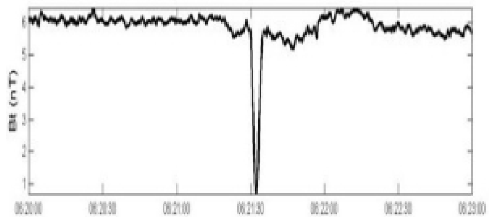

Recent observations of magnetic holes (cavities): from MHD to kinetic scale

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D2620 | EGU2020-6406

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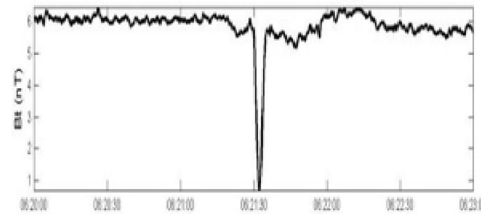
Magnetic hole : observable magnetic field decrease in a short time span
(magnetic cavity, dip, depression…)



magnetic holes in the Cusp (large scale)

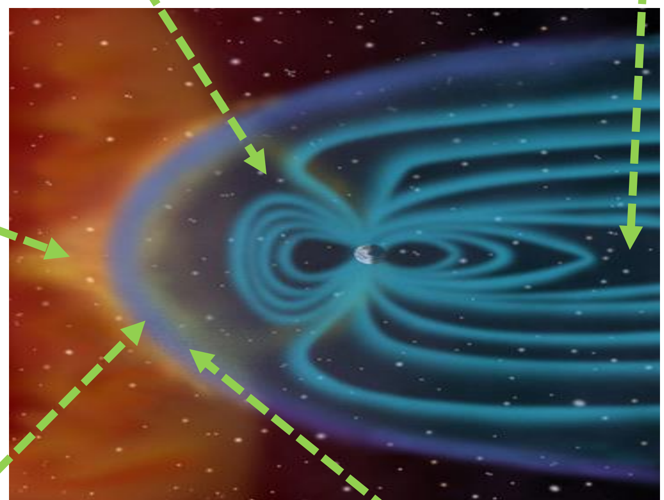
[Shi +, 2009a, JGR]

magnetic holes in the tail (small scale)

[Sun +,2012, AG; Ji +, 2014,JGR;Yao+,2016,JGR]

magnetic holes in the Cusp (large scale)

[Xiao+, 2010, AG;
Xiao+, 2014, SP;]



magnetic holes in the sheath (large scale)

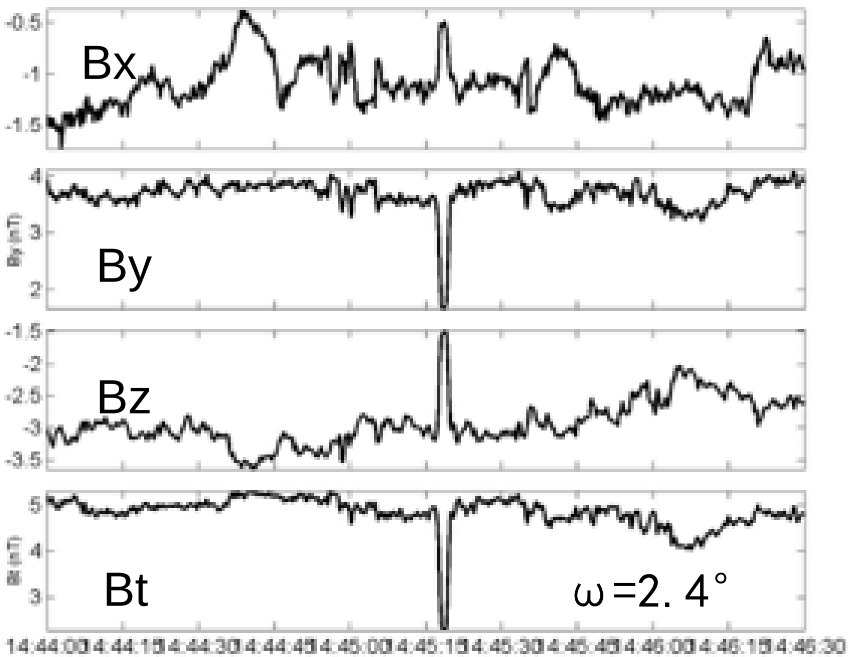
[Yao+, 2018, 2019, JGR]

magnetic holes in the sheath (small scale)

[Yao+, 2017, 2019, JGR;
Yao+, 2019, GRL;Liu+, 2019]

‘Linear’ magnetic hole

- **Linear hole**: field direction does not change much across the structure (e.g.,Turner et al., 1977; Winterhalter et al., 1994). Normally no more than 15°(Zhang et al.,2008; Xiao et al., 2010).



Observations of magnetic holes

- 1) SW (e.g., Turner et al.,1977; Winterhalter et al.,1994;Russell et al., 2008; Zhang et al., 2008; Yao et al., 2008) ;
- 2) magnetosheath of the earth and other planets (e.g. Tsurutani et al., 1982; Lucek et al.,1999; Soucek et al., 2008) ;
- 3) CME sheath behind interplanetary shocks (e.g., Liu et al., 2007) ;
- 4) cometery envioronments (Russell et al., 1987; Plaschke et al., 2018) ;
- 5) Earth's magnetosphere (Rae et al., 2007– drift mirror)
- 6) Earth's cusp (Shi et al., 2009) ;

-> in large scale (~10s-100s of ρi)

- 7) tail plasma sheet (Ge et al., 2011; Sun et al., 2012)

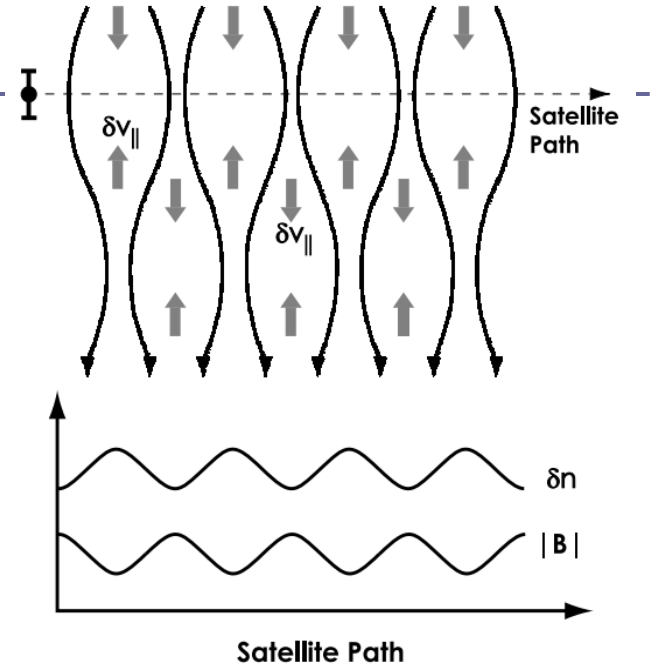
-> in small scale (< ρi)

➢ Formation for large scale MHs

1. **Mirror instability:** High β, anisotropic plasmas (e.g. Hasegawa.,1969, 1975) :

$$R = \frac{T_\perp / T_\parallel}{1 + 1/\beta_\perp} > 1$$

2. **Soliton approach**: 'dark' soliton,'bright' solition (e.g. Baumgärtel., 1999; ...;Ji et al,2016)
3. Phase-steepened Alfvén waves (e.g. Tsurutani et al., 2002a,b)
4. Wave- wave interation (e.g. Tsubouchi and Matsumoto., 2005; Tsubouchi. 2009, 2012).

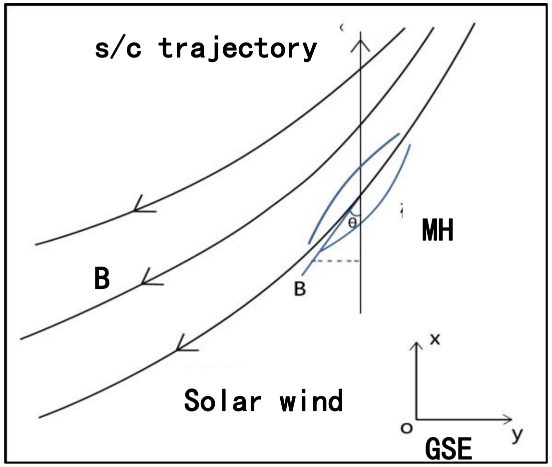


Mirror mode: peaks+dips

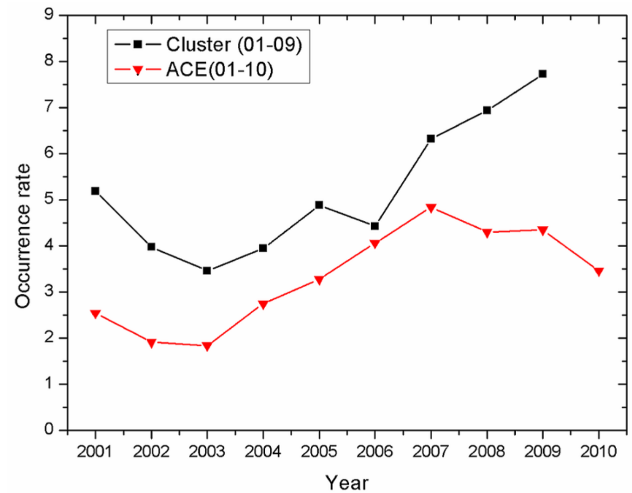
Rae et al. (2007)

mirror mode: field direction change little; N, B antiphase; frozen in background plasmas

- **Mirror mode may carry some information of corona heating** (Russell et al., 2008)
- **Linear MHs in the near earth sw** (Xiao et al., 2010, AG; Xiao et al., 2014,SP)



s/c Crossing of a MH



Liner MH occurrence rate

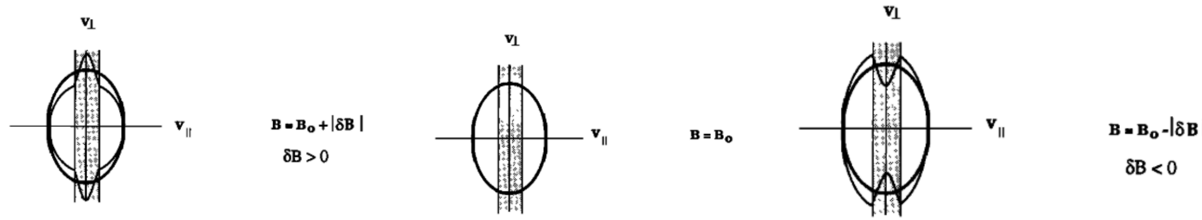
Rotational ellipsoid; ratio of scales along and across the magnetic field ~1.93:1.

