Exploring the evolution of turbulence across a range of terrestrial bow shock configurations using hybrid simulations

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December 27, 2023

Abstract

Observational investigations of Earth's bow shock have highlighted distinct variations in turbulence characteristics when comparing fluctuations in the shock transition with those in the upstream and downstream plasma regions. To gain a more focused understanding in each of these areas, we have examined a range of local 2D and 3D hybrid simulations, using kinetic ions and fluid electrons. Each simulation has been chosen to cover a range of shock geometries, from quasi-parallel to quasi-perpendicular and high to low Mach number. In-situ observations, such as those from the Magnetospheric Multiscale (MMS) mission, are often unable to fully disentangle spatial and temporal effects. This is particularly evident in the shock transition and the magnetosheath, where, for example, whistler waves may have speeds comparable to the bulk flow and thus locally violate Taylor's hypothesis for kinetic-scale fluctuations. Simulations overcome these limitations, enabling us to model the evolution of turbulence in the shock transition and further downstream. We characterize the turbulent fluctuations using the following three methods: Firstly, we examine the magnetic spectral indices spanning the inertial range and extending into the ion range as they change across the shock. Secondly, we investigate intermittency by means of the scale-dependent kurtosis. Lastly, we quantify the correlation lengths as measured across the shock, offering insights into the physical dimensions of fluctuations at scales smaller than the shock width. We will discuss the application of these measures to simulations in understanding the kinetic-scale behaviour of turbulence at Earth's bow shock.

NOTE: This poster was part of the SH022 Session at AGU Fall Meeting 2023.

EXPLORING THE EVOLUTION OF TURBULENCE ACROSS A RANGE OF TERRESTRIAL BOW SHOCK CONFIGURATIONS USING HYBRID SIMULATIONS

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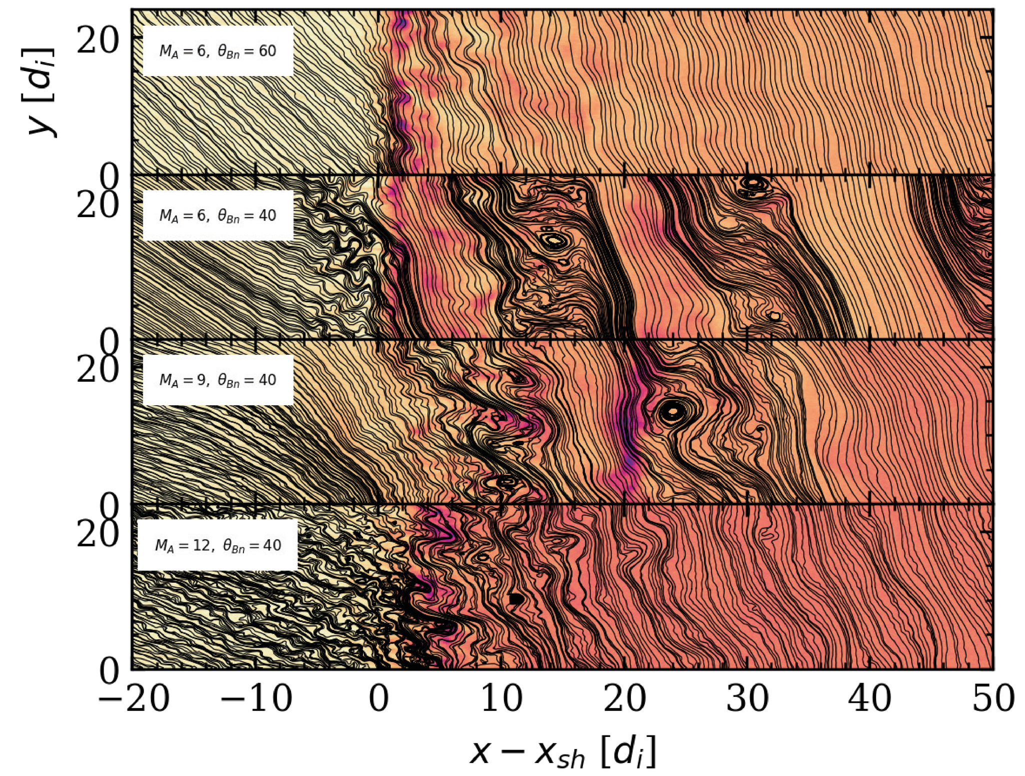
QUICK SUMMARY:

