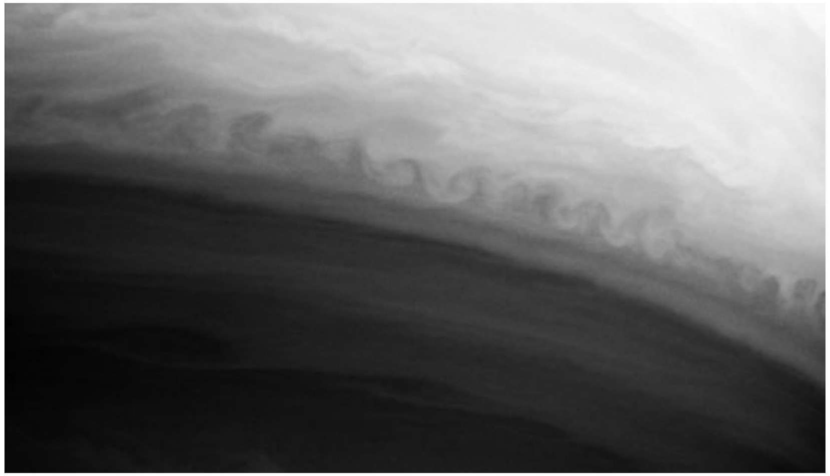
- **on the edge of coronal mass ejections [Foullon et al., 2011]**

1. K-H instability: quick reminder

Jupiter, great spot, Voyager 2 (NASA)



Saturn pictured by Cassini (NASA)

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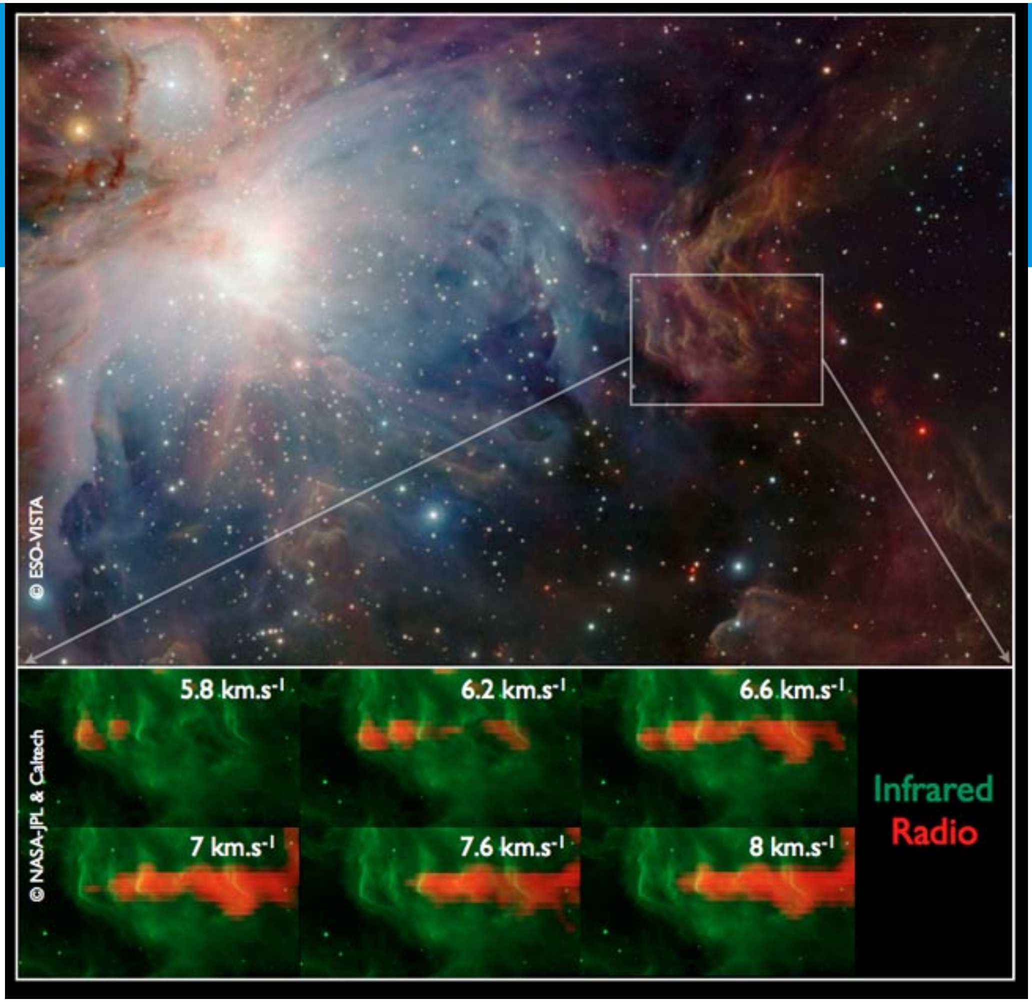
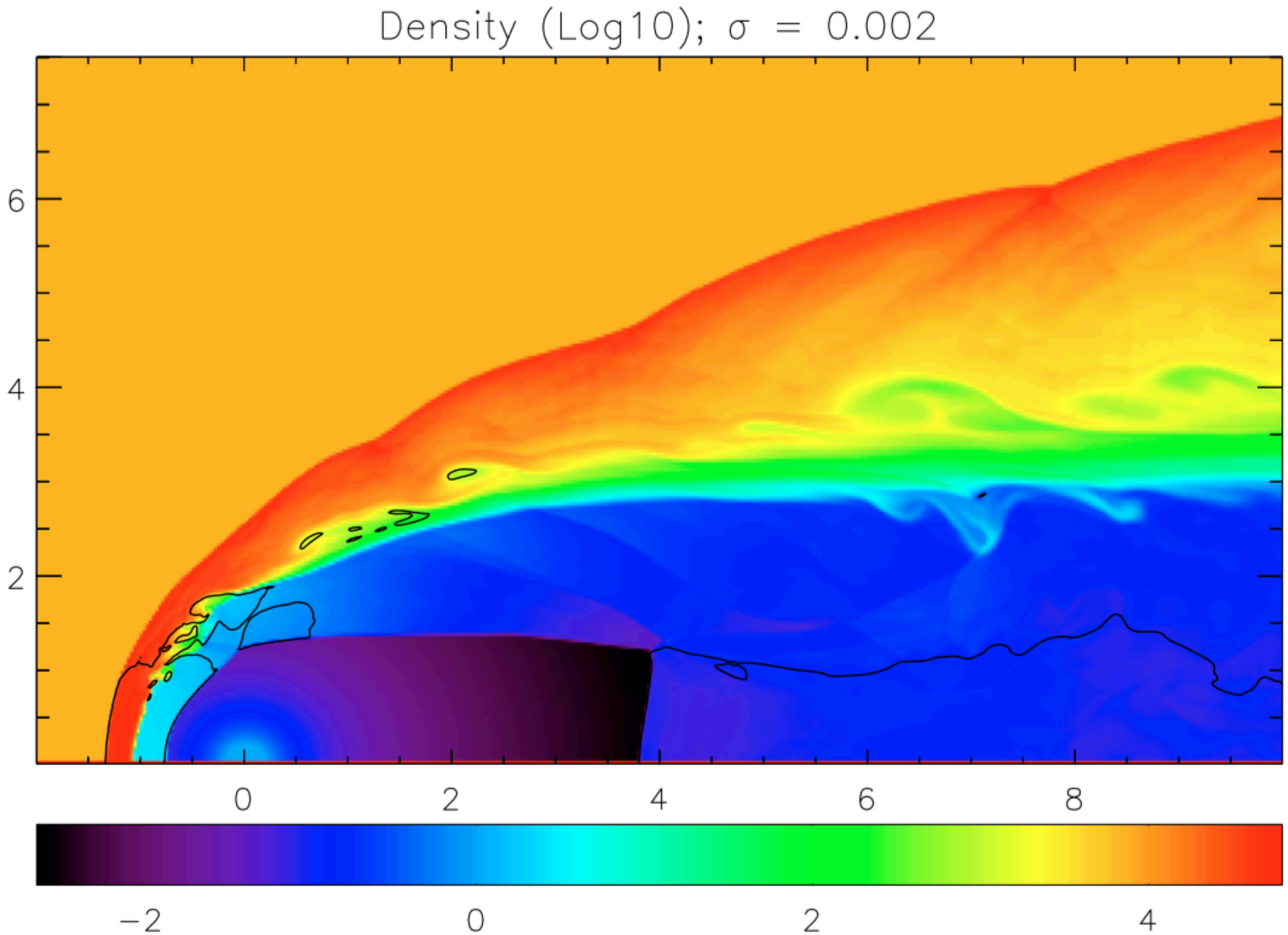
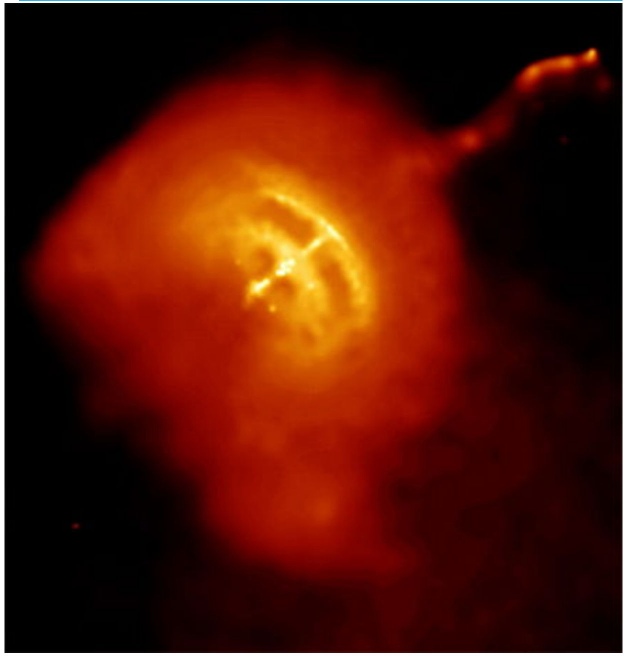
- at the edge of clouds in the Earth's atmosphere (e.g. Houze, 2014)
- on the edge of coronal mass ejections [Foullon et al., 2011]
- **in the atmosphere of giant planets (Jupiter, Saturn)**



