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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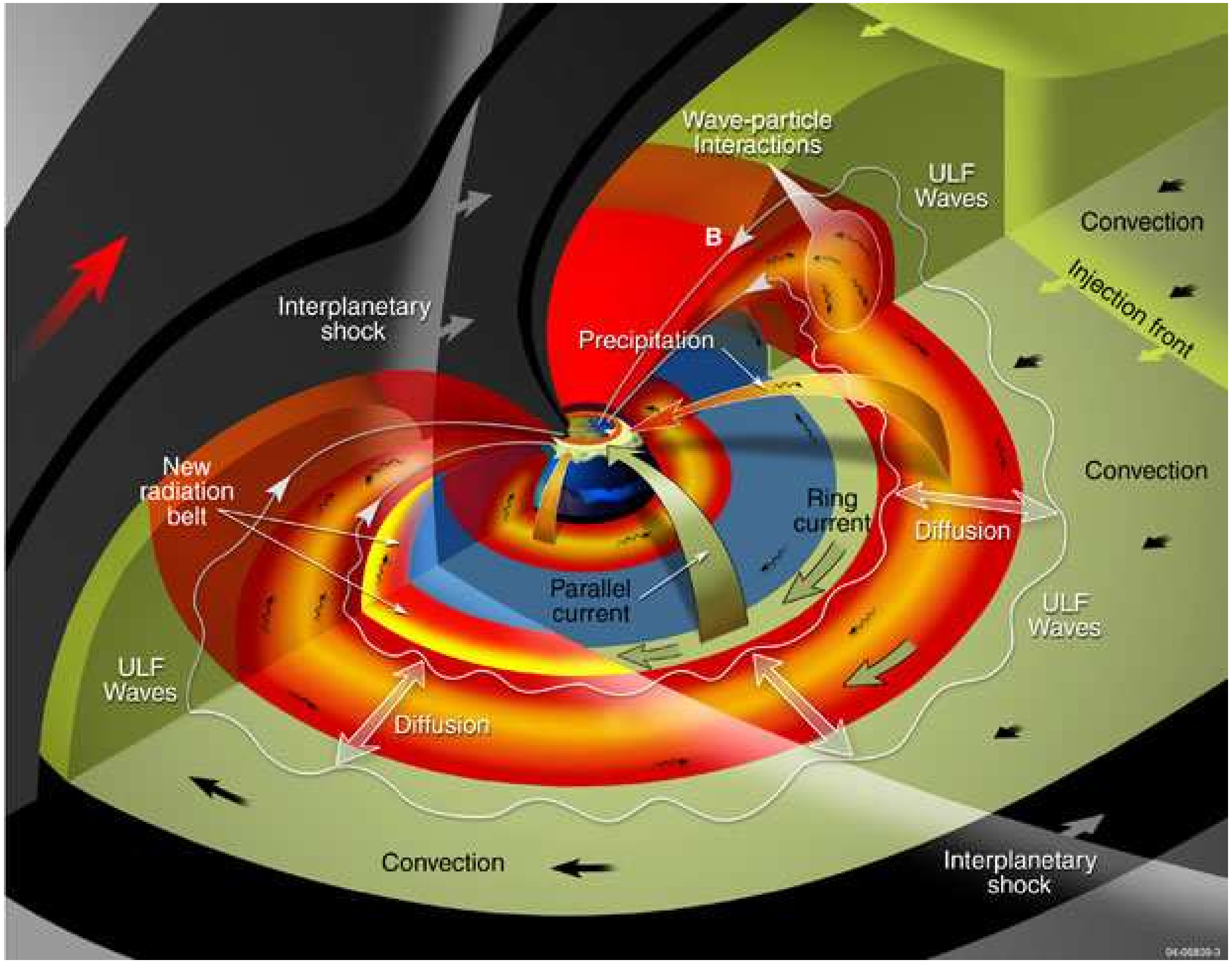
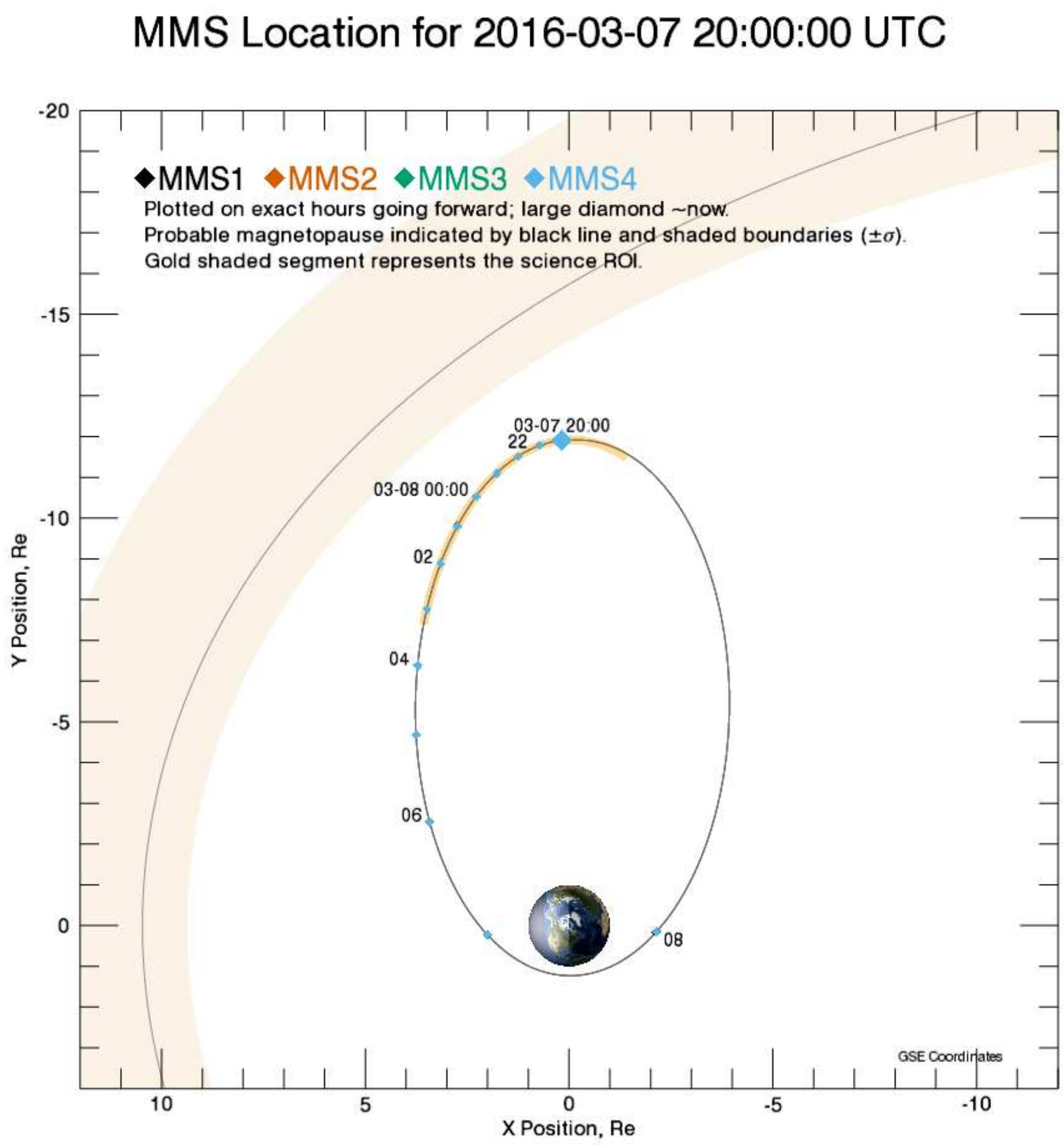
2. Motivation and Applications:

