Solar Orbiter Observations of the Kelvin-Helmholtz Waves in the Solar Wind

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The Kelvin-Helmholtz Instability

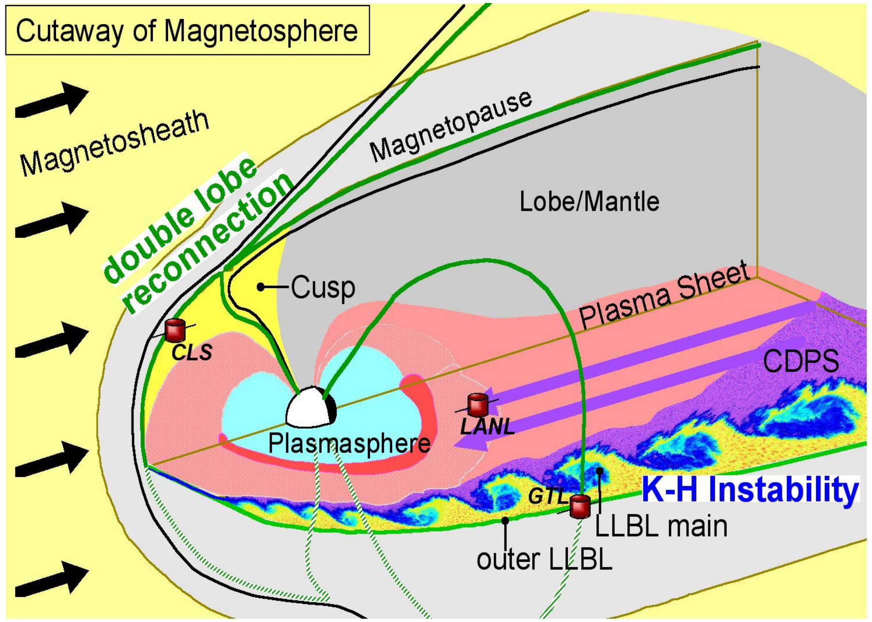
The magnetic Kelvin-Helmholtz instability (KHI) is a MHD shear-driven instability. It can be induced at the interface between two media with different flow velocity and plasma conditions.

KHI onset condition from linear theory [Hasegawa, 1975]:

$$[\mathbf{k}\cdot(\mathbf{V_1}-\mathbf{V_2})]^2 > \frac{n_1+n_2}{\mu_0 m_p n_1 n_2}\left[(\mathbf{k}\cdot\mathbf{B_1})^2+(\mathbf{k}\cdot\mathbf{B_2})^2\right]$$

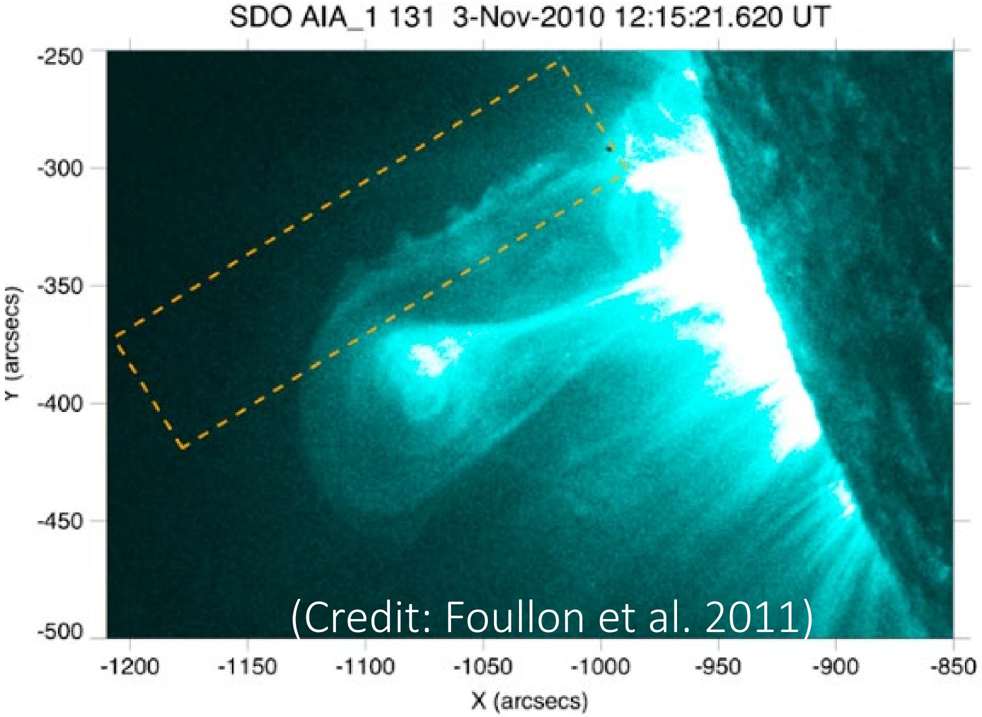
i.e., $\Delta V > 2V_A$ for uniform plasma conditions across the shear layer

KHI at the magnetopause



(Credit: H.E. Koskinen)

KHI at the CME flank



(Credit: Foullon et al. 2011)

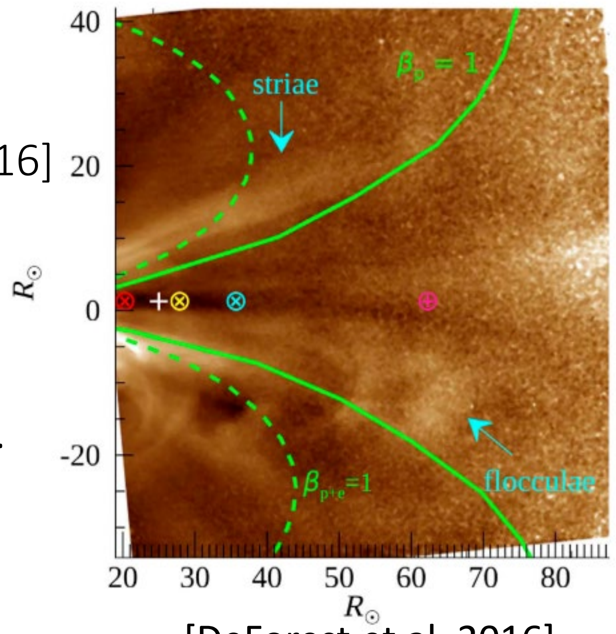
KH waves in the solar wind?

KHI was theoretically postulated to develop in the solar wind at the interface of the adjacent streams of different velocities in the solar wind [e.g., Parker, 1963; Burlaga, 1977; Miura and Pritchett, 1982; Korzhov et al. 1984].