KHI is an ubiquitous physical phenomenon observed in various media including:

- Clouds (e.g. Houze, 2014)
- CME [Foullon et al., 2011]
- Atmosphere of giant planets (Saturn, Jupiter)
- **up to astrophysical objects, for instance within the Orion nebula due to young massive stars. The ripples are due to the interaction between stellar wind from these stars interacting with the interstellar clouds of this nebula [Berné et al., 2010].**





VELA PWN

- Relativistic MHD simulation of a **pulsar bow shock nebulae**;
- Pulsar bow-shock nebulae are a class of pulsar wind nebulae (PWN) that form when the pulsar wind is confined by the ram pressure of the ambient medium, and are usually associated with old pulsars, that have already emerged from a massive star related Supernova Remnant.

[Bucciantini, N., et al., A&A, 2005]

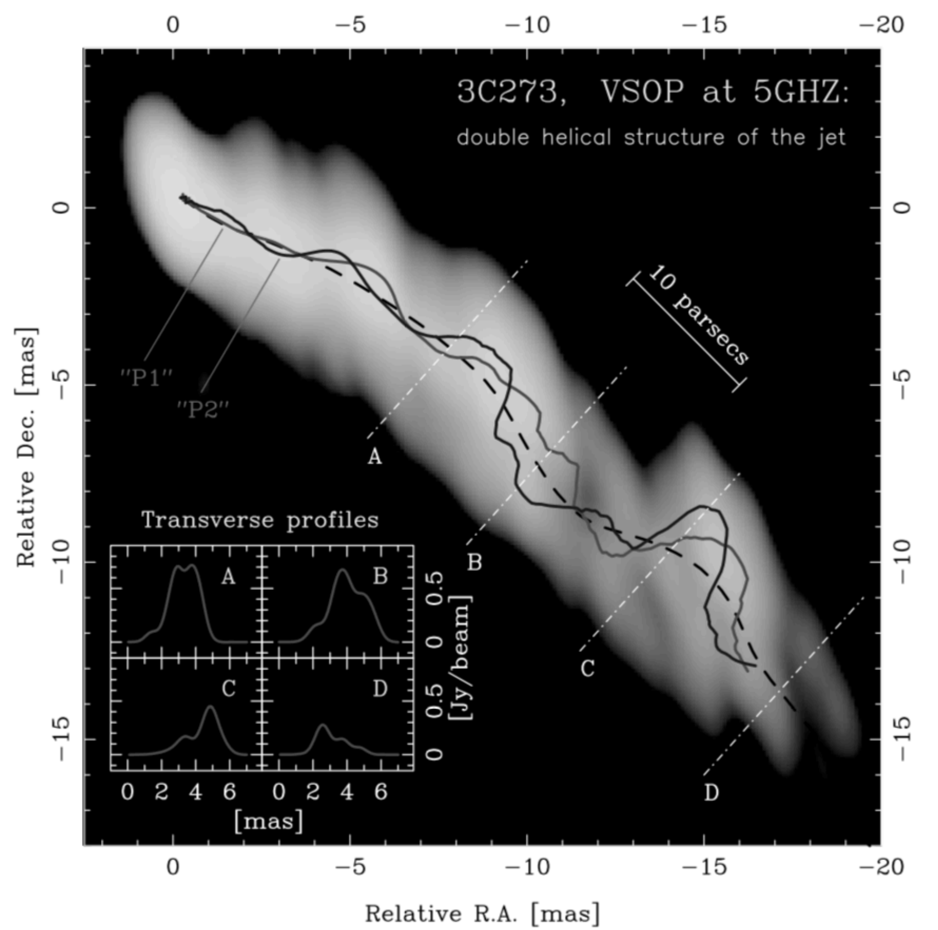


Fig. 1. Parsec-scale radio jet in 3C273 imaged at 5 GHz by the VSOP. The image is restored with