- 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).**

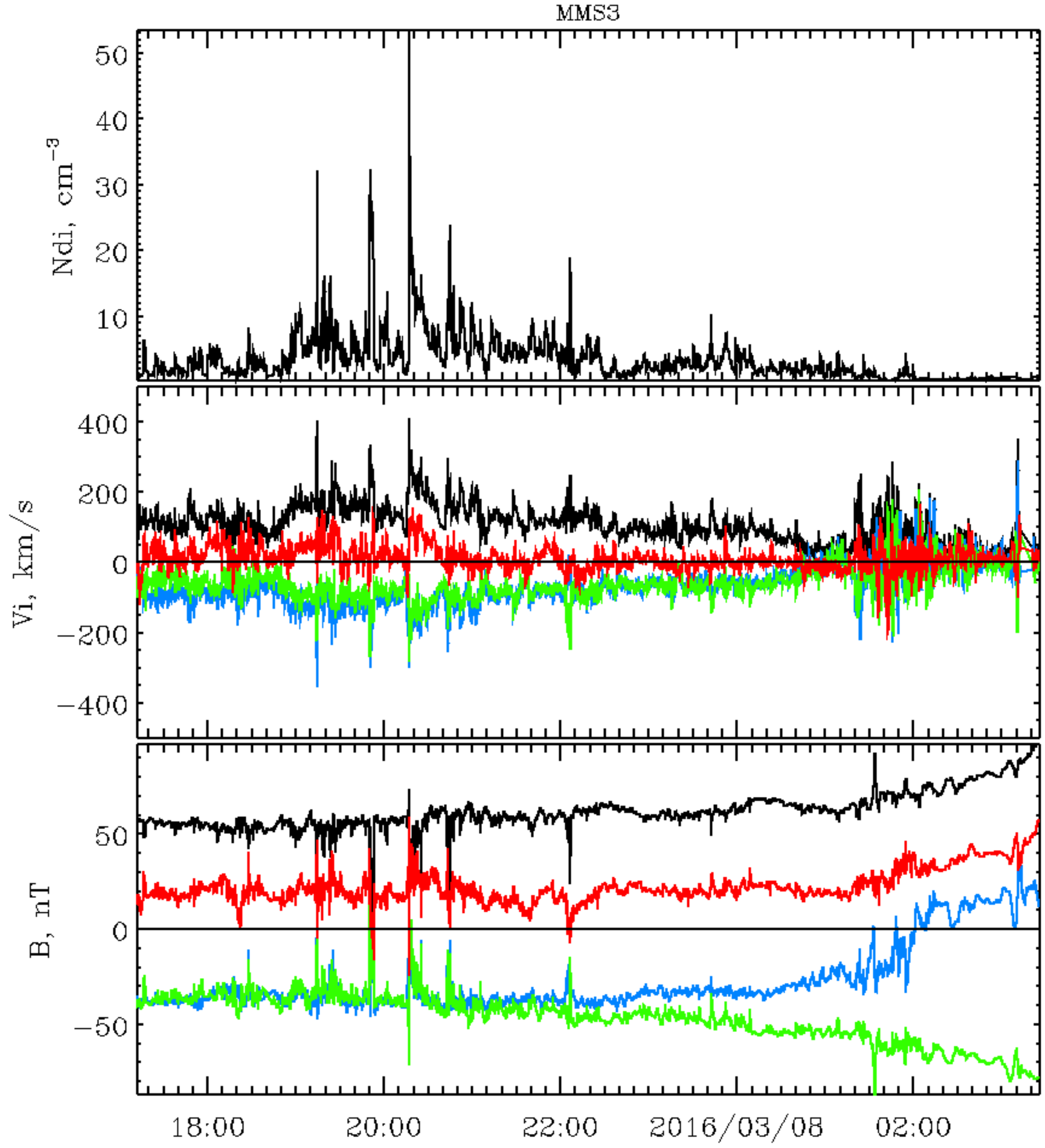
3. Scheme of the Earth magnetosphere, radiation belts and interplanetary shock



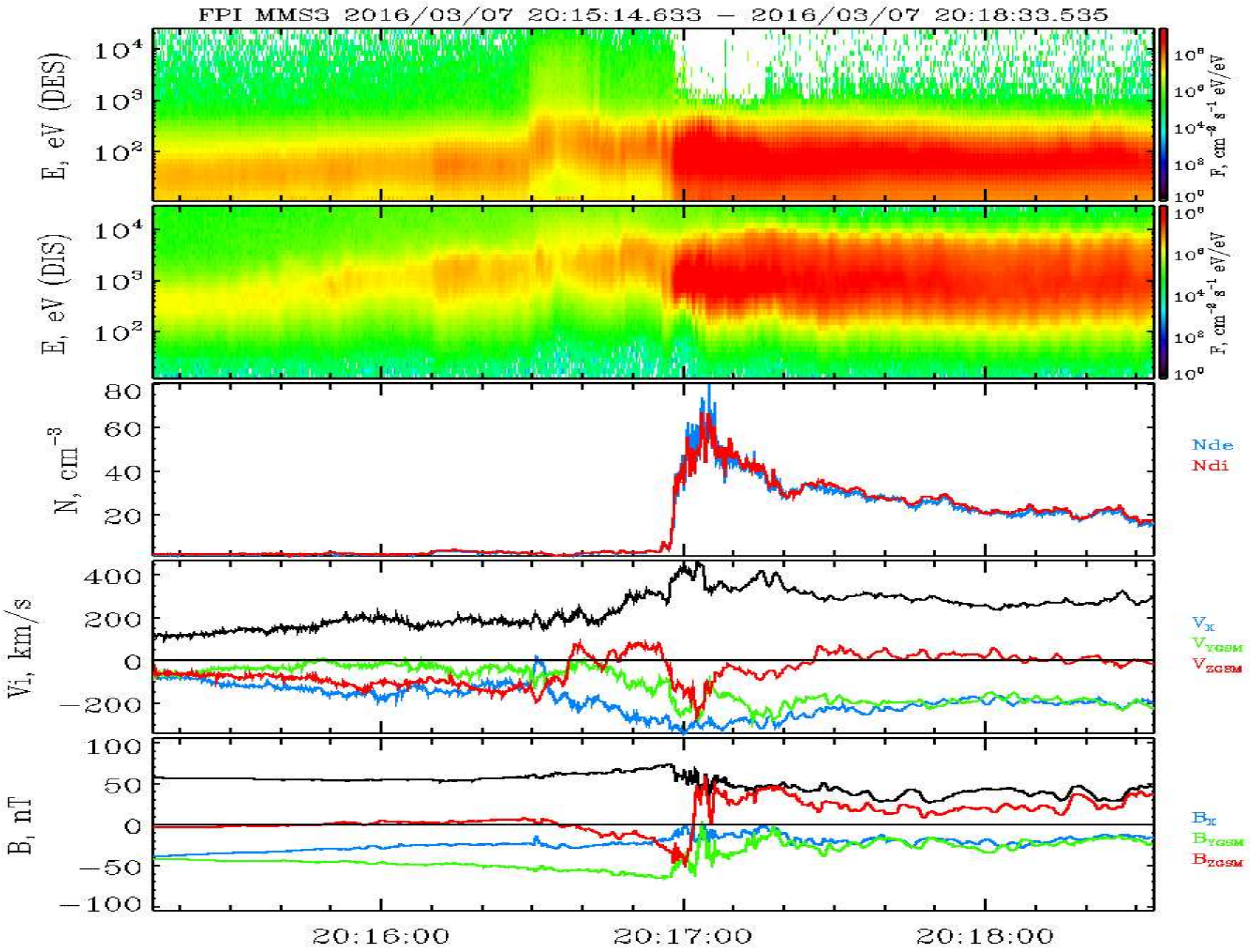
4. MMS satellite position at time 2016-03-07 20:00:00 UTC



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



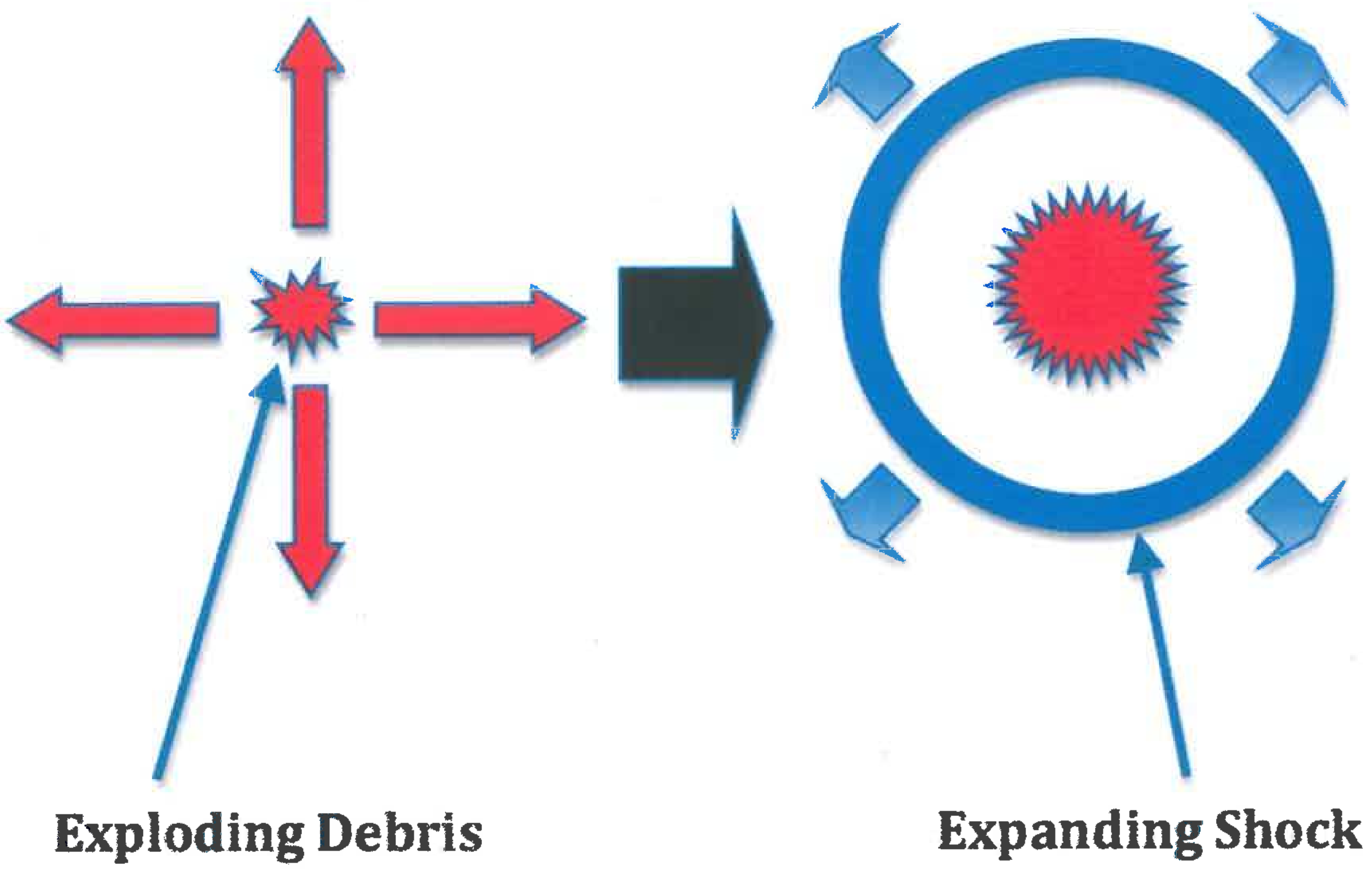
7. Questions to be answered with hybrid modeling:

- 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.