- *Background:* Observations [1] show that turbulent fluctuations observed in the solar wind and magnetosheath differ
- *Question:* How much of this variation is driven by the bow shock? And what is the scale size of shock-driven turbulence?
- *Method:* We use 2.5D hybrid PIC simulations of collisionless shocks to measure magnetic spectral index, kurtosis scaling, and correlation lengths
- *Results:* The magnetic spectral index is much steeper than well developed Kolmogorov inertial range scaling would suggest. The scaling of the kurtosis is highly localised to the shock, implying intermittency is not present far downstream. Correlation lengths remain large. This all suggests that dissipaiton of small scale structures is very efficient, but large structures generated at the shock (and from upstream) remain.

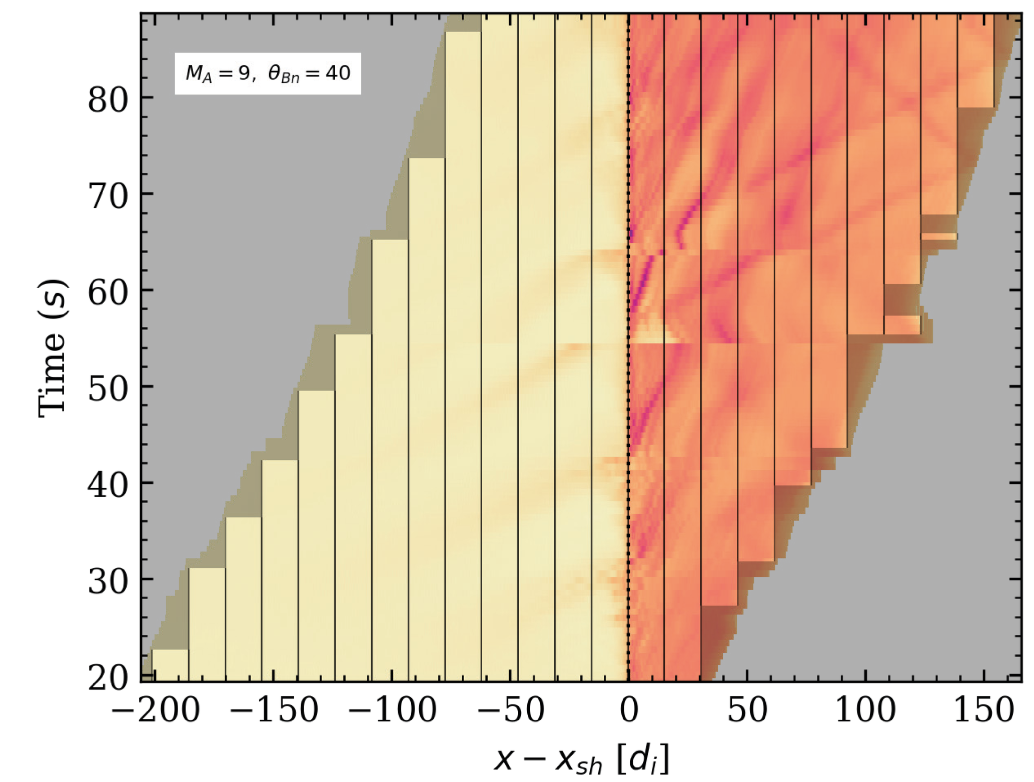
SIMULATIONS

- 2.5D Particle-in-Cell code [2], grid is resolved in 2D, while E and B fields can have z-component.
- Modified [3] to a hybrid method where electrons are modelled as a fluid.
- Grid: 1600x160, x:240, y:24d_i.
- One quasi-perpendicular and 3 quasi-parallel shocks simulated.
- Different Alfvén Mach numbers are also simulated.