Compared to the results in 0.72 AU (Zhang et al.,2008), the occurrence rate and geometrical shape in 1 AU change little from Venus to the earth ➔ fully developed before 0.72 AU

➢ Particle distribution in large scale mirror mode

➢Physical Mechanism of Linear Instability (Southwood and Kivelson ,1993)

$$\Delta W = \Delta W_{\perp} = \mu \Delta B = W \sin^2\theta \left(\frac{\Delta B}{B_0}\right)$$



Betatron acceleration Betatron deceleration

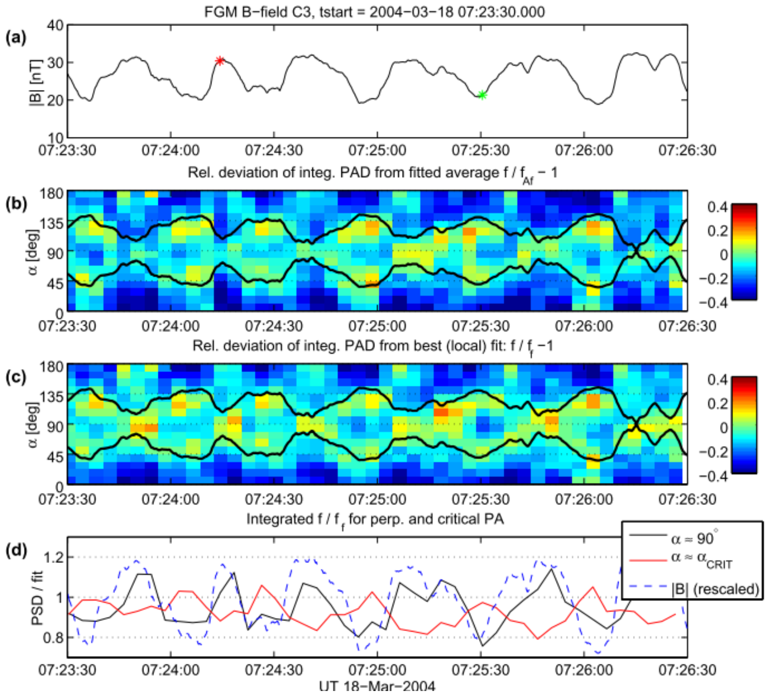
➢The Mechanism of Nonlinear Saturation (Kivelson and Southwood,1996)

When the mirror waves are growing:

- Particles trapped near the center lose perpendicular energy and total energy --both betatron deceleration and Fermi deceleration.

➢**Betatron deceleration in the center of the MHs - > perp flux decrease in the center of the hole.**

➢ Ion distributions in the magnetosheath mirror mode [Soucek and Escoubet, 2011]

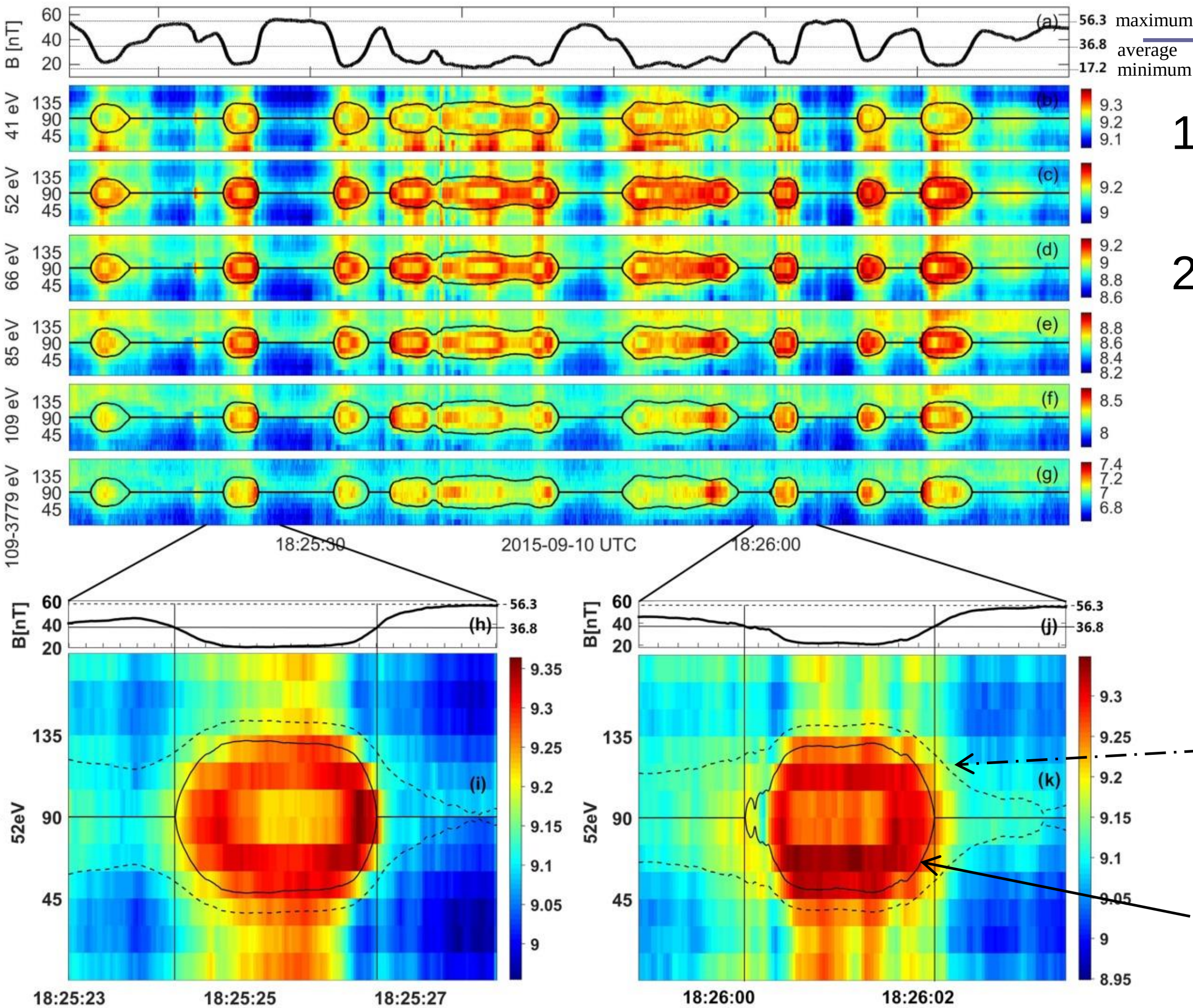


Soucek and Escoubet [2011] explained the ion distributions using theory by Southwood and Kivelson [1993] and Kivelson and Southwood [1996] :

- For **the depletion of ions at α ≈ 90◦** inside the magnetic troughs/dips, they experience the field weaken and thus the Betatron deceleration.

How about the electron distribution?

➢ Sheath mirror mode- **electron ’donut’ distribution** [Yao et al., 2018]



$\theta = arcsin\sqrt{B/B_{max}}$

$\theta = arcsin\sqrt{B/B_{average}}$

1) many electrons are trapped in the magnetic trough.

2) For trapped electrons, the electron flux with pitch angle close to 90° at the minimum magnetic field areas is lower, which displays a “**donut**” distribution.

donut

How will these sheath structures（holes+peaks） propagate and evolve??