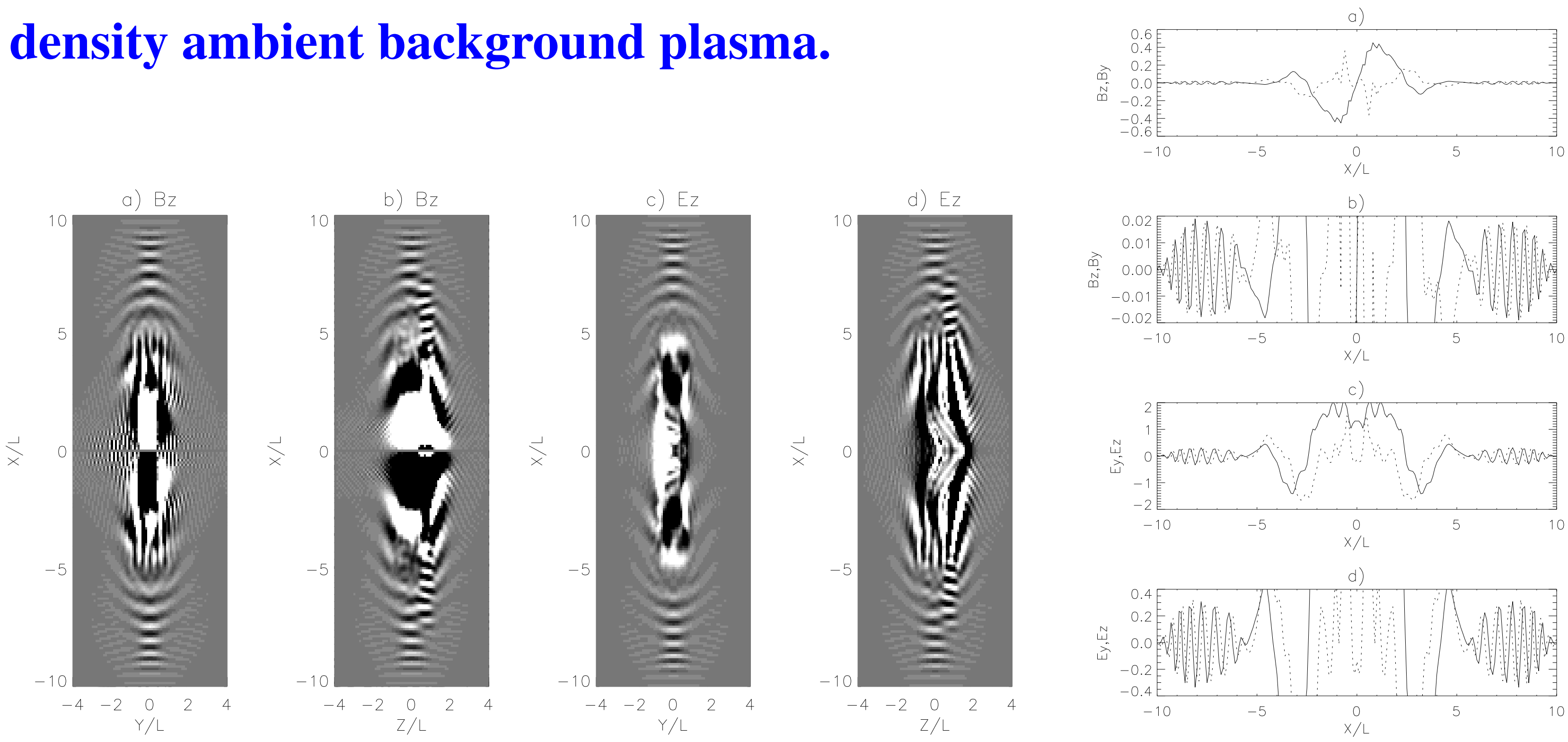


Figure 1: Dense plasma cloud expansion in low density ambient plasma at the initial stage. **Excitation of the right-hand-polarized whistler waves along the magnetic field and left-hand polarized whistler waves in the opposite direction.** 2-D cuts (left), 1-D cuts (right) of 3-D modeling from [Lipatov 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: $B = (40; 40; 20)\,nT$

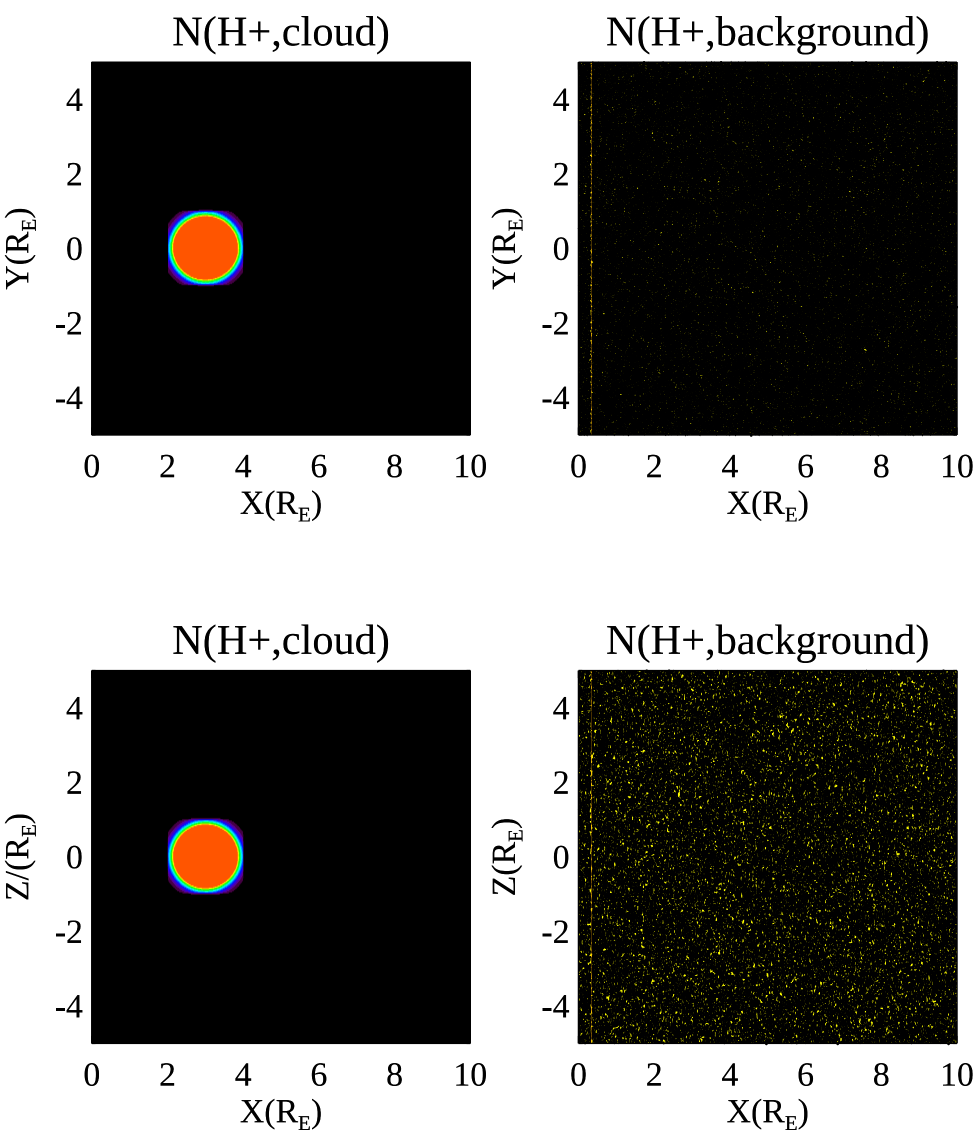
Plasma cloud:

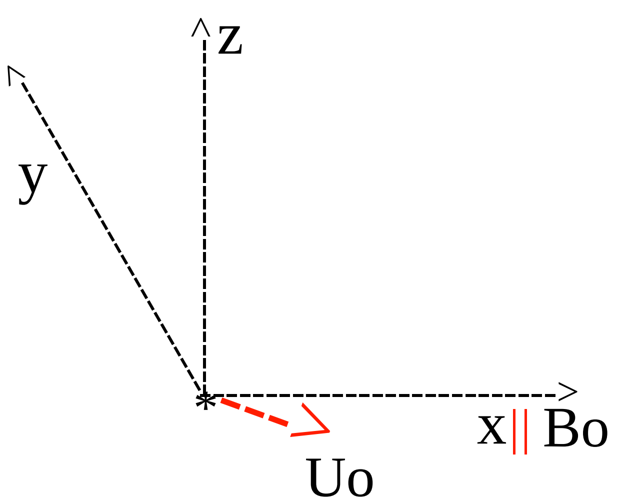
Gaussian 3-D profile for density:

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

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

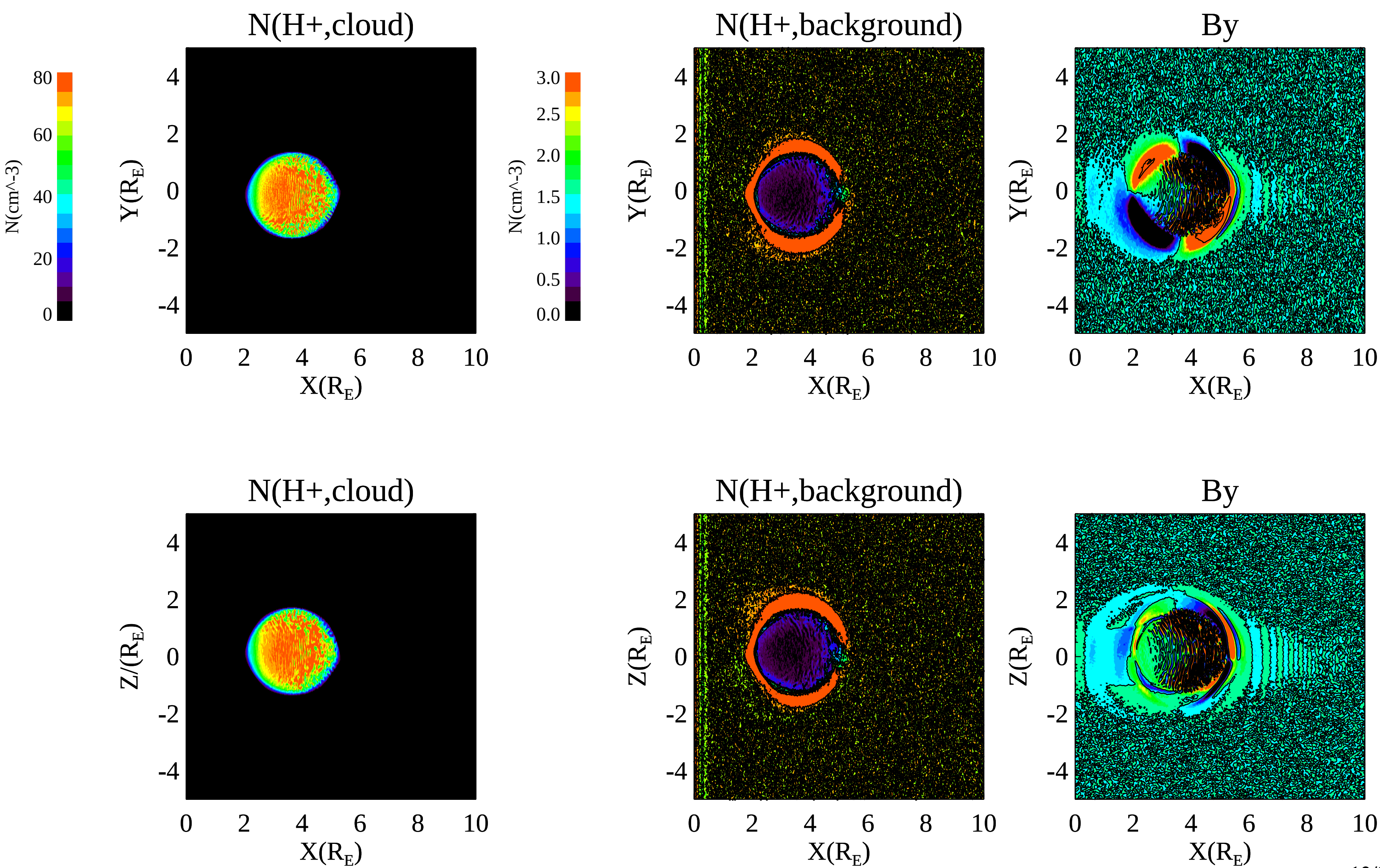
bulk U: $U = (350.0; 250.0; 0.0)\,km/s$



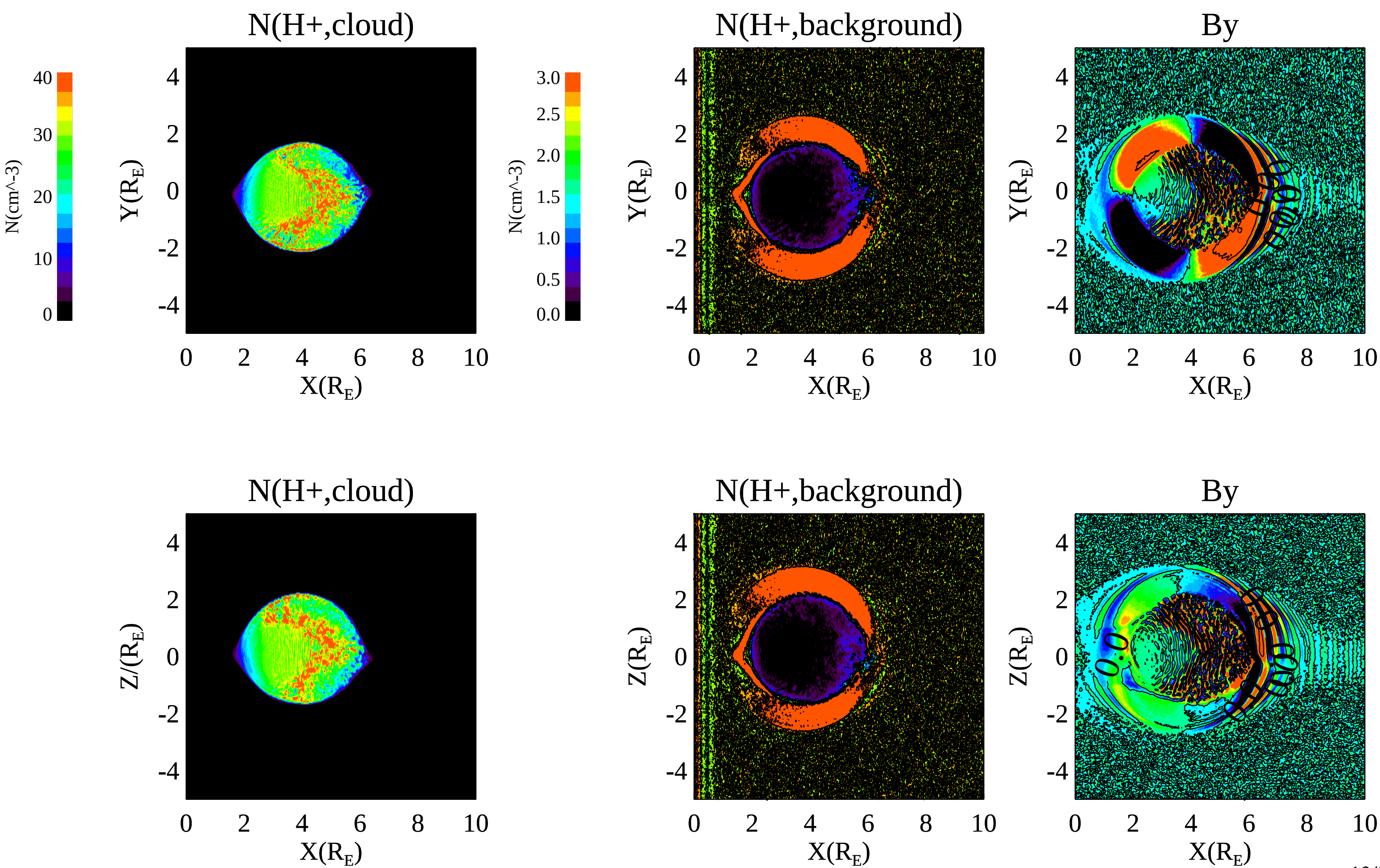


Modeling System of Coordinates

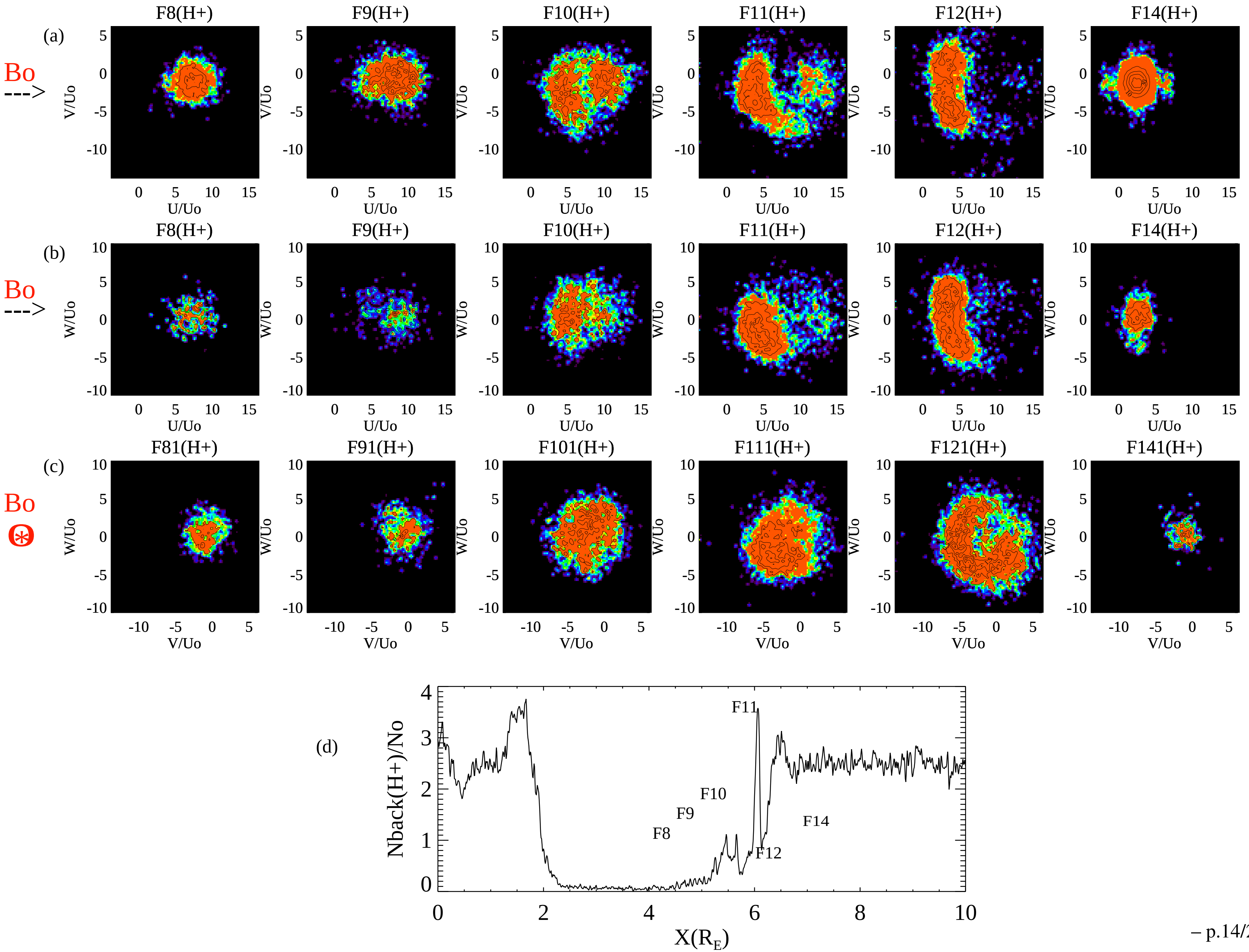
12. After the passage of the cloud. Perturbations in