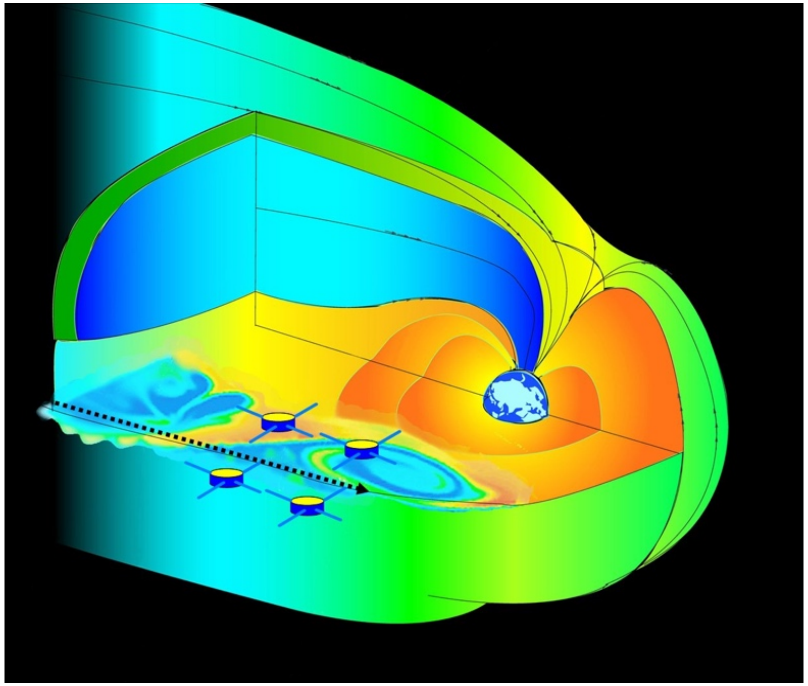
Extragalactic jet compatible with KHI

Direct evidence for plasma instability in extragalactic jets is crucial for understanding the nature of relativistic outflows from active galactic nuclei. Radio interferometric observations of the quasar 3C273 with the HALCA/Haruka space radio telescope and an array of ground telescopes

⇒ an image (above) in which the emission across the jet is resolved, revealing two threadlike patterns that form a double helix inside the jet, consistent with KHI.

[**Lobanov and Zensus, Science, 2001**]

1. K-H instability: quick reminder



The Kelvin-Helmholtz instability (KHI) not only occurs at the Earth's magnetopause but also at the magnetopause of Mercury, Jupiter (remember Jan-Uwe talk this morning!) and Saturn

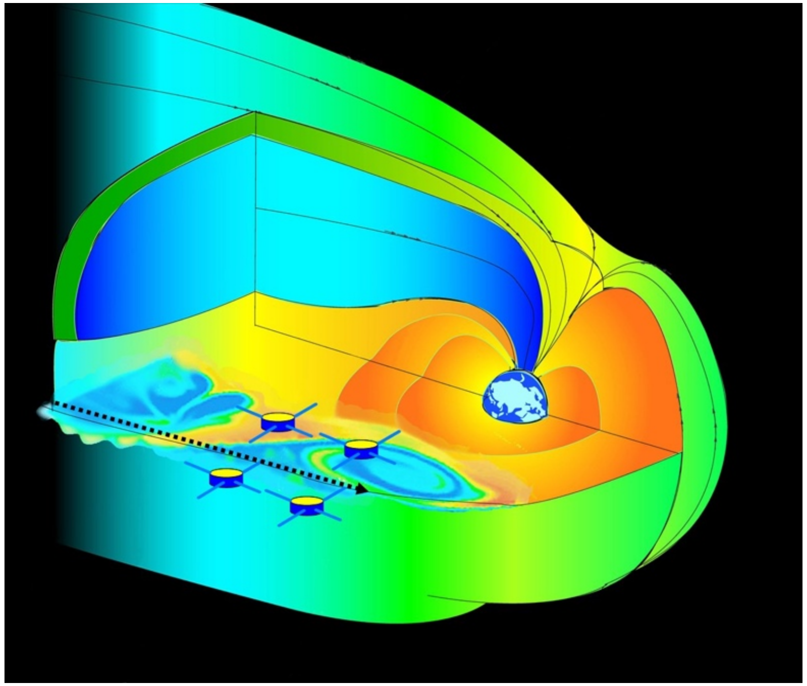
(see [Johnson et al., 2014] for a recent review)

2. K-H instability: lessons learned from Cluster and Themis

Question
KHI a significant physical process for solar wind matter, energy and momentum to enter the magnetosphere with magnetic reconnection? depending on solar activity?

- Rolled-up K-H vortices do exist at the magnetopause?
- Size?
- Are they rare or common events?
- Which process(es) enable solar wind entry?
- KHI occurs under which IMF orientation?
- Cross-scale energy transfer occurs within vortices?

First detection of KH rolled up vortex at the magnetopause



Credit: ESA, adapted from Hasegawa et al., 2004

During a prolonged period of Northward IMF

The Cluster mission enabled the first direct estimate of the size of a K-H plasma vortex thanks to multiple spacecraft
Length scale: 40,000-55,000 km

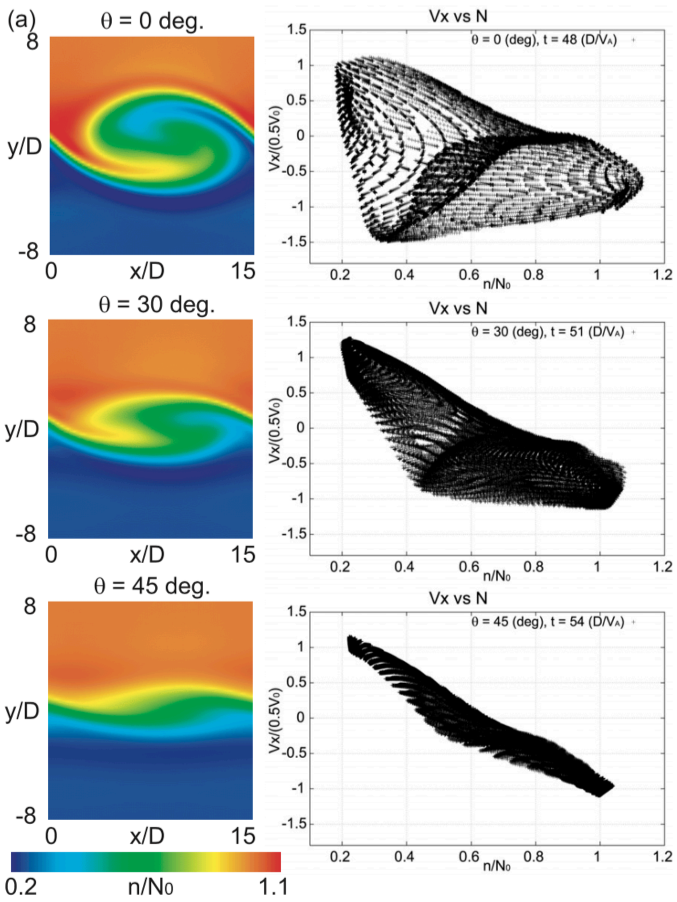
First detection of rolled up vortex

Key observation as according to numerical simulations, plasma transport across the magnetopause can occur within or at the edge of such fully developed vortices.