➢ Large scale MH evolution： mirror mode

[e.g., *Bavassano-Cattaneo et al., 1998; Joy et al., 2006; Soucek et al., 2008; Genot et al., 2009*],

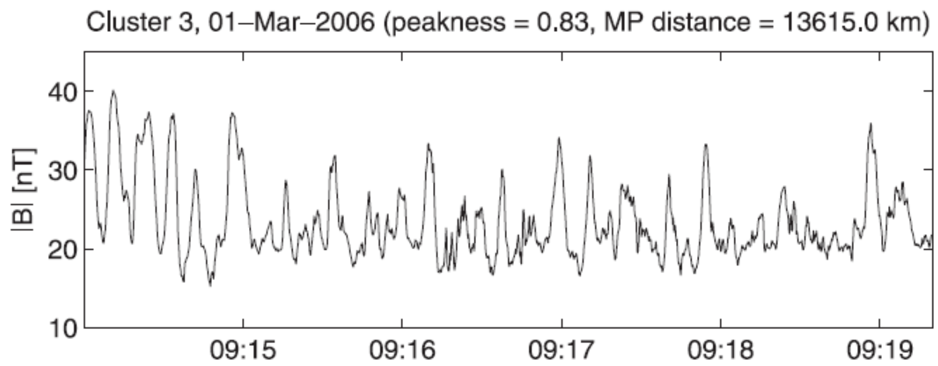
Qperp Shock →sheath-→magnetopause →?cusp？

Quasi-sin peaks&dips dips

Unstable stable

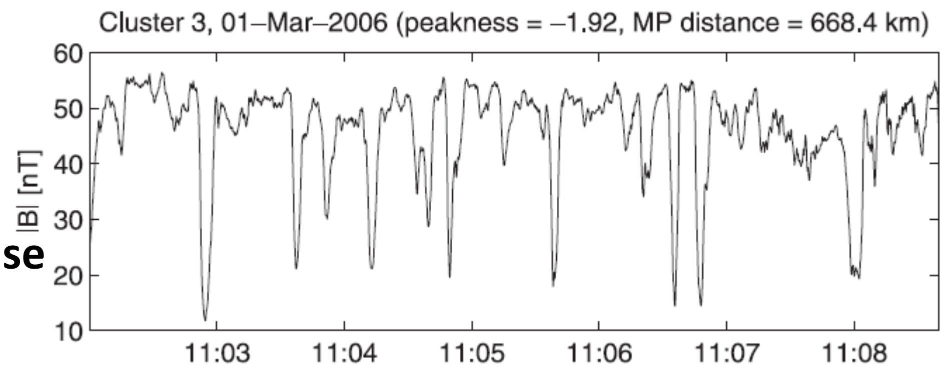
(Tperp>Tpara, high beta)

Sheath



Peaks&dips/holes

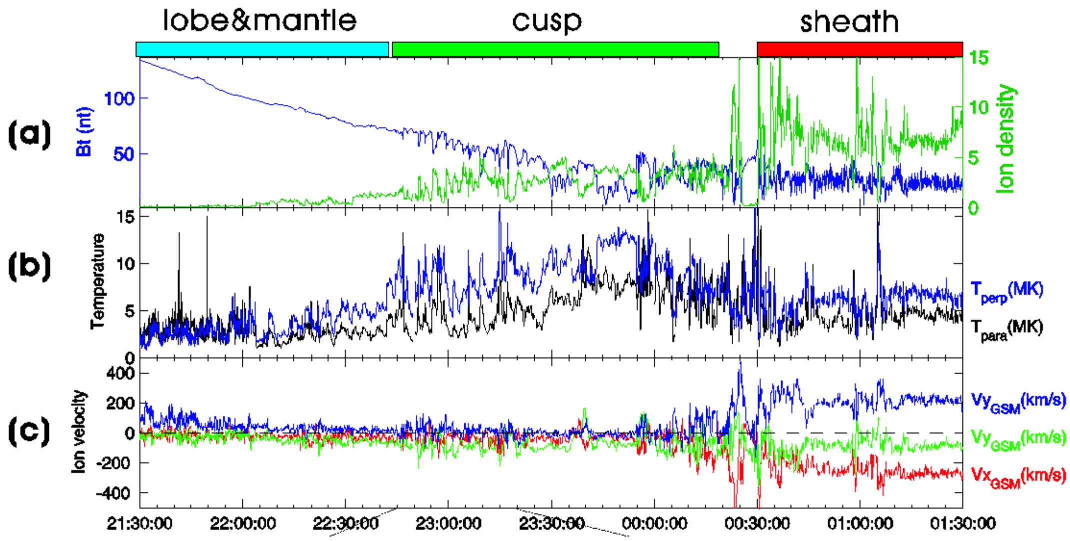
Near the magnetopause

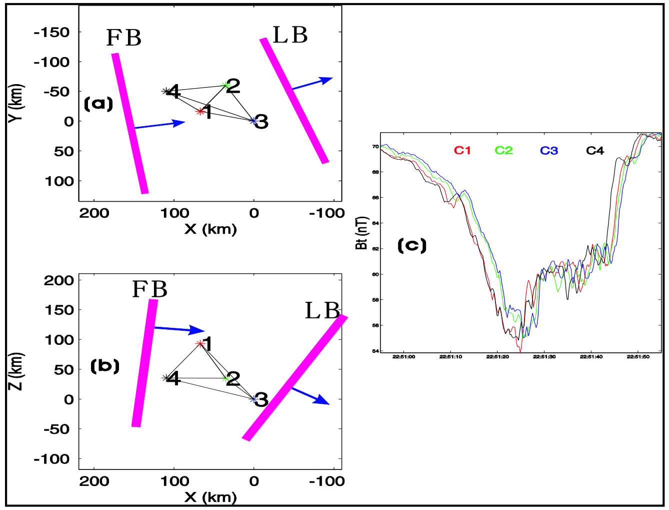


Dips/holes

[*Sucek et al., 2008*]

MHs in the cusp (Shi et al., 2009, JGR)





The angle between the two boundaries is **only** ~20º. The velocities of the two boundaries are almost **parallel to** each other.

Spatial structure！

Tools downloading：
http://themis.ssl.berkeley.edu/socware/bleeding_edge/spdsw_latest.zip
tutorial: http://spedas.org/wiki/index.php?title=Tools_Menu_-_SPEDAS_GUI

▪ Methods

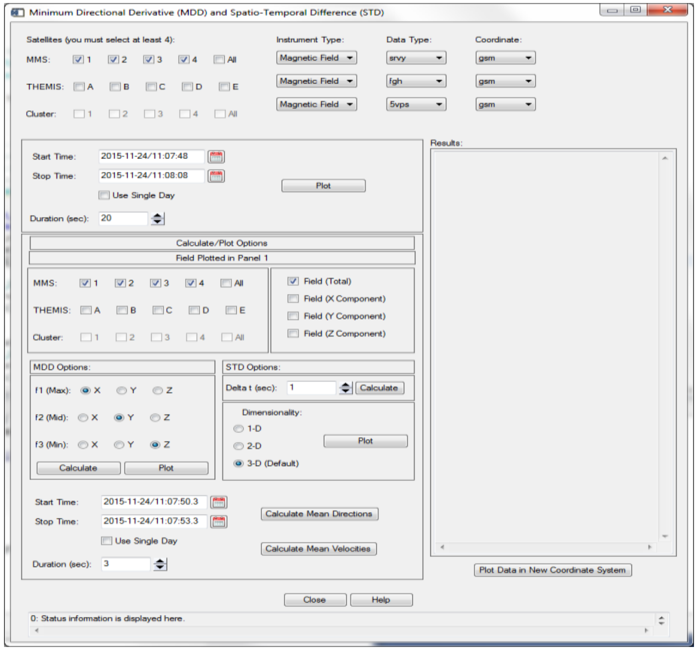
SPEDAS GUI of the methods

- ➢ calculating the eigen directions of the field spatial variations -> D-based coordinate system

calculate $(\partial \vec{B} / \partial n)^2$ maximum/minimum values -->eigen directions

- ➢ Calculating the spatial and temporal variation ->reference frame moving with the field

$$\left.\frac{\partial \vec{B}}{\partial t}\right|_{sc} + \vec{V}_{str} \cdot \nabla \vec{B} = 0$$



MMS> spd_ui_mdd_std

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, A09201, doi:10.1029/2012JA017877, 2012

Test of Shi et al. method to infer the magnetic reconnection geometry from spacecraft data: MHD simulation with guide field and antiparallel kinetic simulation

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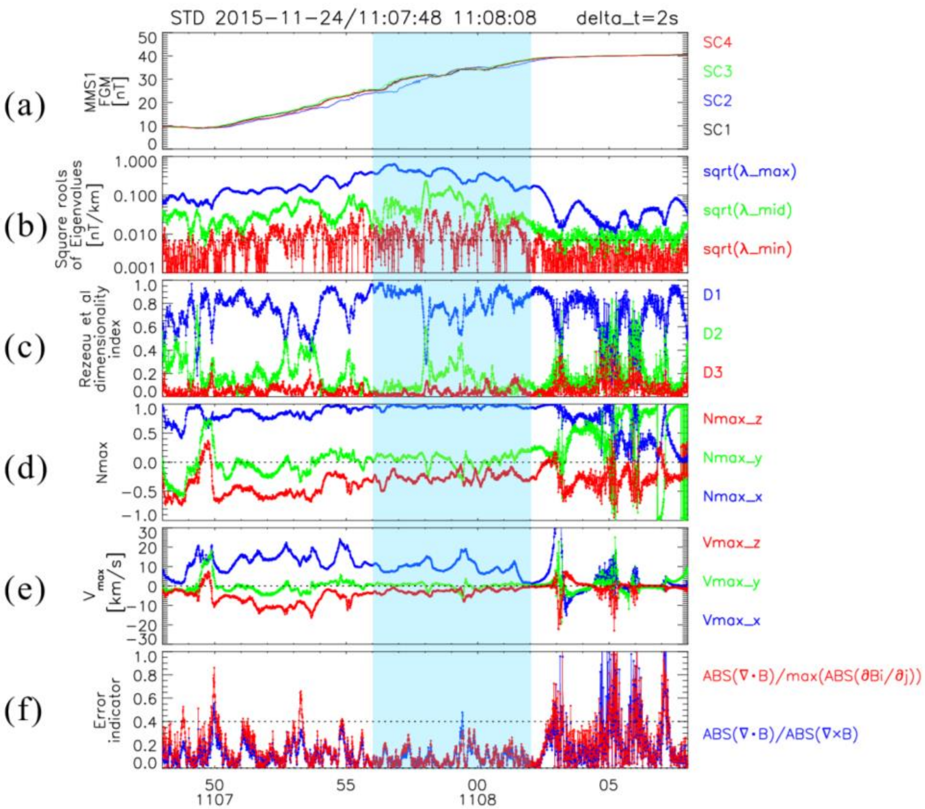
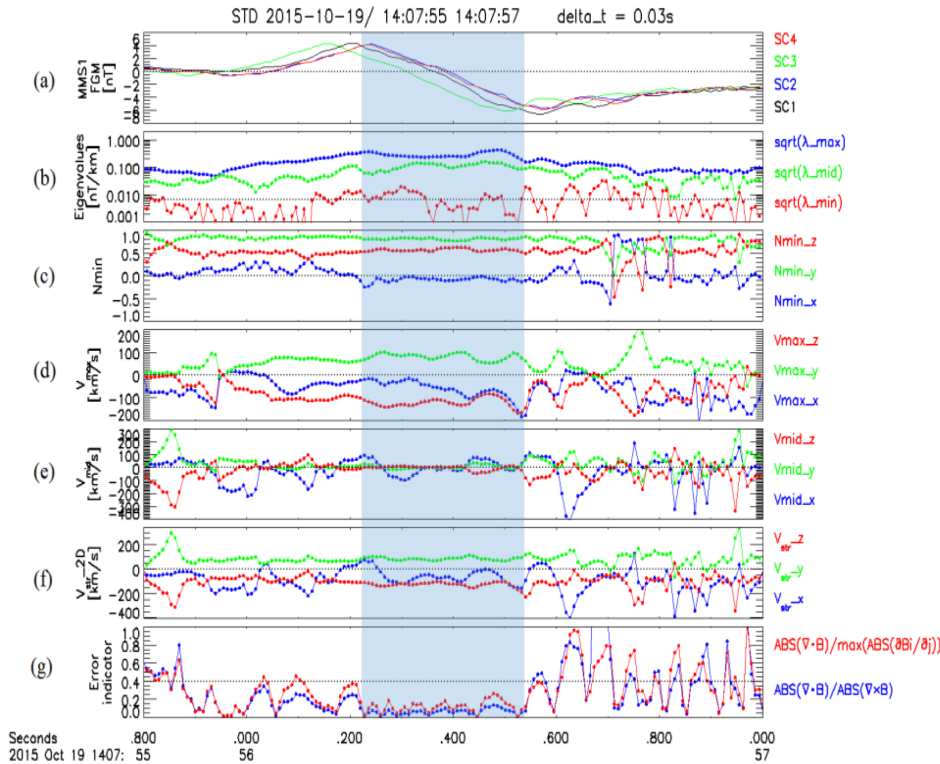
Received 27 April 2012; revised 28 June 2012; accepted 7 July 2012; published 6 September 2012.