magnetic field and density profiles. $U_0 = 100$ km/s at time t=2.5 sec.



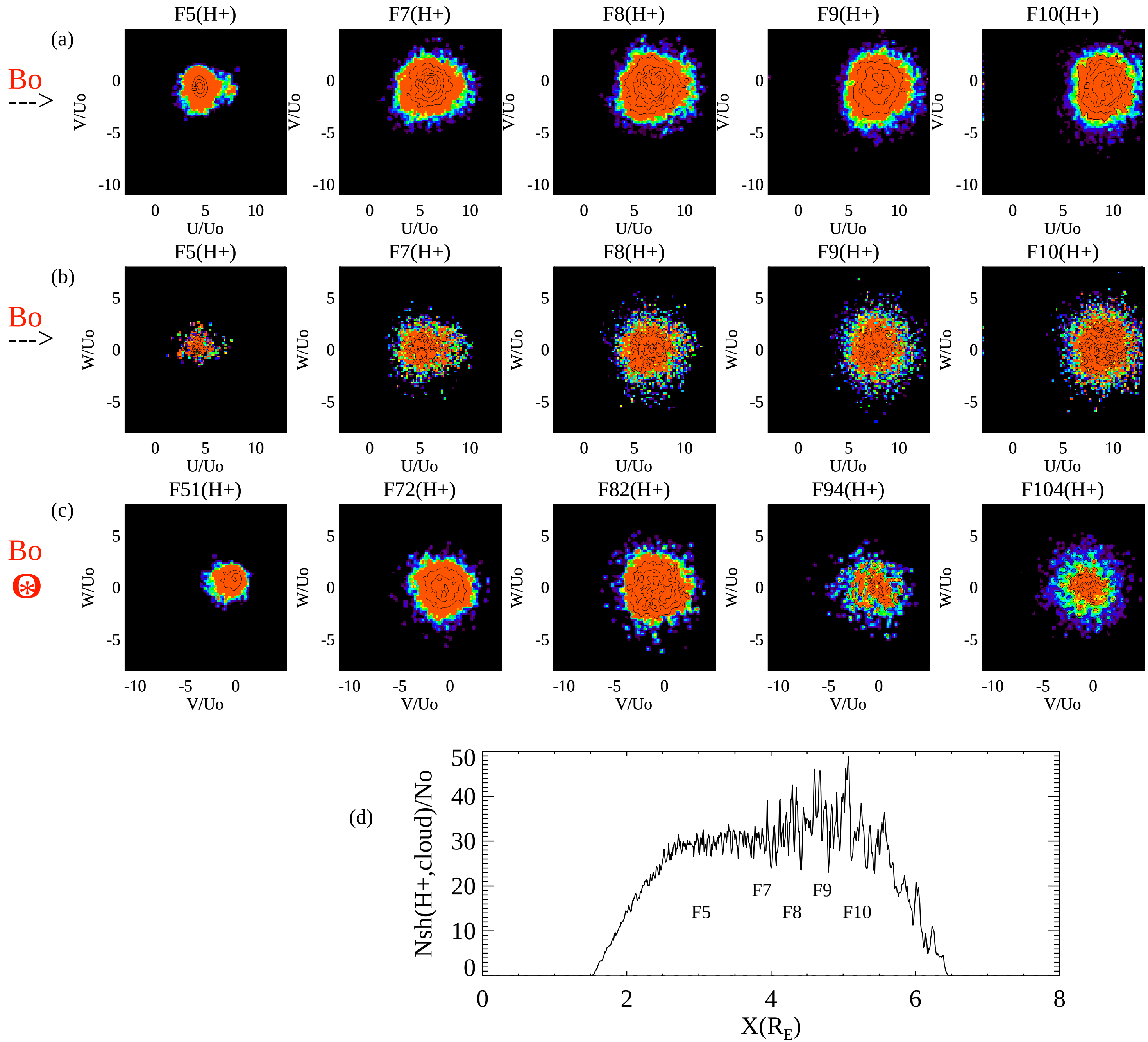
13. After the passage of the cloud. Perturbations in magnetic field and density profiles. $U_0 = 100$ km/s at time t=3.75 sec.



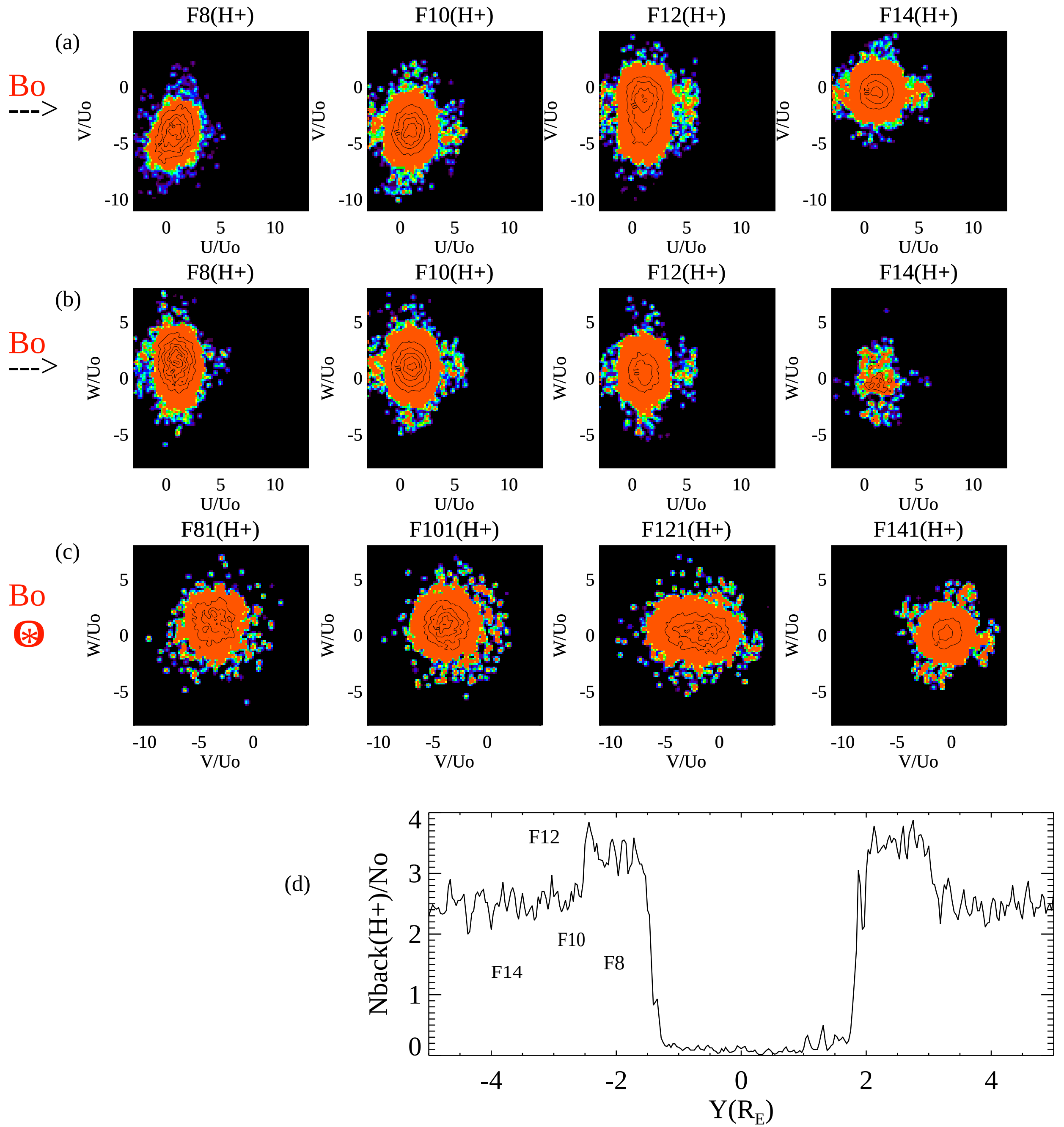
14. Non-Maxwellian ion VDF's (a,b,c-ambient) along x axis at time t=3.5 sec.



