Large-Scale High-Speed Jets in Earth's Magnetosheath: Global Hybrid Simulations

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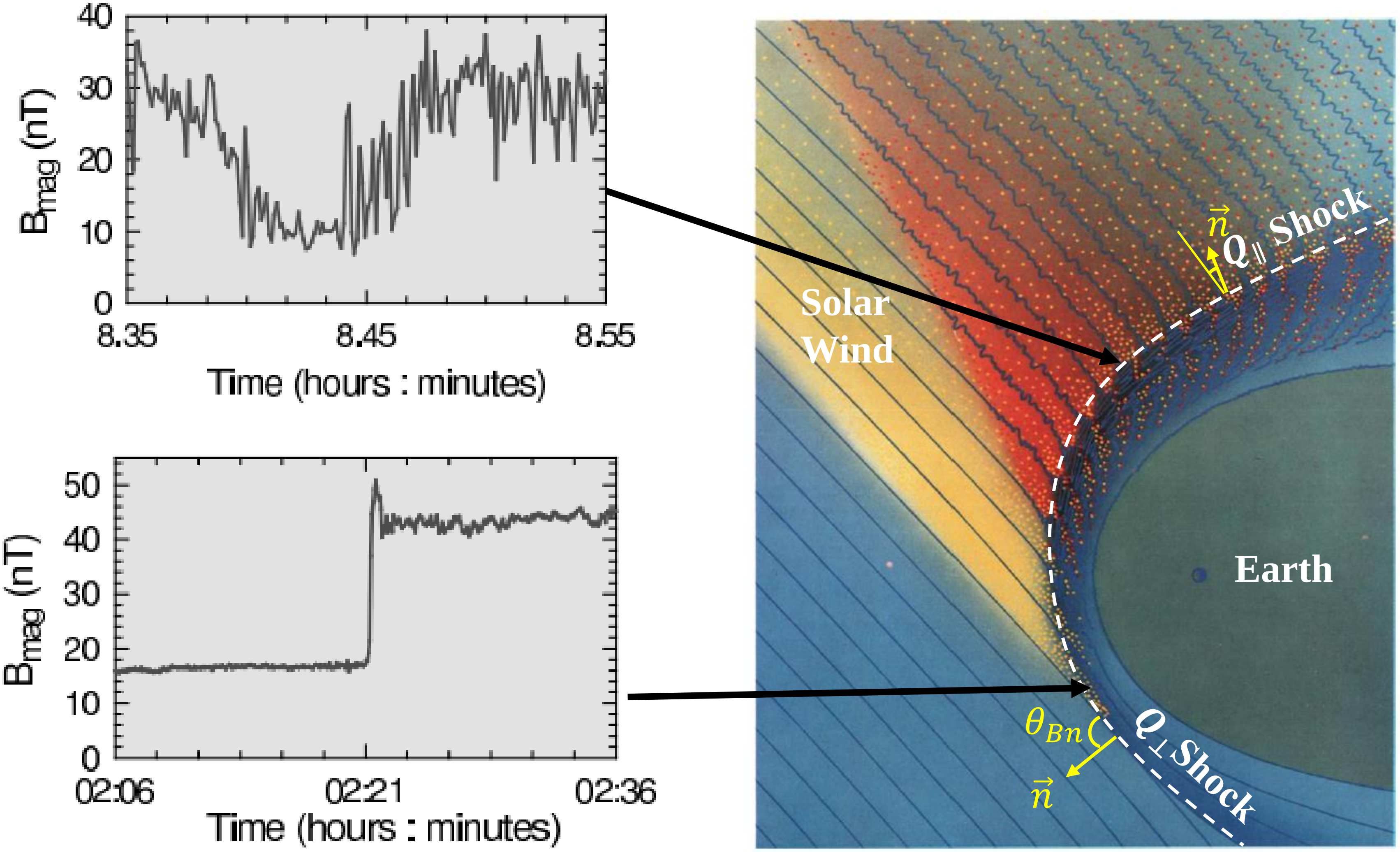
Abstract (New!)

High-speed jets (HSJs) occur frequently in Earth's magnetosheath downstream of the quasi-parallel bow shock. They have great impacts on the magnetosheath and the magnetosphere. Using two-dimensional global hybrid simulations, we investigate the formation and evolution of HSJs with different solar wind conditions. When the quasi-parallel shock is formed, HSJs begin to appear in the quasi-parallel magnetosheath. Some elongated HSJs formed at the quasi-parallel bow shock extend toward the quasi-perpendicular magnetosheath along with the background magnetosheath flow. As the elongated HSJs moves in the magnetosheath, filamentary structures of the velocity, ion density, and temperature occur in the magnetosheath. The filamentary structures are the traces of HSJs moving in the magnetosheath. Moreover, the Kelvin-Helmholtz (K-H) instability can be excited at HSJs, which causes meandering of HSJs. When the IMF is aligned to the solar wind velocity, the large-scale HSJs with a parallel (perpendicular) scale size of about 2.5 R_E (0.3 R_E) are formed at the magnetosheath where the θ_{Bn} is approaching zero. Then, some HSJs converge, leading to the formation of even larger HSJs with a parallel (perpendicular) scale size of 5 R_E (0.6 R_E).

Outlines

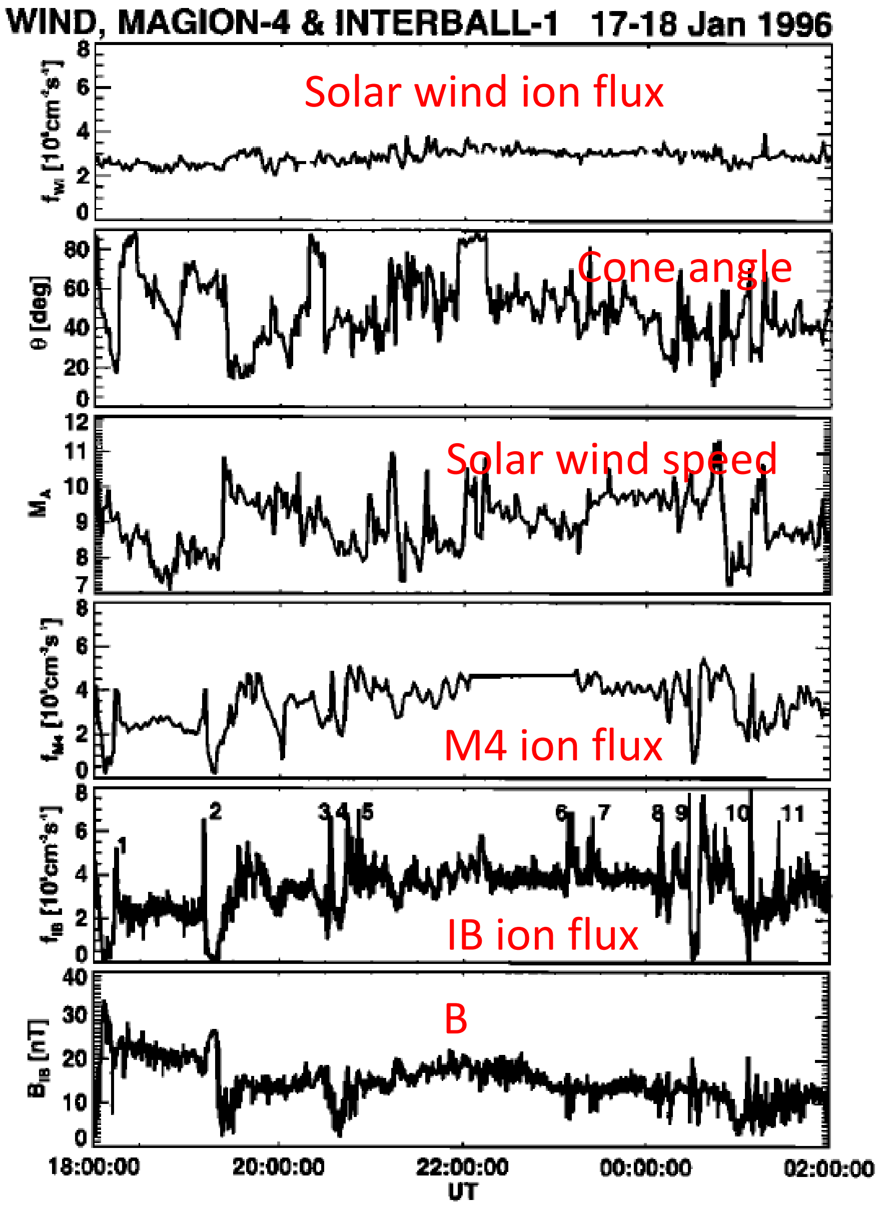
- **Introduction**
  - ✓ Bow shock, Magnetosheath & Magnetopause
  - ✓ Magnetosheath High-Speed Jets (properties, their impact on the Earth’s magnetosphere, & scale size)
- **Simulation Model & Results**
- **Conclusions**

