Sub-Alfvenic/Super-Sonic Impulsive Structures in the Magnetosphere. First Results from Hybrid Fluid-Kinetic Modeling and Comparison with MMS Observations

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Abstract

The magnetosphere of the Earth presents a large scale plasma physics laboratory in which the complex interacting plasma phenomena are involved: global convecting plasma dynamics, wave–particle interactions in the bow shock and transmitted shock waves/impulses and magnetic field reconnection in the plasma current sheets. The NASA magnetospheric multiscale mission (MMS) provides unique observations of the thin structures and wave–particles interactions at the shock-like impulses while the spacecrafts were located at the dawn terminator (the time is 2016-03-07 20:00:00 UTC). It was assumed that these impulses may be created by the interaction between the background flow and plasma clouds. It was also assumed that those clouds were produced by either flux-transfer events or by coalescence/reconnection processes at the magnetopause current layer or by the mirror instabilities inside the low latitude boundary layer. 3-D hybrid kinetic code with separate description of the background and cloud ions was used for interpretation of the observed impulse structures. In this report we will discuss the effects of particle heating and acceleration inside the foreshock of the shock-like impulses, effects of the ion and electron non-Maxwellian velocity distributions, and particle finite gyroradius, and triggering the electromagnetic instability.

Sub-Alfvenic/Super-Sonic Impulsive Structures in the Magnetosphere:

First Results from Hybrid Fluid-Kinetic Modeling and Comparison with MMS Observations

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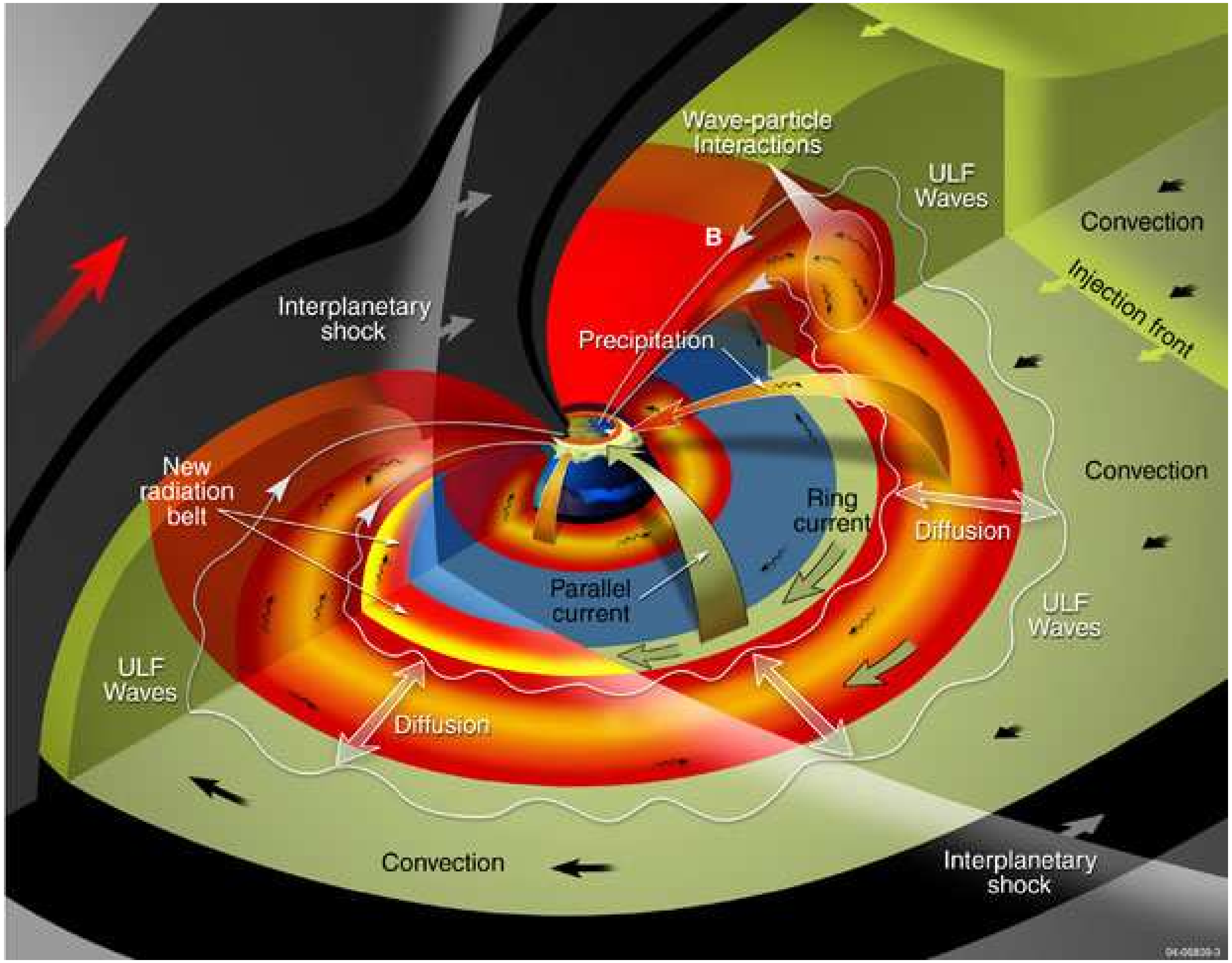
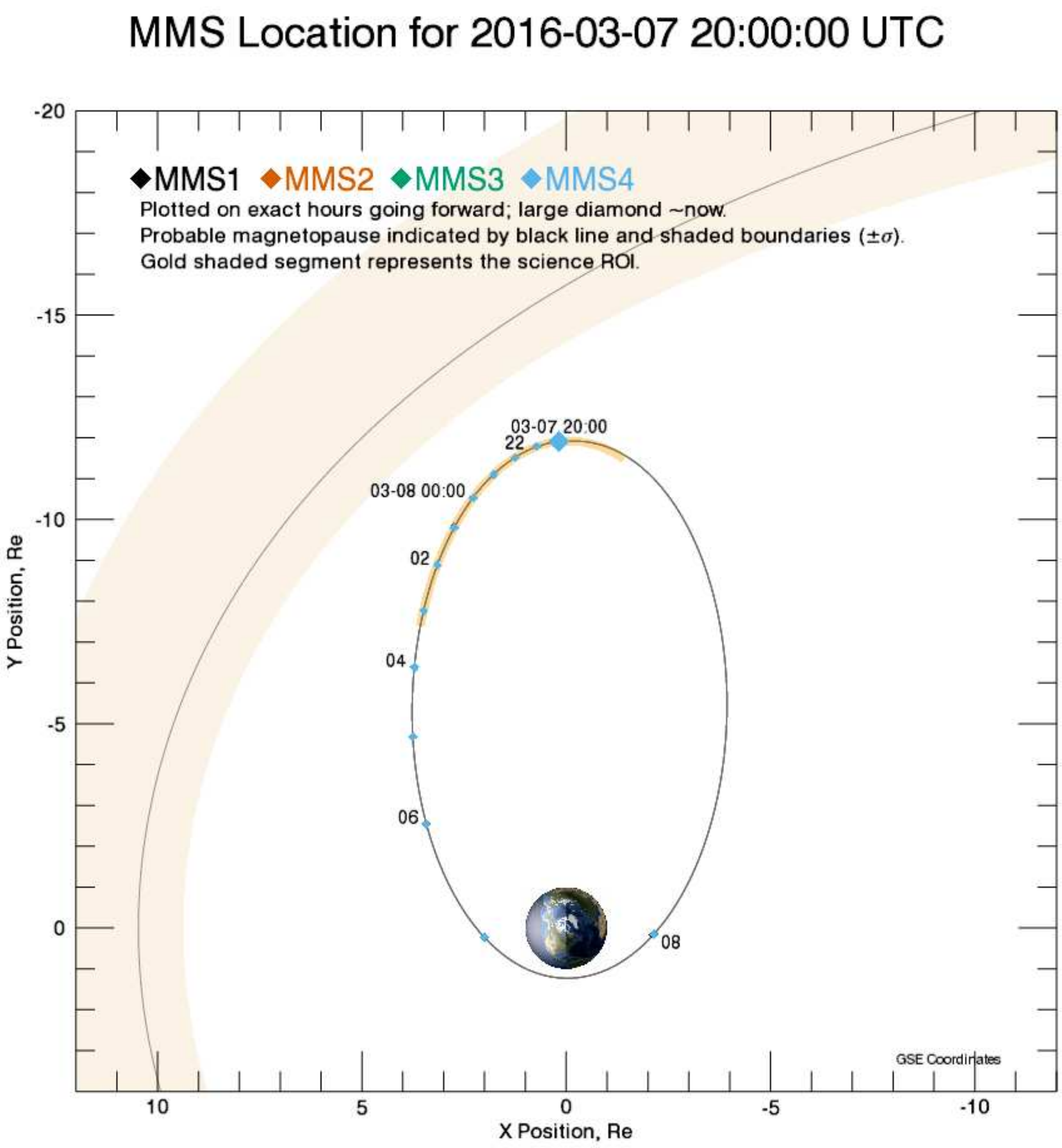
2. Motivation and Applications:

- 1. **Unique MMS observations of impulsive structures.**
- 2. **Plasma physics of impulsive structures inside the inner magnetosphere and ionosphere. Active experiments in space (AMPTE). Plasma clouds in the ionosphere (HANE).**
- 3. **Interaction between the moon's exosphere and planetary magnetospheres. Formation of the whistler and Alfv'en wing near the Parker Solar Probe.**
- 4. **Astrophysical explosions. Observations and modeling on the Large Plasma Device (UCLA). Magnetic reconnection modeling on the Large Plasma Device (UMBC).**