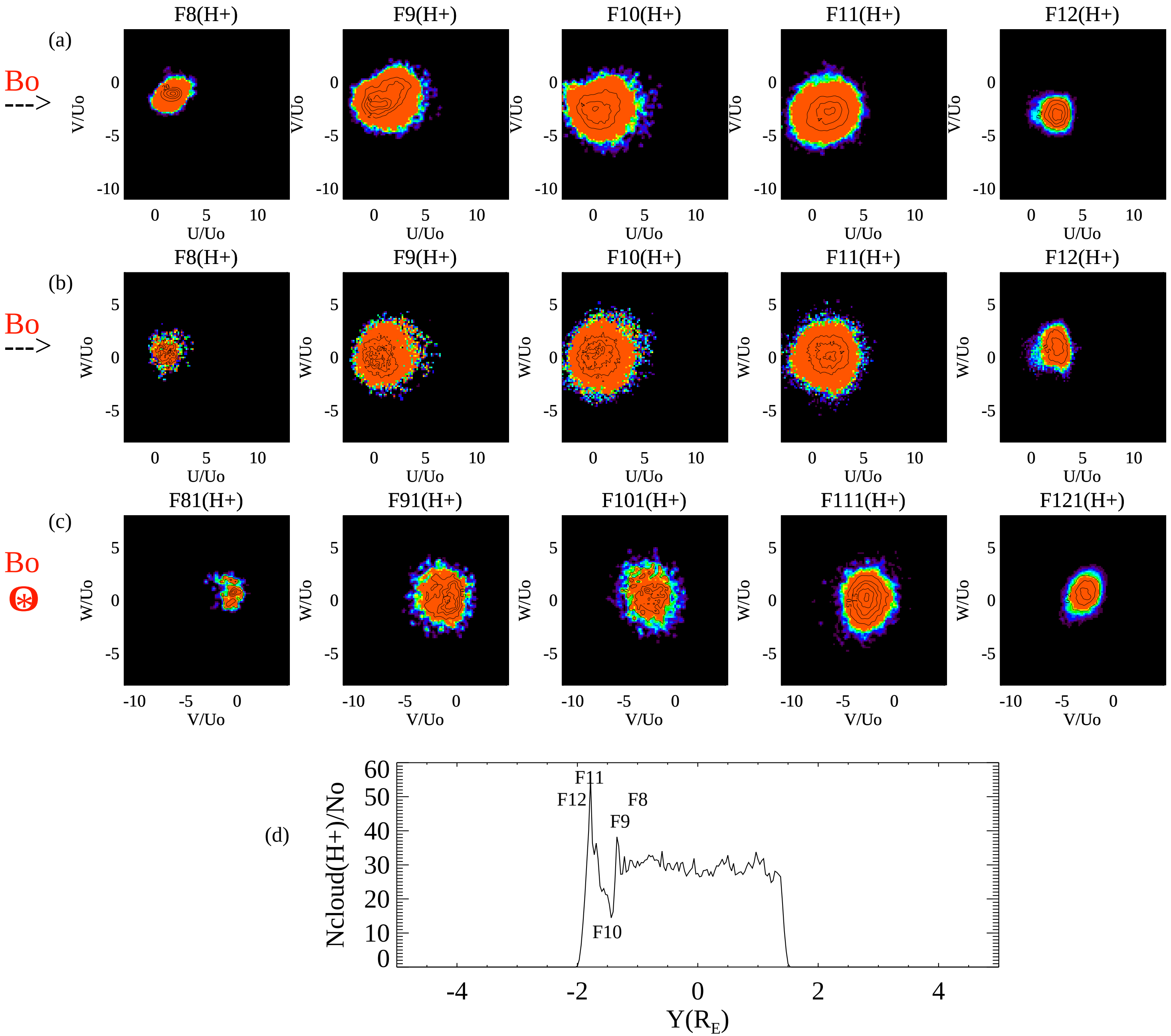
15. Non-Maxwellian ion VDF's (a,c,d-cloud) along x axis at time t=3.5 sec.



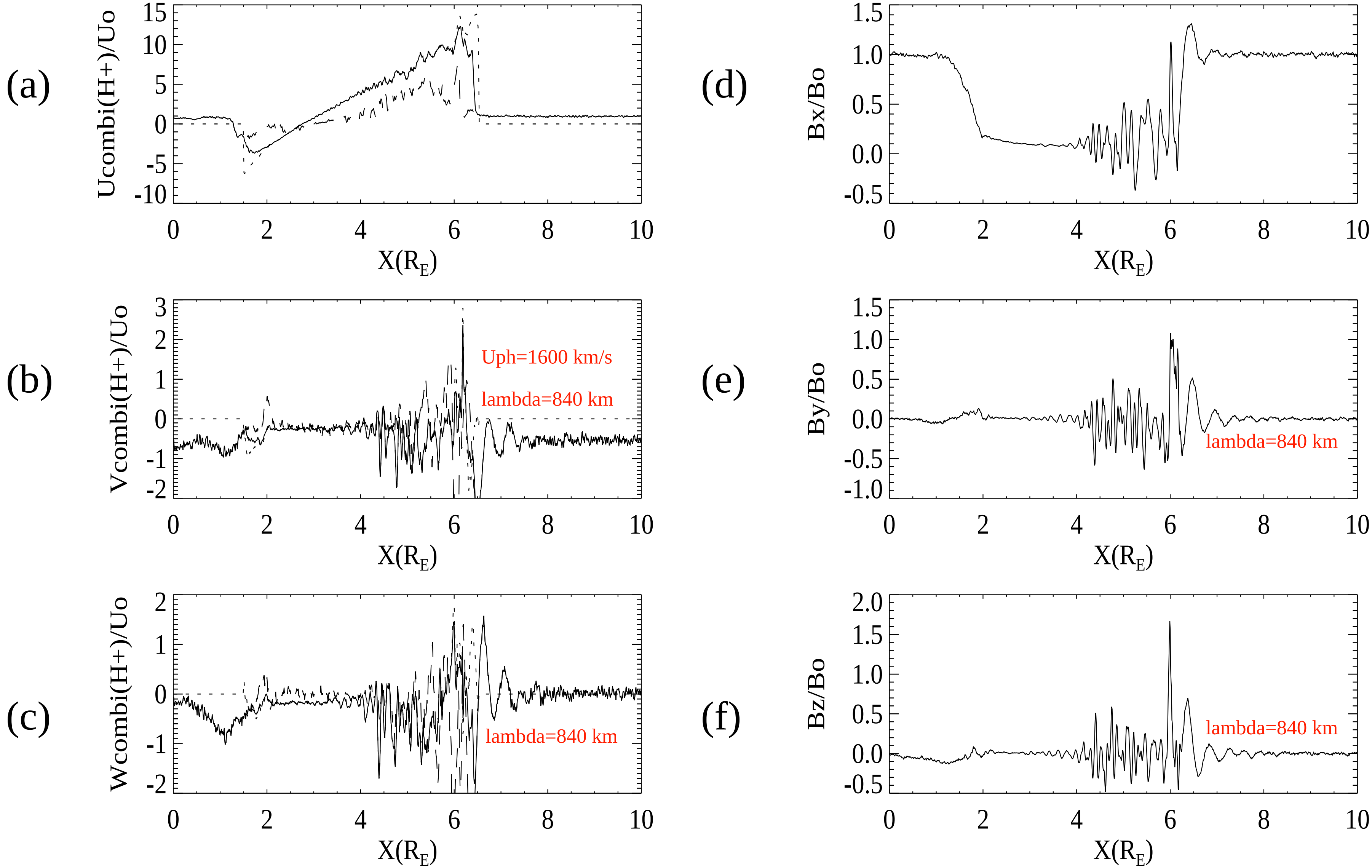
16. Non-Maxwellian ion VDF's (a,b,c -ambient) along y axis at time t=3.5 sec.