Bow Shock



Tsurutani & Rodriguez , 1981

Magnetosheath High-Speed Jets (HSJs)



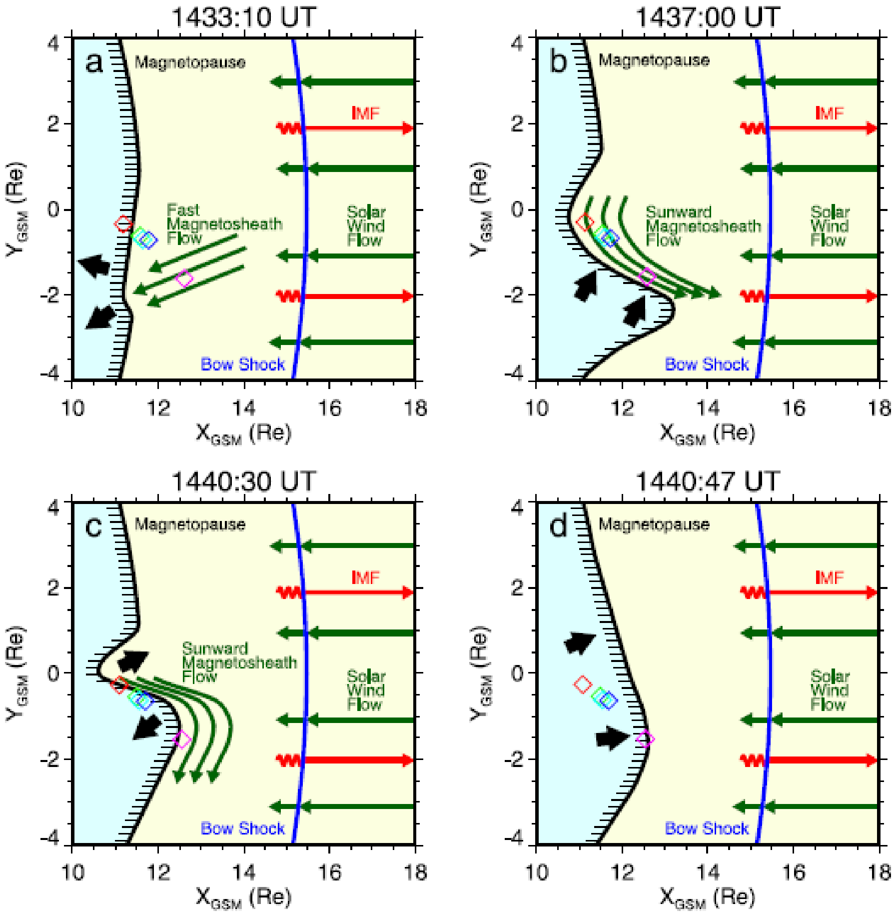
Němeček et al., 1998

- The HSJs were first reported by Němeček et al. (1998), and they called them to be transient ion flux enhancements (TFE).
- The TFE usually occurred at the quasi-parallel magnetosheath with high Alfvénic Mach numbers in the solar wind ($M_A > 7$).

In the HSJs, the dynamic pressure is enhanced, and the velocity is often greater than the local Alfvén velocity, but the plasma temperature is reduced and more isotropic than that in the surroundings *(Archer & Horbury, 2013; Plaschke et al., 2013…)*

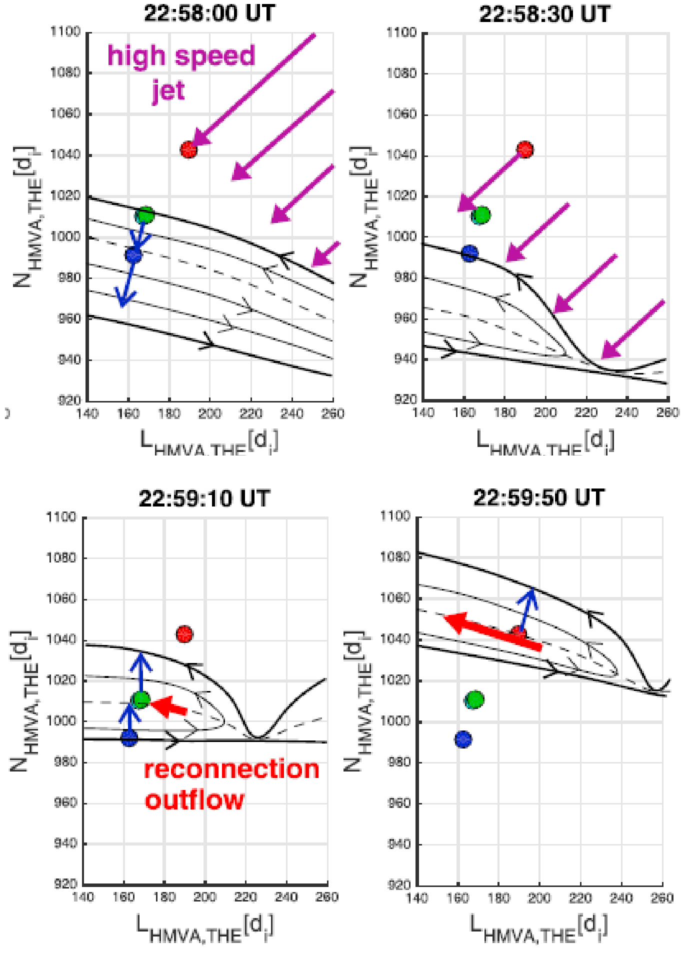
The Impact of Magnetosheath HSJs on the Magnetopause

HSJs are associated with the earthward motion of the magnetopause



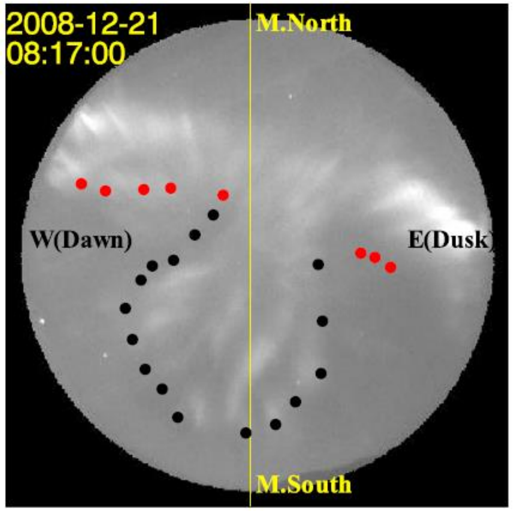
Shue et al., 2009

HSJs may trigger the magnetopause reconnection



Hietala et al., 2018

HSJs may cause throat aurora in the ionosphere



Han et al., 2017

HSJs may have produced enhanced dayside erosion leading to critical flux enhancement into the midtail region prior to substorm Onset *(Nykyri et al., 2017)*

Scale Size

The scale size of HSJs determine how many particles and how much energy from the solar wind they can carry, and the large-scale HSJs have a greater impact on Earth's magnetosphere

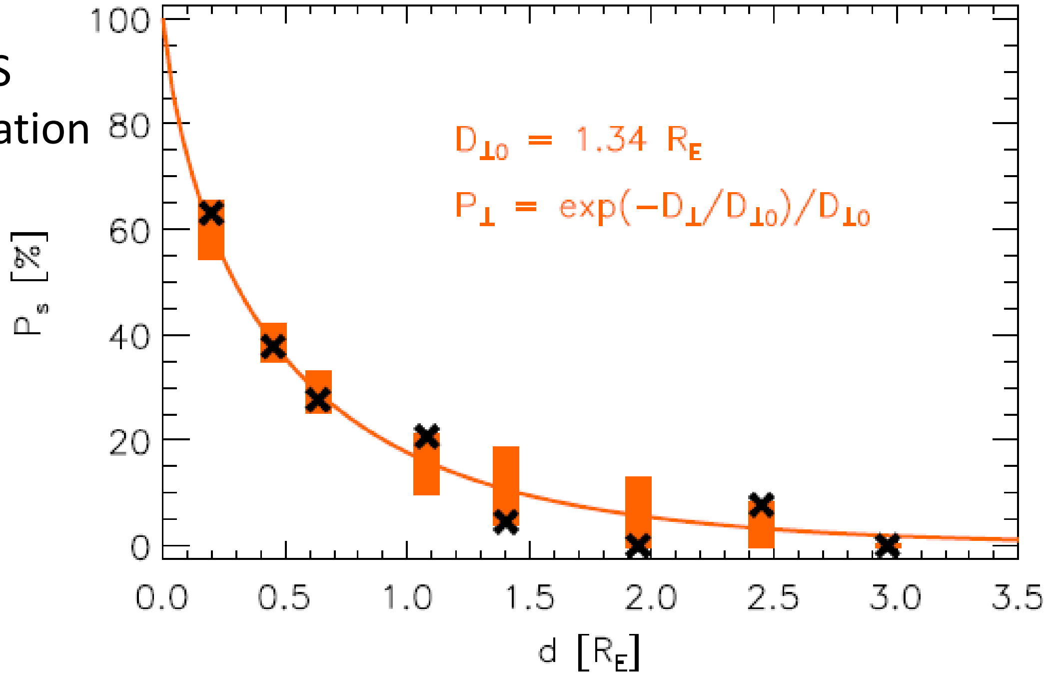
$$P_\perp = \frac{1}{D_{\perp 0}} e^{-D_\perp / D_{\perp 0}},$$