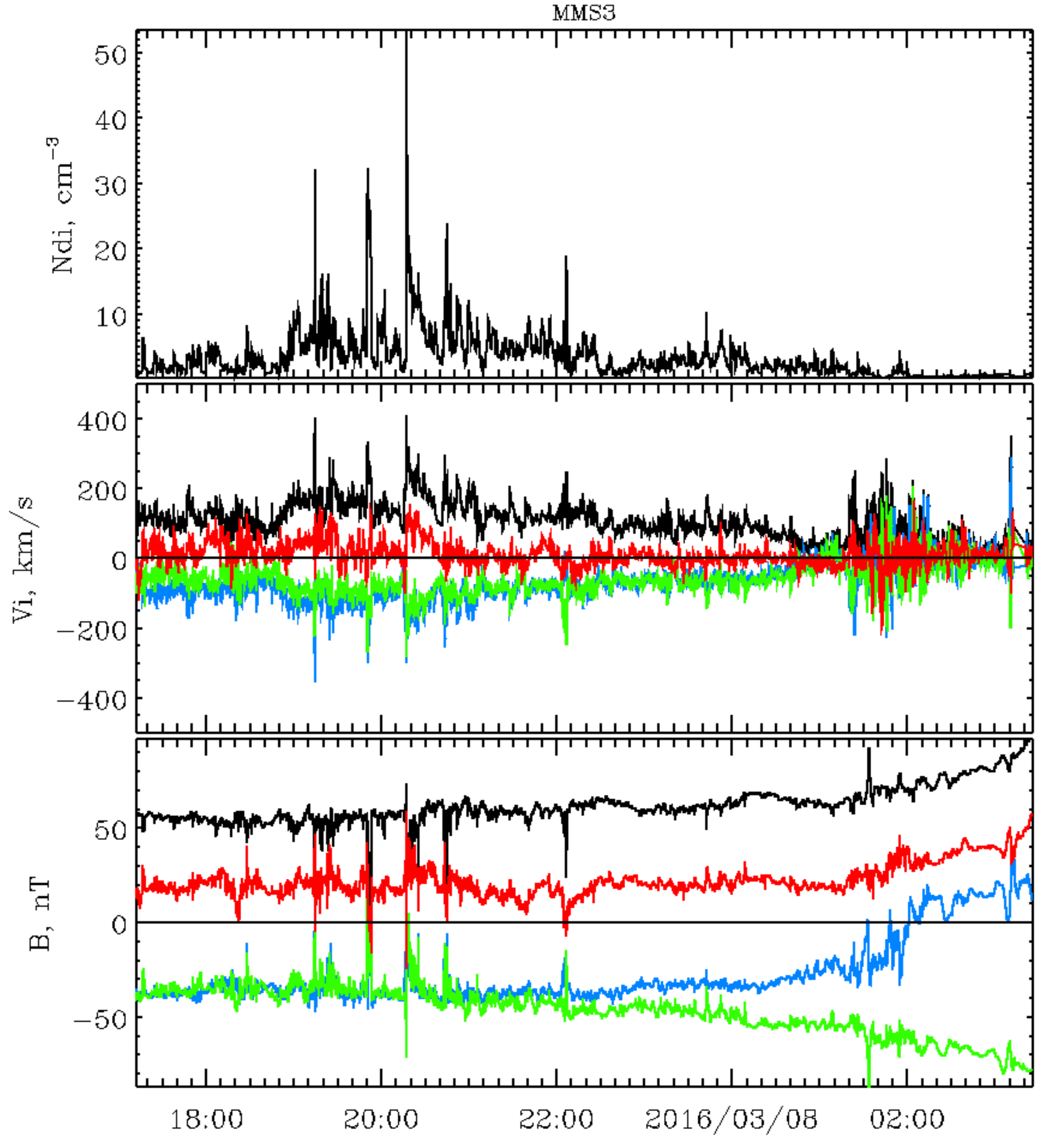
3. Scheme of the Earth magnetosphere, radiation belts and interplanetary shock



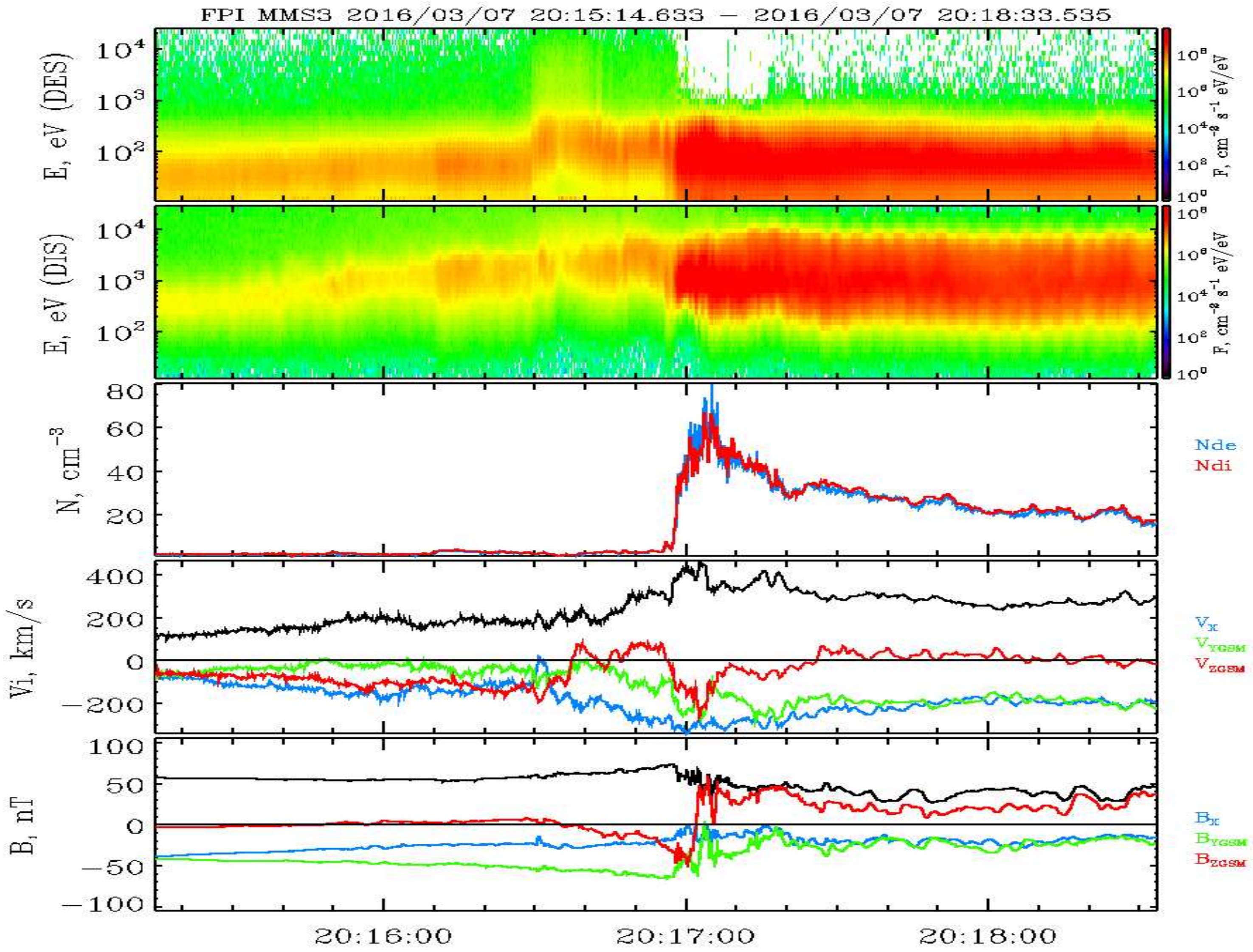
4. MMS satellite position at time 2016-03-07 20:00:00 UTC



5. MMS observations of the impulsive structures at time 2016-03-07 20:00:00 UTC. Density, bulk velocities and magnetic field



6. MMS observations of the impulse at time 2016-03-07 20:15:00–20:19:00 UTC. Density, bulk velocities and magnetic field



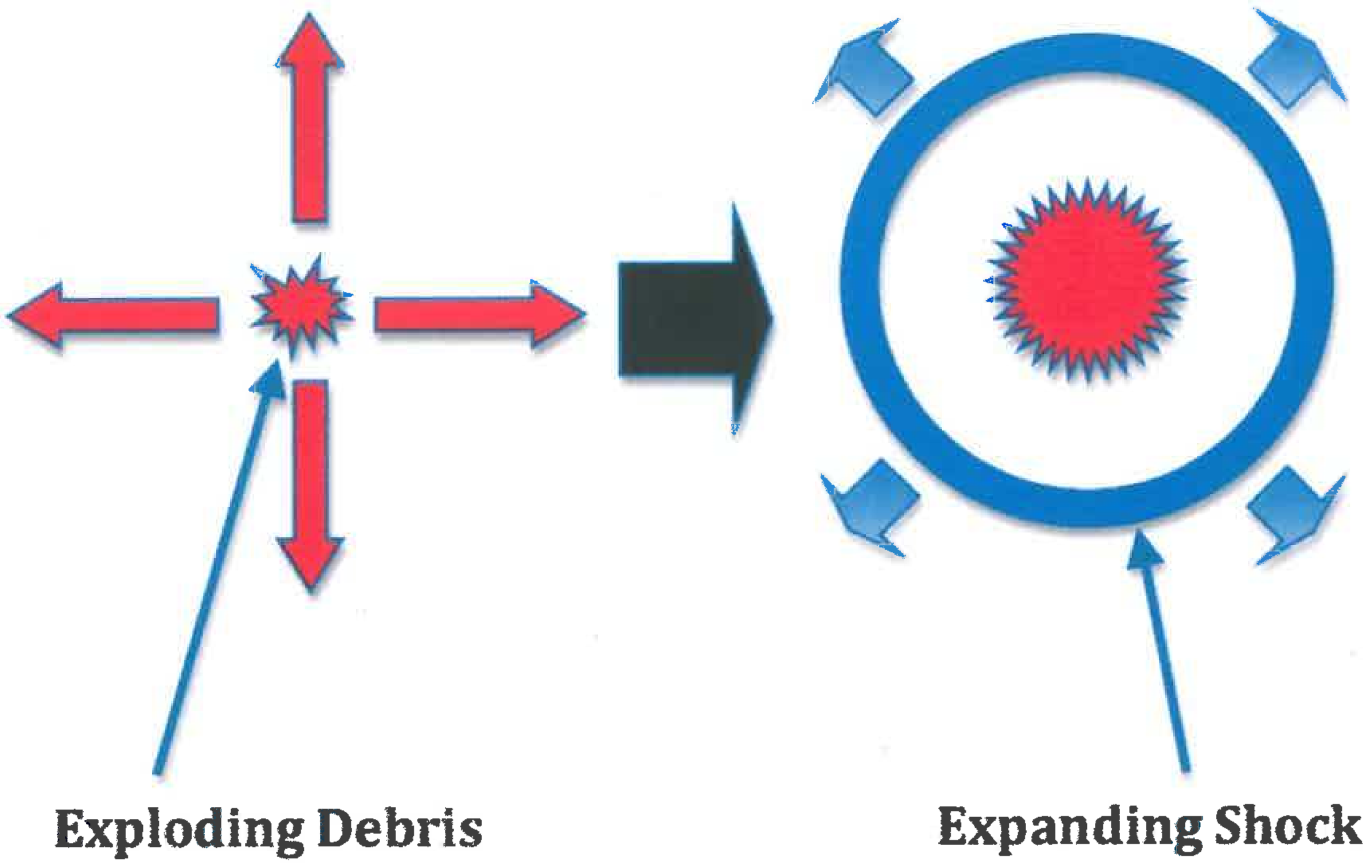
7. Questions to be answered with hybrid modeling:

- 1. **Plasma Cloud Formation and ionospheric plasma? Percolation/Reconnection at the magnetopause** (**Akhavan-Tafti et al. [2018, 2019]**).
- 2. **Formation of the shock-like impulses, whistler/shear Alfvenic waves, collapsing diamagnetic cavern triggered by plasma cloud** (**Recent Rev. by Winske, Huba, Niemann et al. [2019], Ed. by J.E. Borovsky**).
- 3. **Particle velocity distribution function dynamics and wave-particle interactions in plasma clouds environment.**

8. Hybrid Model

- *Kinetic - ions.*
- *Fluid - electrons. Scalar (tensor) electron pressure. Electron inertia.*
- *Interpenetrating flows*
- *Effects of finite ion gyroradius estimated with thermal and bulk velocities:* $k_\perp \rho_{ci} \geq 1$, $k_\| \rho_{ci} \geq 1$ *and* $l \approx \rho_{ci}; \quad \omega \approx \Omega_{ci}$
- *Energetic ion gyroradii are about* 10^4 *km in the ring current and outer radiation belt*
- *The modeling tool: (a)* **Standard PIC** *[Harlow, 1957, LANL Report]; (b)* **Shape Function Kinetics (SFK)** *[Larson & Young 2015] is a logical extension of* **Complex Particle Kinetics (CPK)** *[Hewett 2003; Lipatov 2012] and* **Finite Mass Method (FMM)** *[Yserentant et al. 1996-2007]*
- *The SFK and CPK* **aim to bridge the gap** *between continuum and kinetic methods. This method may save a computational resources by factor more than* 100 *in compare with Standard PIC method*

9. Scheme of the plasma cloud expansion. From Winske [2014].



10. Early research for dense plasma cloud/debris expansion in low density ambient background plasma.

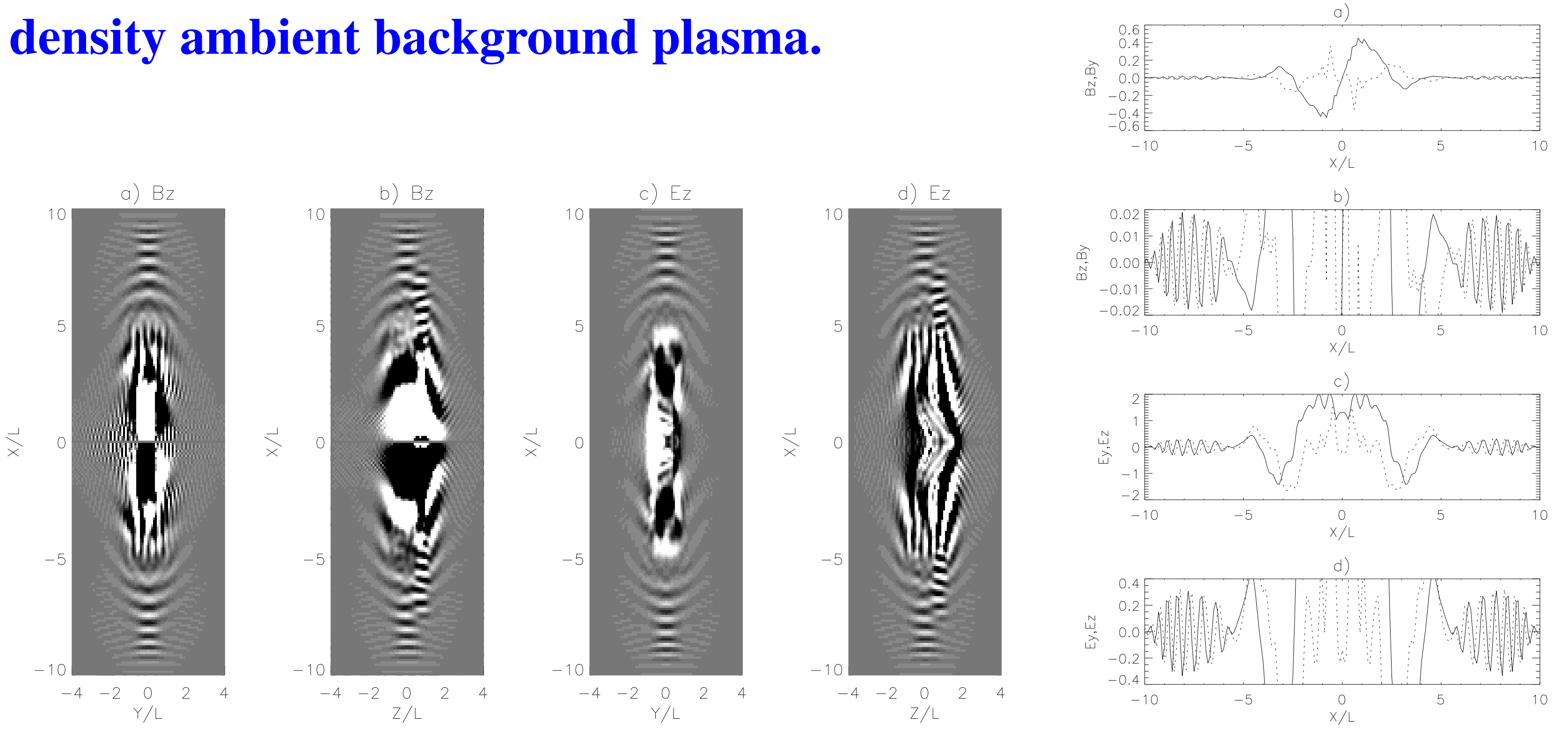


Figure 1: Dense plasma cloud expansion in low density ambient plasma at the initial stage. **Excitation of the right-hand-polarized whistler waves along the magnetic field and left-hand polarized whistler waves in the opposite direction.** 2-D cuts (left), 1-D cuts (right) of 3-D modeling from [Lipatov 1996; 2002]. 2.5-D in [Lipatov, Sharma, & Papadopoulos 1994]. **Shock formation by explosive debris** was observed in 2.5-D [Winske, Gary 2007], in 3-D Hewett, Larson, Brecht [2011]. See also Golubev et al. [1979]; Bashurin et al. [1983]; Antonov et al. [1985]; Brecht, Thomas [1987].

11. Set up the plasma cloud and ambient plasma configuration for our modeling:

Ambient upstream plasma:

density: $N_p = 2.5\,cm^{-3}$;

thermal velocity: $V_{th,p} = 100.0\,km/s$;

$V_{th,e} = 1000.0\,km/s$;

Alfvenic velocity: $V_A = 1217$ km/s;

bulk U: $U = (80; 80; 20)\,km/s$

B-field: $B = (40; 40; 20)\,nT$

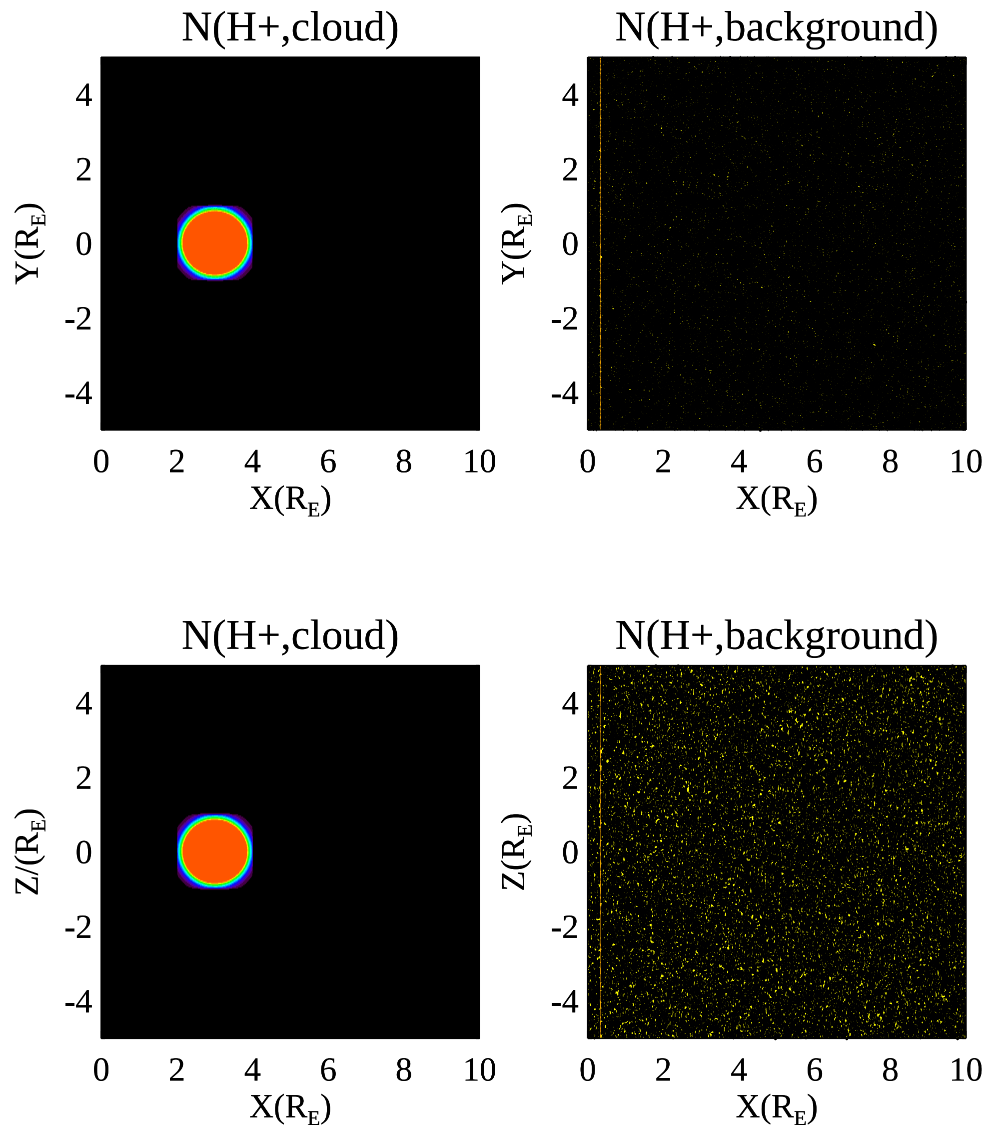
Plasma cloud:

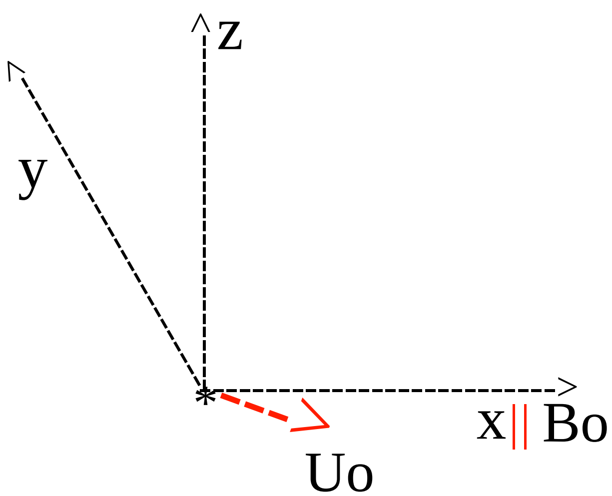
Gaussian 3-D profile for density:

$N_i = 400.0\,cm^{-3}$;

$V_{th,i} \approx 120\,km/s$; $V_{th,e} \approx 2500\,km/s$;

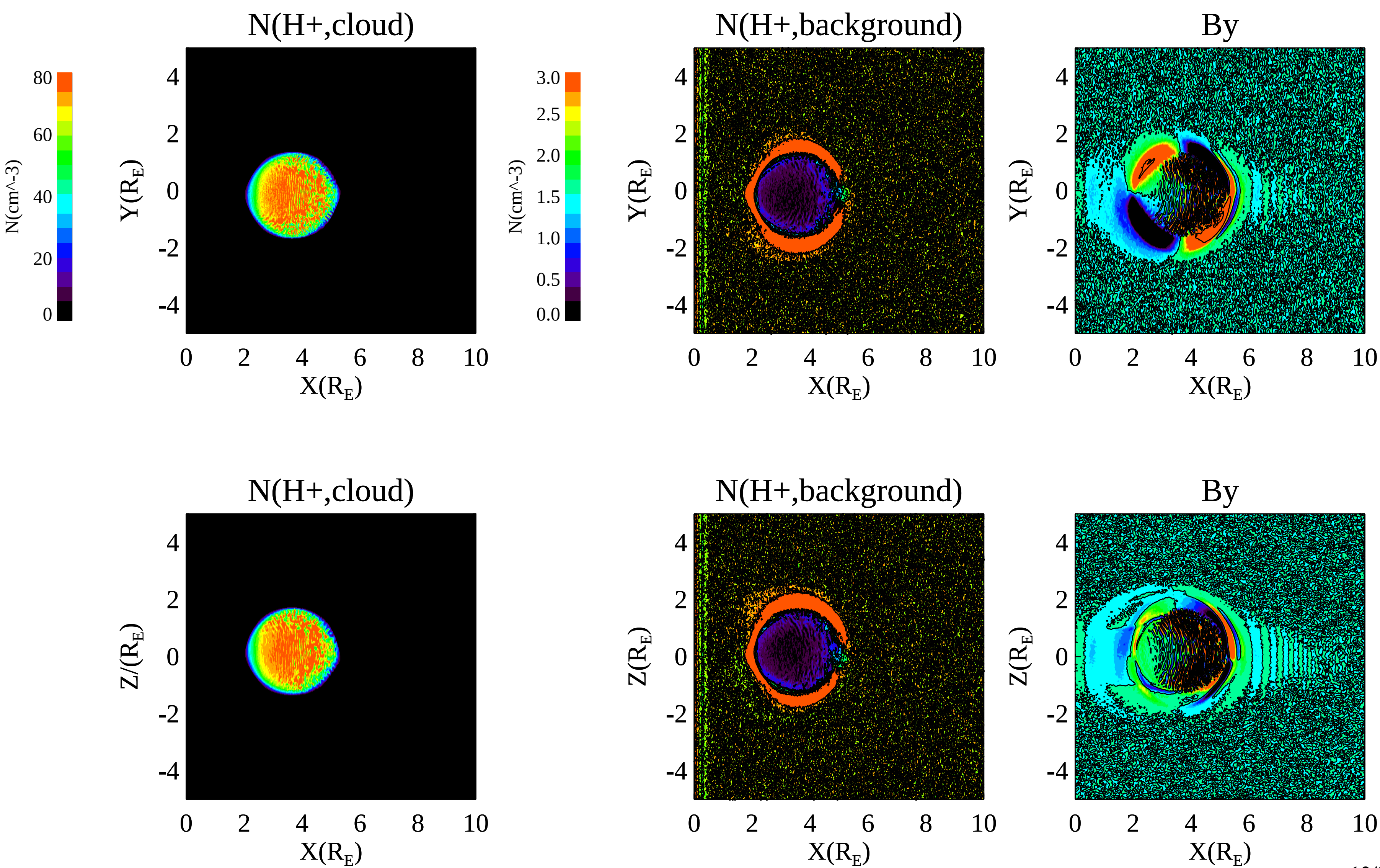
bulk U: $U = (350.0; 250.0; 0.0)\,km/s$



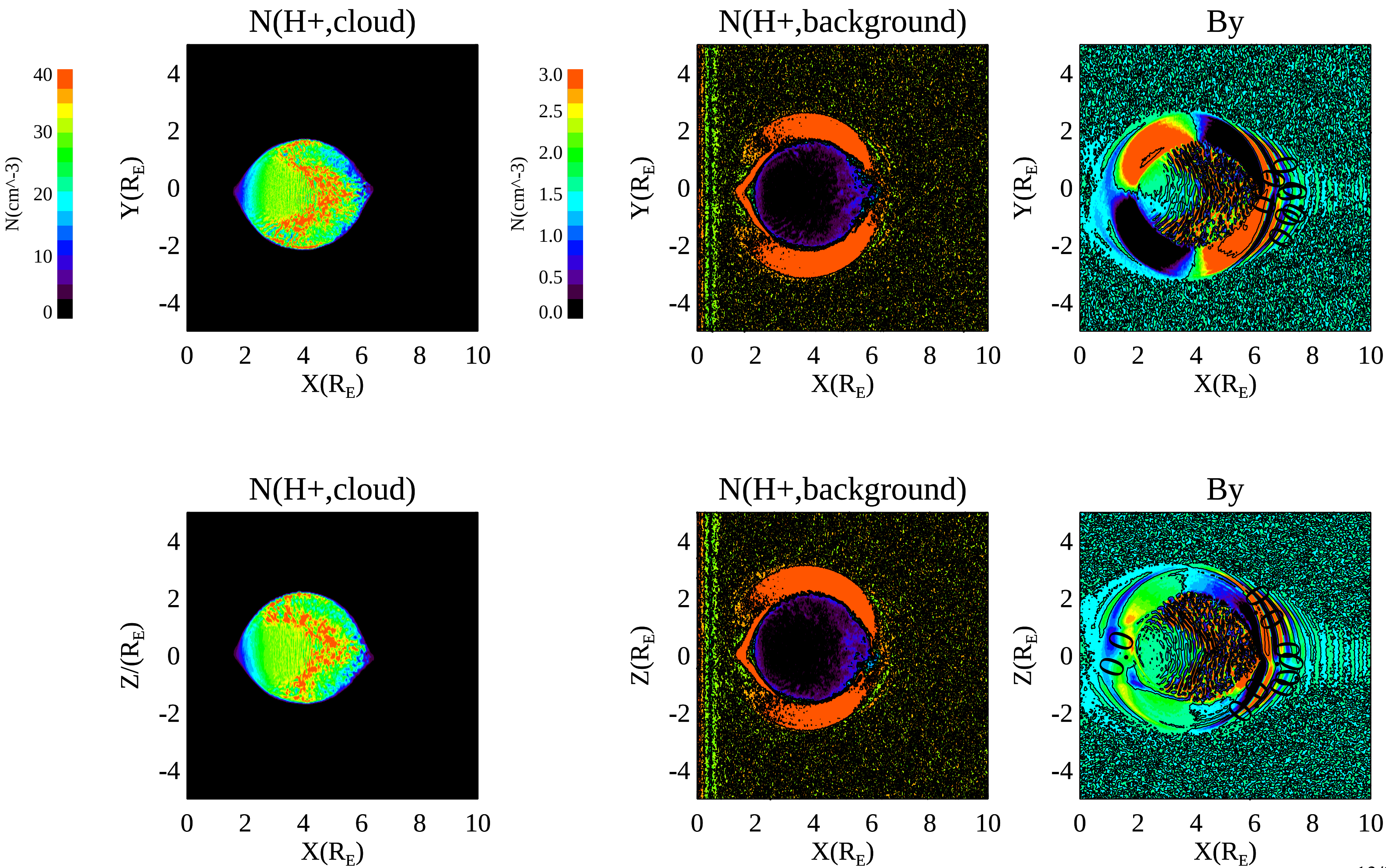


Modeling System of Coordinates