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

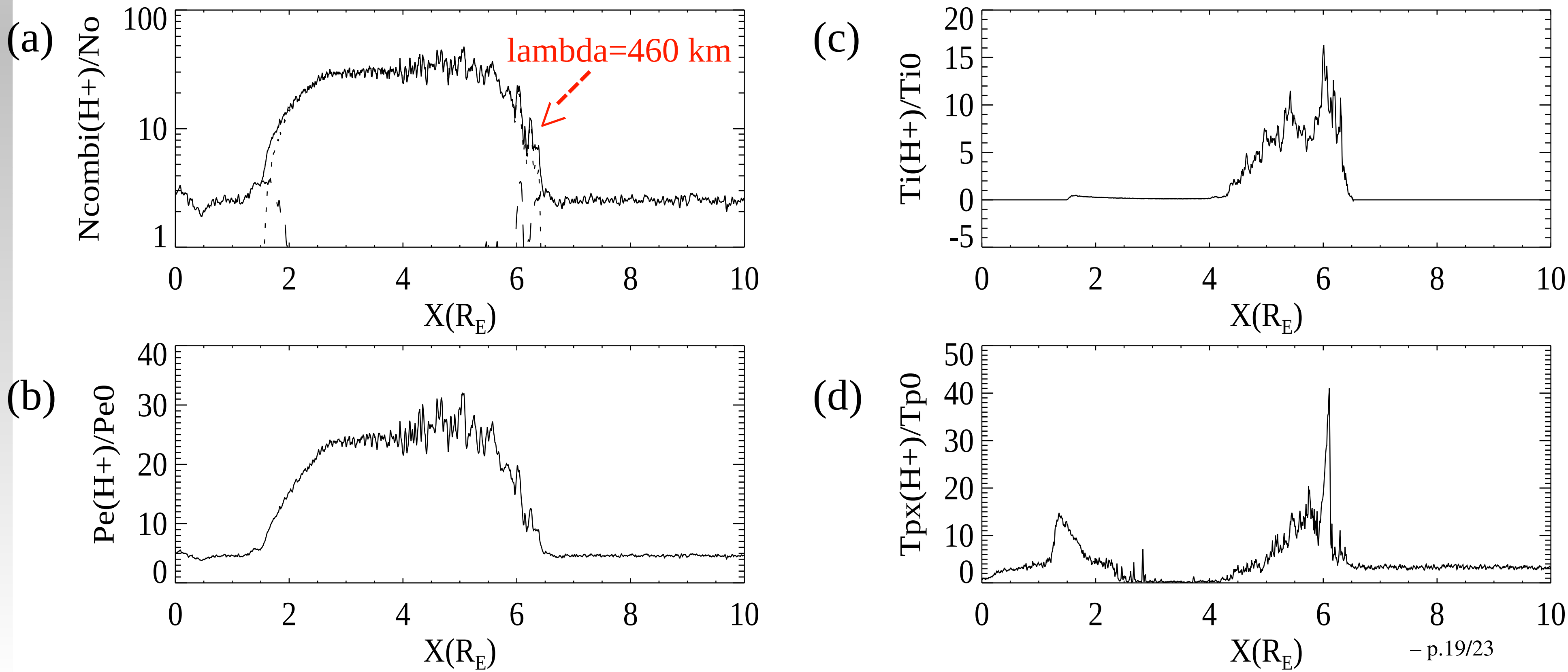


18. 1-D cuts of profiles for velocity and magnetic field along x axis at time t=3.5 s.

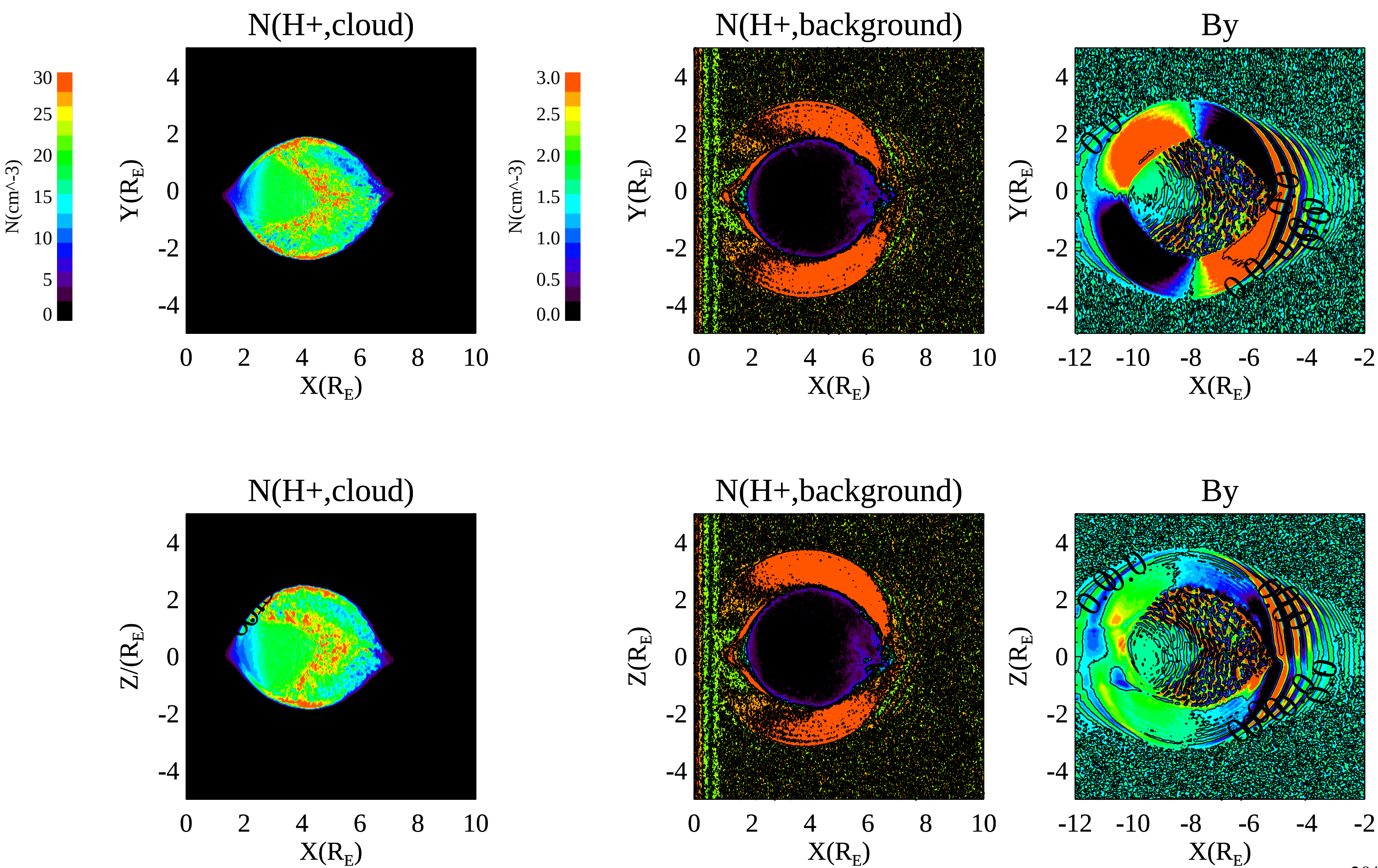


19. 1-D cuts of profiles along x axis at time t=3.5 sec.

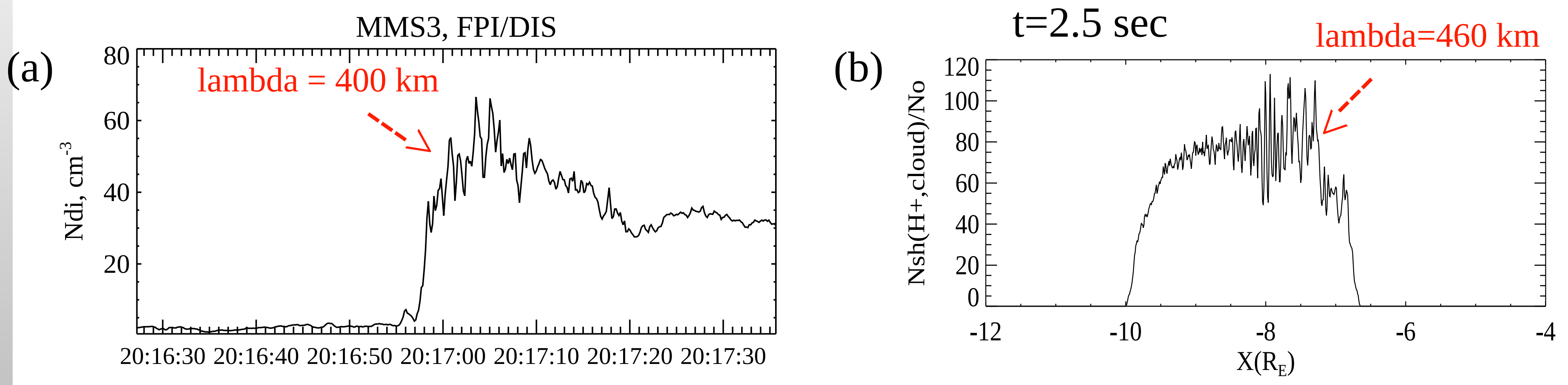
Quasi-overshoot and fluctuations in density profile