Method examples

1-D CS



2-D flux rope



For methods, please refer to this review:

Space Sci Rev (2019) 215:35
https://doi.org/10.1007/s11214-019-0601-2

Dimensionality, Coordinate System and Reference Frame for Analysis of In-Situ Space Plasma and Field Data

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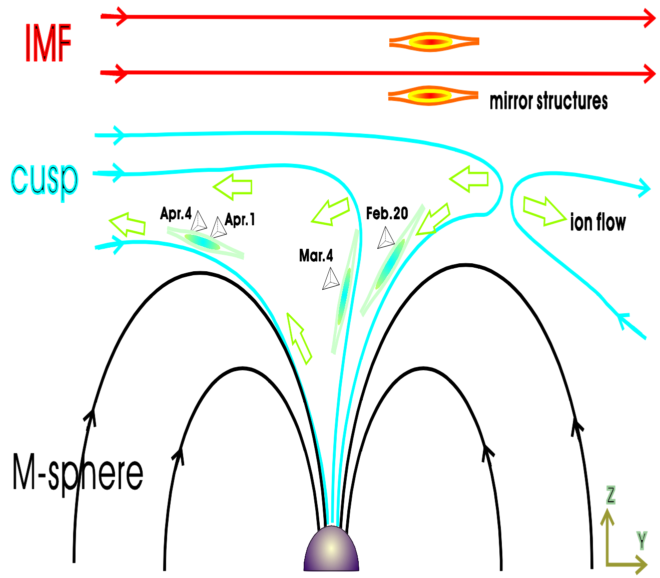
Received: 22 November 2018 / Accepted: 6 May 2019

Abstract In the analysis of in-situ space plasma and field data, an establishment of the coordinate system and the frame of reference, helps us greatly simplify a given problem and provides the framework that enables a clear understanding of physical processes by ordering the experimental data. For example, one of the most important tasks of space data analysis is to compare the data with simulations and theory, which is facilitated by an appropriate choice of coordinate system and reference frame. While in simulations and theoretical work the establishment of the coordinate system (generally based on the dimensionality or dimension number of the field quantities being studied) and the reference frame (normally moving with the structure of interest) is often straightforward, in space data analysis these are not defined *a priori*, and need to be deduced from an analysis of the data itself. Although various ways of building a dimensionality-based (D-based) coordinate system (i.e., one that takes account of the dimensionality, e.g., 1-D, 2-D, or 3-D, of the observed system/field), and a reference frame moving along with the structure have been used in space plasma data analysis for several decades, in recent years some noteworthy approaches have been proposed. In this paper, we will review the past and recent approaches in space data analysis for the determination of a structure's dimensionality and the building of D-based coordinate

continue…

In the cusp the plasma beta is lower than that in the sheath; the temperature anisotropy is not very strong: **the mirror instability** could **hardly** be generated **locally**.

Open field geometry of the cusp + mirror frozen in the plasmas → sheath mirror structures in the nonlinear stage (MHs) entering the cusp

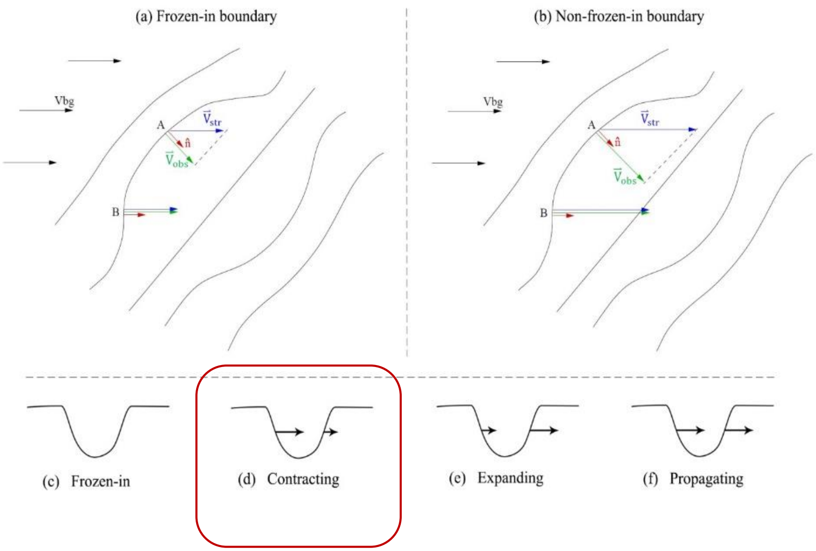


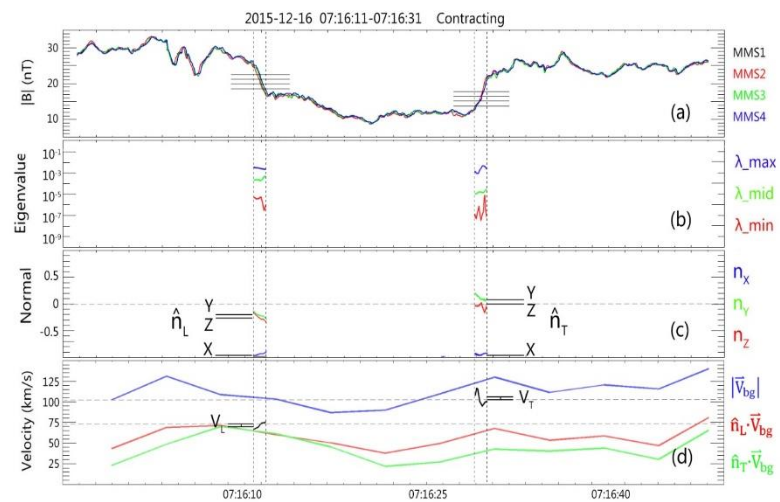
Q⊥ Shock → sheath →magnetopause →Cusp

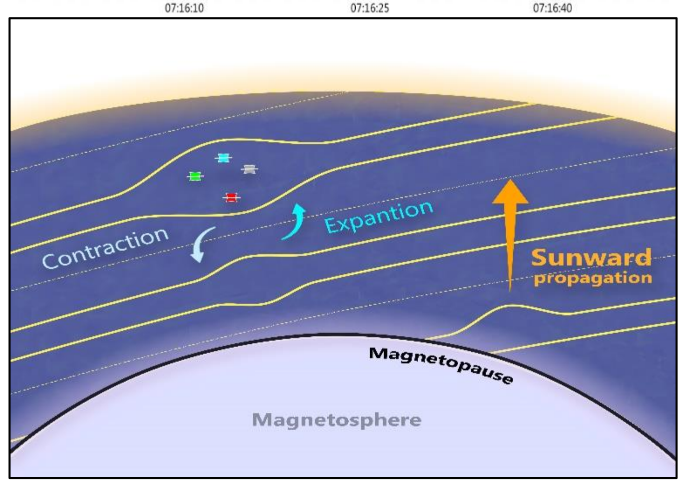
Quasi-sin peaks&dips dips dips

(Shi et al., 2009, JGR)

- Another way of evolution: shrinking vs expansion
  Yao et al., 2020, JGR: sheath MHs can be contracted while propagating