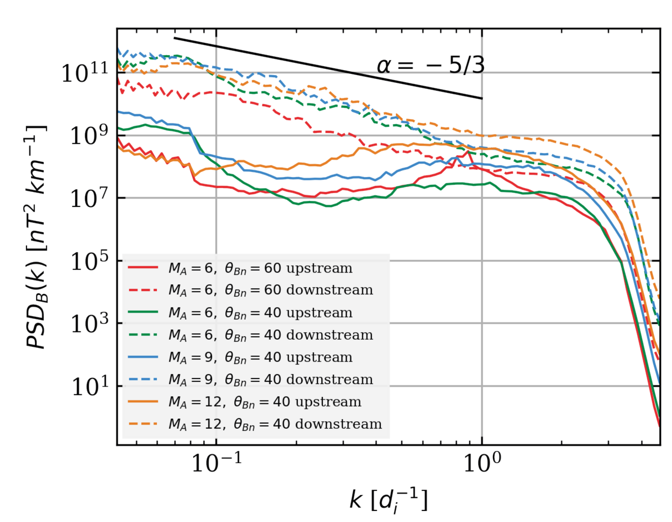
SHOCK IDENTIFICATION & X-X$_{SH}$ QUANTITY

- The shock moves at a near-constant speed, however the shock reformation cycle influences its precise location
- The shock is defined to be the first instance of the ion number density increasing to greater than 1/e times the maximum density (averaged in y) for each time step
- This exploits the homogeneous upstream conditions, which guarantee that upstream structures such as foreshock bubbles or current sheets will not be present.
- The shock-aligned simulation is split into 'chunks' of equal width (12d_i)