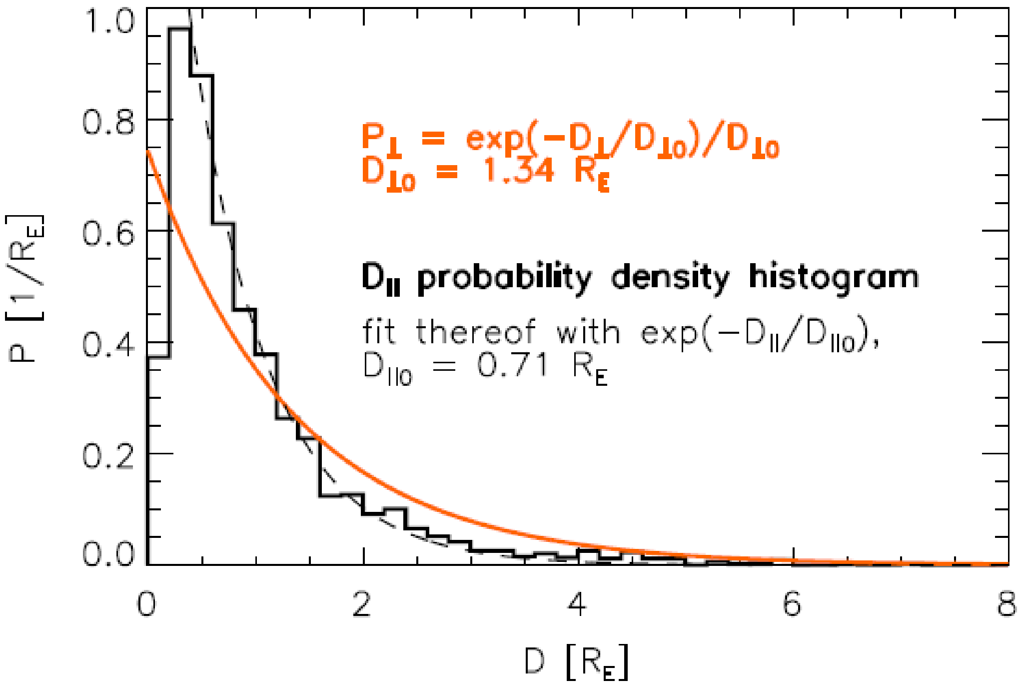
651 HSJs

$$P_\parallel = \frac{1}{D_{\parallel 0}} e^{-D_\parallel / D_{\parallel 0}}$$

2859 HSJs

THEMIS observation





$D_\parallel$: parallel scale size (parallel to the propagation direction)

$D_\perp$: perpendicular scale size (perpendicular to the propagation direction)

Plaschke et al., 2016

Scale Size

Paper	Scale size (parallel)	Scale size (perpendicular)
Němeček et al., 1998	0.5-2.8R_E	
Savin et al., 2008	1.3R_E	
Hietala et al., 2009		1.2R_E
Aecher et al., 2012	1R_E	0.1-0.5R_E
Hietala et al., 2012		1-6R_E
Gunell et al., 2012		0.2R_E
Karlsso et al., 2012	0.3-3R_E	0.3-10R_E
Gunell et al., 2014	4.9R_E	
Karimabadi et al., 2014 (2-D global sim.)	2.4R_E	0.3R_E
Guynska et al., 2015	<0.8R_E	0.8R_E
Karlsson et al., 2015	1.2R_E	
Plaschke et al., 2016	0.71R_E	1.34R_E
Hao et al., 2016 (2-D local sim.)	1R_E	0.2R_E
Palmroth et al., 2018 (2-D global sim.)	2.6R_E	0.5R_E
Omelchenko et al., 2021 (3-D global sim.)	4R_E	6R_E and 0.6R_E

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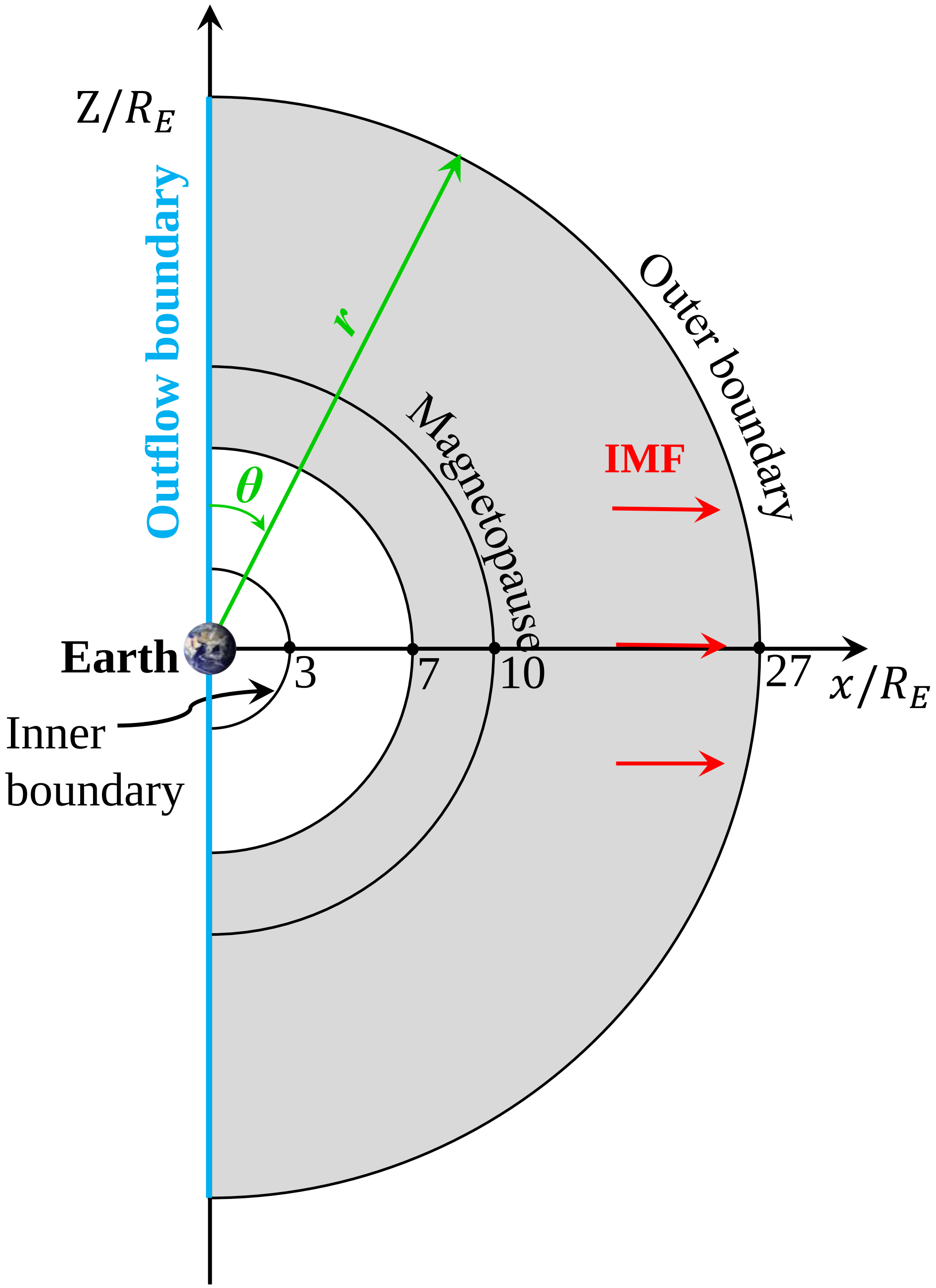
Hietala et al., 2012		1-6R_E
Gunell et al., 2012		0.2R_E
Karlsso et al., 2012	0.3-3R_E	0.3-10R_E
Gunell et al., 2014	4.9R_E	
Karimabadi et al., 2014 (2-D global sim.)	2.4R_E	0.3R_E
Guynska et al., 2015	<0.8R_E	0.8R_E
Karlsson et al., 2015	1.2R_E	
Plaschke et al., 2016	0.71R_E	1.34R_E
Hao et al., 2016 (2-D local sim.)	1R_E	0.2R_E
Palmroth et al., 2018 (2-D global sim.)	2.6R_E	0.5R_E
Omelchenko et al., 2021 (3-D global sim.)	4R_E	6R_E and 0.6R_E

The formation of the large-scale HSJs is still not adequately explained!