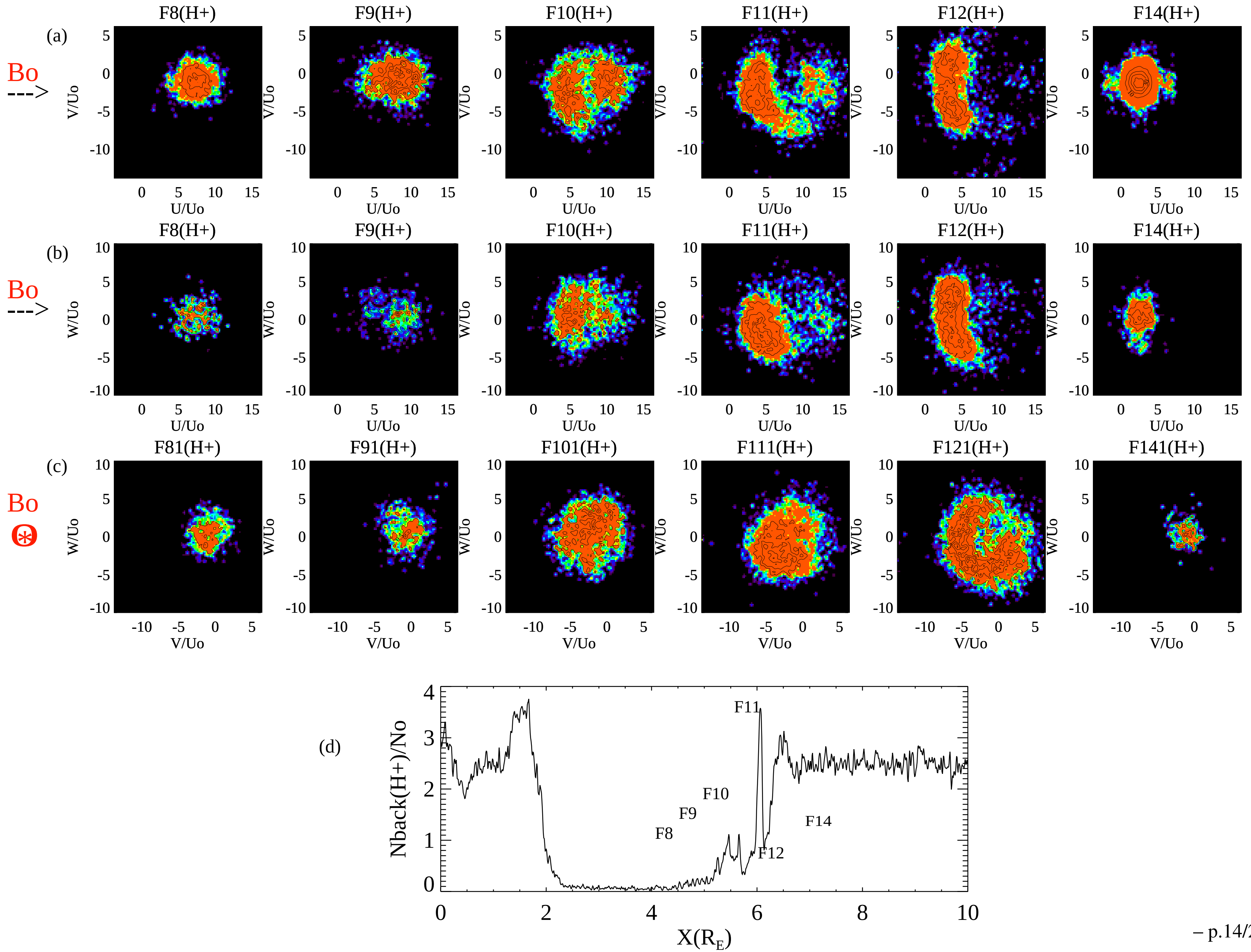
12. After the passage of the cloud. Perturbations in magnetic field and density profiles. $U_0 = 100$ km/s at time t=2.5 sec.



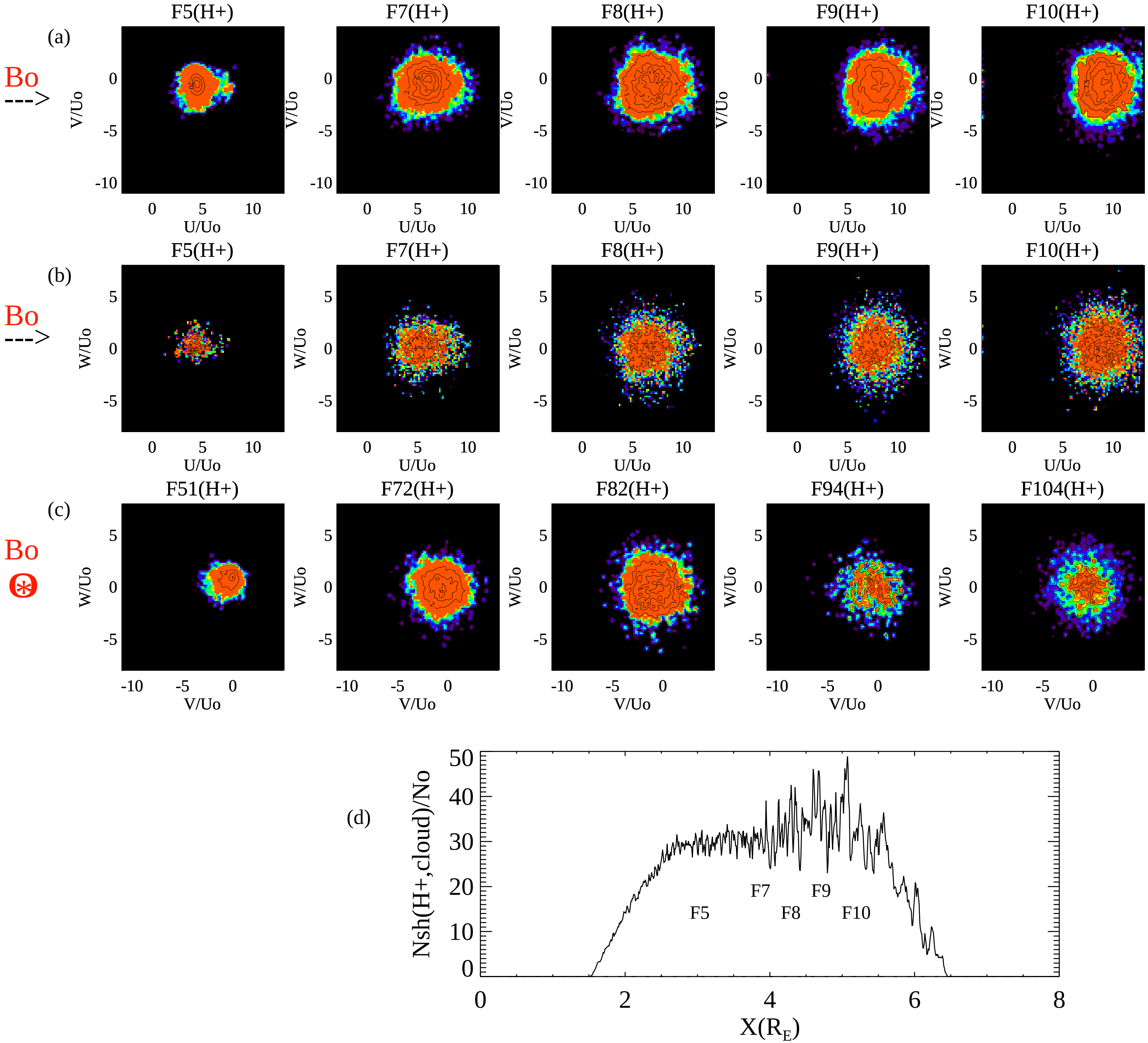
13. After the passage of the cloud. Perturbations in magnetic field and density profiles. $U_0 = 100$ km/s at time t=3.75 sec.



