The Influence of Turbulence on the Earth's Solar Wind Interaction

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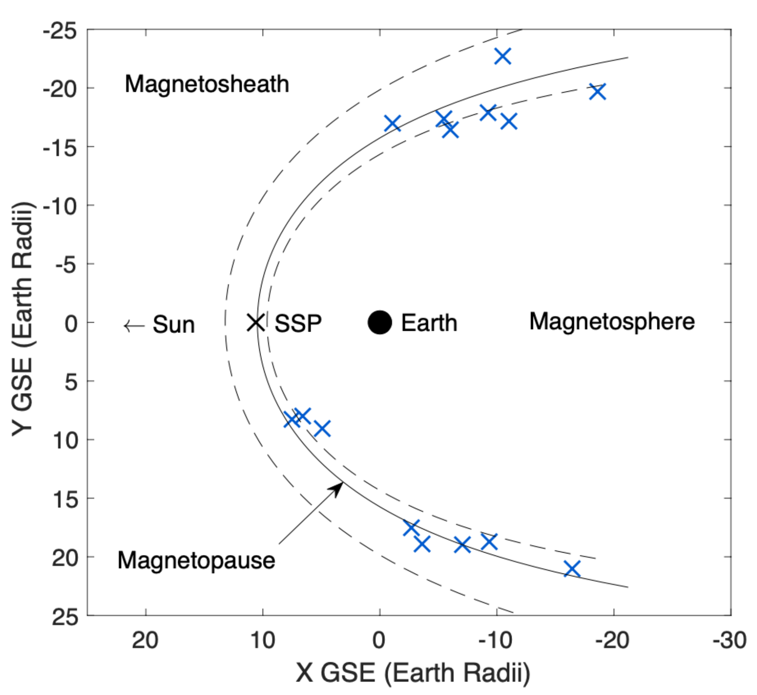
1) Background and Motivation

- The fast solar wind plasma meets the Earth's static magnetosphere plasma at the magnetopause, where a significant velocity shear exists. This boundary is therefore susceptible to the Kelvin-Helmholtz instability (KHI) which mixes the two plasmas, causing plasma transportation into the Earth's local magnetic environment.
- This phenomenon was measured using NASA's Magnetospheric Multiscale (MMS) mission [1], which observed the nonlinear stage of the instability. Recent simulation work has shown that turbulent fluctuations, which are frequently observed in the magnetosheath significantly enhance the growth of the instability [2].
- We extend on previous work, to analyse fifteen KHI candidate events observed by MMS between 2015 and 2020. To better understand each instability, we also perform numerical simulations using measured parameters for twelve events.

2a) Methods – Data Analysis Objectives

- To identify KHI events at the magnetopause from MMS data.
- To run the simulations, we need to quantify background parameters such as the magnetic field and ion/electron velocities/number densities/temperatures, inside, and either side of the magnetopause during a KHI event.
- To quantify various properties of turbulence within each region and to measure the wavelength associated with the KHI. Turbulent fluctuations typically follow a power law in frequency space, the index tells us how quickly energy is transferred to smaller length scales.