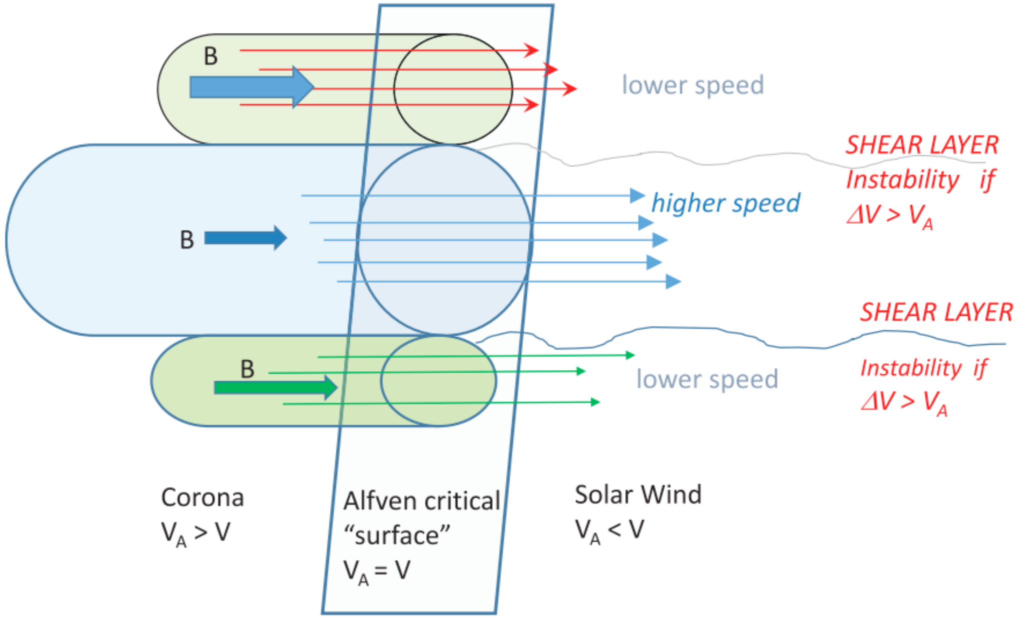
KH waves were ***remotely observed*** in solar corona (Ofman & Thompson, 2011), at the CME flank (Foullon et al. 2011, 2013; Möstl et al. 2013) via EUV using SDO, and in a solar prominence (Hillier & Polito, 2018) using IRIS.

Recently, remote observations revealed a transition in texture of the solar wind [DeForest et al. 2016]

Ruffolo et al. [2020] proposed that the transition is powered by shear-driven instabilities, e.g. KHI.



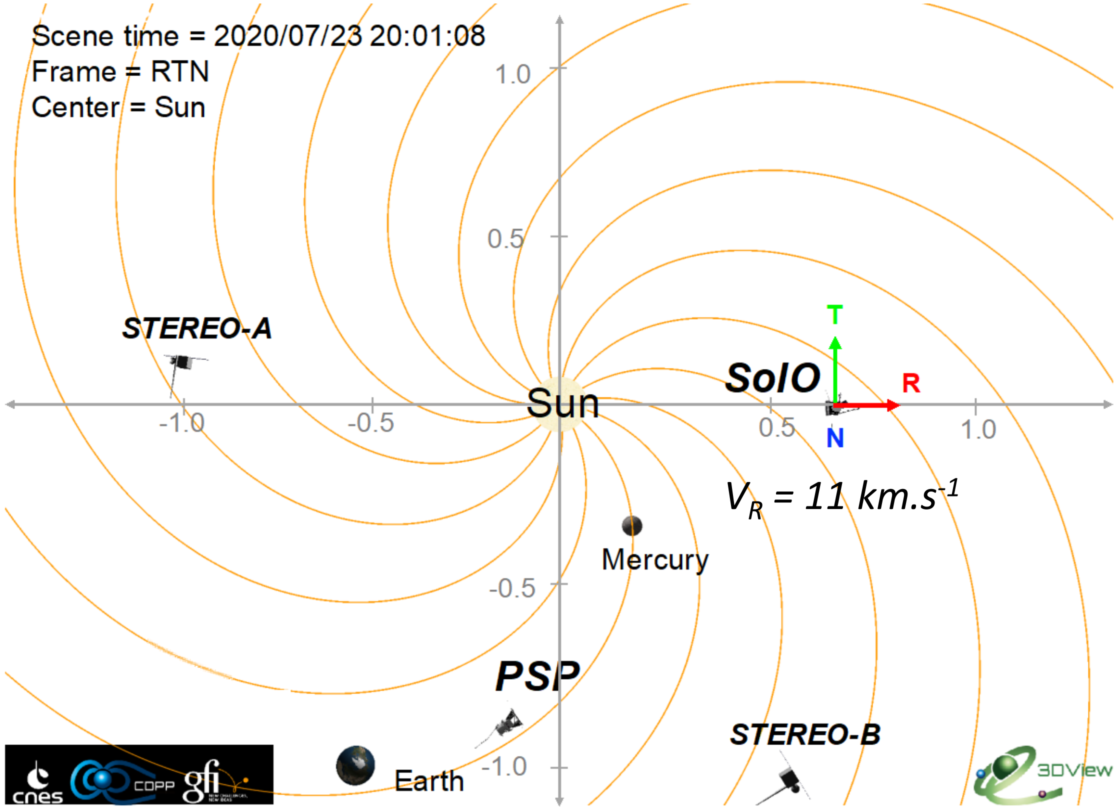
[DeForest et al. 2016]



[Ruffolo et al. 2020]

Solar Orbiter position

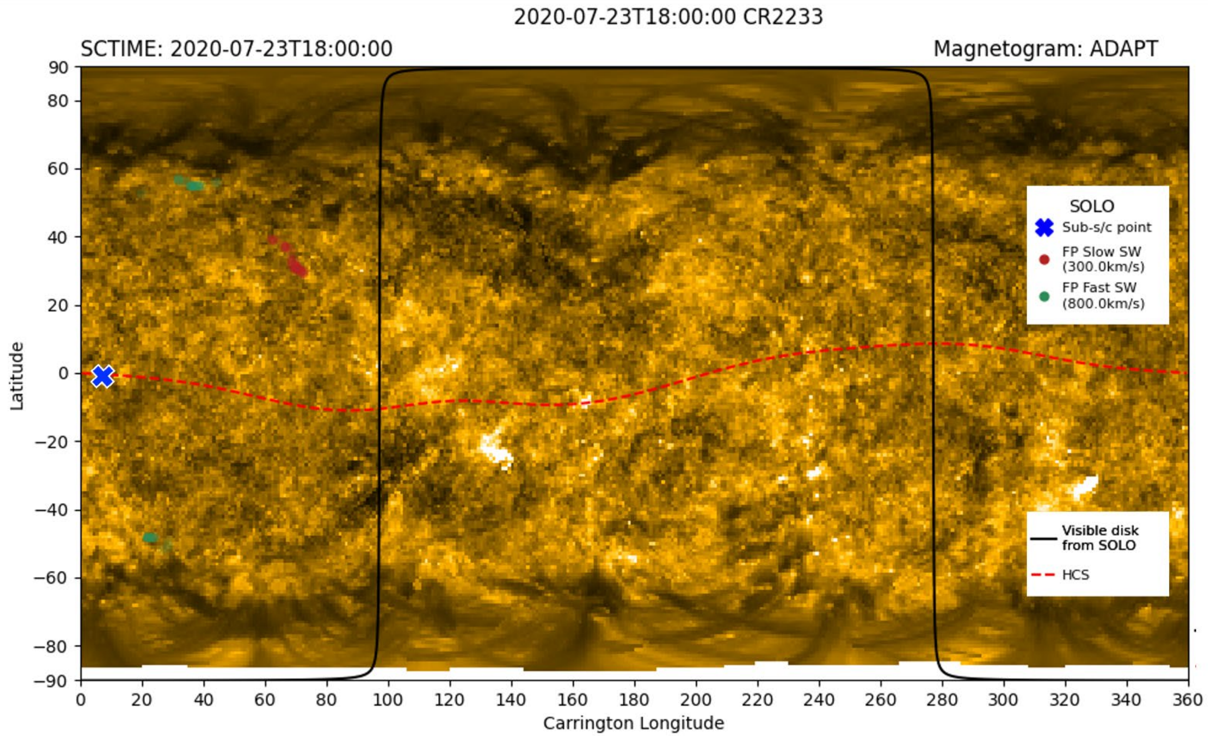
On July 23, 2020, Solar Orbiter was at R = 0.69 AU. It observed several structures in the slow solar wind.