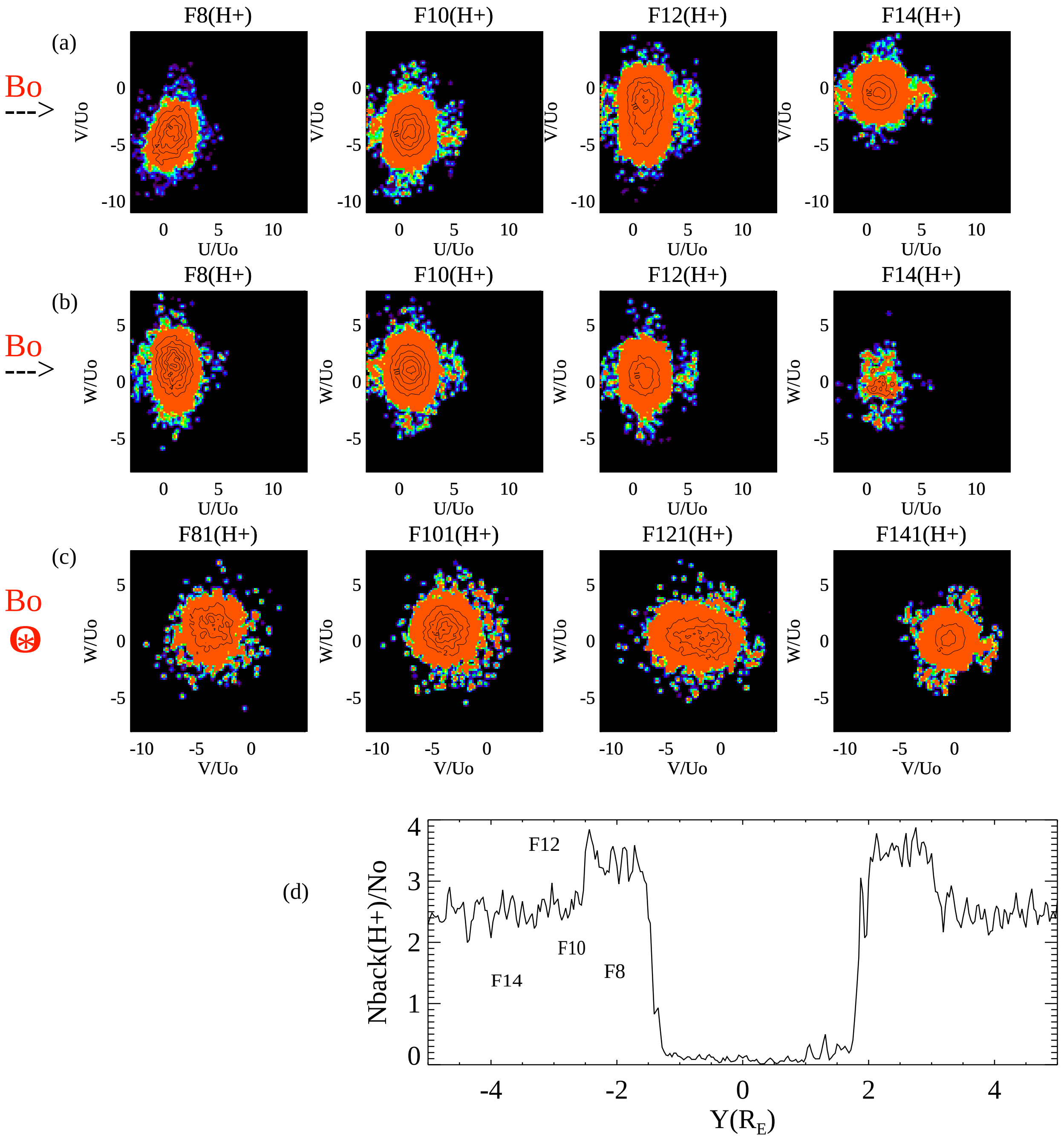
14. Non-Maxwellian ion VDF's (a,b,c-ambient) along x axis at time t=3.5 sec.



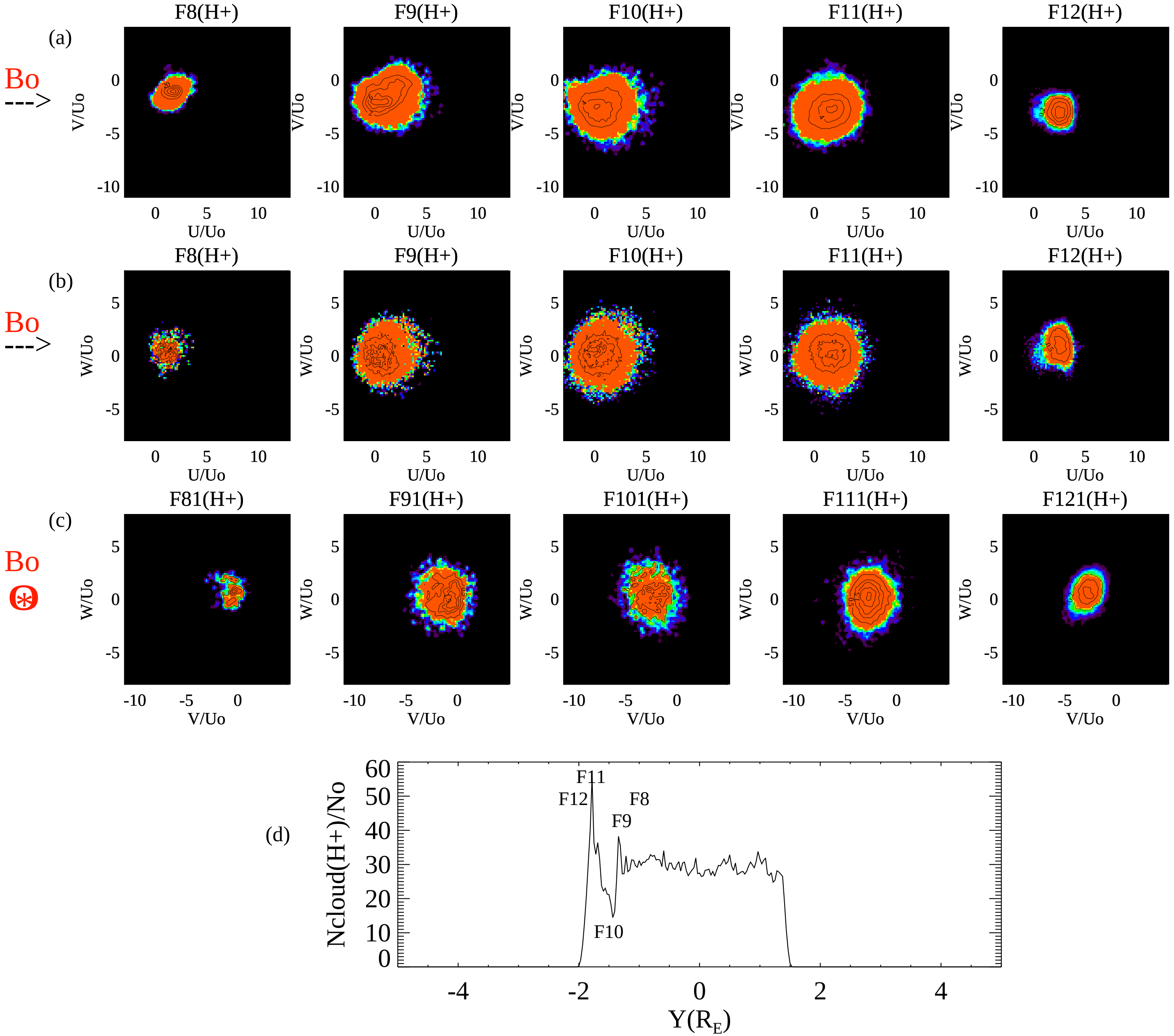
15. Non-Maxwellian ion VDF's (a,c,d-cloud) along x axis at time t=3.5 sec.



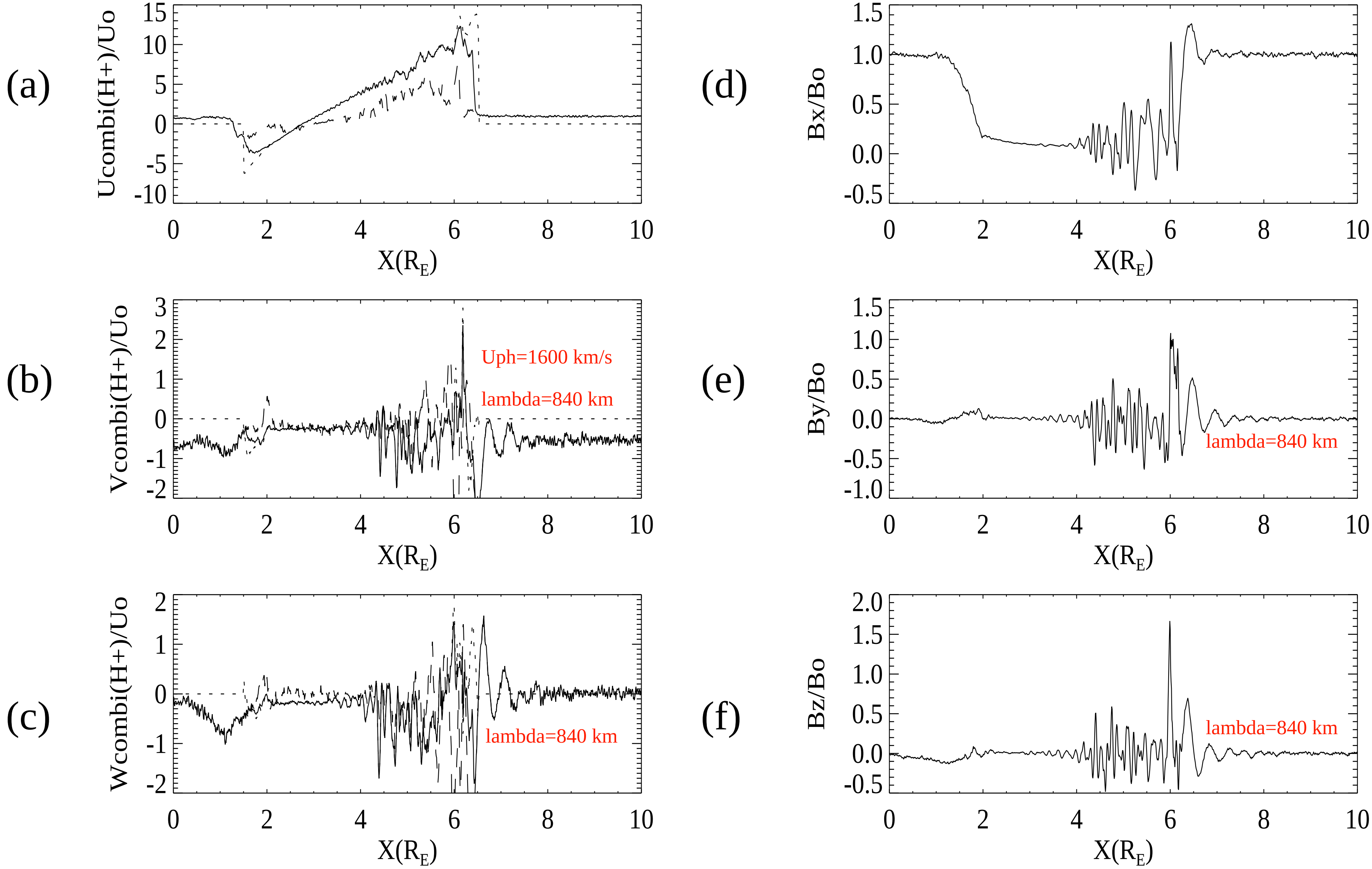
16. Non-Maxwellian ion VDF's (a,b,c -ambient) along y axis at time t=3.5 sec.