[Hasegawa et al., Nature, 2004]

2. K-H instability: lessons learned from Cluster and Themis

KH rolled up vortex at the magnetopause by 1 spacecraft



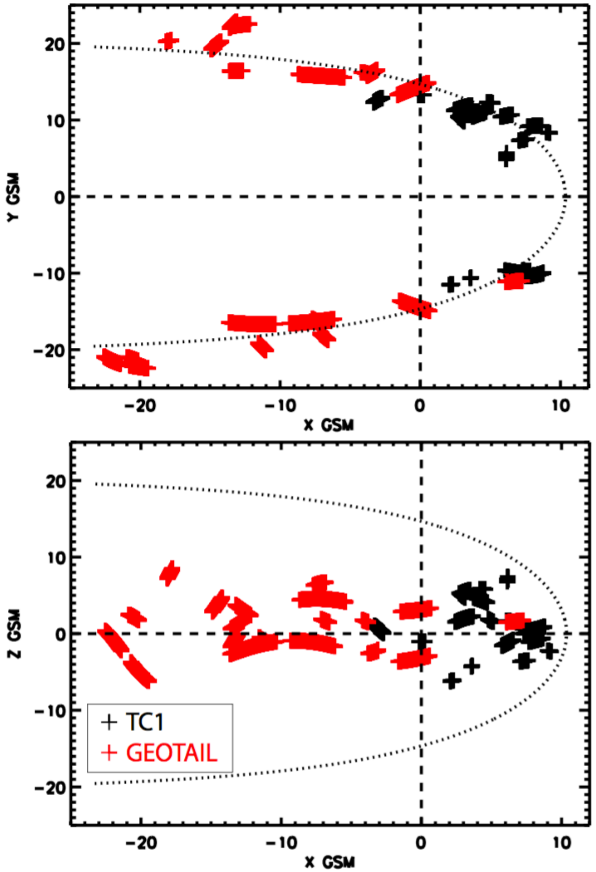
From Takagi et al., 2006

At a certain radial distance from the center of a rolled-up vortex, tenuous plasma must rotate faster than a denser plasma for the force balance in the radial direction to be maintained [Nakamura et al., 2004, Takagi et al., 2006].

Hence, the tailward speed of at least a fraction of the low-density magnetospheric plasma must exceed the speed of the dense magnetosheath plasma.

As this feature is characteristic of a fully developed K-H vortex and potentially detectable by a single spacecraft, Takagi et al. (2006) suggested to use it as a tracer of the presence of such vortices.

KH rolled up vortices at the magnetopause: first statistics



[Taylor et al., 2012]

Survey of Geotail and Double Star TC-1 data:

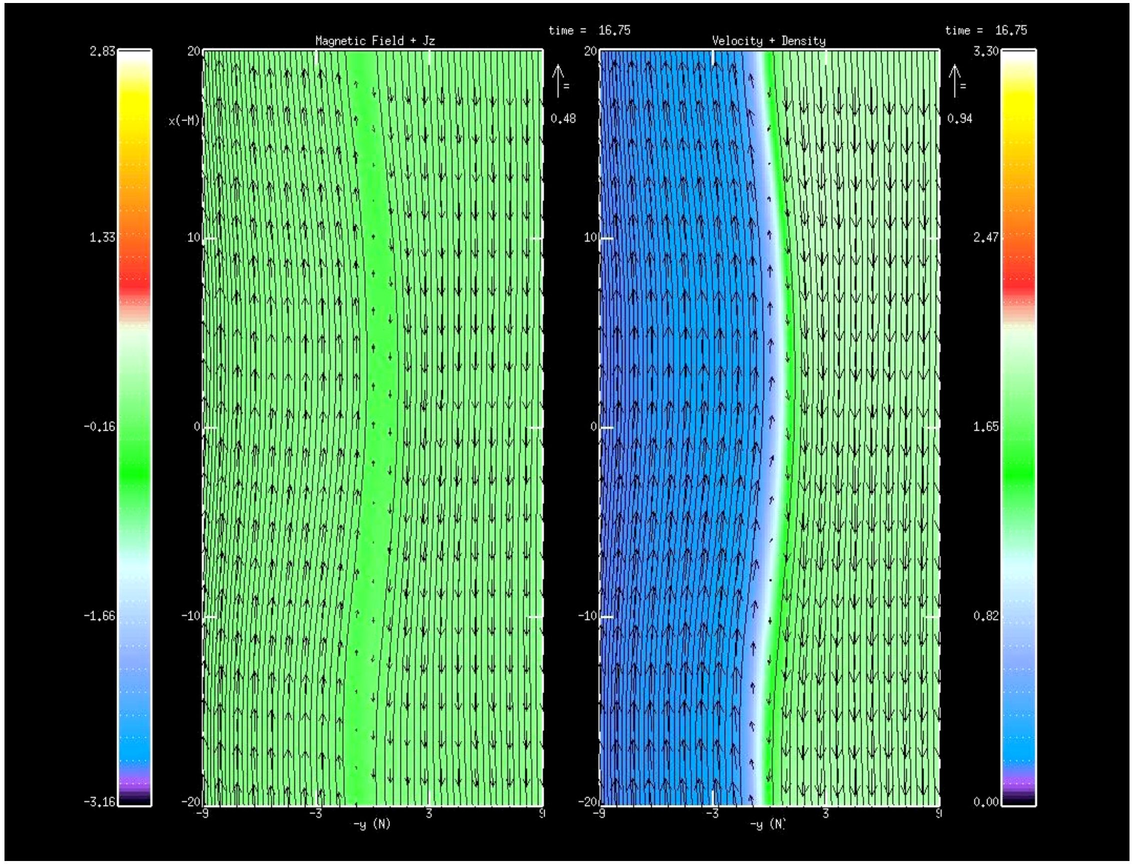
Detection of 36 events during northward IMF

Dawn-dusk asymmetry towards dusk in 62% of the cases [Taylor et al., 2012]