3dview.cdpp.eu

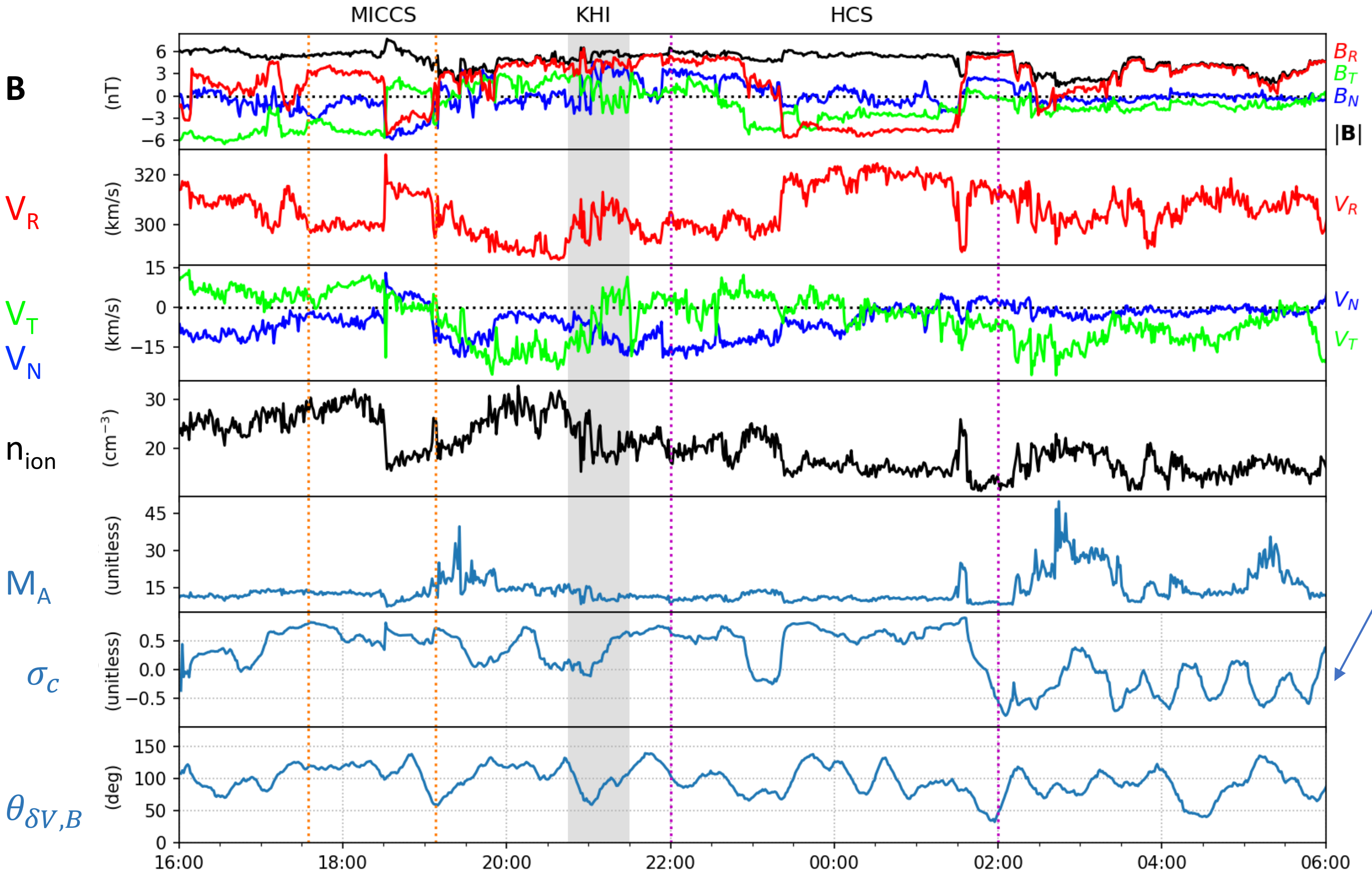
Sun to Solar Orbiter Connectivity

MULTI-VP (Pinto & Rouillard, 2017), (Rouillard et al., 2020)



connect-tool.irap.omp.eu

Observation context



Heliospheric Current Sheet (HCS)

Magnetic Increase with Central Current Sheet (MICCS; Fargette et al. 2020b)

Velocity shear near the HCS

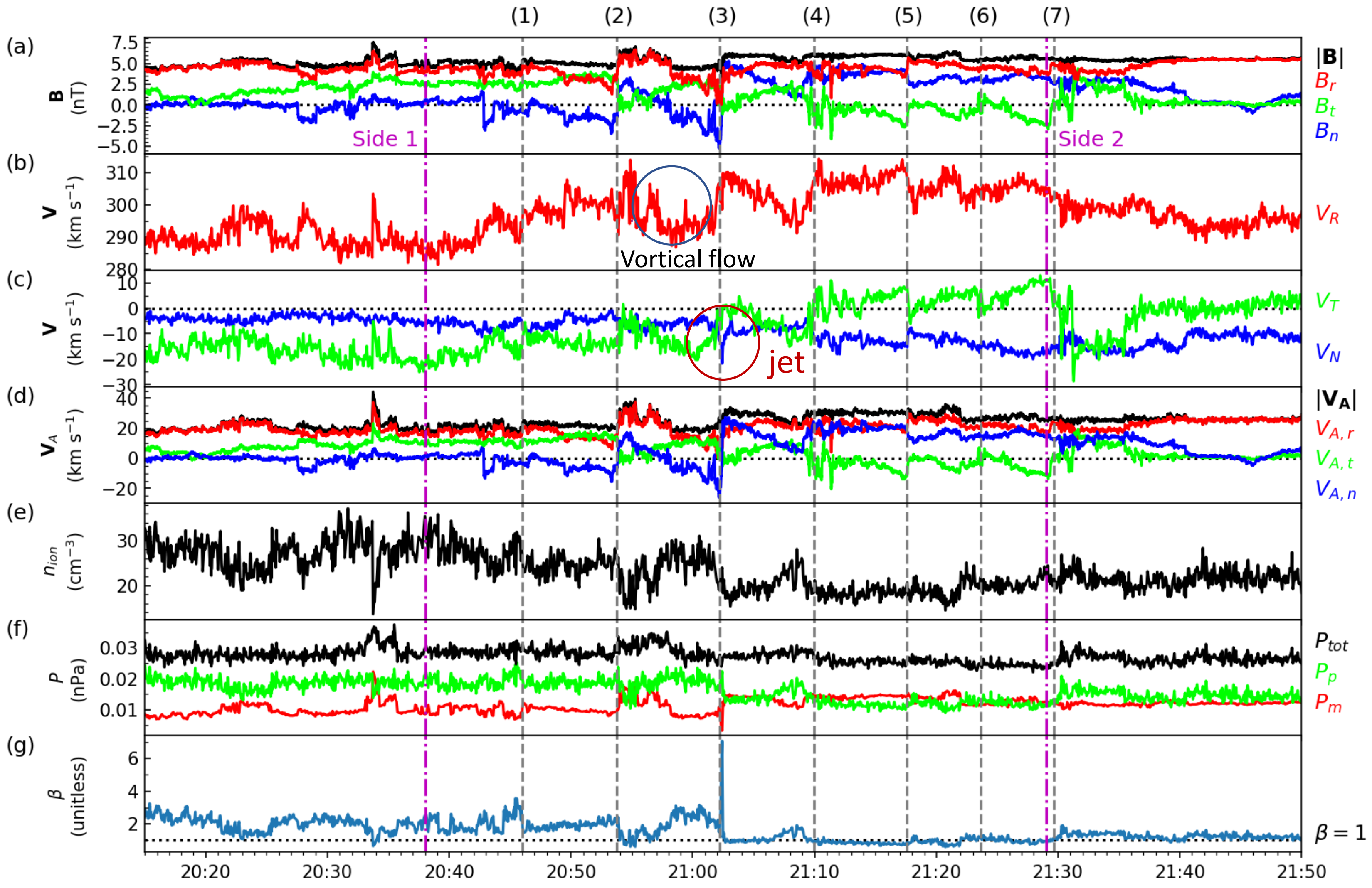
ΔV_T = 30 km s^{-1}, ΔV_N = 15 km s^{-1}