17. Non-Maxwellian ion VDF's (a,c,d-cloud) along y axis at time t=3.75 sec.

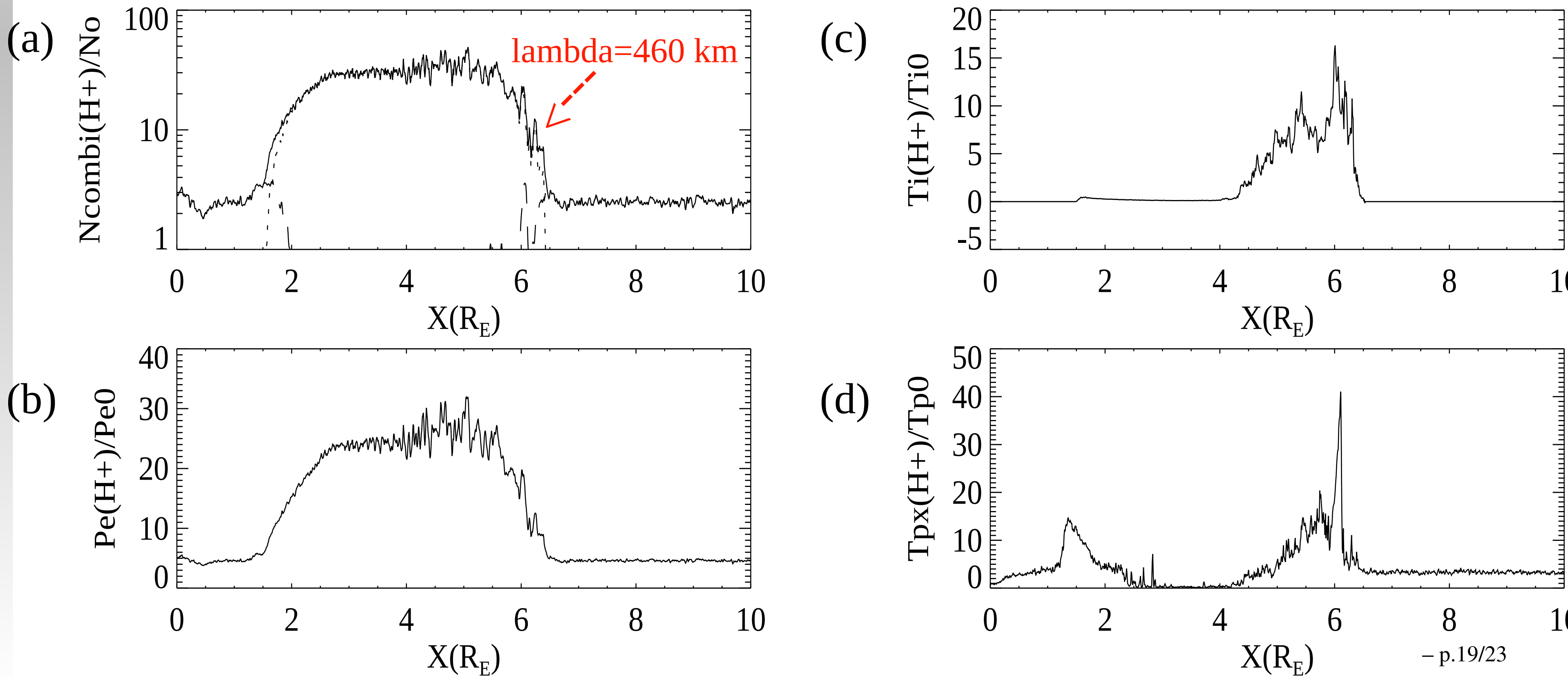


18. 1-D cuts of profiles for velocity and magnetic field along x axis at time t=3.5 s.

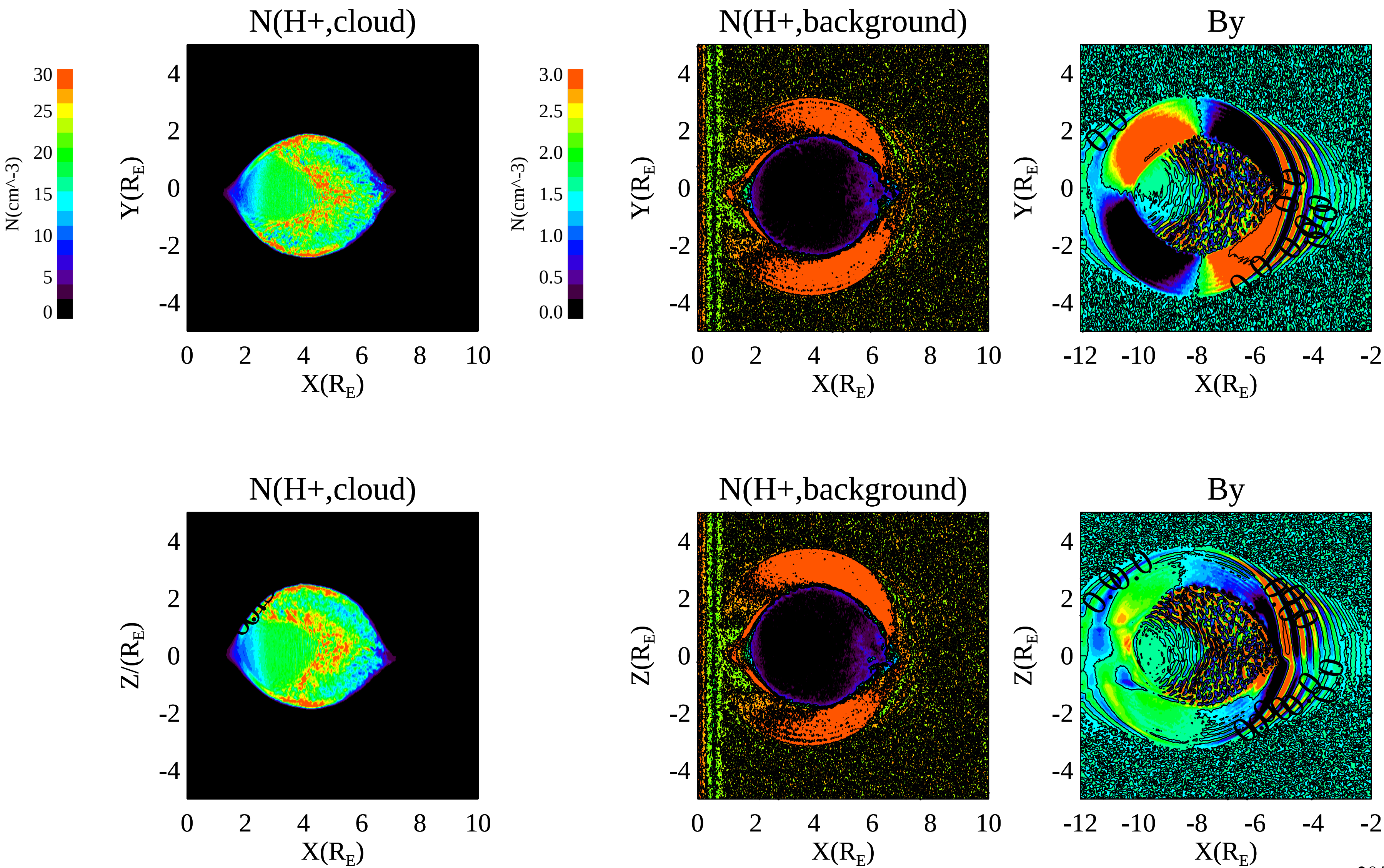


19. 1-D cuts of profiles along x axis at time t=3.5 sec.

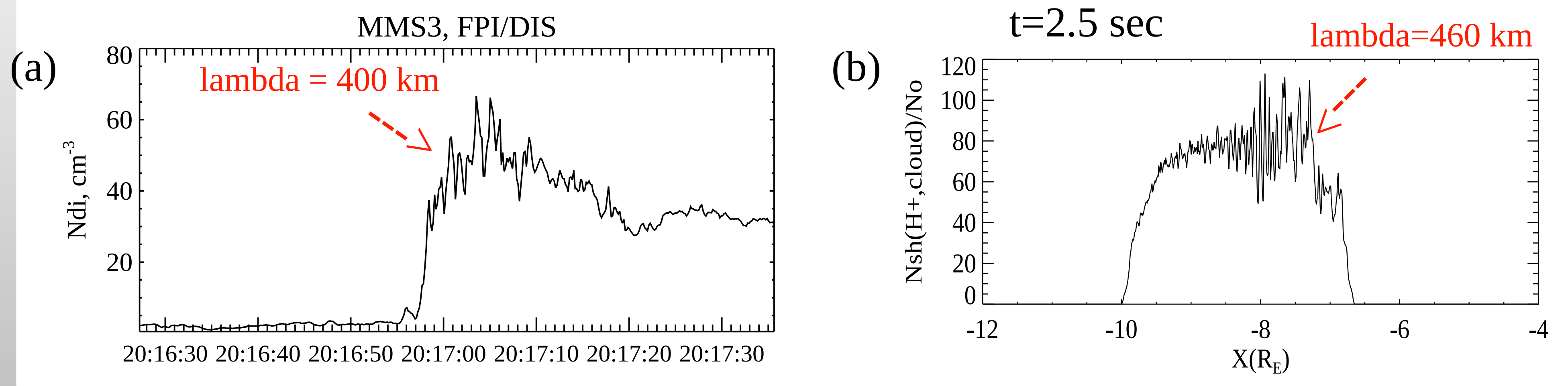
Quasi-overshoot and fluctuations in density profile