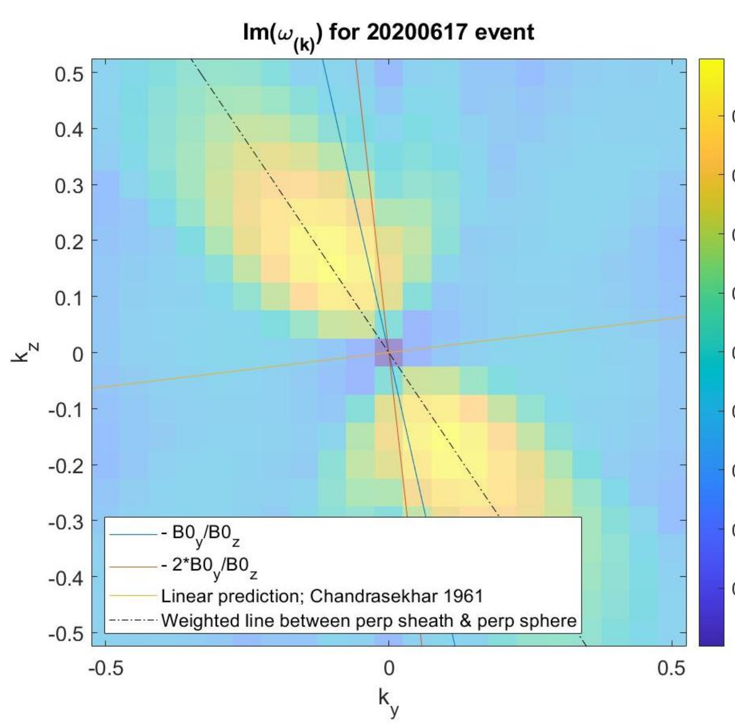


Figure 1 (left): Blue crosses represent events. The sub-solar point (SSP) is the closest point along the magnetopause to the sun. The magnetopause position is estimated using an empirical model.
Figure 2 (right): 2D map of the linear growth rate as a function of wavenumber, obtained from the simulation. The four lines plotted on top represent potential theoretical predictions on the dispersion relationship.

2b) Methods – Linear 3D KHI Simulation

We numerically solve the ideal magnetohydrodynamic (MHD) equations (below), which describe the plasma flow [3], using the measured background parameters from 2a.

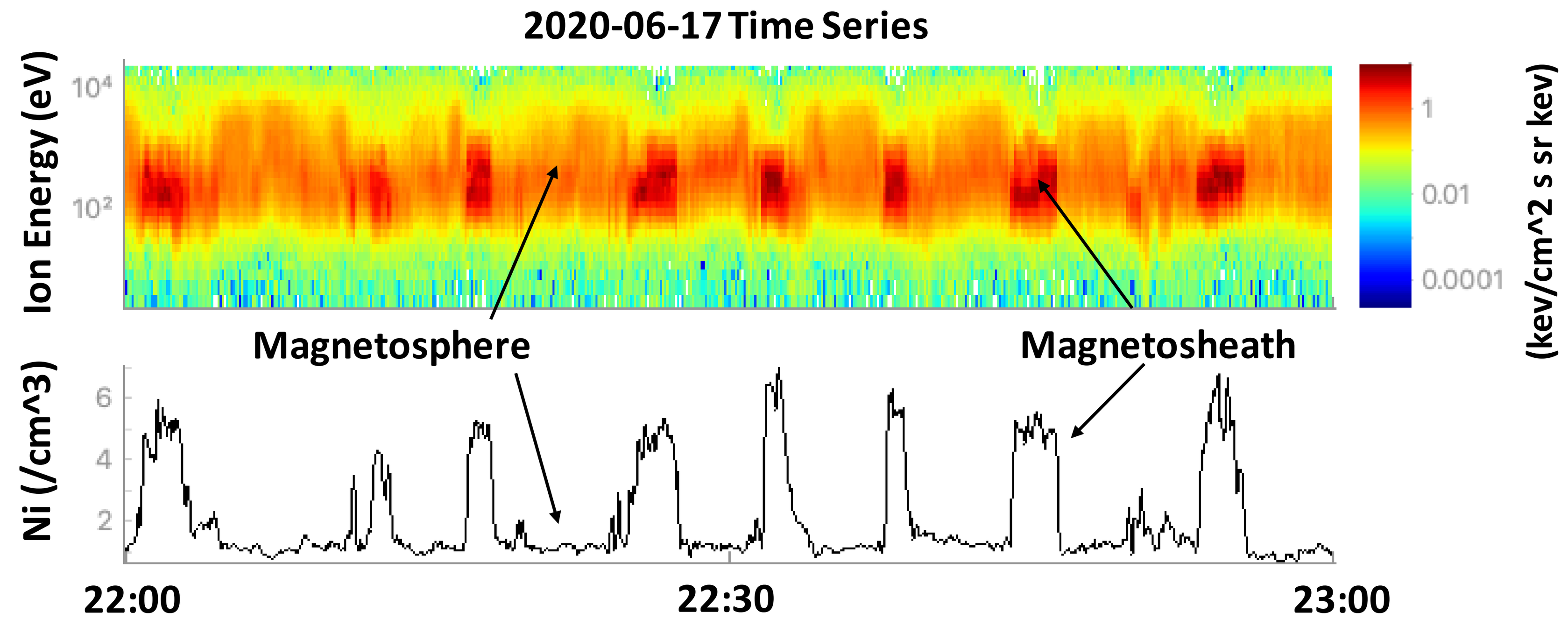
$$\partial\rho/\partial t = -\nabla\cdot(\rho\mathbf{v}) \quad (1)$$

$$\rho\, d\mathbf{v}/dt = -\nabla\left(p + B^2/2\mu_0\right) + \mu_0^{-1}(\mathbf{B}\cdot\nabla)\mathbf{B} \quad (2)$$