No asymmetry found with the 18 Geotail cases

Larger statistics and simultaneous dawn-dusk observations needed

2. K-H instability: lessons learned from Cluster and Themis

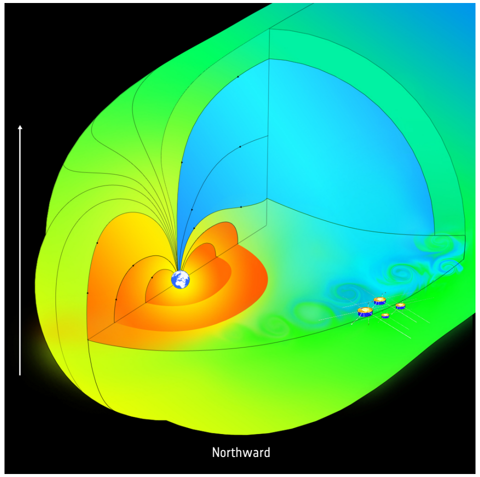


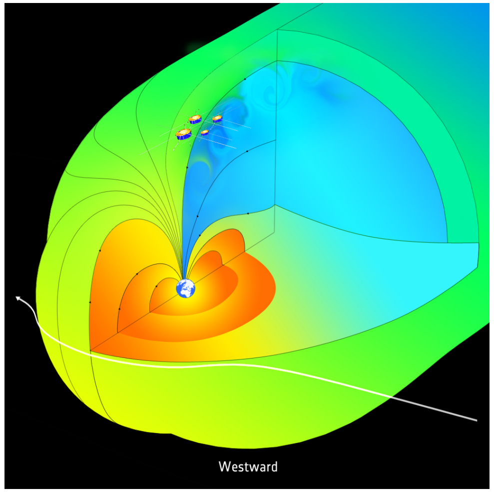
Magnetic reconnection found to be one microphysical process causing the **plasma transport** in the KH vortices (Cluster+2D simulations)
[Nykyri et al. , Ann Geo., 2006]

Diffusive particle transport via **turbulence** [Matsumoto and Hoshino, 2004; Nakamura et al., 2004]

Anomalous transport due the conversion of KH surface waves to kinetic Alfvén waves [Chaston et al., 2007]

KH instability at the magnetopause: under any IMF conditions



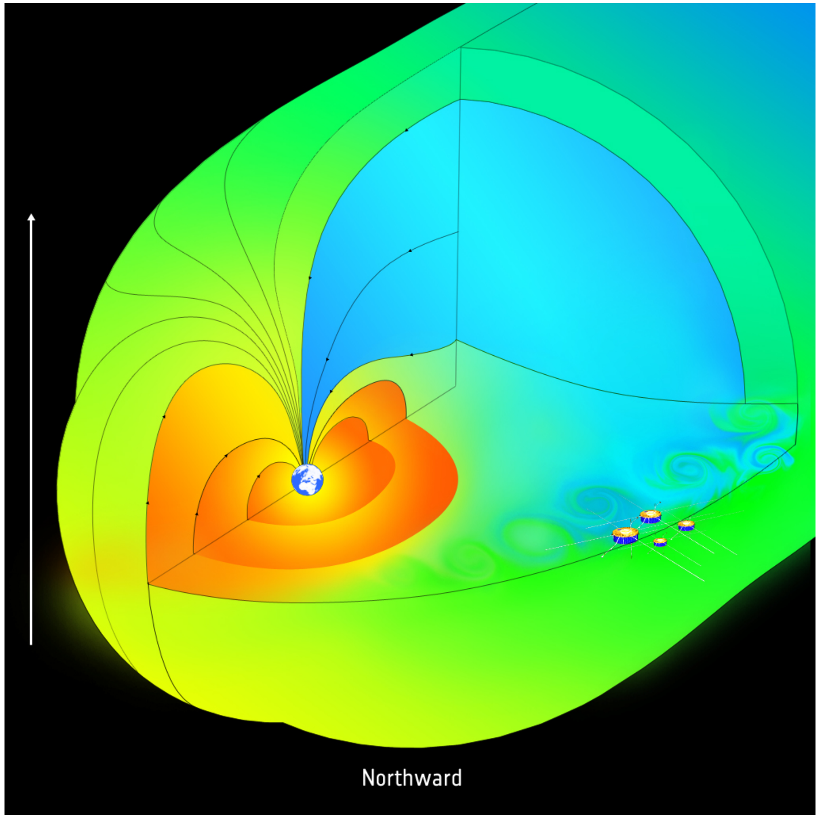


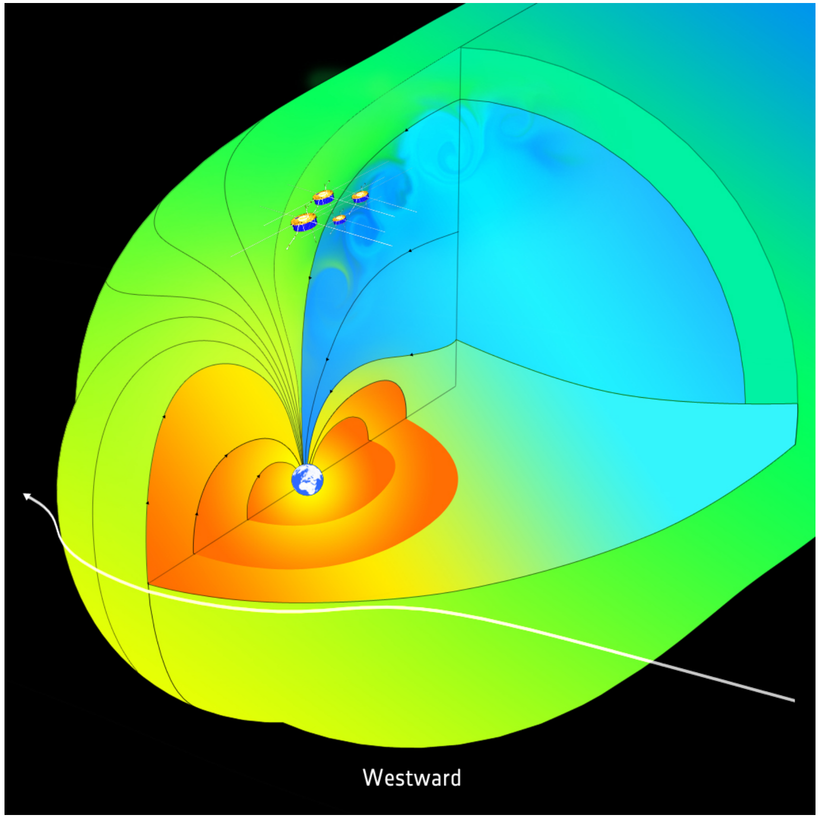
K-H instability has been heavily scrutinized under Northward IMF to explain the presence of the LLBL and the CDPS during Northward IMF

But fundamentally **this physical process does not require the IMF to be Northward**