Simulation Model: 2-D Global Hybrid Simulation



In the solar wind:

Plasma density: $N_0 = 6\ cm^{-3}$

Ion inertial length: $d_{i0} = 0.02R_E$

Magnetic field: $B_0 = 10\ nT$

Plasma beta values: $\beta_i = \beta_e = 0.5$

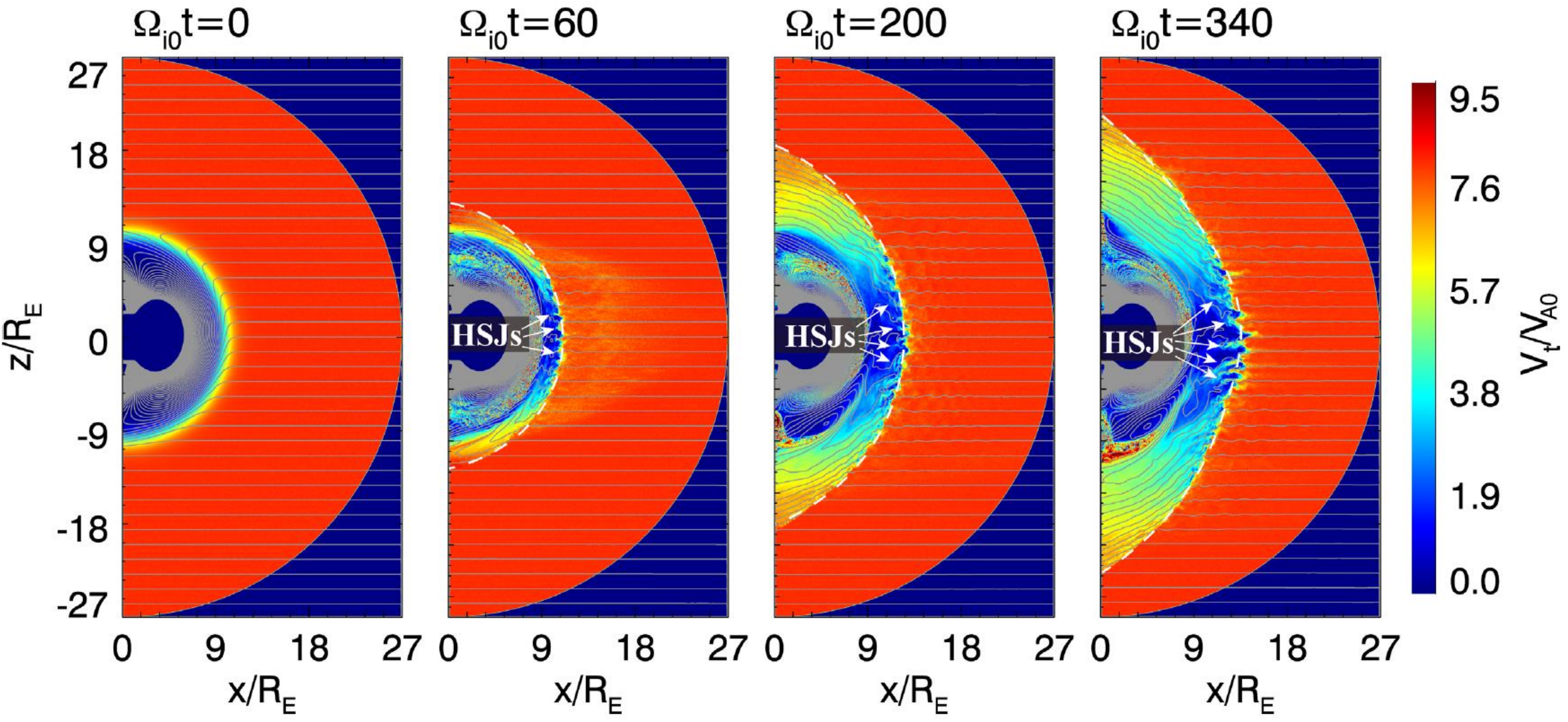
Case 1: the radial IMF is $\boldsymbol{B_0} = \left(B_{x0}, B_{y0}, B_{z0}\right) = (1, 0, 0)B_0$, i.e., the cone angle of IMF is 0°, and the solar wind velocity $U_{SW} = \left(U_{SWx}, U_{SWy}, U_{SWz}\right) = (-8, 0, 0)V_{A0}$ are along the -*x* direction

Case 2: the IMF is $(0.94, 0, 0.34)B_0$, i.e., the cone angle of IMF is 20°, and the solar wind velocity $(-8.5, 0, 0)V_{A0}$ are also along the -*x* direction. At the parallel shock ($\theta_{Bn} \approx 0$), the solar wind velocity along the bow shock normal is about $8\ M_A$.

Formation of the bow shock and HSJs

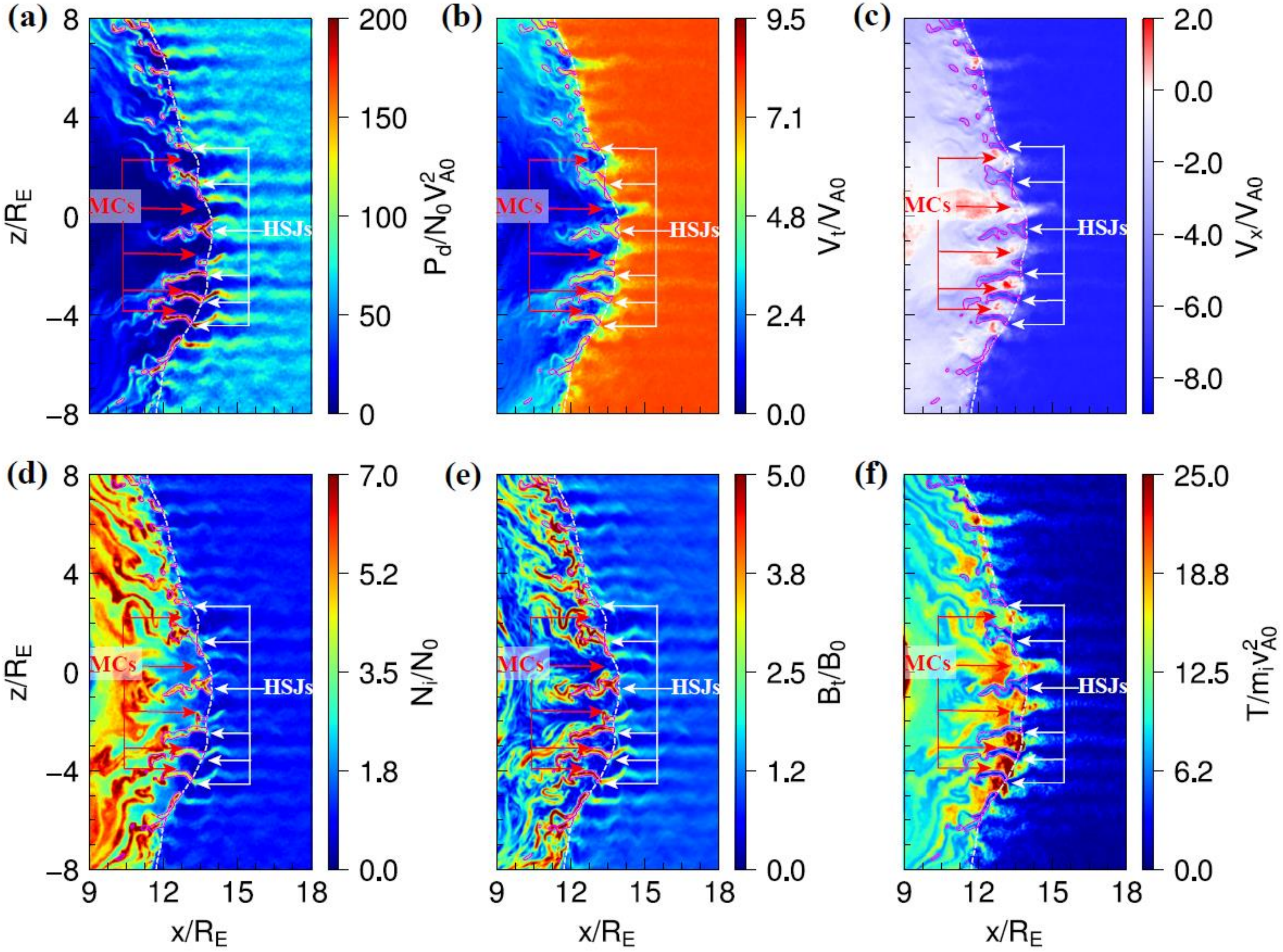
Case 1:
$\left(B_{x0}, B_{y0}, B_{z0}\right) =$
$(1, 0, 0)B_0;$
$\left(U_{SWx}, U_{SWy}, U_{SWz}\right) =$
$(-8, 0, 0)V_{A0}$