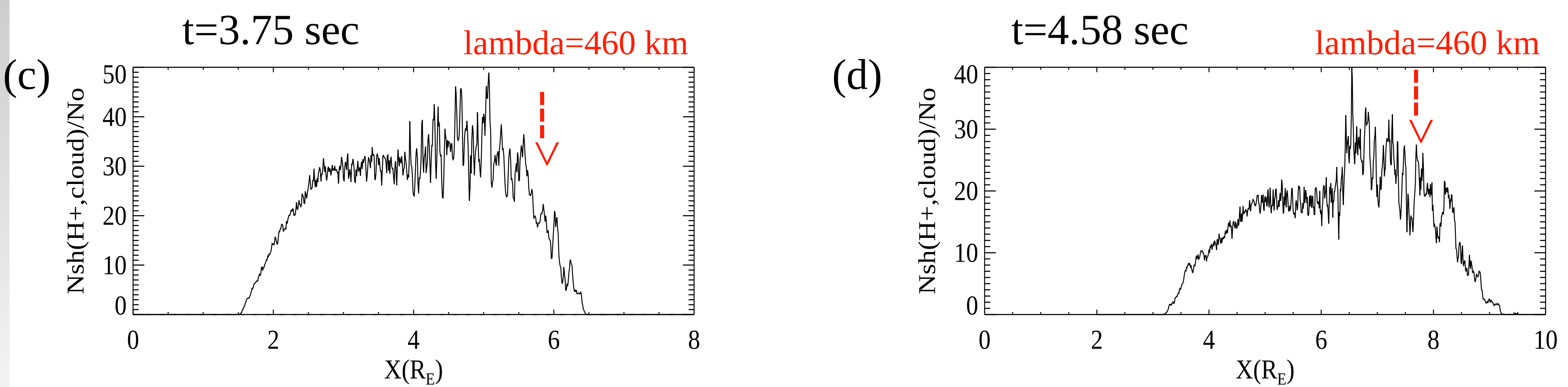
20. After the passage of the cloud. Perturbations in magnetic field and density profiles. $U_0 = 100$ km/s at time t=4.58 sec.



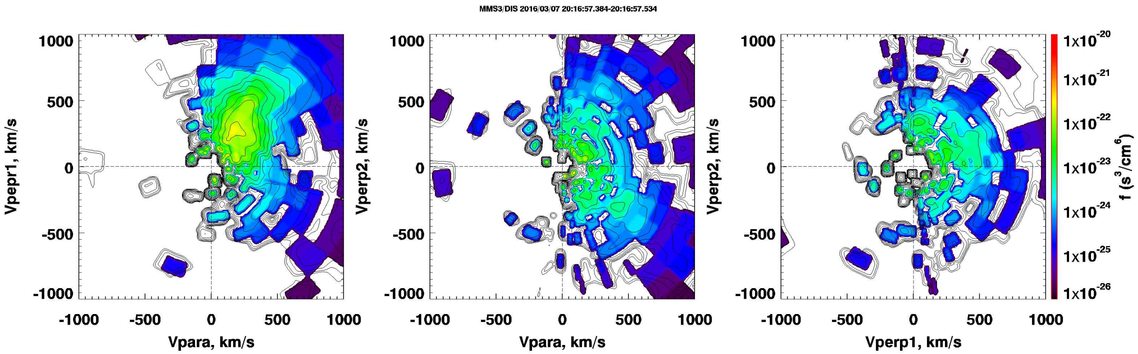
21. Comparison between MMS observation and modeling. Density profiles.

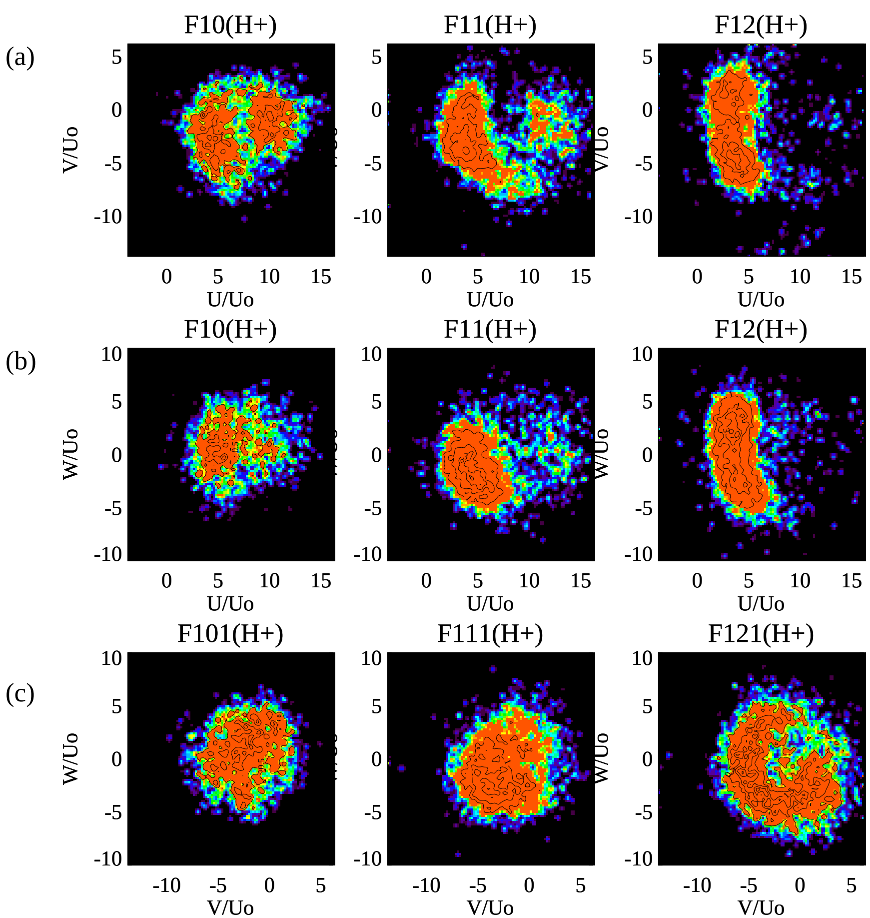


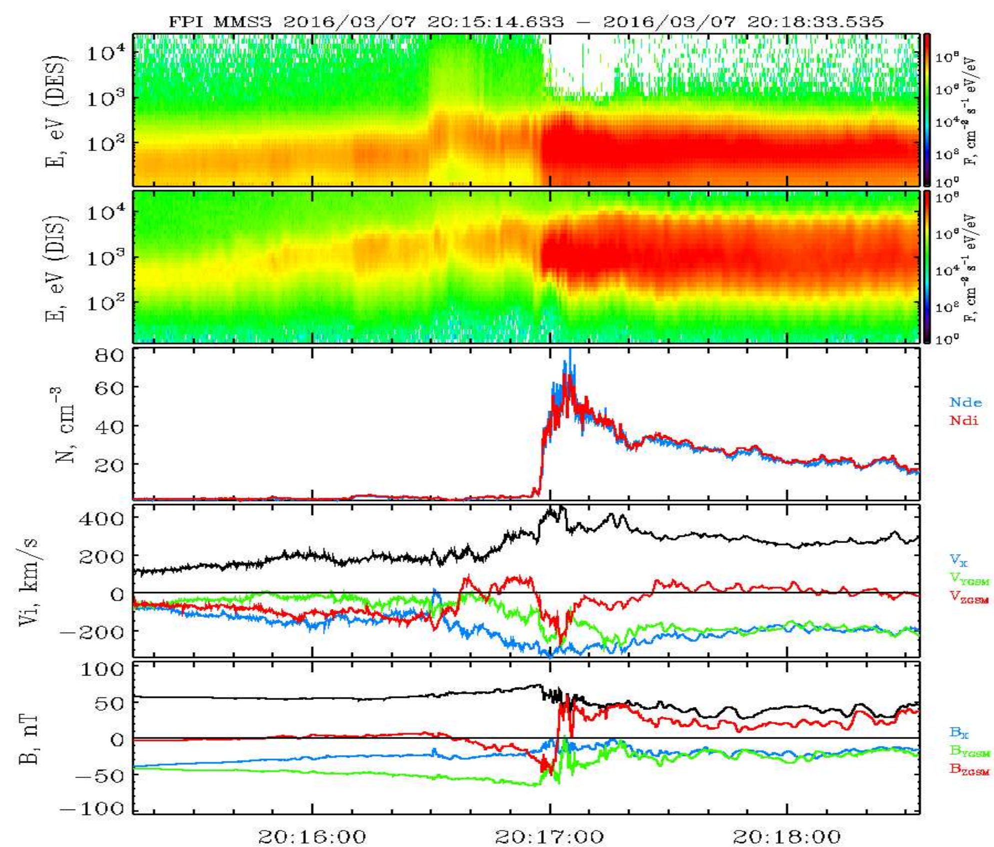
Quasi-overshoot and fluctuations in density profile



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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