The normalized cross-helicity [Matthaeus & Goldstien, 1982]

$$\sigma_c = 2\langle \delta \mathbf{v} \cdot \delta \mathbf{b} \rangle / \langle \delta \mathbf{v}^2 + \mathbf{b}^2 \rangle = \frac{2H_c}{E}$$

$$\theta_{\delta V,B} = \arccos\left(\frac{\delta \mathbf{v} \cdot \mathbf{B}}{|\delta \mathbf{v} \cdot \mathbf{B}|}\right)$$

Shear layer observations



Quasi-periodic fluctuations in **B** (and **V**) within the shear layer

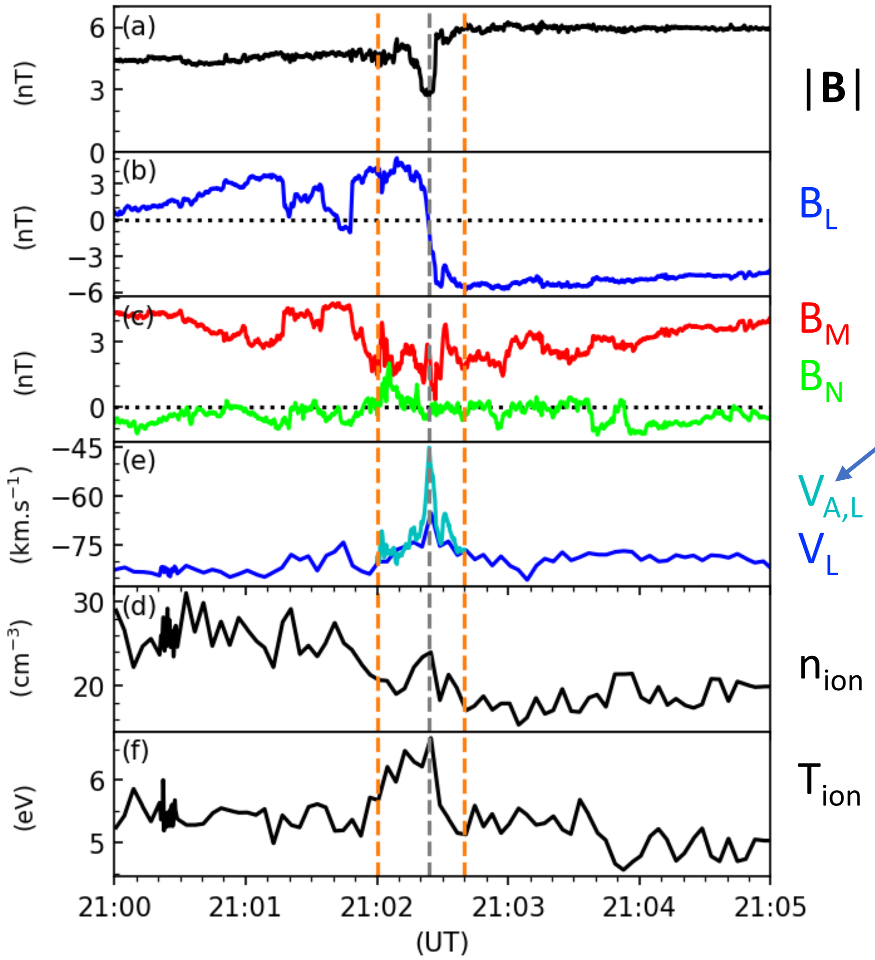
We mark the wave edges (1) – (7).
Periodicity ≈ 7.3±0.9 minutes

Side 1	Side 2
Vr = 285 km/s Vt = -20 km/s Vn = 5 km/s	Vr = 305 km/s Vt = 10 km/s Vn = 16 km/s
Br = 4 nT Bt = 2 nT Bn = 0 nT	Br = 4 nT Bt = -2 nT Bn = 3 nT
N = 30 cm^{-3}	N = 22 cm^{-3}

$|\Delta V|$ = 44 km s^{-1}, V_A = 26 km s^{-1}
$\Delta V \,/\, V_A$ = 1.7

Magnetic reconnection

Near the wave edge (3), we observe an ion jet of ΔV = 13 km s^{-1} co-located with the magnetic field rotation.



We transform the data into the local current sheet *lmn* coordinates using the hybrid MVA technique [Gosling & Phan, 2013]

l: reconnecting component; *m*: out-of-plane (guide-field) component

l = [−0.29, 0.25, −0.92],
m = [0.88, 0.44, −0.16],
n = [0.37, −0.86, −0.34]

The Walén test predicts $\Delta V_{A,L}$ = 33 km s^{-1}

$$\Delta \mathbf{V}_A \sim \frac{\pm \Delta \mathbf{B}}{(\mu_0 m_p n_{ion})^{1/2}}$$