Cone angle of IMF is 0°



- At $\Omega_{i0}t$ = 60, about 10 small HSJs with a parallel scale size (parallel to the propagation direction) of less than $1R_E$ are formed in the quasi-parallel magnetosheath.
- Then, the HSJs grow larger. At $\Omega_{i0}t$ = 340, there are about 20 obvious HSJs in the meridian plane, and the parallel scale size of many HSJs is large than 1 R_E

Properties of the HSJs



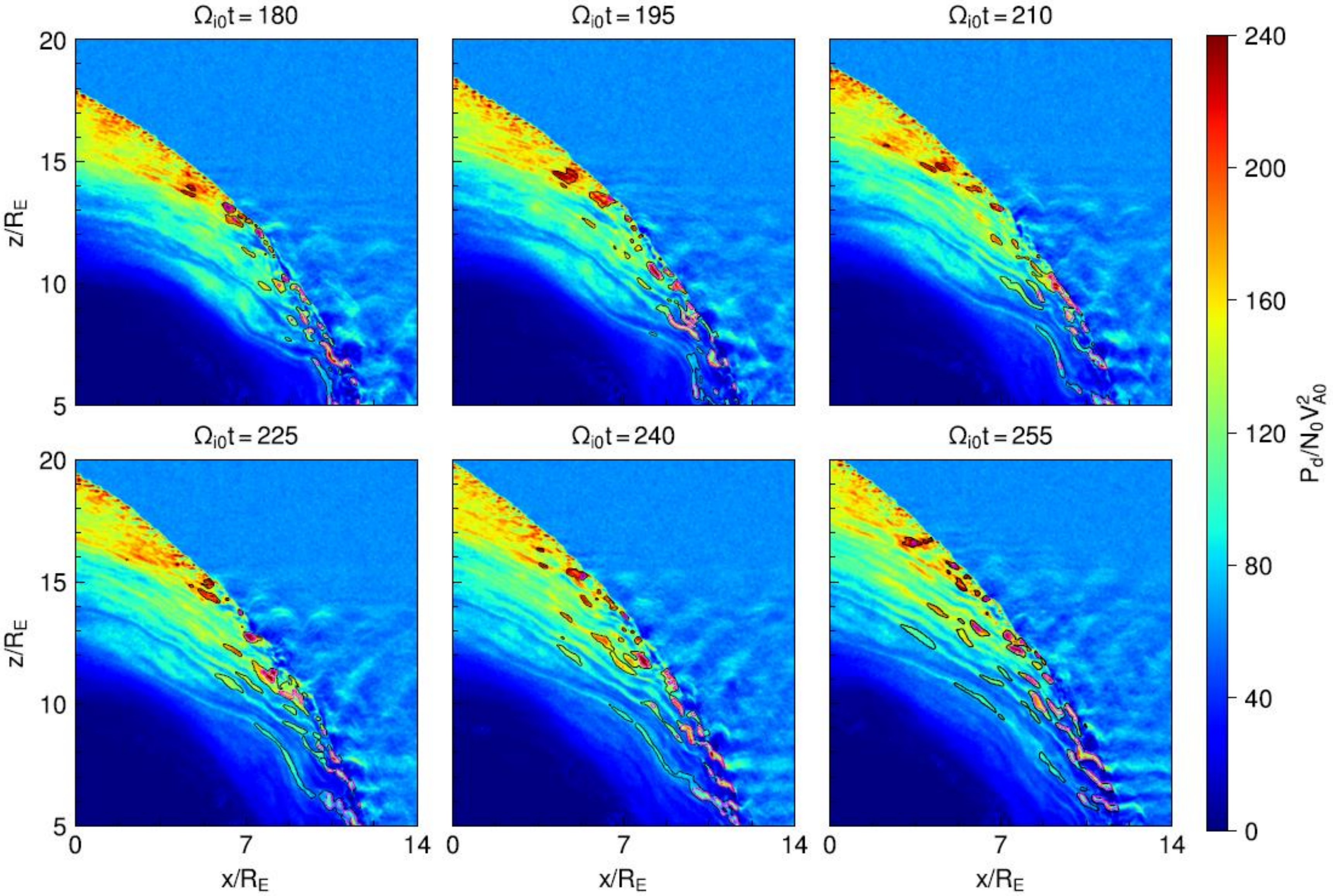
Violet contours represent the HSJs identified to possess a dynamic pressure two times the background magnetosheath value

HSJs: enhanced dynamic pressure, velocity, density, magnetic field; low temperature; anti-sunward flows

Magnetosheath cavities (MCs): decreased dynamic pressure, velocity, density, magnetic field; enhanced temperature; anti-sunward flows

The scale sizes of these HSJs are about 1.1-2.5 R_E in the parallel direction and about 0.2-0.5 R_E in the perpendicular direction

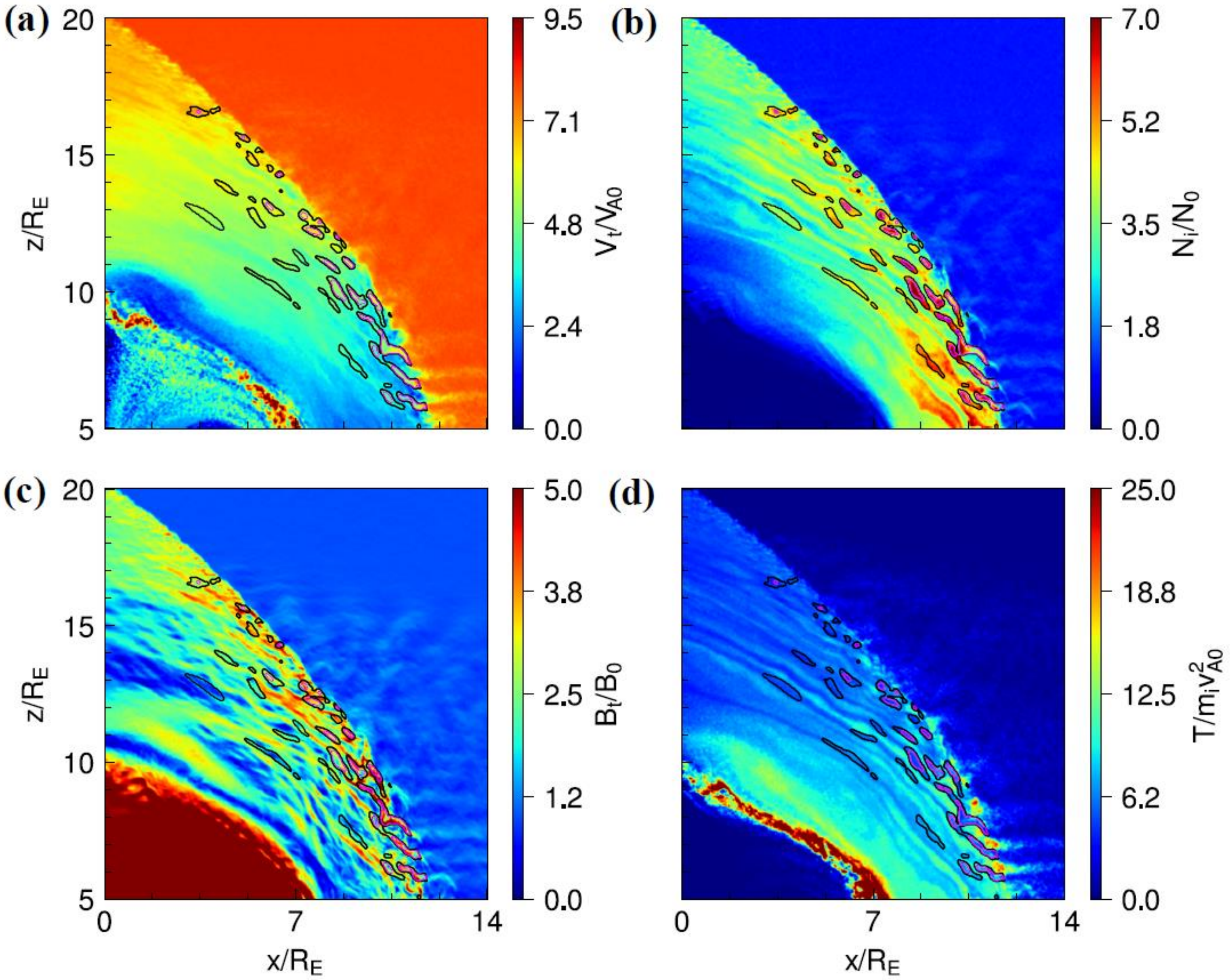
High-latitude HSJs & Filamentary structures



Violet (black) contours represent the HSJs identified to possess a dynamic pressure two (1.5) times the background magnetosheath value