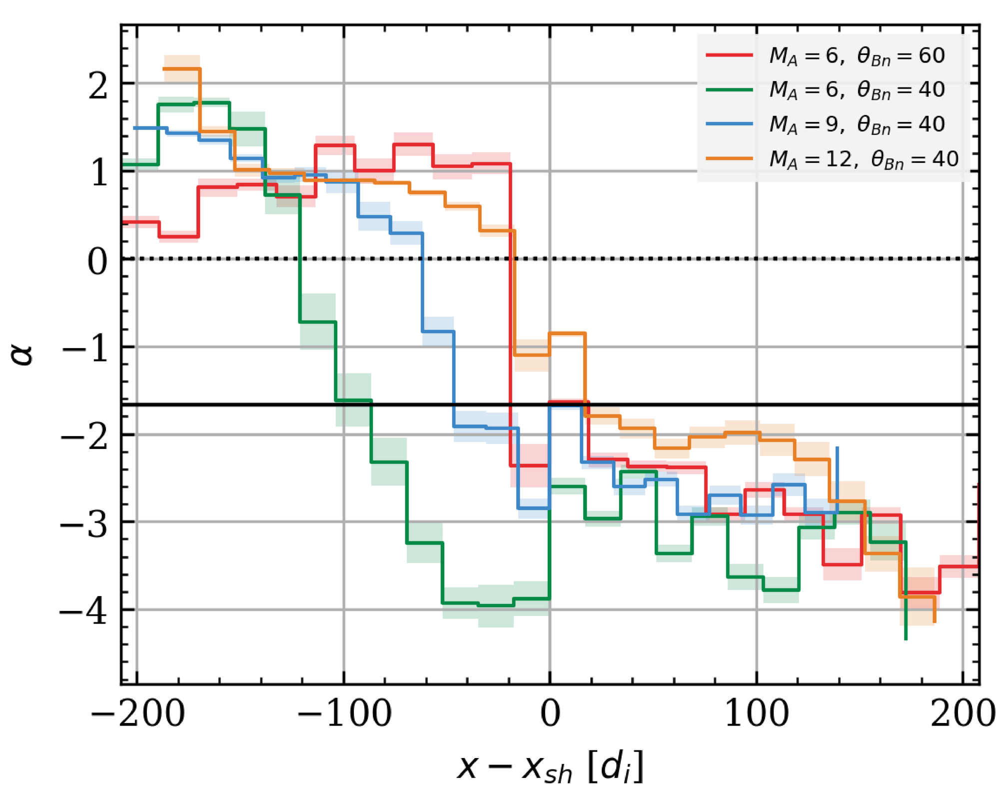
MAGNETIC SPECTRAL INDEX

- The power spectrum of the magnetic field is obtained from the 2D Fourier transform in x and y, which is then transformed to a single average radial wavenumber, k.
- In well-developed Kolmogorov turbulence, a power-law is observed at inertial scales (k<1/d_i) with a spectral index α=-5/3.
- The plot shows average power spectra for the entire upstream and downstream of four simulations at a single timestep.
- We see that upstream conditions (solid) are not representative of turbulence, while downstream conditions (dashed) show slopes similar to (but steeper than) -5/3.
- At k>2 we observe unphysical behaviour due to the fluid electron approximation.



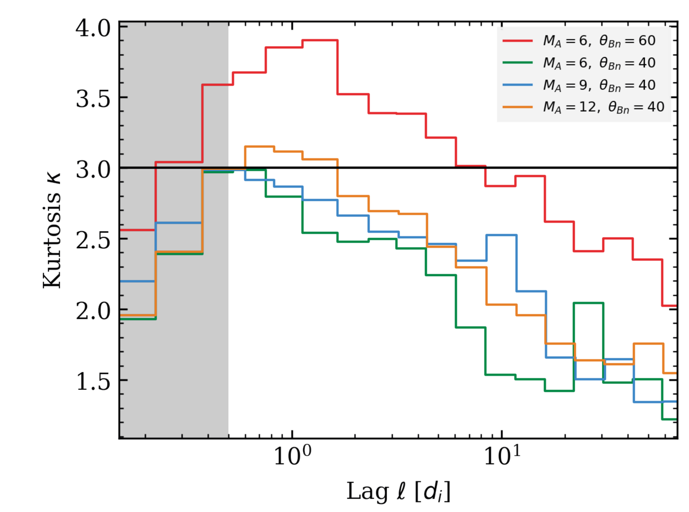
RESULTS

- Quasi-parallel shocks (red, blue, orange) all exhibit steepening of spectral index upstream of the shock.
- The steepest spectral index appears in the lowest Mach quasi-parallel shock.
- Quasi-perp shock (red) does not show any steepening until the shock foot.
- All shocks in the downstream show slopes much steeper than -5/3.