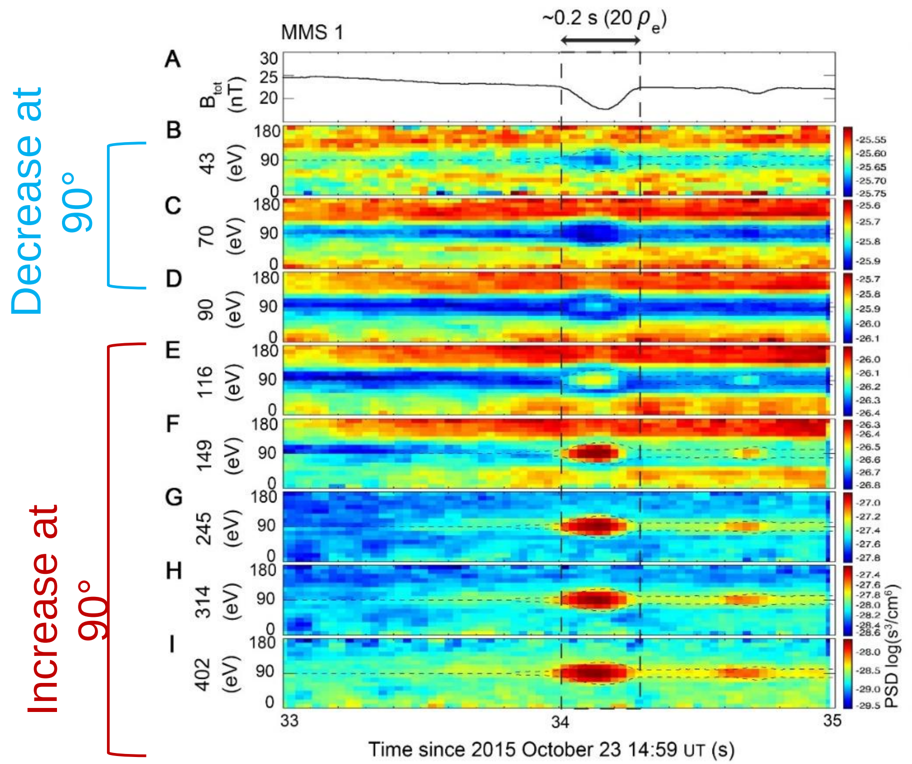


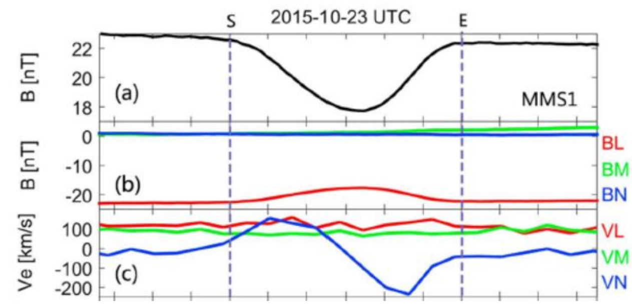


How small will it be contracted?

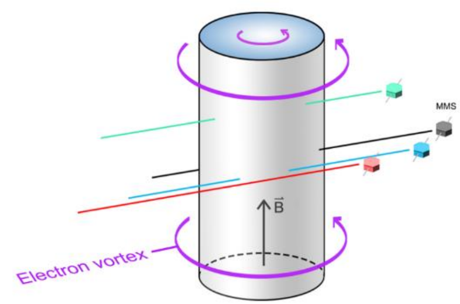
Tools downloading:
http://themis.ssl.berkeley.edu/socware/bleeding_edge/spdsw_latest.zip
tutorial: http://spedas.org/wiki/index.php?title=Tools_Menu_-_SPEDAS_GUI

Kinetic scale magnetic hole in the sheath (Yao et al., 2017)





electron vortex!

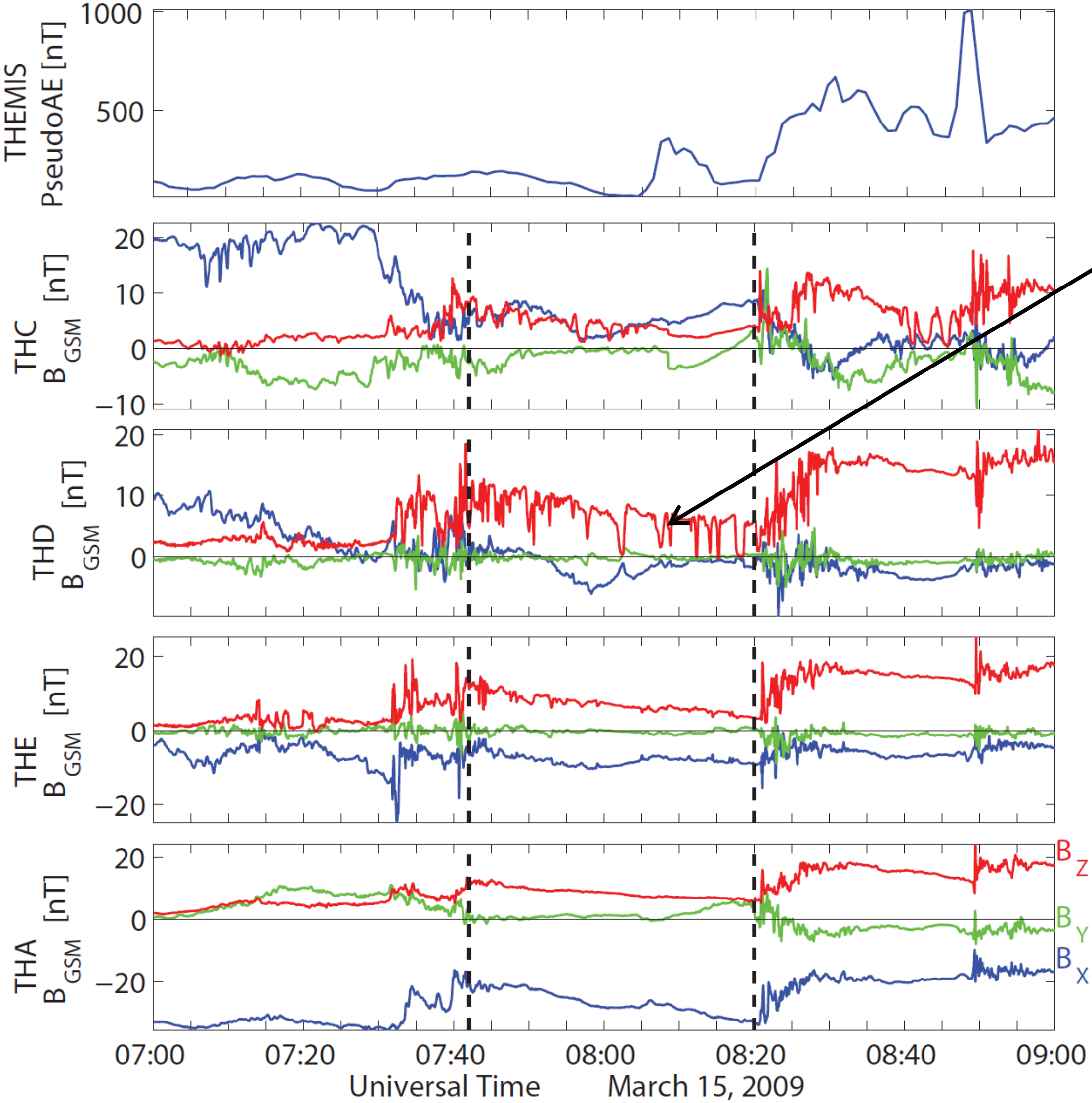


<u>significant effect on the electron distributions</u>:

- the flux of the trapped electrons are substantially **increased at high energy;**
- the flux of **lower energy electrons are decreased**.

Also see Huang et al., 2017, ApJ: Electron vortex magnetic hole (EVMH) – coherent structures in turbulence

similar to the small MHs in the tail

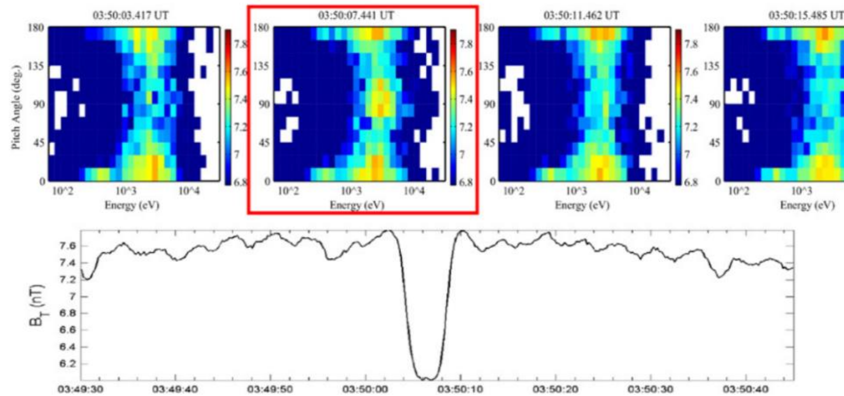


Ge et al. [2011]： THEMIS observation of MHs (small scale) between two depolarization fronts – mirror?