2. K-H instability: lessons learned from Cluster and Themis

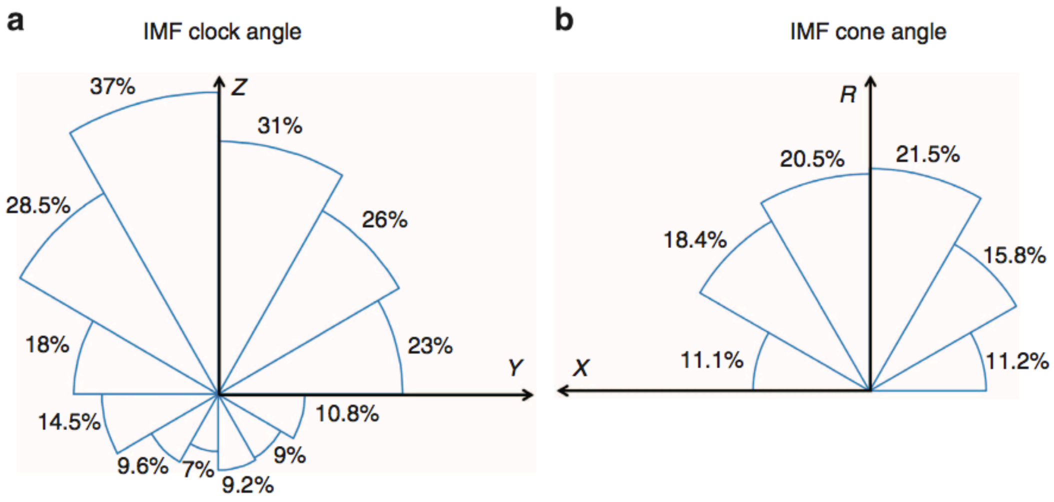
KH instability at the magnetopause: under any IMF conditions





See in particular Hwang et al., JGR, 2011, 2012

KH instability at the magnetopause: Themis statistics

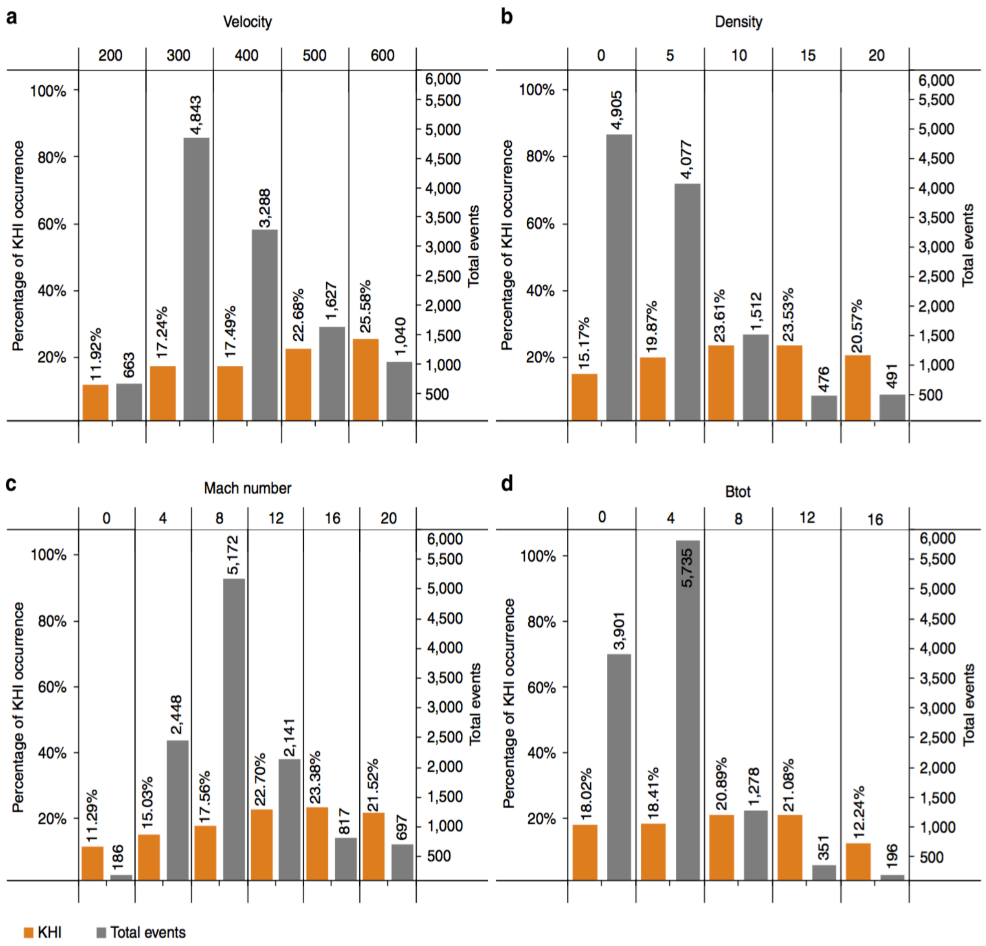


7 years Themis data statistics confirm its importance

19% under any IMF conditions
40% under Northward
10% under southward
South V > 400, |B|<5
[Kavosi and Raeder, 2015]

Themis orbits the equatorial plane
⇒19% is most probably a lower limit
⇒ Not a negligible mechanism of plasma entry