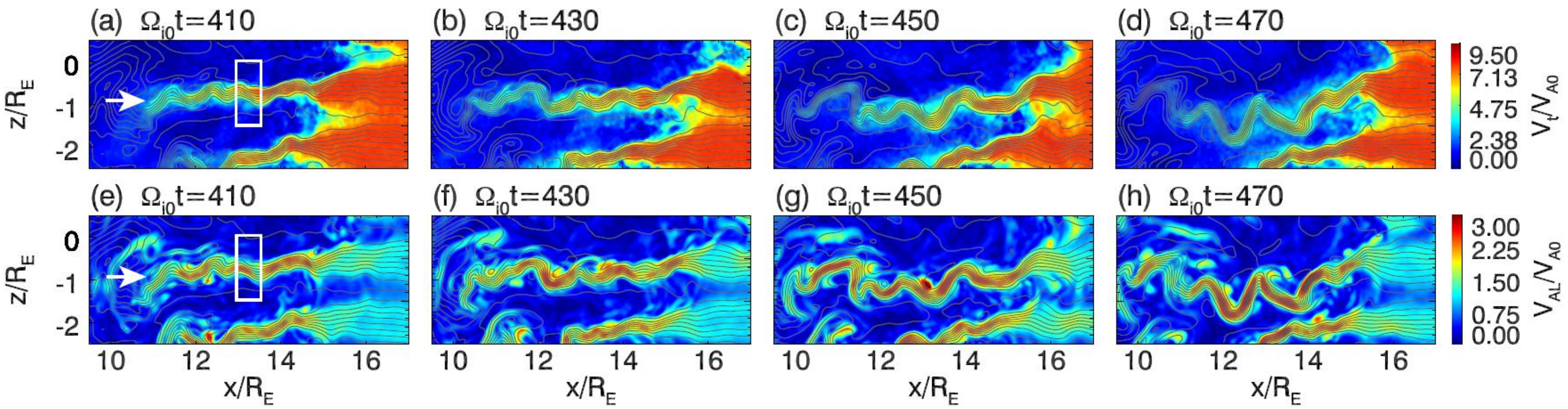
The HSJs formed at the quasi-parallel bow shock extend over a long distance and toward the quasi-perpendicular magnetosheath along the magnetic field and the background flows, but the dynamic pressure in them gradually **decreases**

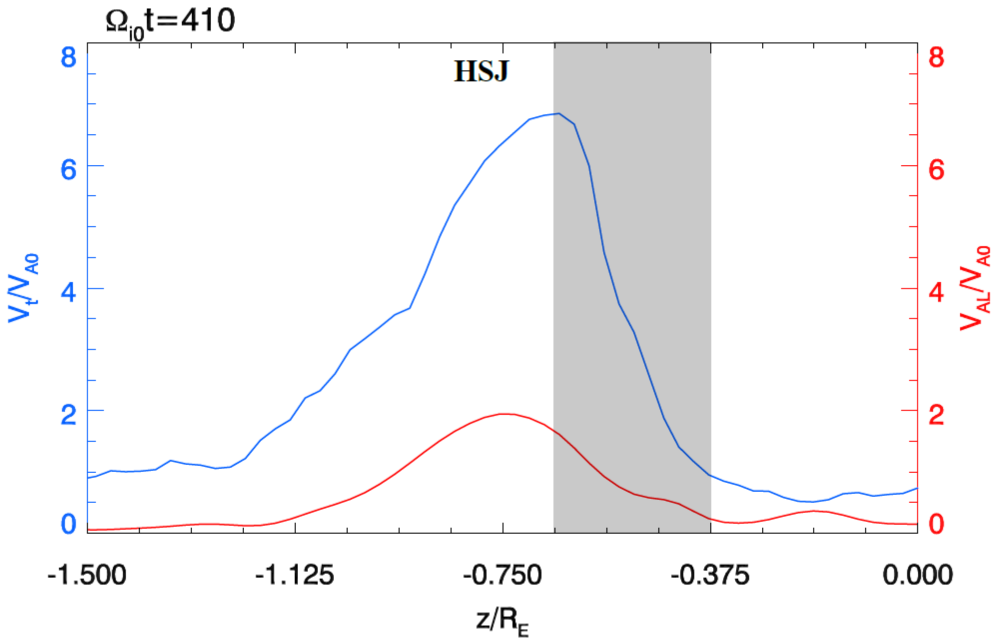
High-latitude HSJs & Filamentary structures

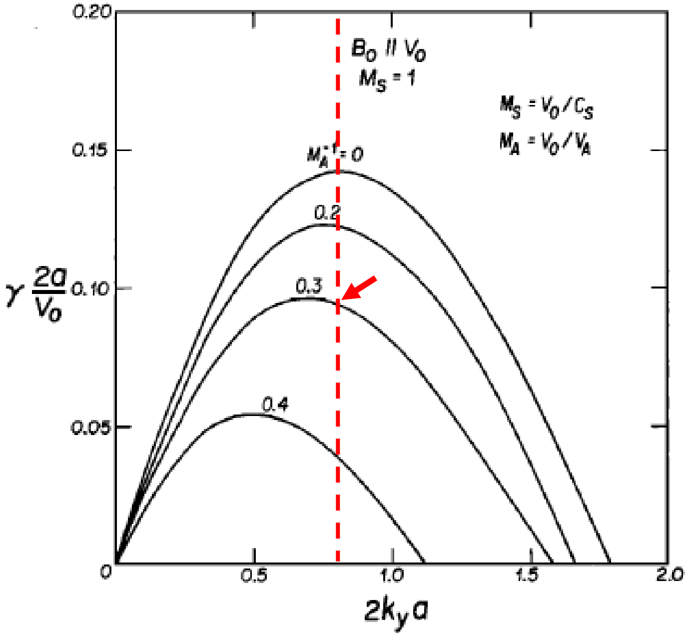


- As the elongated HSJs moves in the magnetosheath, filamentary structures of the velocity, ion density, and temperature occur in the magnetosheath.
- The filamentary structures are the traces of HSJs moving in the magnetosheath, and they can be up to 15 R_E long and about 0.1-0.2R_E wide.

Kelvin-Helmholtz Instability at HSJs







Miura & Pritchett et al., 1982

- For the representative HSJ ($M_A^{-1} = 0.29$), it yields a maximum growth rate at $2ka \approx 0.7$ according to Figure 4 in Miura & Pritchett (1982)
- K-H instability can grow and is responsible for the meandering of the HSJs

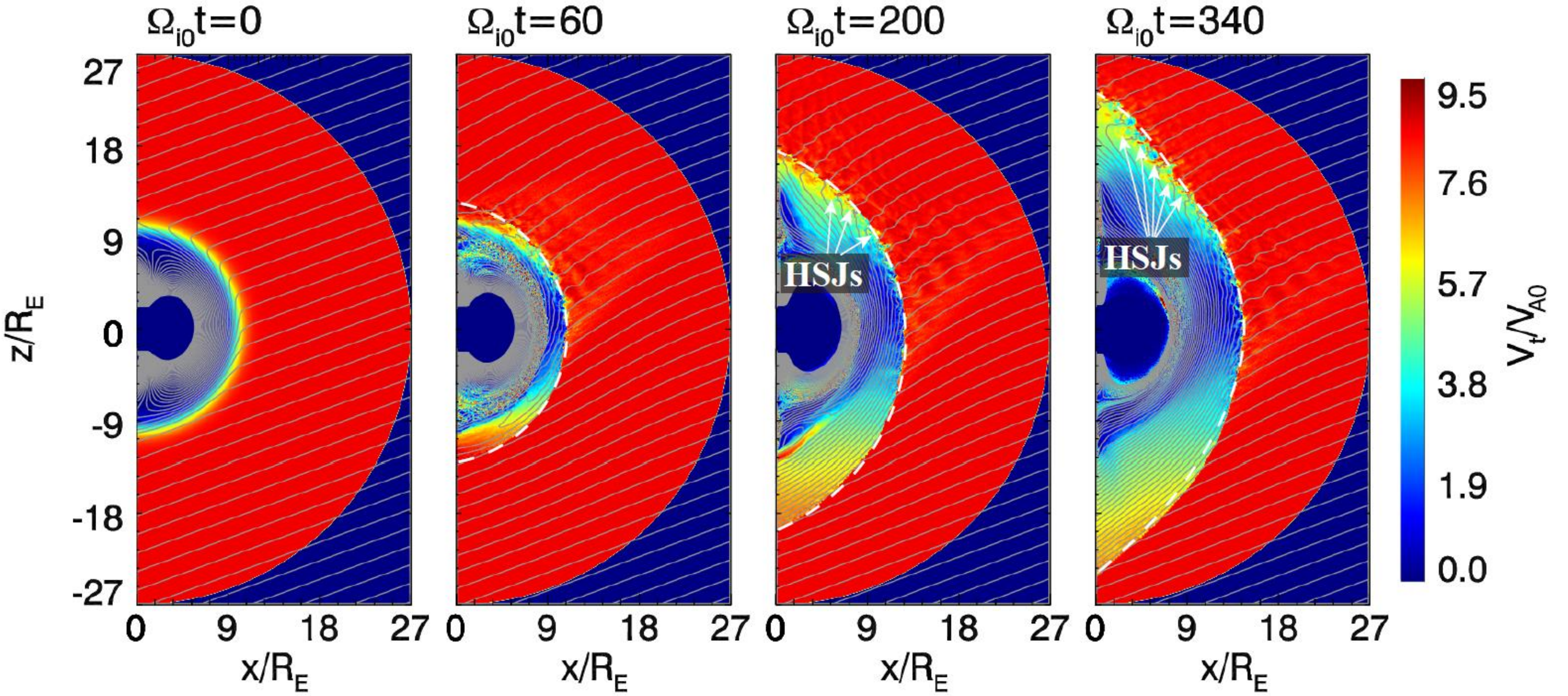
$$M_A = V_0/V_{AL\_HSJ}$$

What controls the formation of large-scale HSJs?