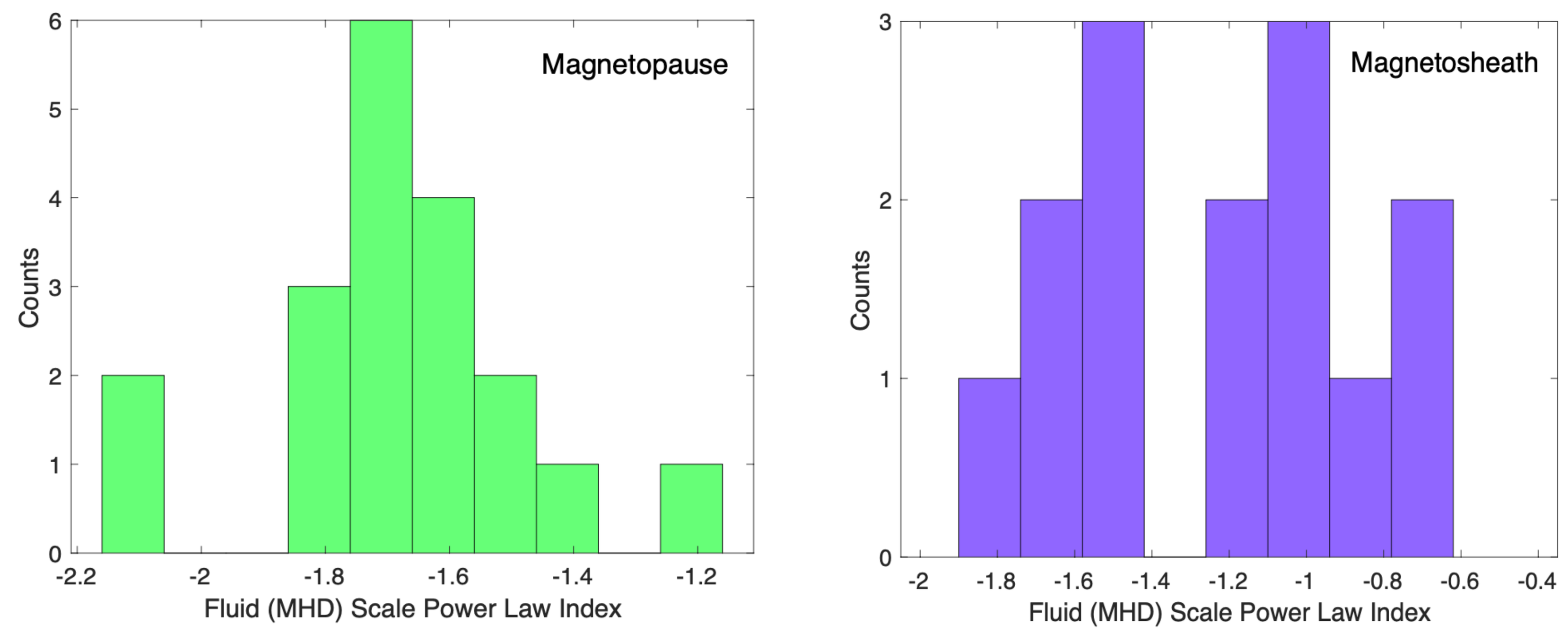
$$\partial\mathbf{B}/\partial t = \nabla\times(\mathbf{v}\times\mathbf{B}) \quad (3)$$