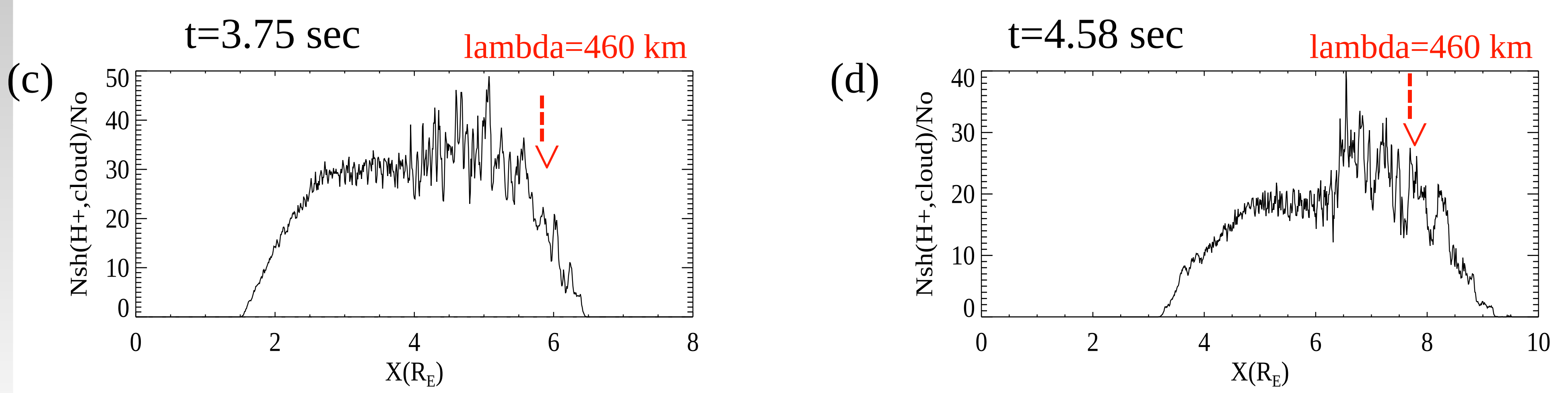
20. After the passage of the cloud. Perturbations in magnetic field and density profiles. $U_0 = 100$ km/s at time t=4.58 sec.



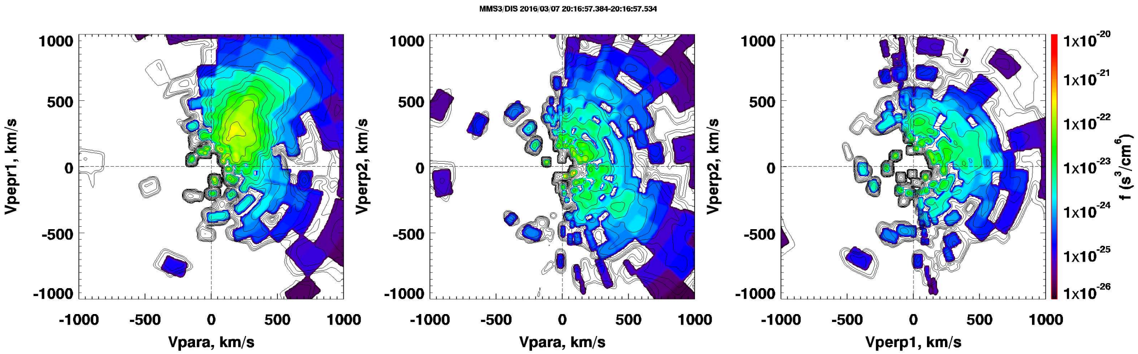
21. Comparison between MMS observation and modeling. Density profiles.

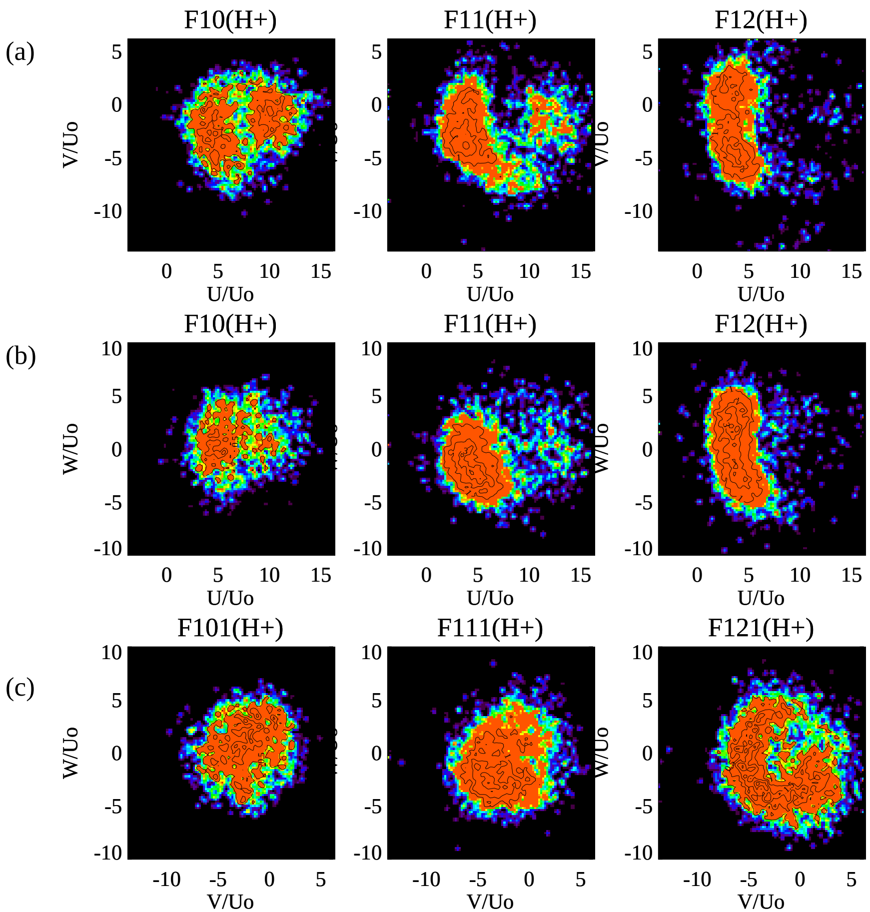


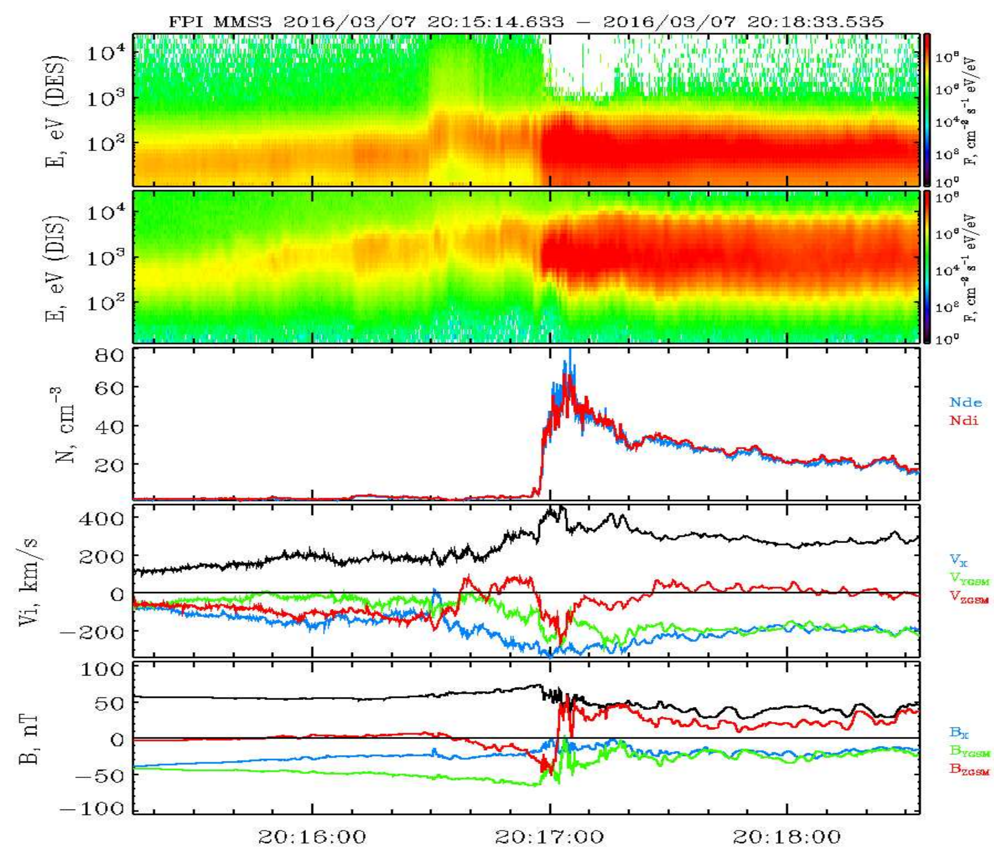
Quasi-overshoot and fluctuations in density profile



22. Ion VDFs. MMS observations (top) & modeling (bottom, left).







23. Summary

- **1. The interaction between plasma cloud and moving low-plasma beta ambient plasma produced a complicated 3-D structure of the plasma cloud.**
- **2. The plasma cloud forms a strong whistler/shear Alfvén waves directed along the external magnetic field while a strong compression waves are formed across the external magnetic field.**
- **3. A strong heating and acceleration of the ambient ions are observed in the regions at the interface between the plasma cloud and ambient plasma.**
- **4. The modeling shows a strong depletion in the ambient plasma due to the cloud expansion. Such effect is a similar to a formation of the diamagnetic cavern observed in the active experiment for plasma injection (AMPTE) into the magnetosphere and plasma cloud generation in the ionosphere.**
- **5. The anisotropy of the ion VDF's may trigger EMIC waves and other instabilities like the mirror-ballooning instability.**

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