Case 2:
$(B_{x0}, B_{y0}, B_{z0}) = (0.94, 0, 0.34)B_0$;
$(U_{SWx}, U_{SWy}, U_{SWz}) = (-8.5, 0, 0)V_{A0}$

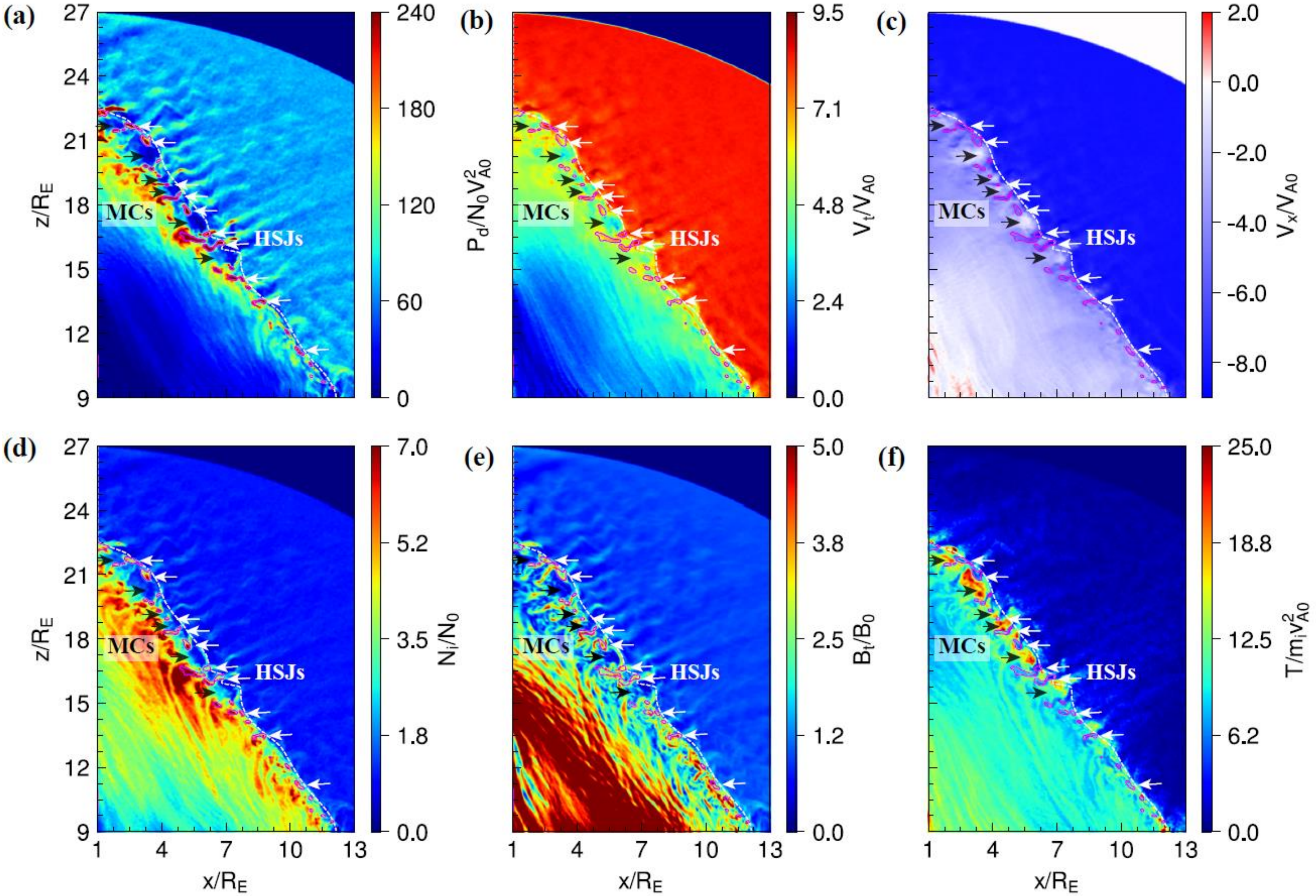
Cone angle of IMF is 0°

At the parallel shock ($\theta_{Bn} \approx 0$), the solar wind velocity along the bow shock normal is about $8\ M_A$



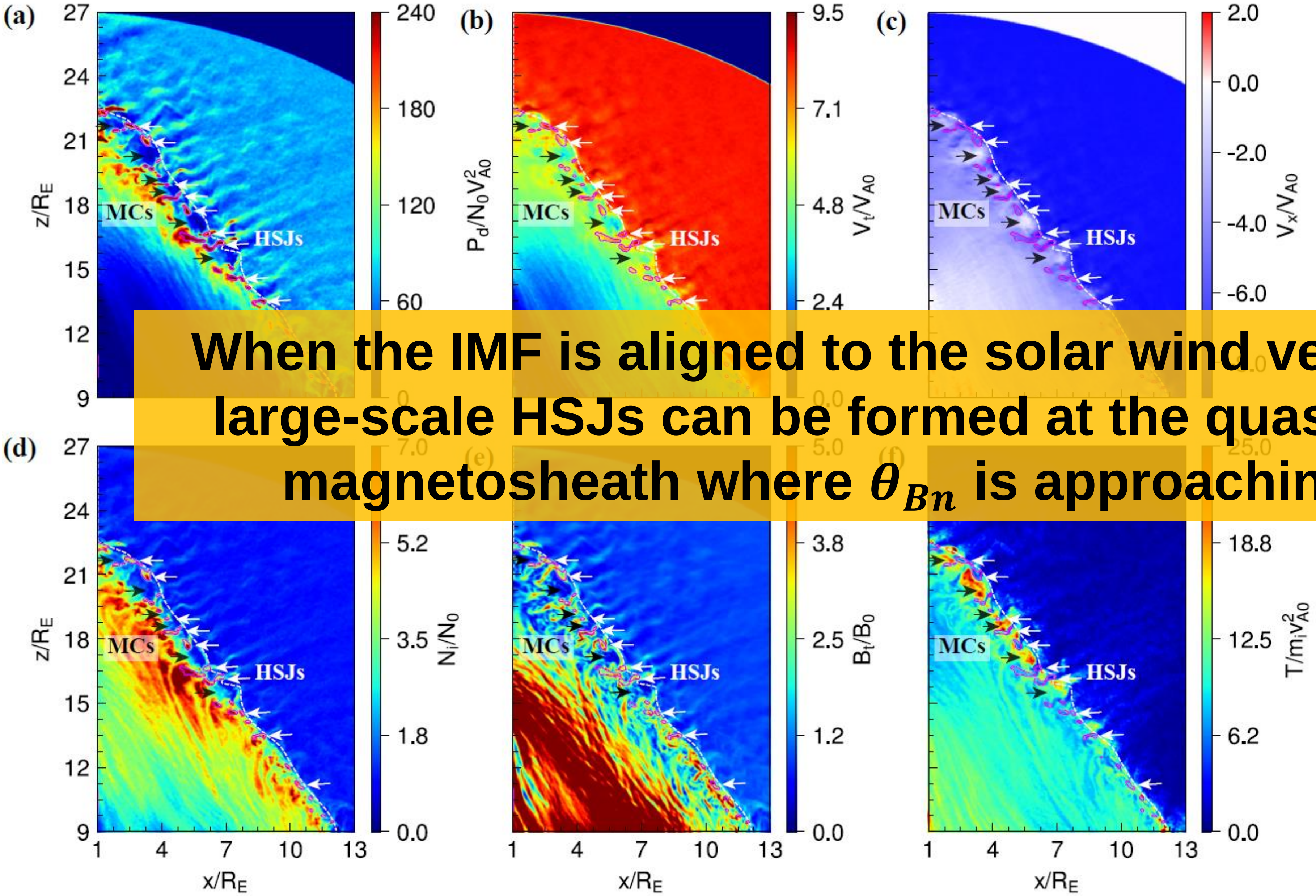
- The quasi-parallel shock is mainly located in the northern hemisphere, and the quasi-perpendicular shock is located in the southern hemisphere.
- The HSJs have a parallel (perpendicular) scale size of about **0.3-1.4 R_E (0.1-0.3 R_E),** and they are smaller than those in Case 1

What controls the formation of large-scale HSJs?