Adapted from Ge et al., [2011]

Double Star + Cluster observation:
small scale MHs in the tail plasma sheet

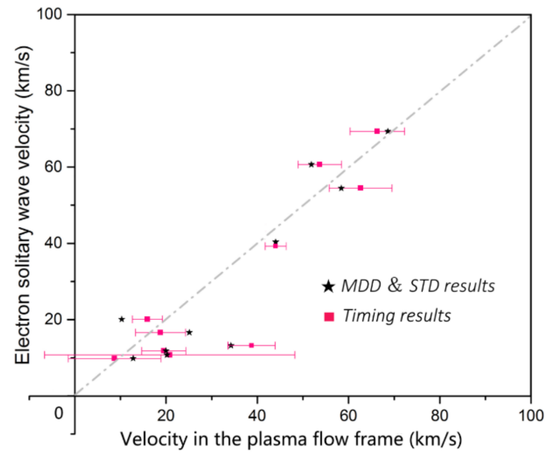
- **[Sun et al. 2012, AG]:**
  1. **L< ρi**
  2. **Electron flux increased around 90° in the center**
  3. **From Cluster (mid-tail) to TC-1 (near earth), MHs deeper.**



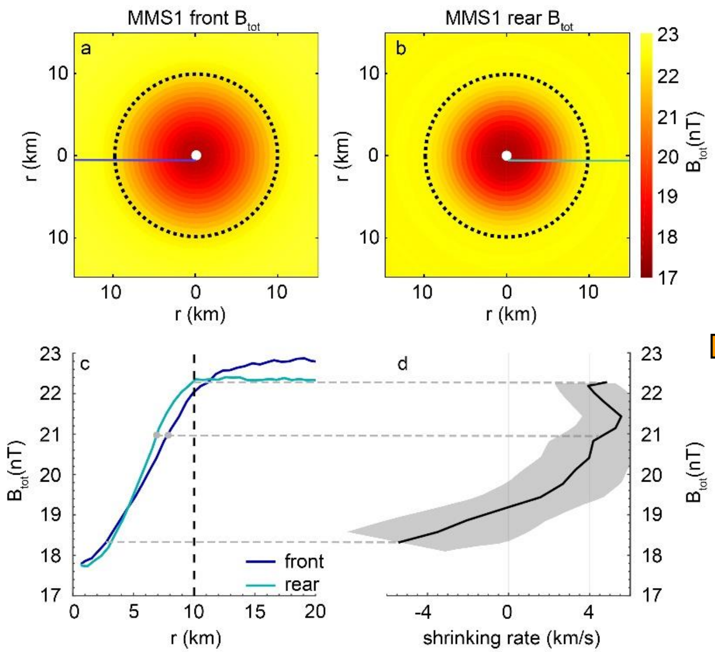
Cluster PEACE

- **EMHD soliton approach & observations**
  [Ji et al., 2014, JGR; Li et al., 2016, JGR]

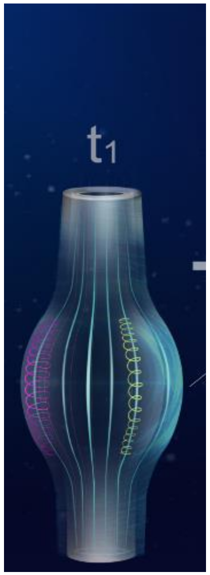
- Tail small MHs can propagate in the background plasmas - EMHD soliton
  [Yao et al., 2016, JGR]

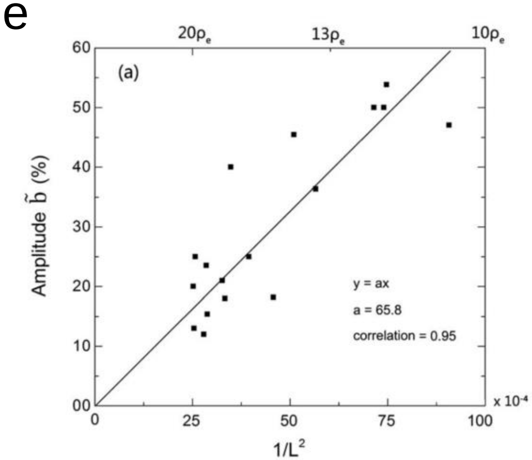


Sheath small scale MHs – structure and evolution?



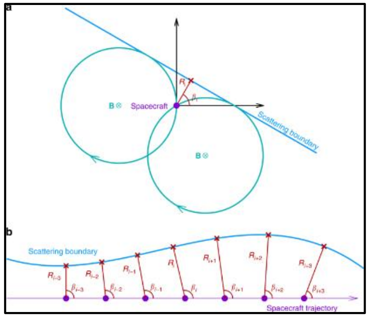
3-D magnetic bottle





Shrinkage + deepening(Yao et al., 2017):
In line with EMHD soliton (Ji et al., 2014; Li et al., 2017) prediction.

[Liu et al., 2019, NC]:Sounding technique
1.Rounded cross section
2.Shrinking (data from the 1st and 2nd half)
3. Magnetic field decrease in the center

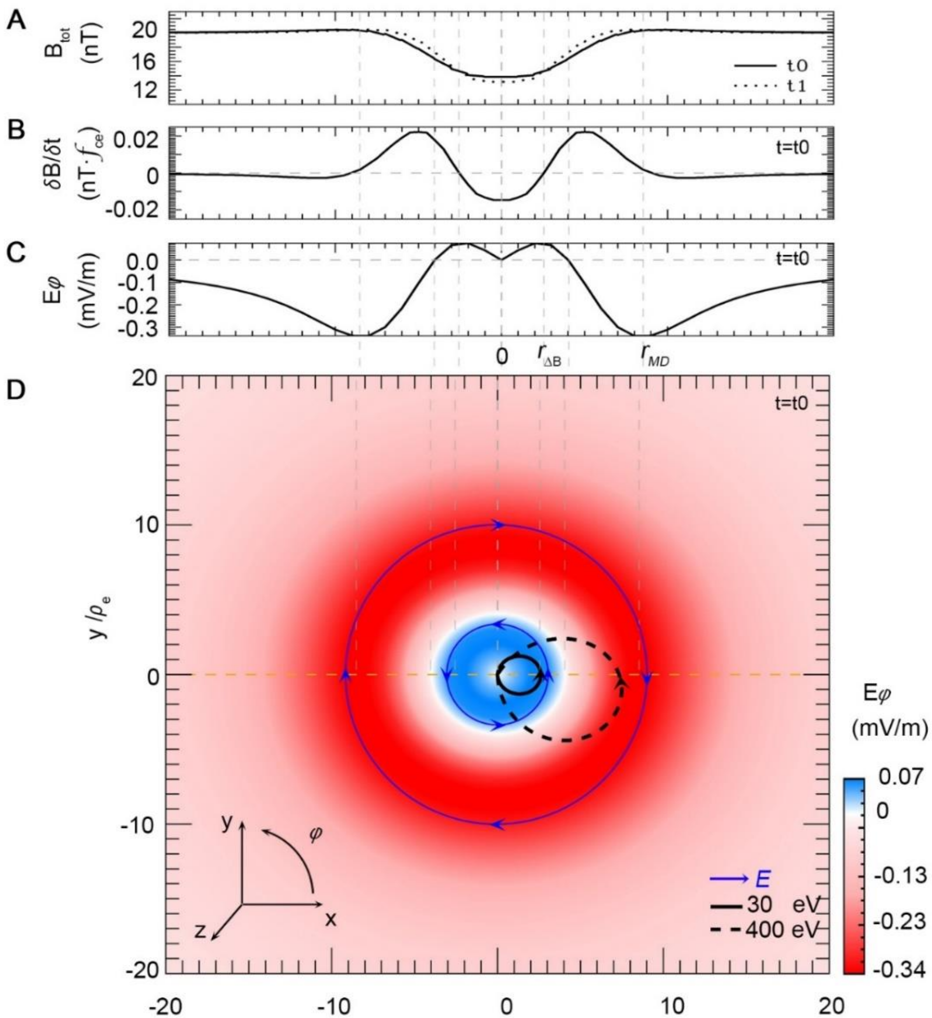


Sounding:
Electron as a detector
-see where the boundary is.

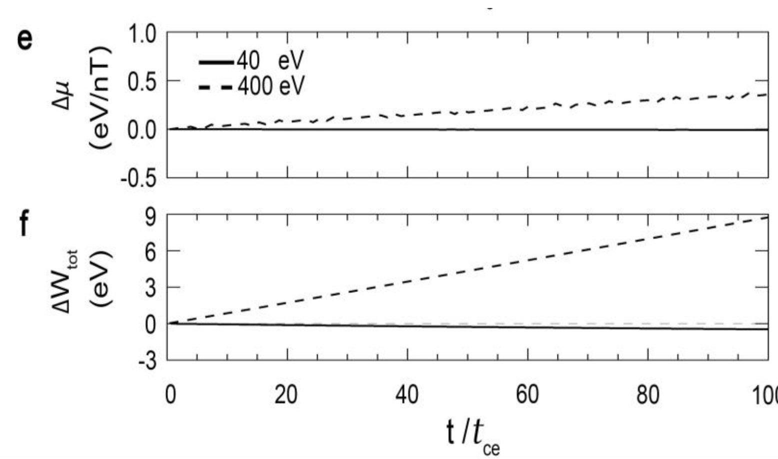
(An analytical model: Zhou et al., 2019, in preparation)

MH shrinkage + magnetic field decrease in the center

→induced electric field → particle non-adiabetic acceleration



The higher energy electrons are accelerated, while the lower energy electrons are decelerated inside the shrinking MH