KH instability at the magnetopause: Themis statistics



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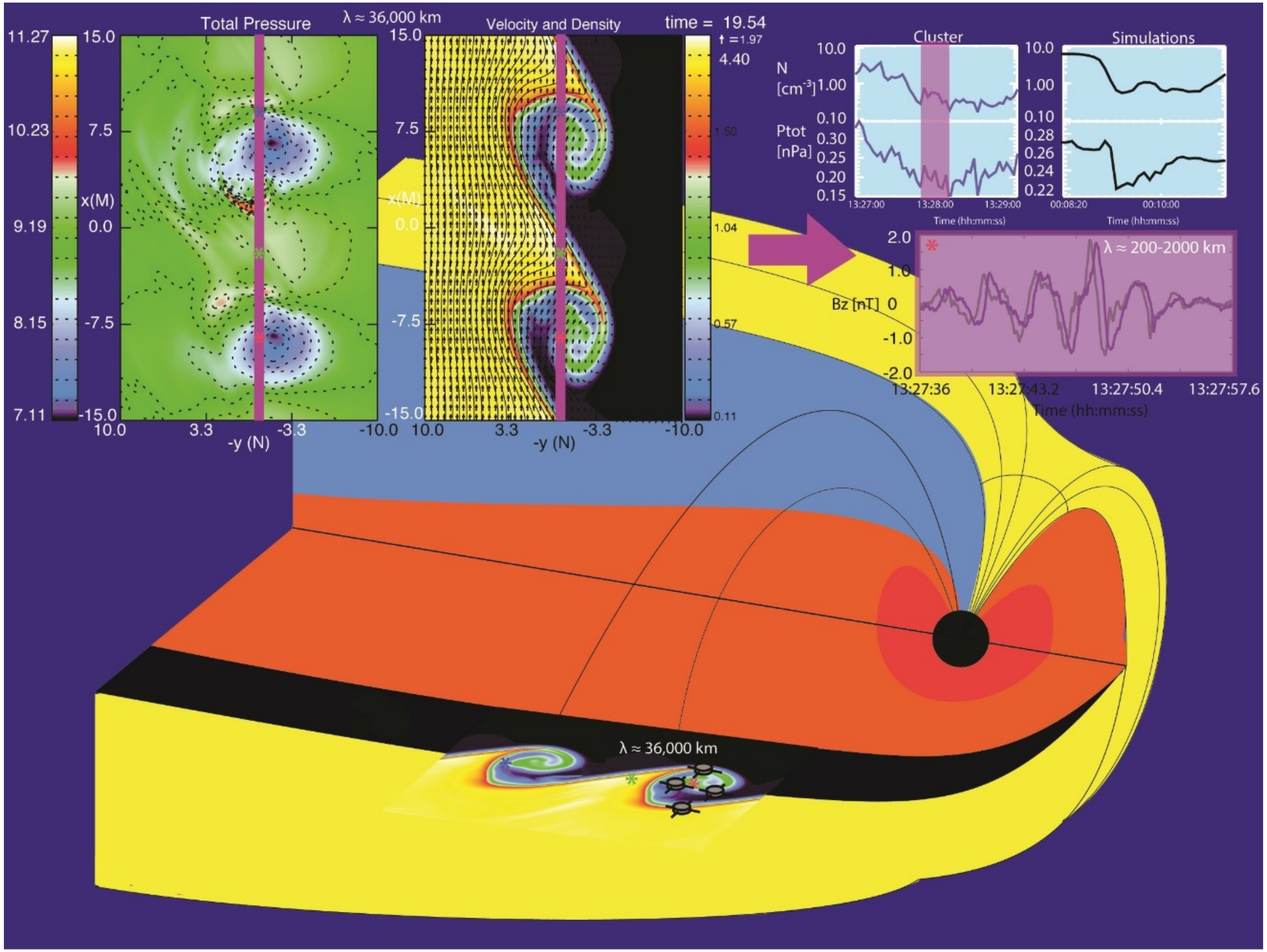
KH instability at the magnetopause: cross-scale energy transfer



Discovery

Giant KH waves of 36,000 km wavelength can radiate ion-scale waves, 200-2,000 km wavelength, that have sufficient energy to heat the plasma to the energies we observed.

This process transfers the kinetic energy from the solar wind into the heat energy of magnetospheric ions, explaining the rapid temperature increase through Earth's magnetic barrier.

Moore et al., Nature Physics, 2016

2. K-H instability: lessons learned from Cluster and Themis

What have we learned

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What have we learned

+ Rolled-up K-H vortices do exist at the magnetopause
+ Size can be as large as 40,000-55,000 km
+ There are not rare events under Northward IMF
+ MR within these vortices can enable solar wind entry
+ KHI occurs under any IMF orientation even Southward
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esa

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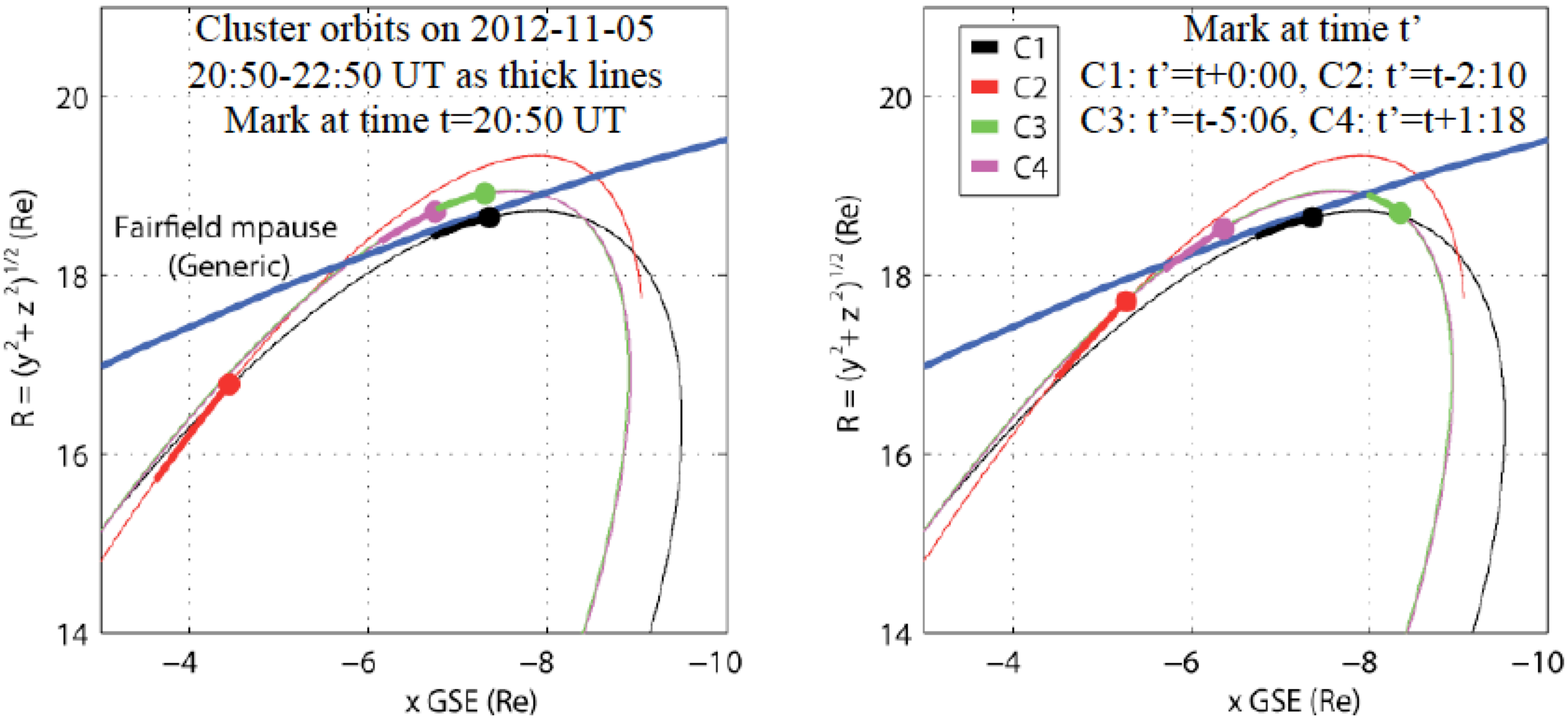
Open questions