- Similar to Case 1, besides the obvious velocity enhancement, the plasma density and magnetic field are also enhanced, while the temperature is low.
- However, the magnetosheath cavities are small than that in Case 1, and the sunward flows in the magnetosheath cavities are missing.
- The filamentary structures are also formed by the HSJs but are shorter than those in Case 1.

What controls the formation of large-scale HSJs?



When the IMF is aligned to the solar wind velocity, the large-scale HSJs can be formed at the quasi-parallel magnetosheath where θ_{Bn} is approaching zero

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- However, the magnetosheath cavities are small than that in Case 1, and the sunward flows in the magnetosheath cavities are missing.
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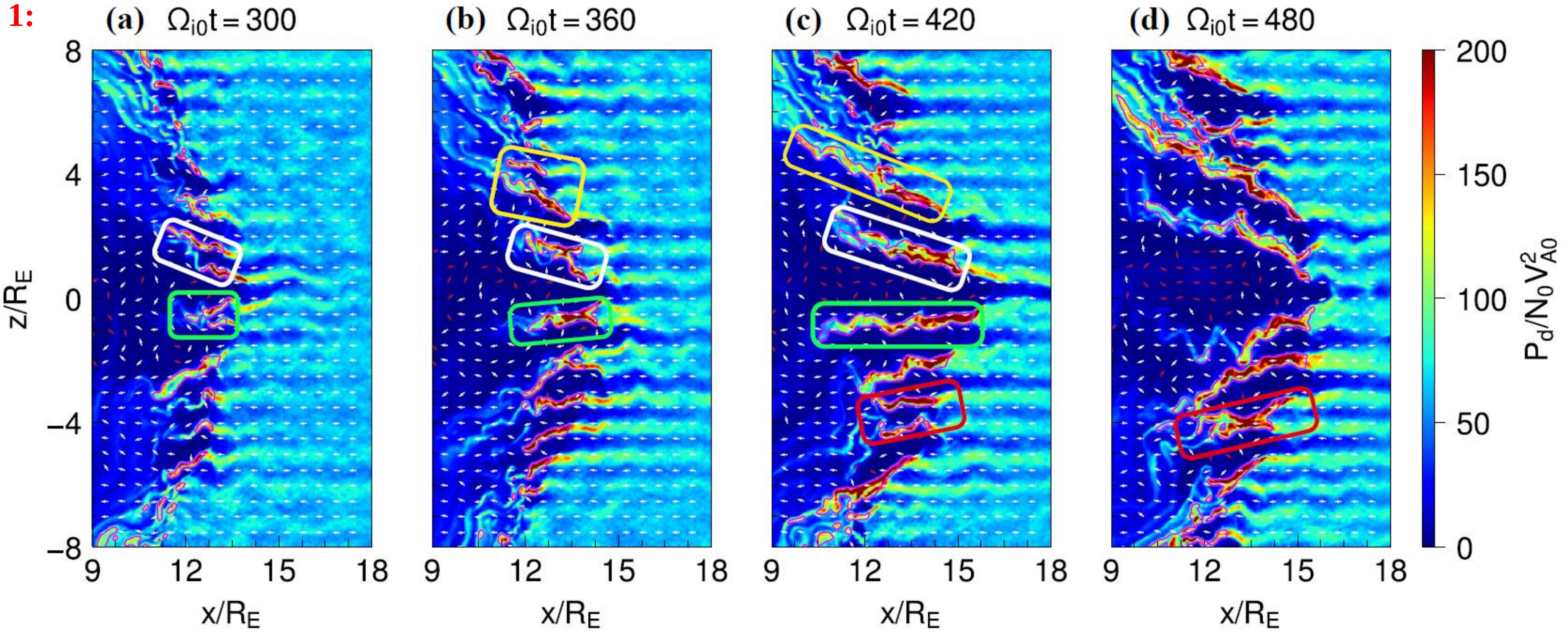
What controls the formation of large-scale HSJs?

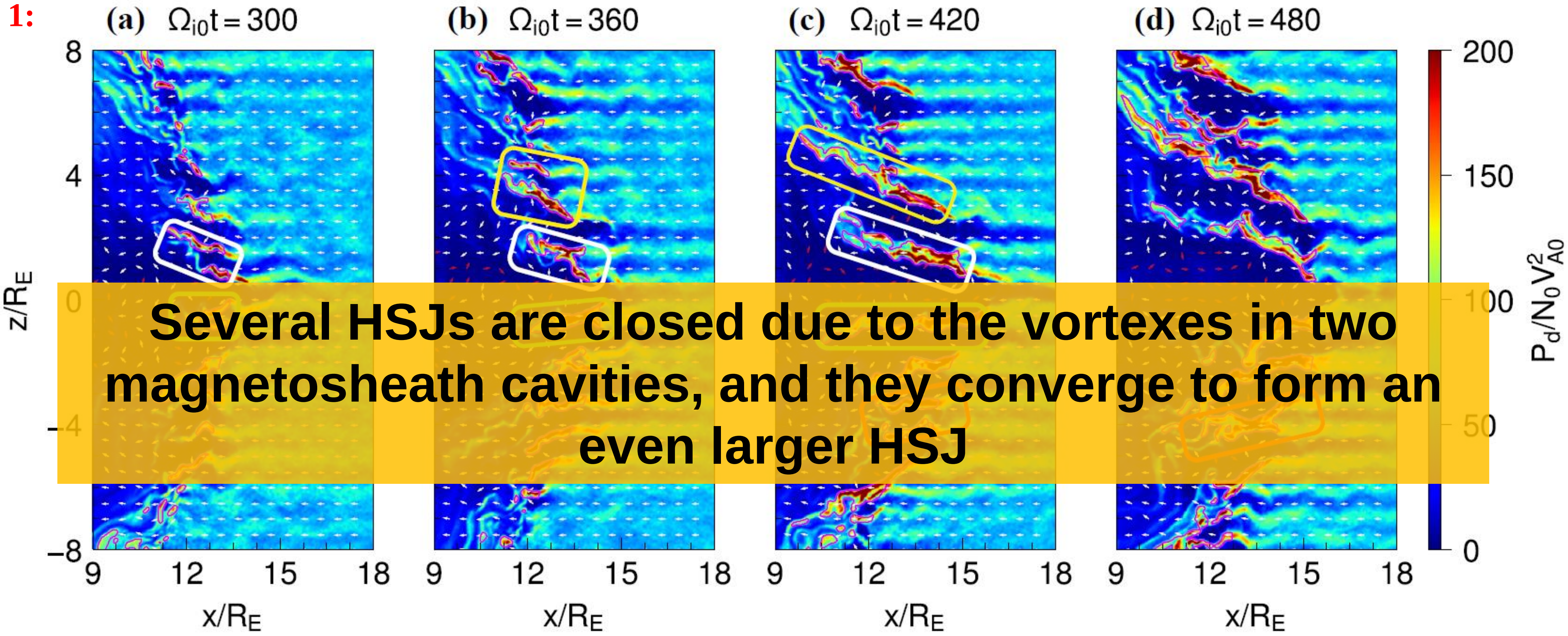
Case 1:



- The HSJs in the white box get very close due to the push of two vortexes beside the HSJs at $\Omega_{i0}t$ = 360, and they converge to form a larger one at $\Omega_{i0}t$ = 420
- The scale sizes of the large-scale HSJ in the white box (Figure 9c) are about 4.5 R_E in the parallel direction and 0.6 R_E in the perpendicular direction

What controls the formation of large-scale HSJs?

Case 1:



Several HSJs are closed due to the vortexes in two magnetosheath cavities, and they converge to form an even larger HSJ

- The HSJs in the white box get very close due to the push of two vortexes beside the HSJs at $\Omega_{i0}t$ = 360, and they converge to form a larger one at $\Omega_{i0}t$ = 420
- The scale sizes of the large-scale HSJ in the white box (Figure 9c) are about 4.5 R_E in the parallel direction and 0.6 R_E in the perpendicular direction

Conclusion

1. Along with the background magnetosheath flow, many elongated HSJs formed at the quasi-parallel bow shock extend toward the quasi-perpendicular magnetosheath. **As the elongated HSJs moves in the magnetosheath, filamentary structures of the velocity, ion density, and temperature occur in the magnetosheath.** The filamentary structures are the traces of HSJs moving in the magnetosheath.

2. The K-H instability is more likely to be excited in the HSJs between two MCs with a rapid growth rate, which causes meandering of the HSJs.

3. The alignment between the IMF and the solar wind velocity favors the formation of large-scale HSJs with a parallel scale size of about 2.5 R_E. Several of these HSJs can converge and form even larger HSJs with a parallel (perpendicular) scale size of 5 R_E (0.6 R_E).