$$(d/dt)(p\rho^{-\gamma}) = 0 \quad (4)$$

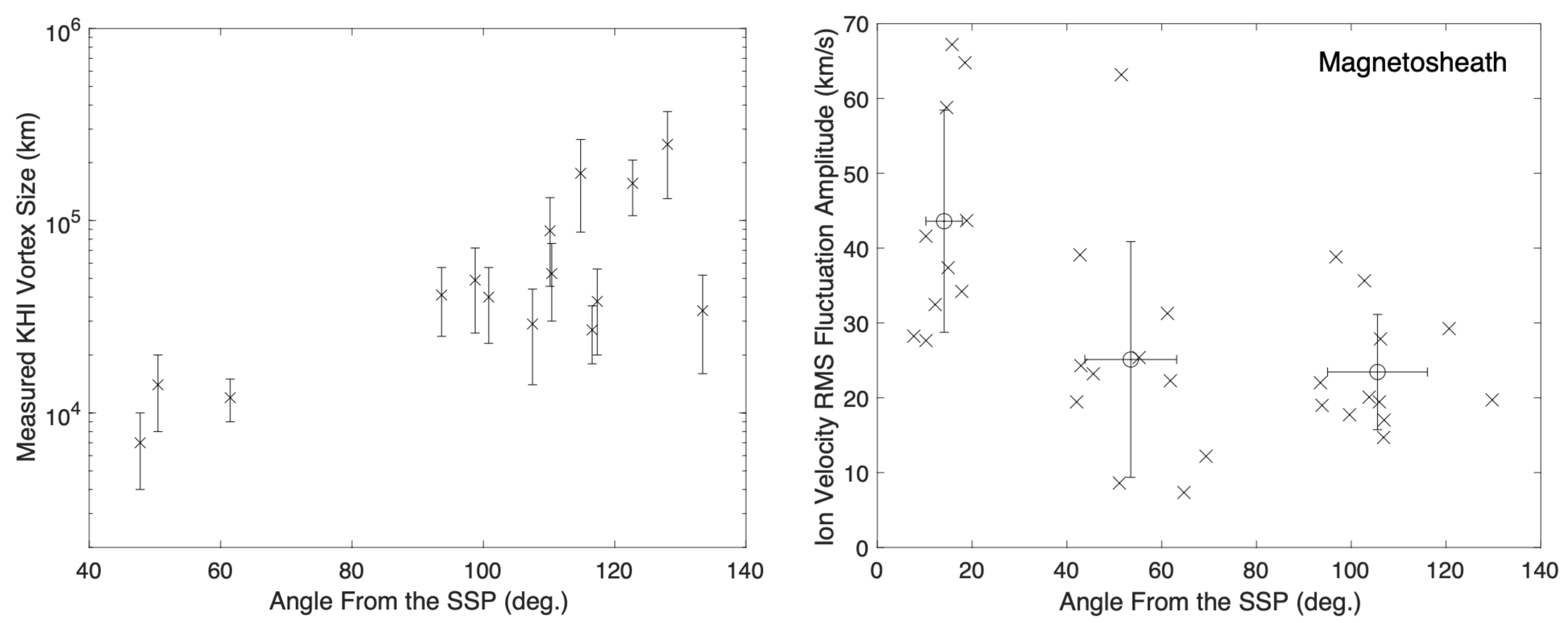
3a) Results – Observed Turbulence and KHI Properties



- We find fifteen KHI candidate events. In the above example we see periodic behaviour where there are clear transitions between the magnetosheath and magnetosphere plasmas.