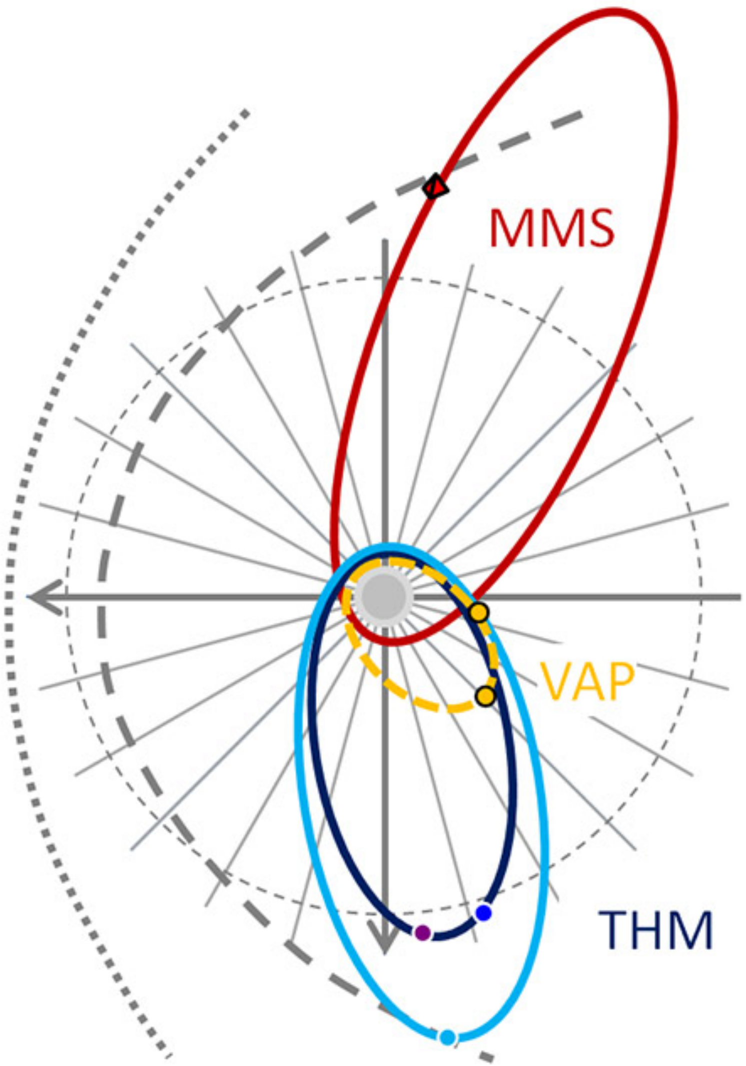
- What is their evolution from birth to collapse of KHI?
- Is there a Dawn-Dusk asymmetry and why?
- How is magnetic reconnection initiated within K-H rolled-up vortices?
- Do they enable solar wind plasma to enter into magnetospheres? What is their role in the formation and existence of the cold dense plasmasheet?

3.1 GI operations at the magnetopause (2012 and 2016)



European Space Agency

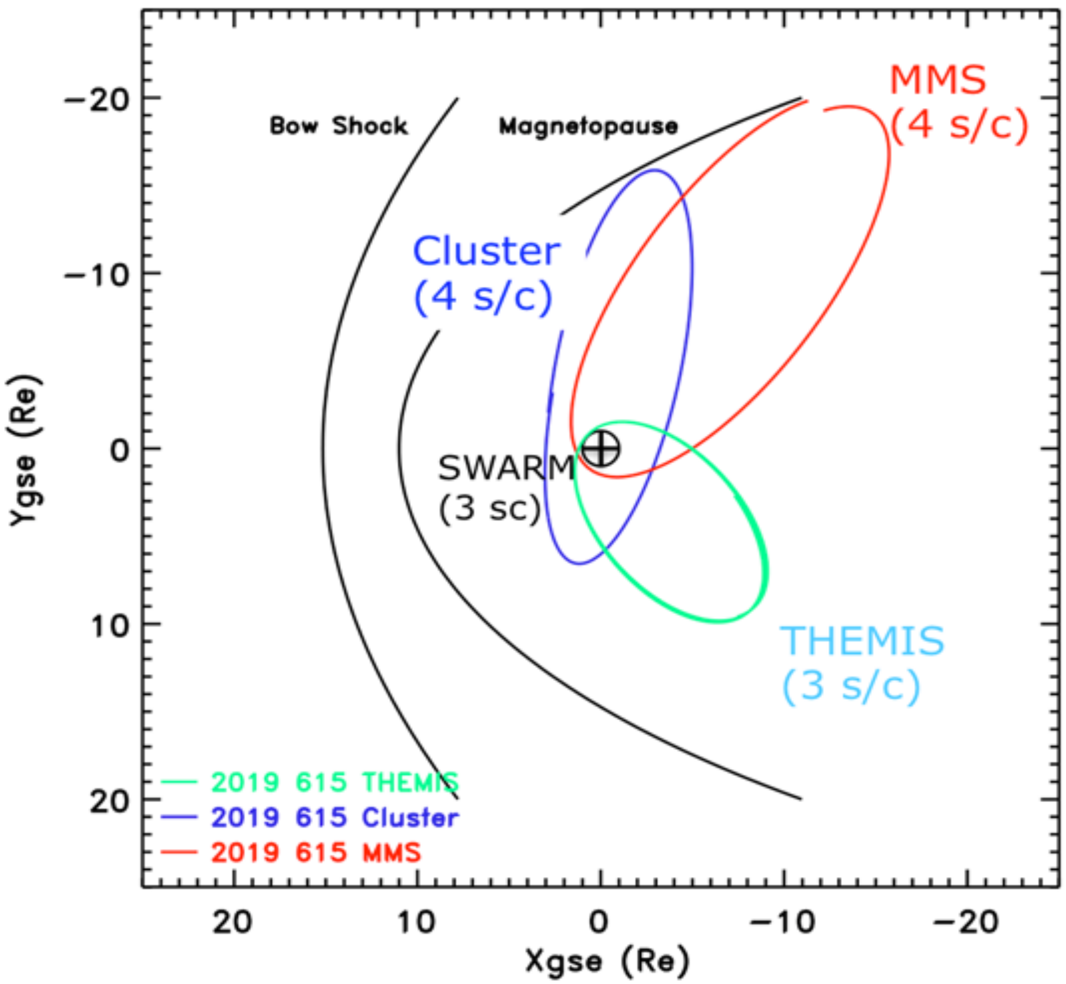
3.2. Dawn-dusk asymmetry of K-H waves in 2018



MMS and THEMIS upcoming observations

Dawn-dusk asymmetry
(May-August 2018)

3.3. K-H waves evolution along the MP and impact on CPS 2018-2020



1. In 2019, both missions will be skimming the dawn flank of the magnetosphere at different positions
2. => evolution of K-H waves as they propagate downstream over 12 Re
3. => reconnection inside vortex with 4 points measurements
4. Evolution of turbulence level and cross-scale energy transfer
5. CPS and possibly CDPS can be studied simultaneously with Themis

4. Conclusion

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4. Possible ways forward

At the moment, we try to predict tsunami in the pacific ocean with a couple buoys…

Possible scenario
Many micro/small-sat with electric propulsion along the magnetopause (at the moment only GEO)
Orbit of Equator-S type and "Polar-S" type
Minimum instrumentation: B, ions
+
Large soft X-ray telescope to visualize FTE and dayside reconnection