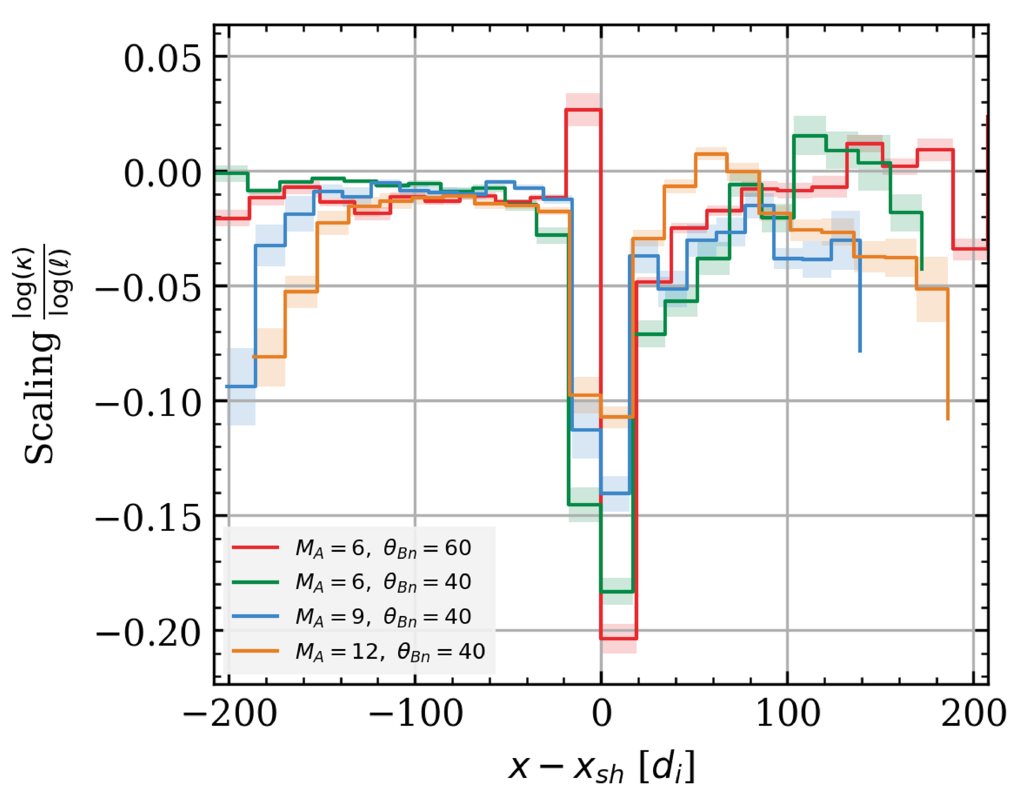
KURTOSIS SCALING

- Kurtosis, κ, is the fourth order statistical moment, representing heavy-tailedness.
- When κ>3 the distribution has more high/low amplitude observations than would be expected from a Gaussian.
- Scaling of the kurtosis (intermittency) is required for a fluid to be considered turbulent.
- We use the kurtosis of $\delta\vec{b}(\vec{x}) - \delta\vec{b}(\vec{x}+\vec{\ell})$ at lag ℓ to obtain the scale dependent kurtosis, where $\delta\vec{b} = \vec{B} - \langle \vec{B} \rangle_T$.
- The slope of this (at ℓ>1d_i) describes the scaling of the kurtosis. More negative means that kurtosis increases with scale more strongly.
- Therefore, steeper negative slope indicates stronger intermittency.



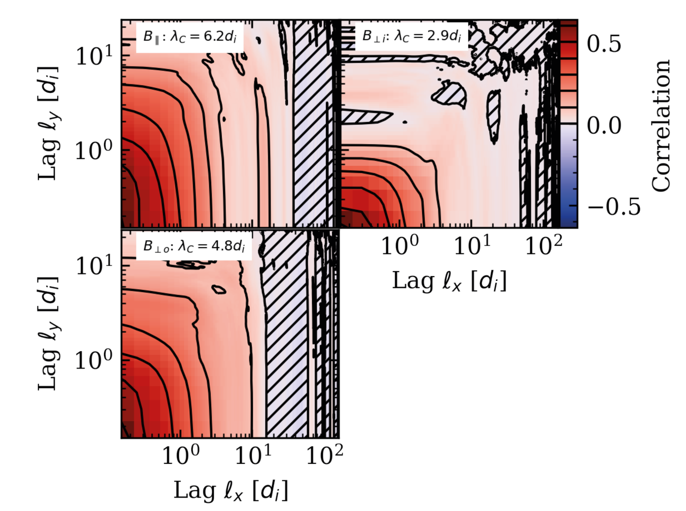
RESULTS

- In the upstream away from possible inflow effects, there is no evidence of intermittency.
- The 'chunks' either side of the shock exhibit the strongest scaling relationship, and hence the strongest intermittency.
- The kurtosis scaling rapidly decays for all shocks.