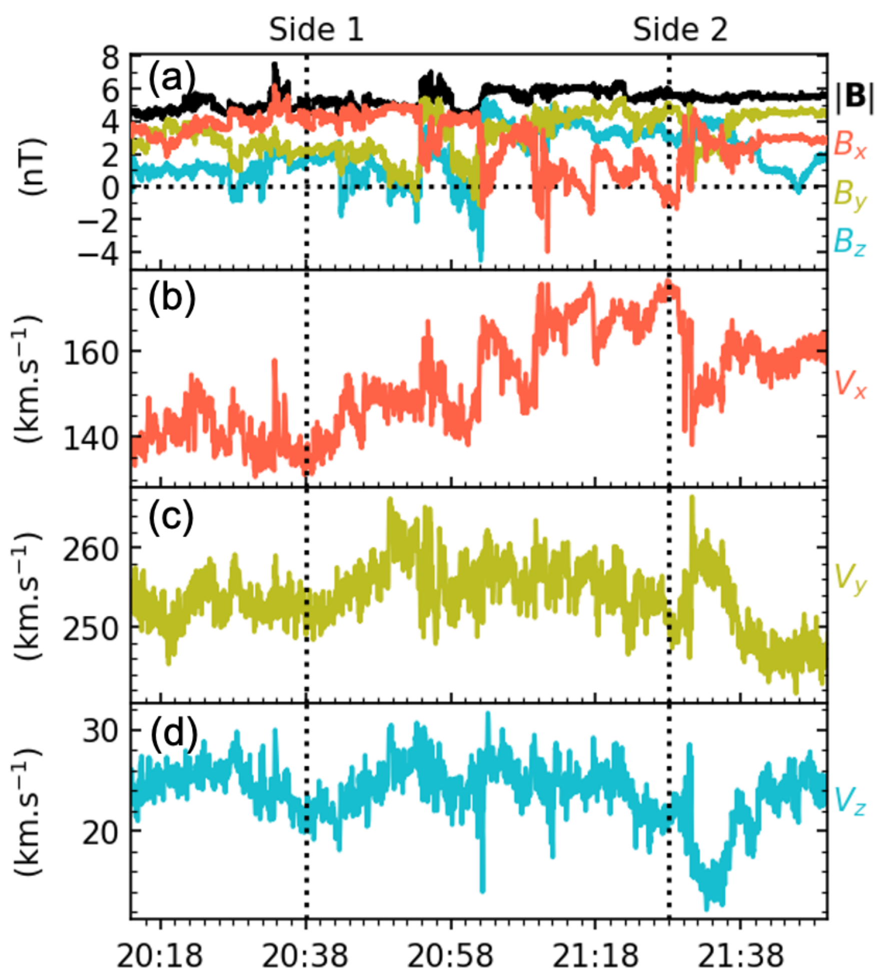
The observed jet is sub-Alfvénic.
Sub-Alfvénic jets are not unusual [e.g., Haggerty et al. 2018]

Several reconnection signatures

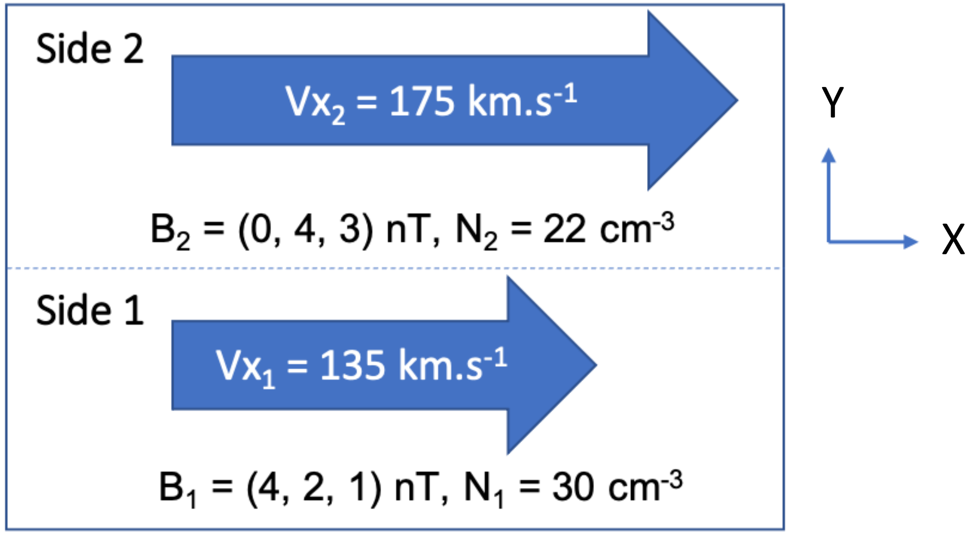
- A drop in |B|
- Ion number density enhancement [Gosling et al. 2005]
- Ion heating [Phan et al. 2014]

Velocity shear configuration

To best see the shear layer, we perform the maximum variance analysis [Sonnerup & Cahill, 1967] on the ion bulk velocity.



Maximum variance direction: X = [0.53, **0.79**, -0.32] (i.e., shear direction ≈ T, R)
Intermediate variance direction: Y = [**0.84**, -0.53, 0.07] (i.e., inhomogeneous direction)
Minimum variance direction: Z = [-0.12, -0.31, -**0.95**] (i.e., invariant ≈ N)



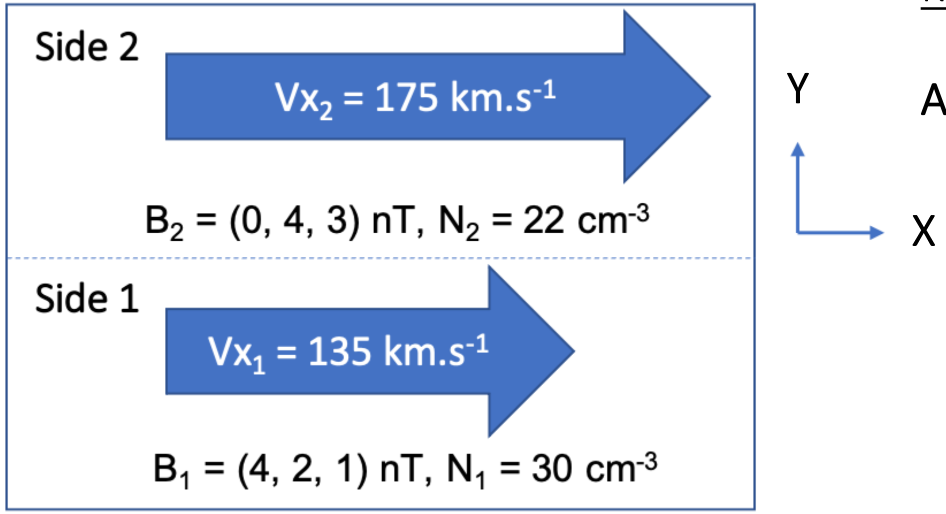
However, this configuration is not a TD because there is non-zero magnetic field (B_Y) along the surface normal. Complex 3-D configuration?

Linear theory analysis

Assumptions

1. The initial shear layer was in an equilibrium
2. There was no B flux across the initial shear layer

(i.e., both are later introduced by the KH dynamics).