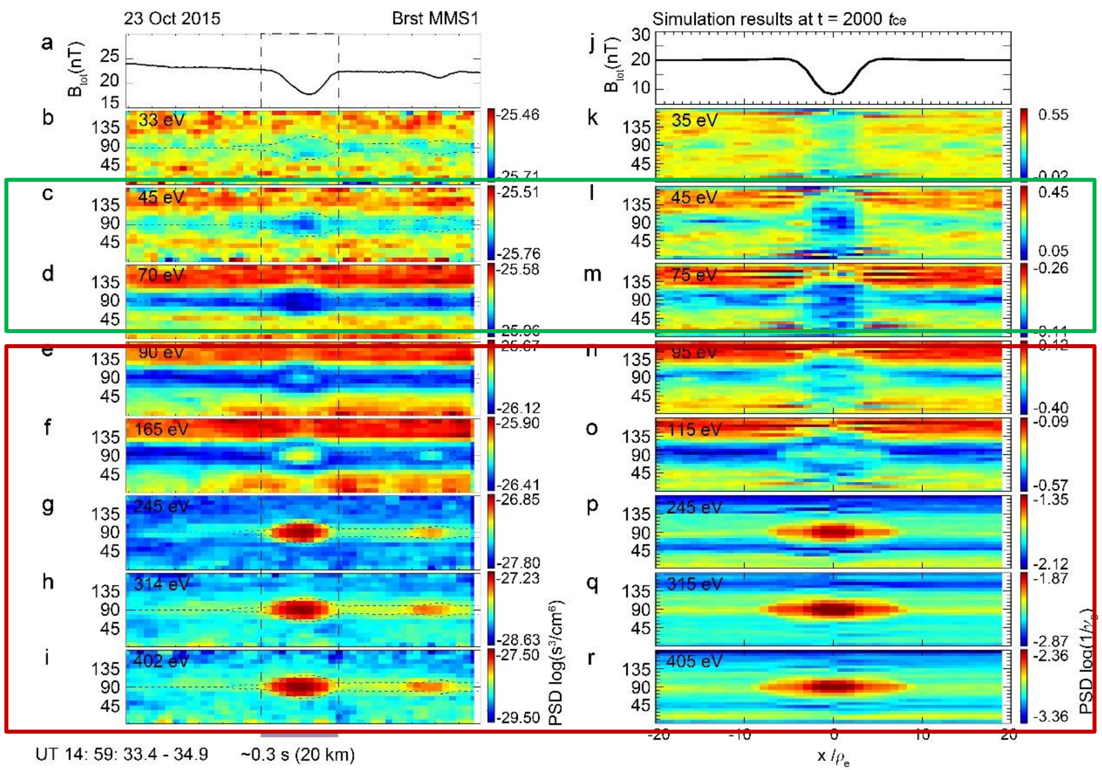
Test particle simulation for two electrons

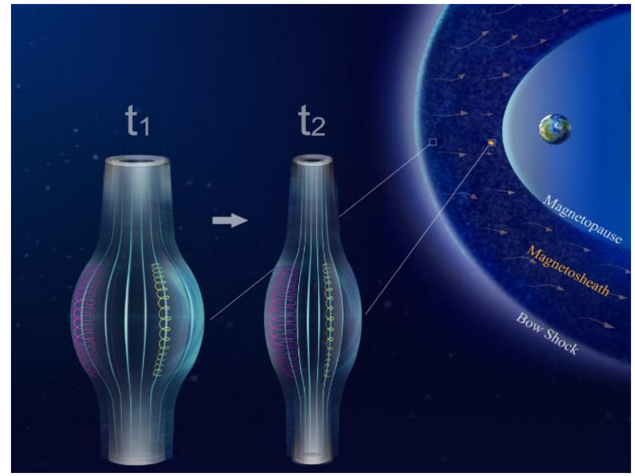
Test particle simulation (Liu J et al. 2019, just Rejected by NP ☹)

The **<u>significant effect on the electron distributions</u>**:

- the flux of the trapped electrons are substantially **increased at high energy;**
- the flux of **lower energy electrons are decreased**.

Observation **Simulation**



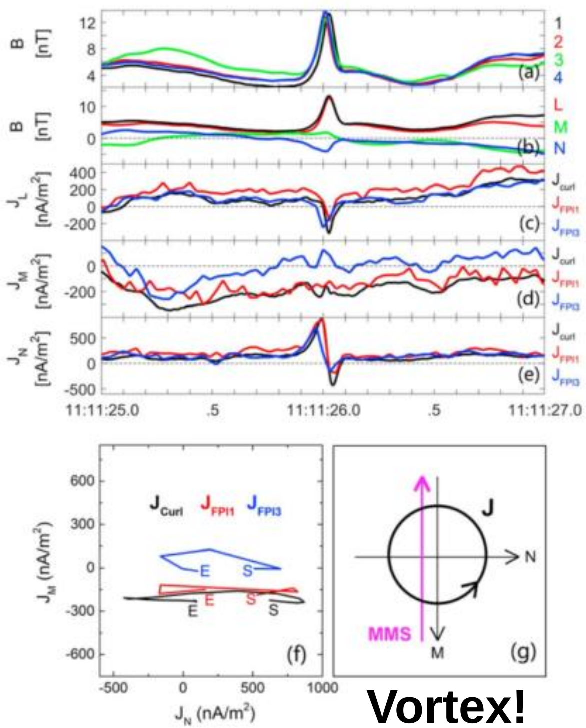


MHs(magnetic bottle) are generated near the Bow Shock. While propagating toward the MP, due to the pressure increase , MHs will shrink+deepen ->induced E-> high energy particles accelerated & lower energy particles decelerated --non-adiabetic!

List of several other related observations

➢ Magnetic peaks with electron vortex (Yao et al. 2018a, GRL)

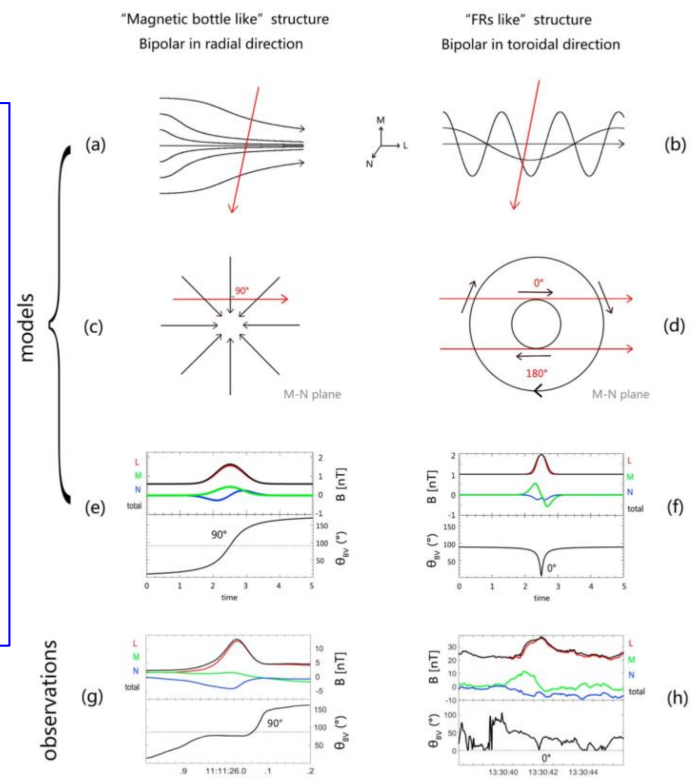
- Electron scale MP in the magnetosheath: **~7 electron gyroradii** and a duration of ~0.18 s.
- **Electron vortex** is found **perpendicular to the field lines**



Vortex!

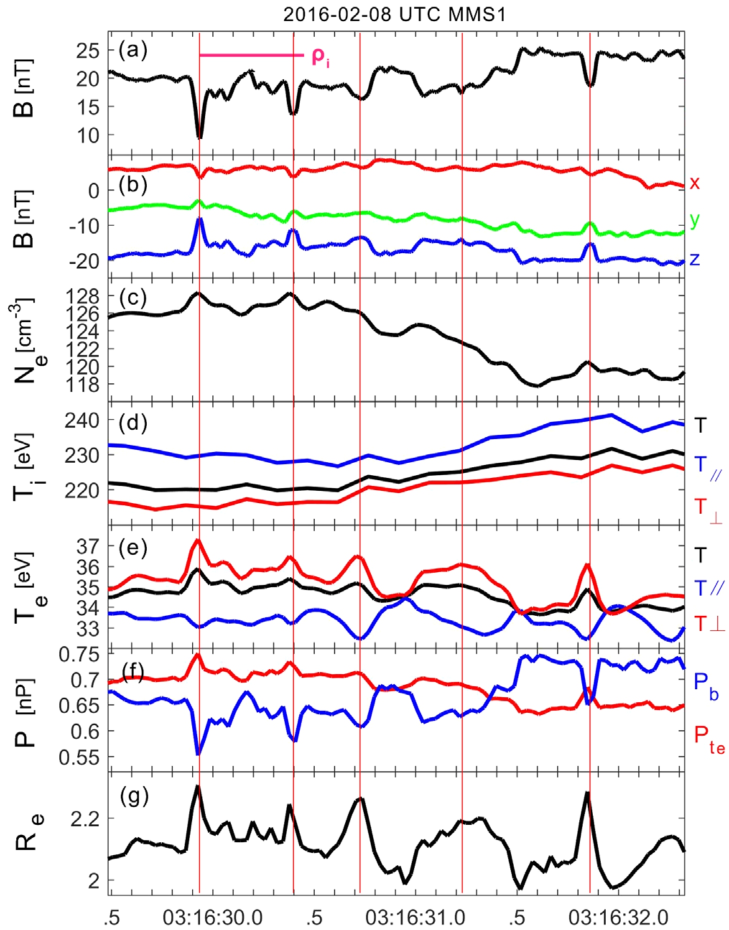
B-field bipolar: Magnetic bottle or Flux rope?

- The angle between the s/c trajectory and the field in M-N plane to determine!