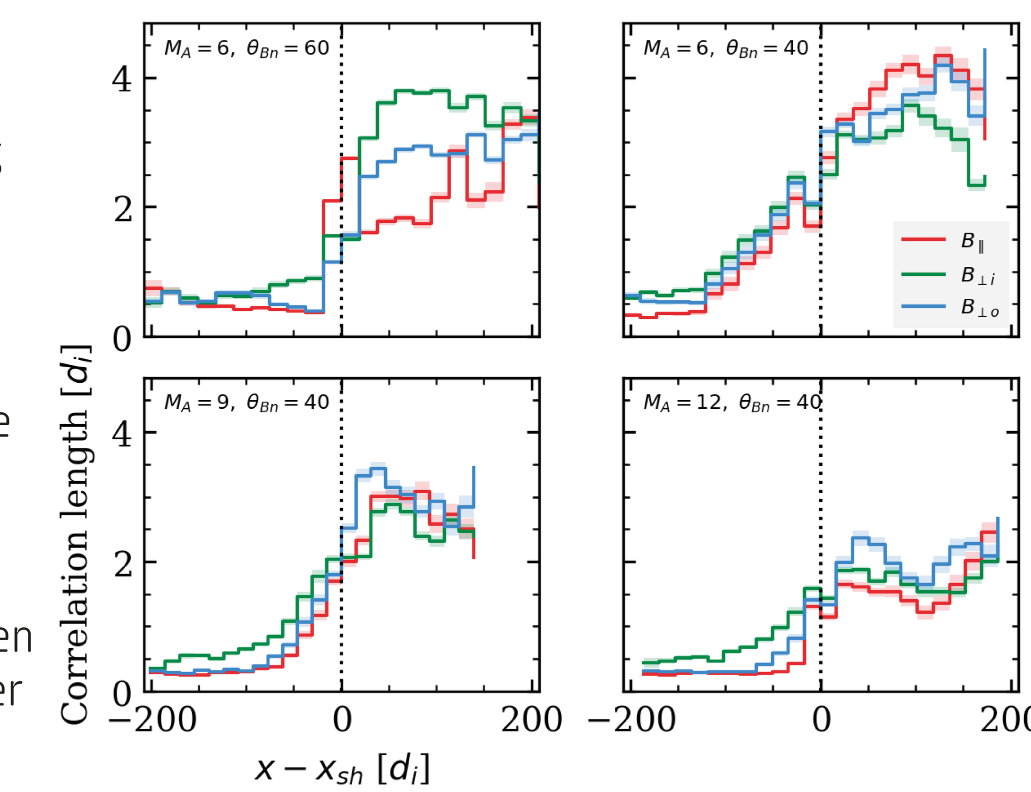
CORRELATION LENGTH

- This can be used [1,4] to describe the average size of the dominant fluctuations observable in the data.
- It is defined as the area underneath the 2D autocorrelation of the magnetic field in x and y, up to the first zero crossing, $\lambda_C^2 = \iint_0^{\ell_{0C}} R(\vec{\ell})\, d\vec{\ell}$. Where R($\ell$) is the autocorrelation.
- Here, we have rotated the components of the magnetic field bx,by,bz, into components parallel, perpendicular in the x-y plane and perpendicular out-of-plane, relative to the mean magnetic field in each 'chunk' of data.
- From this we can observe how the size of the dominant structures changes across the shock.



RESULTS

- All quasi-parallel shocks show a steadily increasing correlation length approaching the shock.
- Fluctuations in the quasi-perp shock do not start to grow significantly until the shock foot.
- Counterintuitively, the largest downstream correlation lengths are seen in the lowest Mach number shock (top right).



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[2] Arber, et al., (2015), Contemporary particle-in-cell approach to laser-plasma modelling, https://doi.org/10.1088/0741-3335/57/11/113001
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[4] Stawarz, et al., (2019), Properties of the Turbulence Associated with Electron-only Magnetic Reconnection in Earth's Magnetosheath, https://doi.org/10.3847/2041-8213/ab21c8