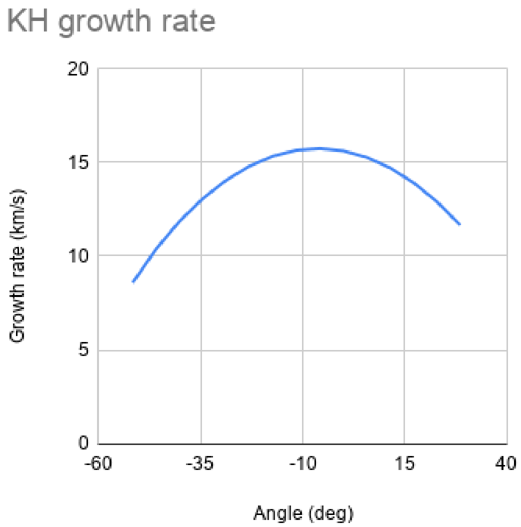
<u>KH growth rate</u>

$$\gamma = [\alpha_1\alpha_2[(\mathbf{V}_1 - \mathbf{V}_2)\cdot\mathbf{k}]^2 - \alpha_1(\mathbf{V}_{\mathbf{A},\mathbf{1}}\cdot\mathbf{k})^2 - \alpha_2(\mathbf{V}_{\mathbf{A},\mathbf{2}}\cdot\mathbf{k})^2]^{1/2}$$

Assuming

$$\Delta\mathbf{V} = \mathbf{V}_2 - \mathbf{V}_1 \approx (40, 0, 0)$$
$$\mathbf{k} = (k\cos\phi, 0, k\sin\phi)$$

$$\left(\frac{\gamma}{k}\right)^2 = \frac{\rho_1\rho_2}{(\rho_1+\rho_2)^2}[\Delta V_x\cos\phi + \Delta V_z\sin\phi]^2 - \frac{1}{\mu_0(\rho_1+\rho_2)}[B_{1,x}\cos\phi + B_{1,z}\sin\phi]^2 - \frac{1}{\mu_0(\rho_1+\rho_2)}[B_{2,x}\cos\phi + B_{2,z}\sin\phi]^2$$



KHI unstable!

Maximum growth rate (γ/k) of 16 km s^{-1}

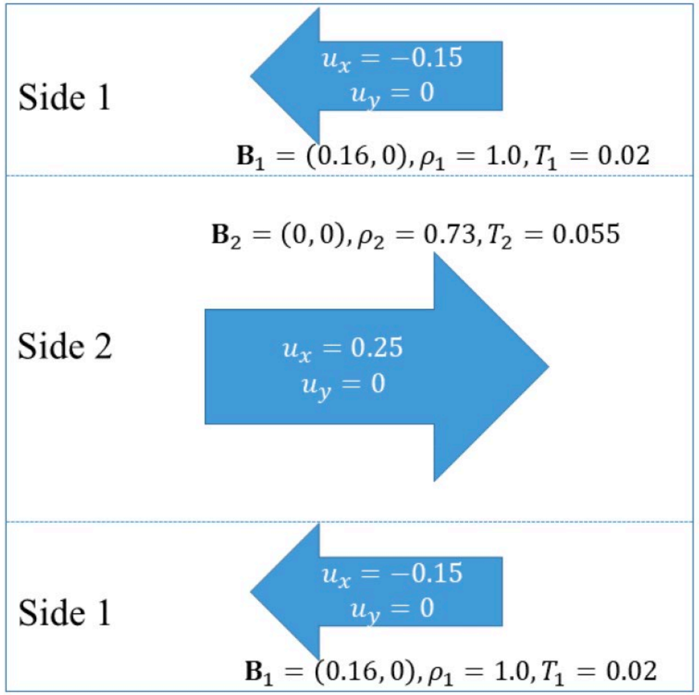
V_{ph} = 152 km s^{-1}. τ_{KH} = 7.3 $\pm$ 0.9 mins

λ_{KH} = 66,400 $\pm$ 8,400 km (0.10 $\pm$ 0.01 R_{sun})

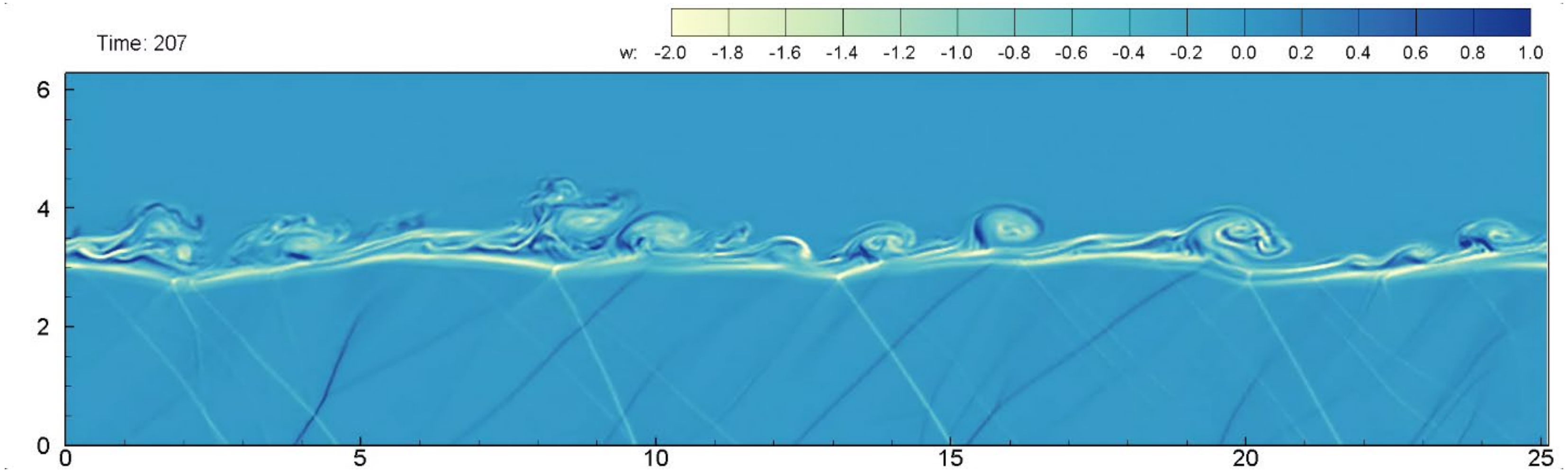
MHD simulation

To further test whether the observed conditions would support the KHI, we exploit an MHD simulation [Yang et al. 2016b; Ruffolo et al. 2020] using the empirical values as boundary conditions.

We set up a simulation box in the local KH frame, which moves at the KH wave phase speed ($V_{ph} \approx 150$ km s^{-1}).
Since **B** perpendicular to the shear flow does not impact the KHI, we keep only in-plane **B**.