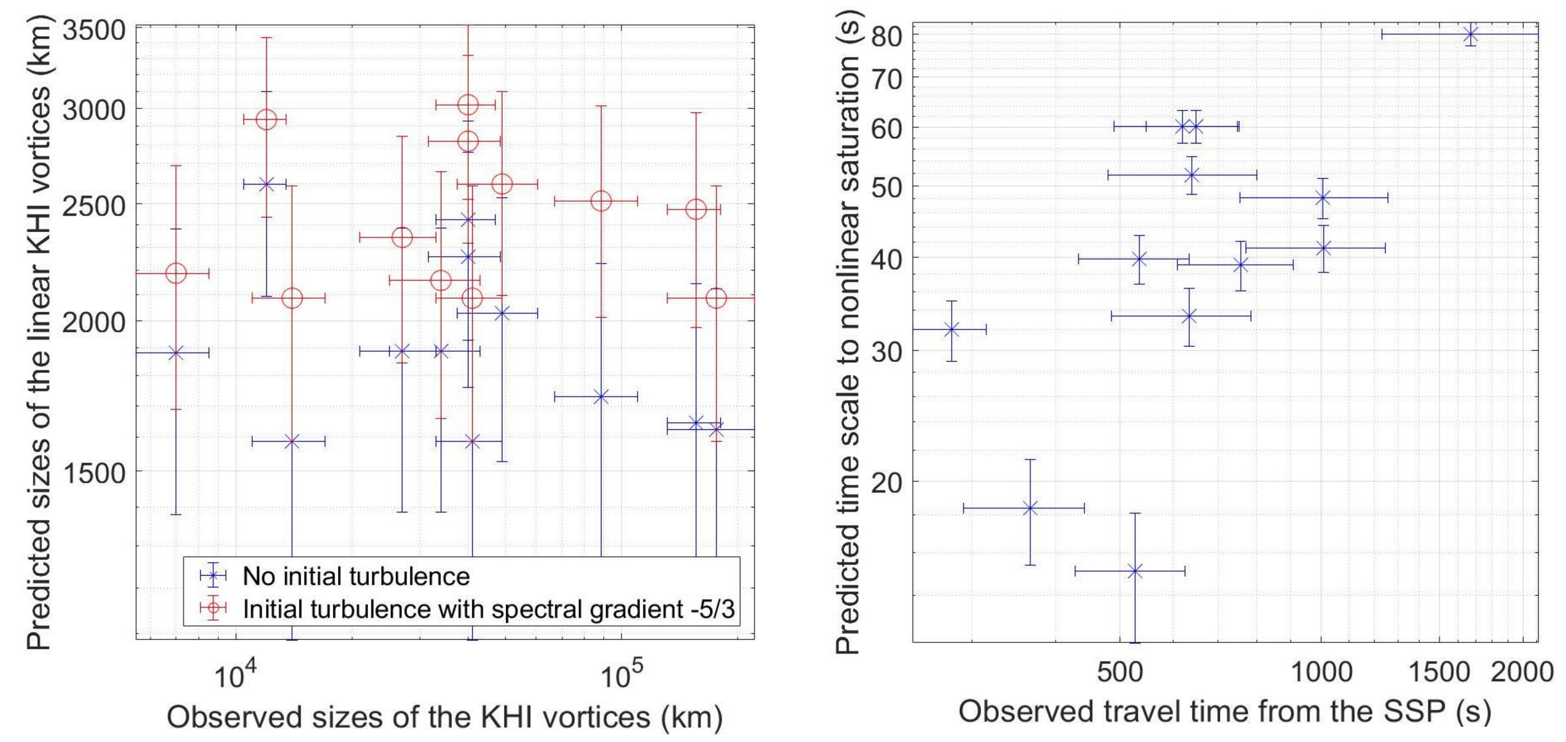
- We generally measure well-developed fluid scale turbulent fluctuations at the magnetopause, and more varied turbulent fluctuations in the neighbouring magnetosheath; both shown above. Both results are consistent with previous work [1,4].



- The measured vortex size is typically in agreement with previous studies, and increases with distance from the SSP, due to further growth of the instability and highly non-linear effects such as vortex merging. We also find that turbulent fluctuations are strongest in the magnetosheath closer to the SSP, where the instability is initiated.

3b) Results – Comparison between Observations and Simulations

- From the simulation we are able to obtain values for the time to reach nonlinearity and the dominant length scale corresponding to the KHI wavelength
- The observed KHI vortex size at the magnetopause is larger than the value predicted from our linear theory simulations, consistent with previous studies [2].
- When the MHD scale spectral gradient of the turbulent ion velocity RMS fluctuations is taken into consideration, not only the transition time scale from the linear to the non-linear regime decreases, but also the length scale corresponding to this transition increases, shifting the result closer to the observed value.



- These results suggest that the instability becomes become more nonlinear towards the flanks; the simulation predicts the linear KHI growth. These findings well agree with previous theoretical and simulation work [2, 4].

4. Conclusions

1. We have analysed fifteen MMS magnetopause crossings, showing signatures of KHI activity and find that the vortex size increases with distance from the SSP.
2. We have successfully performed linearised simulations using observed system parameters for twelve of these KHI events and find that initial turbulent perturbations improve the agreement between simulation and observation for the fastest growing mode, as expected from previous work [2]. A more detailed comparison is ongoing.
3. Further work building on our research should seek to analyse these events in more detail. For instance, what is the effect of turbulence on the KHI vortices during the later stages of the instability?

References

[1] Stawarz, J. E. et al. (2016) "Observations of turbulence in a Kelvin-Helmholtz event on 8 September 2015 by the Magnetospheric Multiscale mission" *J. Geophys. Res. Space Physics, 121.*
[2] Nakamura, T. K. M. et al. (2020) "Effects of fluctuating magnetic field on the growth of the Kelvin-Helmholtz instability at the Earth's magnetopause." *Journal of Geophysical Research: Space Physics*, *125* .
[3] Miura, A. and Pritchett, P. L. "Nonlocal Stability Analysis of the MHD Kelvin-Helmholtz Instability in a Compressible Plasma.", *J. Geophys. Res.* Vol. 87 (1982): 7431 – 7444.
[4] Sahraoui, F., Hadid, L. and Huang, S. "Magnetohydrodynamic and kinetic scale turbulence in the near-Earth space plasmas: a (short) biased review", *Reviews of Modern Plasma Physics* (2020) 4:4.