List of several other related observations

Electron mirror (Yao et al., 2019, ApJL) – if we do not need shrinkage



- Small scale <ρ_i - No ion response
- Electron mirror threshold exceeded

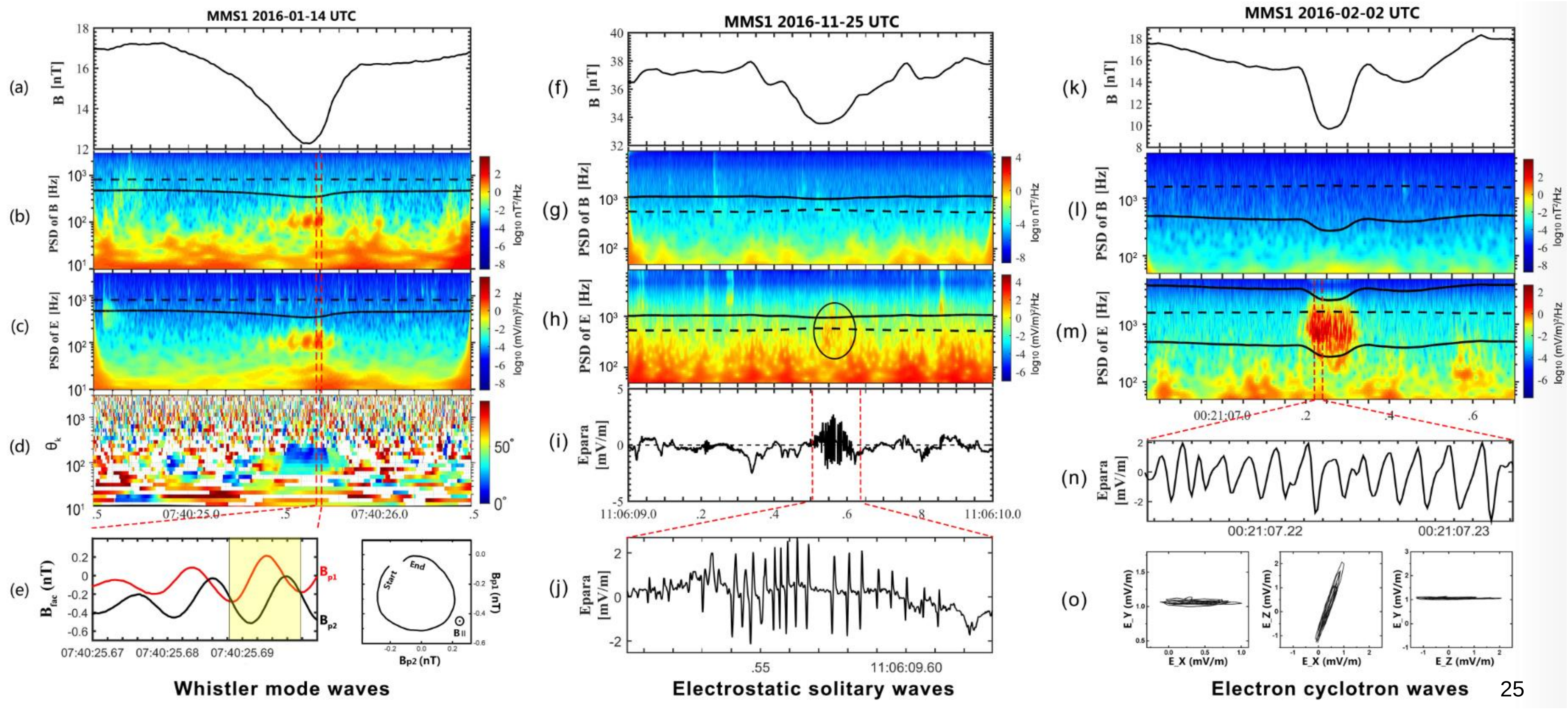
$$R_e = \frac{T_{e\perp} / T_{e\parallel}}{1 + 1/\beta_{e\perp}} > 1$$

- structure non-propagating (4.2±8.6 km s−1) in the plasma flow frame.

List of several other related observations

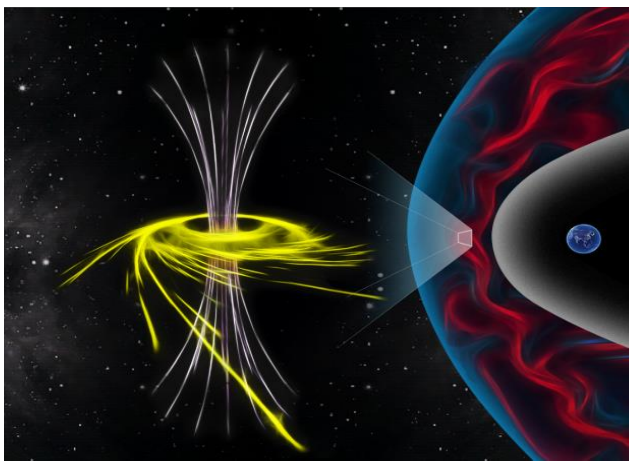
➢ **Waves in kinetic-scale MHs**(Yao et al., 2019, GRL)

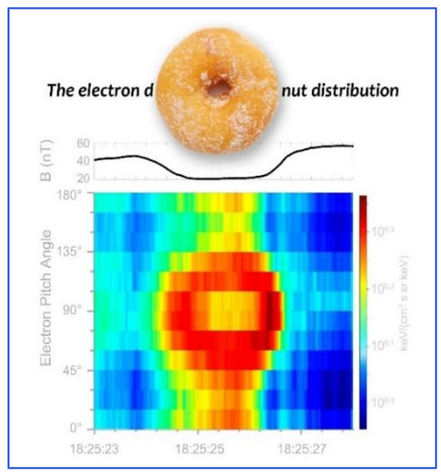
Yao et al. [2019] reported observations of **whistler mode** waves, **electrostatic solitary** waves, and **electron cyclotron** waves inside KSMHs in the magnetosheath.

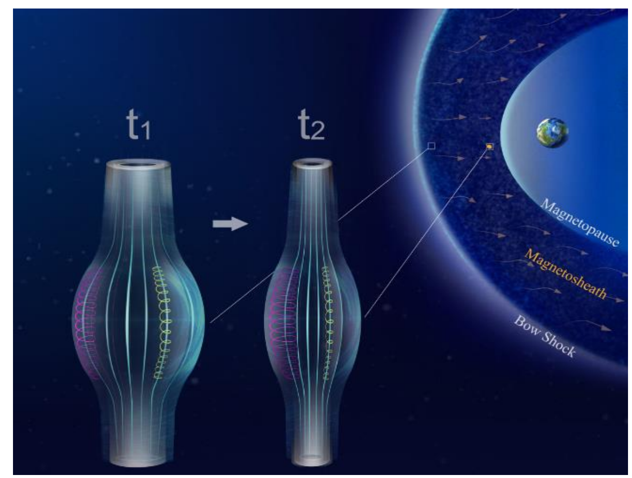


Summary & discussion

- Small structure(小)， complicated physical processes：Particle trapping/acceleration/deceleration- adiabetic/non-adiabetic; electron vortex; energy conversion; various kind of waves.
- Contribution to turbulent energy dissipation?







Thanks！

See more details in:
D2611 EGU2020-4394 & D2627 EGU2020-2719 of this Session

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Yao, S. T., Shi, Q. Q., Yao, Z. H., Li, J. X., Yue, C., Tao, X., et al. (2019). Waves in kinetic-scale magnetic dips: MMS observations in the magnetosheath. Geophysical Research Letters, 46, 523–533. https://doi.org/10.1029/2018GL080696

Yao, S. T., Shi, Q. Q., Liu, J., Yao, Z. H., Guo, R. L., Ahmadi, N., et al (2018). Electron dynamics in magnetosheath mirror-mode structures. Journal of Geophysical Research: Space Physics, 123. https://doi.org/10.1029/2018JA025607

Yao, S. T., Q. Q. Shi, R. L.Guo, Z. H. Yao, A. M. Tian et al. (2018), Magnetospheric Multiscale Observations of Electron Scale Magnetic Peak, Geophys. Res. Lett., 45, 527-537, doi: 10.1002/2017GL075711

S. T. Yao, X. G. Wang, Q. Q. Shi, T. Pitkänen, M. Hamrin, Z. H. Yao et al. (2017), Observations of kinetic-size magnetic holes in the magnetosheath, J. Geophys. Res. Space Physics, 122, 1990–2000, doi:10.1002/2016JA023858

Yao, S. T., Q. Q. Shi, Z. Y. Li, X. G. Wang, A. M. Tian, W. J. Sun, M. Hamrin et al. (2016), Propagation of small size magnetic holes in the magnetospheric plasma sheet, J. Geophys. Res. Space Physics, 121, 5510-5519, doi: 10.1002/2016JA022741

Xiao, T., et al. (2015), Propagation characteristics of young hot flow anomalies near the bow shock: Cluster observations, J. Geophys. Res. Space Physics, 120, doi:10.1002/2015JA021013.

T. Xiao, Q.Q. Shi, A.M. Tian, W.J. Sun, H. Zhang et al. , Plasma and Magnetic field characteristics of magnetic decreases in the solar wind at 1AU Cluster-C1 observations. Solar Physics, 2014, 289(8): 3175-3195.

Sun, W. J., Shi, Q. Q., Fu, S. Y., Pu, Z. Y., Dunlop, M. W. et al.: Cluster and TC-1 observation of magnetic holes in the plasma sheet, Ann. Geophys., 30, 583-595, doi:10.5194/angeo-30-583-2012, 2012.

Xiao, T., Shi, Q. Q., Zhang, T. L., Fu, S. Y., Li, L., Zong, Q. G., Pu, Z. Y. et al.: Cluster-C1 observations on the geometrical structure of linear magnetic holes in the solar wind at 1 AU, Ann. Geophys., 28, 1695-1702, doi:10.5194/angeo-28-1695-2010, 2010.

Shi, Q. Q., Z. Y. Pu, J. Soucek, Q.-G. Zong, S. Y. Fu et al.(2009), Spatial structures of magnetic depression in the Earth's high-altitude cusp: Cluster multipoint observations, J. Geophys. Res., 114, A10202, doi:10.1029/2009JA014283.

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