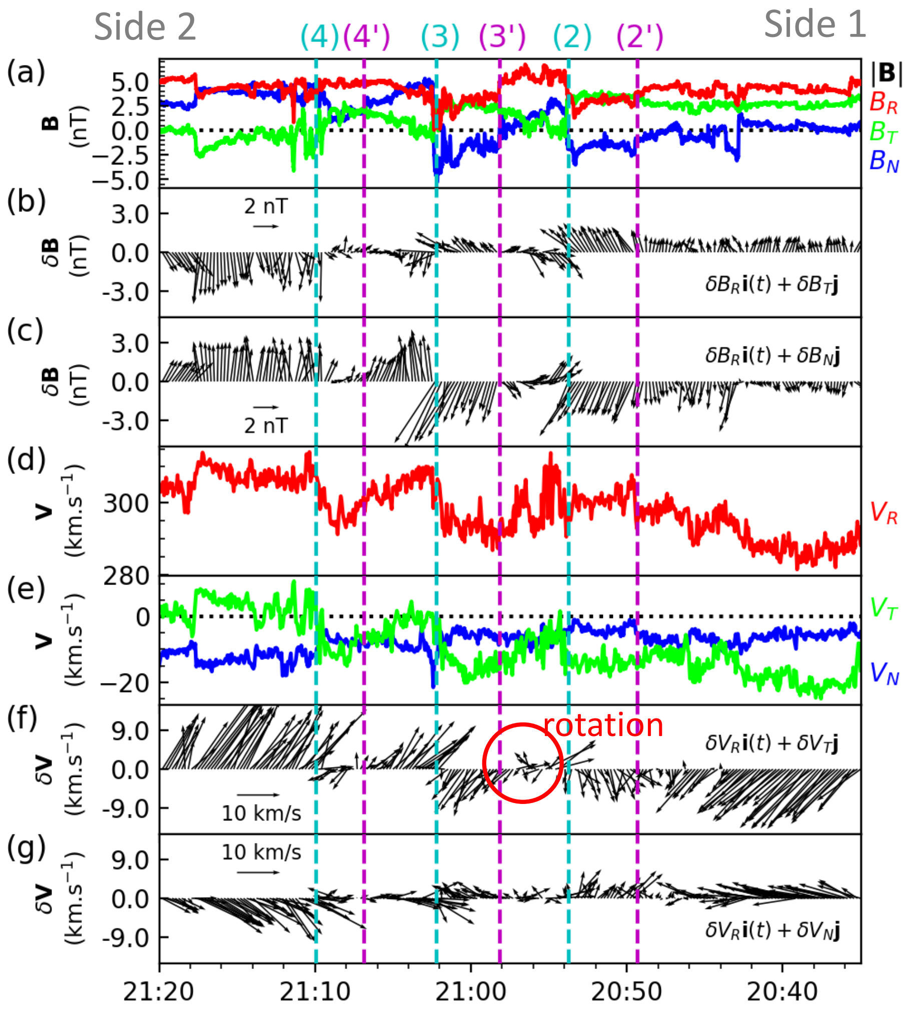
Example of KHI development



The observed event is consistent with KH waves as supported by the linear theory and MHD simulation using the considered assumptions.

B and V perturbation and boundary layer analysis

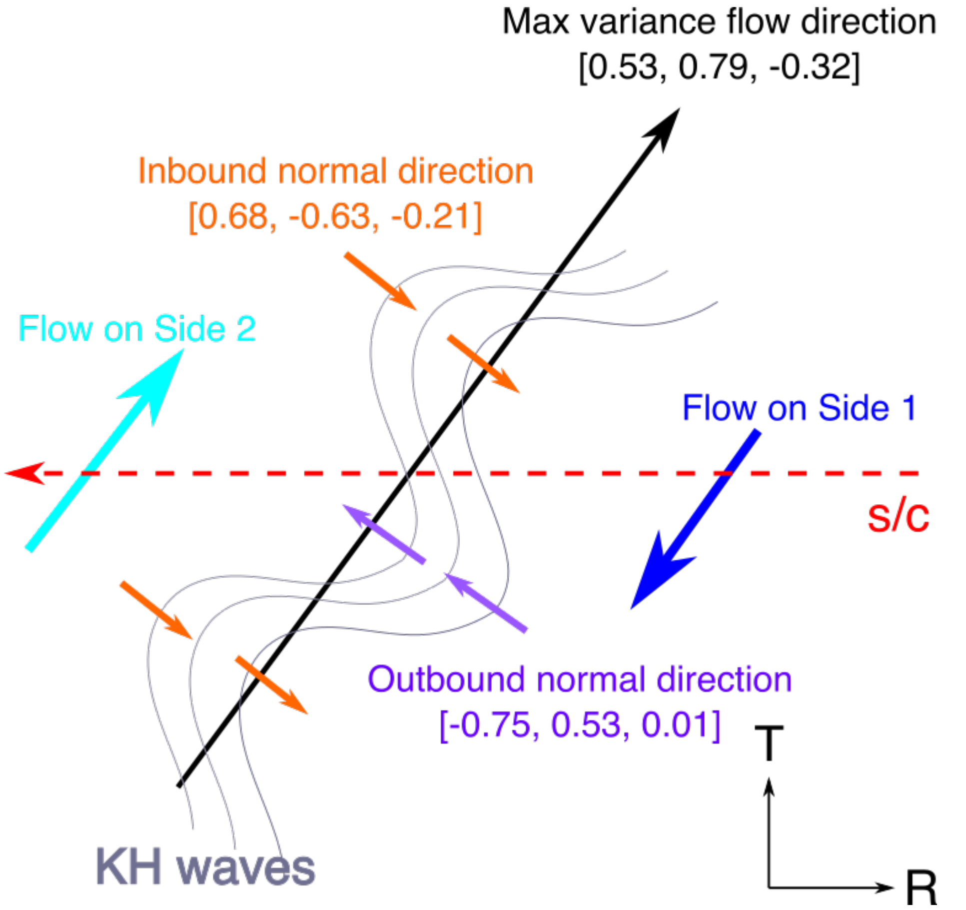
To understand the local configuration of the KHI, we derive normals of the magnetic discontinuities using $\mathbf{n} = \pm \frac{(\langle \mathbf{B}_1 \rangle \times \langle \mathbf{B}_2 \rangle)}{|\langle \mathbf{B}_1 \rangle \times \langle \mathbf{B}_2 \rangle|}$



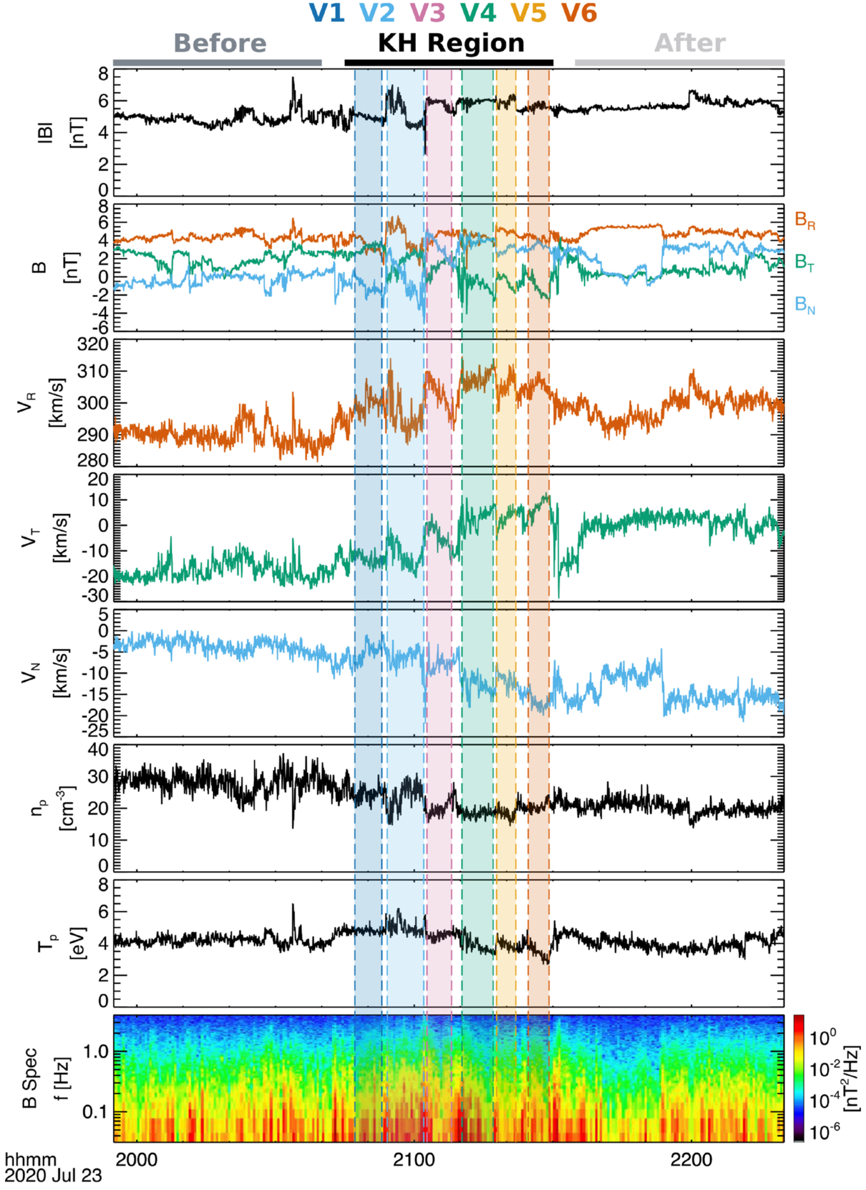
<u>Two types of magnetic rotations</u>

Sharp transitions: (2), (3), (4) => outbound / KH trailing edges

Smaller (reverse) transitions: (2’), (3’), (4’) => inbound / KH leading edges

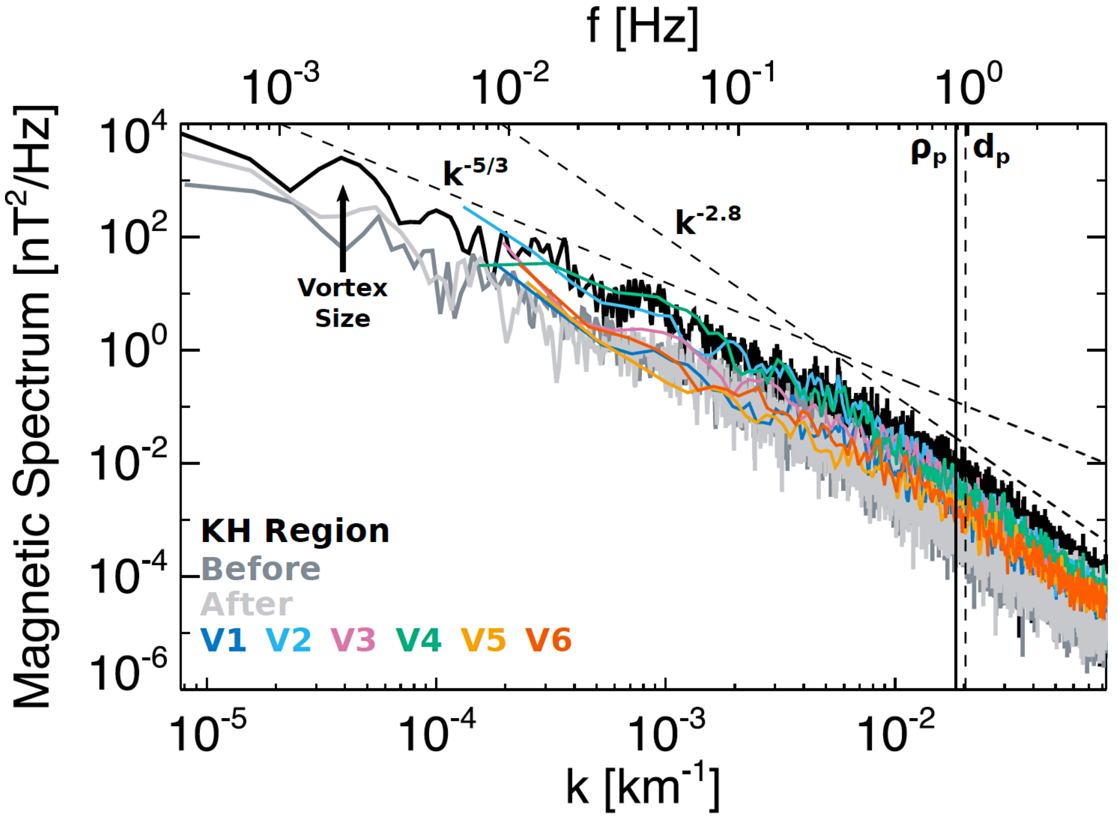


Magnetic spectra



To examine turbulence properties of the KH event,

(1) we compare magnetic spectra of the KH interval to the outside region
(2) we examine individual vortices (excluding current sheets)



The KH waves excite additional fluctuations!

The magnetic spectrum of the KHI approximately follows both power laws.

Discussion

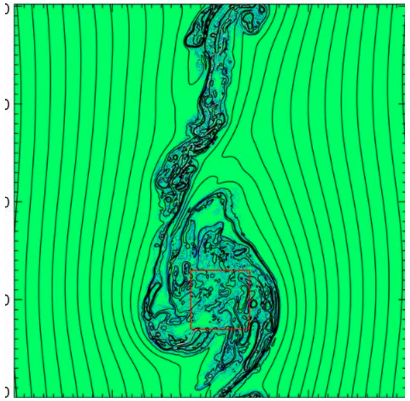
Why in-situ KH waves were not observed before in the solar wind?

(1) KHI criterion in the solar wind, which prefers $\Delta V > 2V_A$ and weak B in the ΔV direction
  - Near the Sun, B and V_A are large => KHI stabilized
  - In the interplanetary medium, V_A is decreasing and B and V becomes less aligned

(2) KHI timescale
  - The timescale for the decay of a KH vortex is on the order of one over a few folding times. This time scale is estimated to be ~ 10 minutes for the event.
  - This timescale on the order of minutes should be typical.

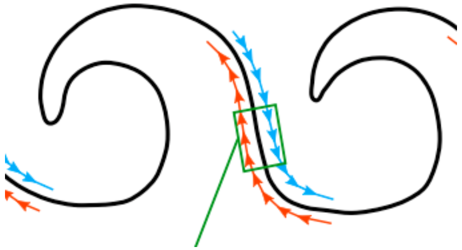
Implications of KH waves in the solar wind

KH waves are expected to play important roles such as allowing for plasma mixing and generating turbulence in the solar wind as mediated by KH vortex dynamics.



KH-generated turbulence

[e.g., Rossi et al. 2015]



vortex-induced reconnection

[Erikkson et al. 2016]

Summary & Discussion

We report observations of the KH waves with Solar Orbiter on July 23, 2020 at 0.69 AU, during the cruise phase.
The KH wave interpretation is supported by the linear theory, MHD simulation, and boundary layer analysis.

Several KH waveforms are observed within a shear layer near the HCS with a period of ∼ 7 minutes but only a few vortices are clearly noticed. The KH wavelength is approximately 66, 400 ± 8,400 km or 0.10 ± 0.01 solar radii.

Additionally, we report the observation of an ion jet consistent with magnetic reconnection at one of the outbound (trailing) edges, likely as a result of current sheet compression in between two KH vortices.

The power of the magnetic spectrum of the entire KHI interval approximately follows the power law scalings of $k^{-5/3}$ and $k^{-2.8}$ in the inertial and kinetic ranges, respectively, consistent with turbulence cascade in the solar wind.

This event provides evidence for the existence of the KH waves in the solar wind. It sheds new light to solar wind shear processes in the interplanetary medium with direct applications to shear-driven turbulence mediated by the KHI, likely contributing to the solar wind fluctuations observed at 1 AU.

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