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The evolution of turbulence through the transition region of Earth's quasi-parallel bow shock

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1. INTRODUCTION Reconnection has been observed at Earth's bow shock [1], and has also been observed to influence properties of turbulence [2,3]. At shocks, reconnection can occur in a disordered/turbulent transition region [4,5]. Observations from Magnetospheric Multiscale (MMS) have been used to identify an event (Fig. 1) that shows in detail how the magnetic spectrum evolves as solar wind plasma crosses a quasi-parallel bow shock and enters the transition region downstream of the shock.

2. POWER LAWS AT DECREASING SCALES The magnetic spectrum (Fig. 2, 3) displays power law relationships at inertial, ion and electron scales. The steepness of the slope both in relative (compared to smaller/larger scales) and absolute terms is related to turbulent energy cascades.

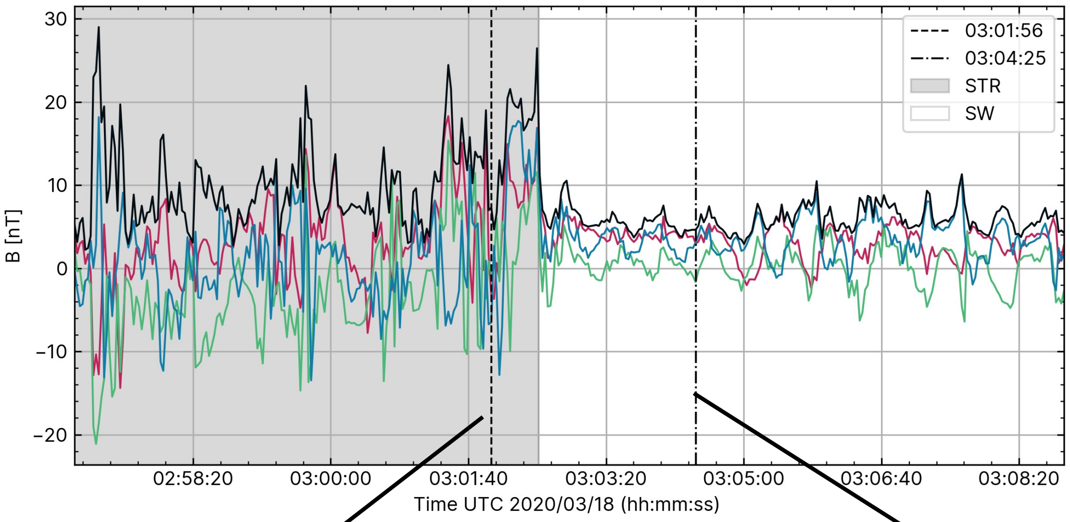


Fig. 1 Plot of magnetic field (**B**) components in GSE x, y & z coordinates. |**B**| in black. Shaded grey is the shock transition region (STR), solar wind (SW) is shaded white. The bow shock is at the boundary.

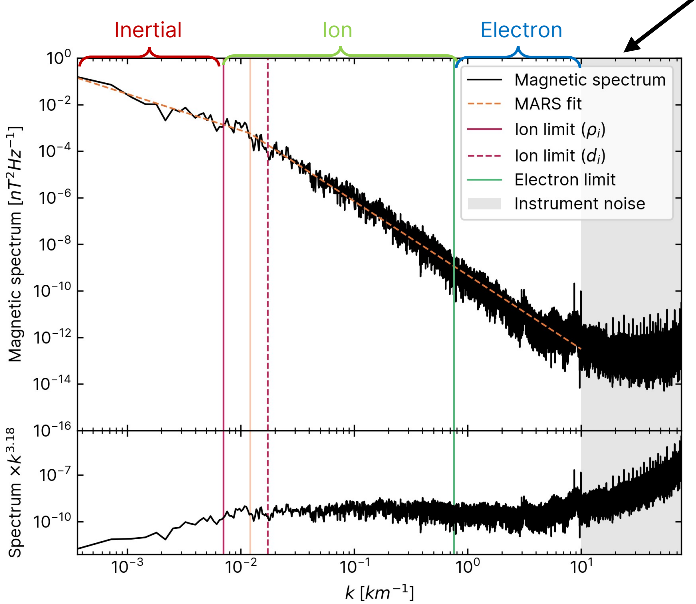
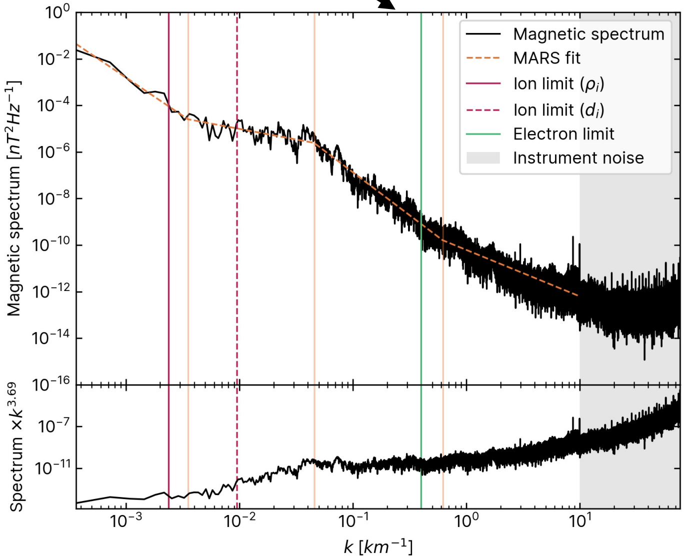


Fig. 2 *Top:* Magnetic spectrum in STR (6.7s window). There is a distinct change in power law slope visible at ~ion scale, however, there is no clear change at the electron scale. *Bottom:* Magnetic spectrum multiplied by sub-ion scale power law slope. Slope stays flat from ~ion scale almost down to instrument limit.

Fig. 3 The magnetic spectrum in SW (6.7s window). Multiple power law slopes are visible. Two power laws have been identified by MARS algorithm in the ion range. There is also a separate power law visible for electron scales. *Bottom:* Multiplying by k^{slope} visually accentuates changes in slope.



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3. EVOLUTION OF SPECTRUM ACROSS SHOCK By splitting the event into ~6.7s intervals (two examples Fig. 1 & Fig. 2), we can show how power law slopes change for each range of scales.

METHOD A Assuming spectral breaks occur at $k = \rho_i$ and $k = \rho_e \approx d_e$, the slope associated with each region can be calculated with a linear regression. The evolution of the slopes can be seen in the middle panel of Fig. 4

METHOD B Using the MARS [5] algorithm we chain (an arbitrary number of) linear fits end-to-end across the entire spectrum $-3.6 \leq \log k \leq 1$ (Fig. 4, bottom). The spectral break is not guaranteed to be placed exactly on the ion/electron gyroradius (see Fig. 2 & 3). Hence, this results in a more accurate fit to the magnetic spectrum.

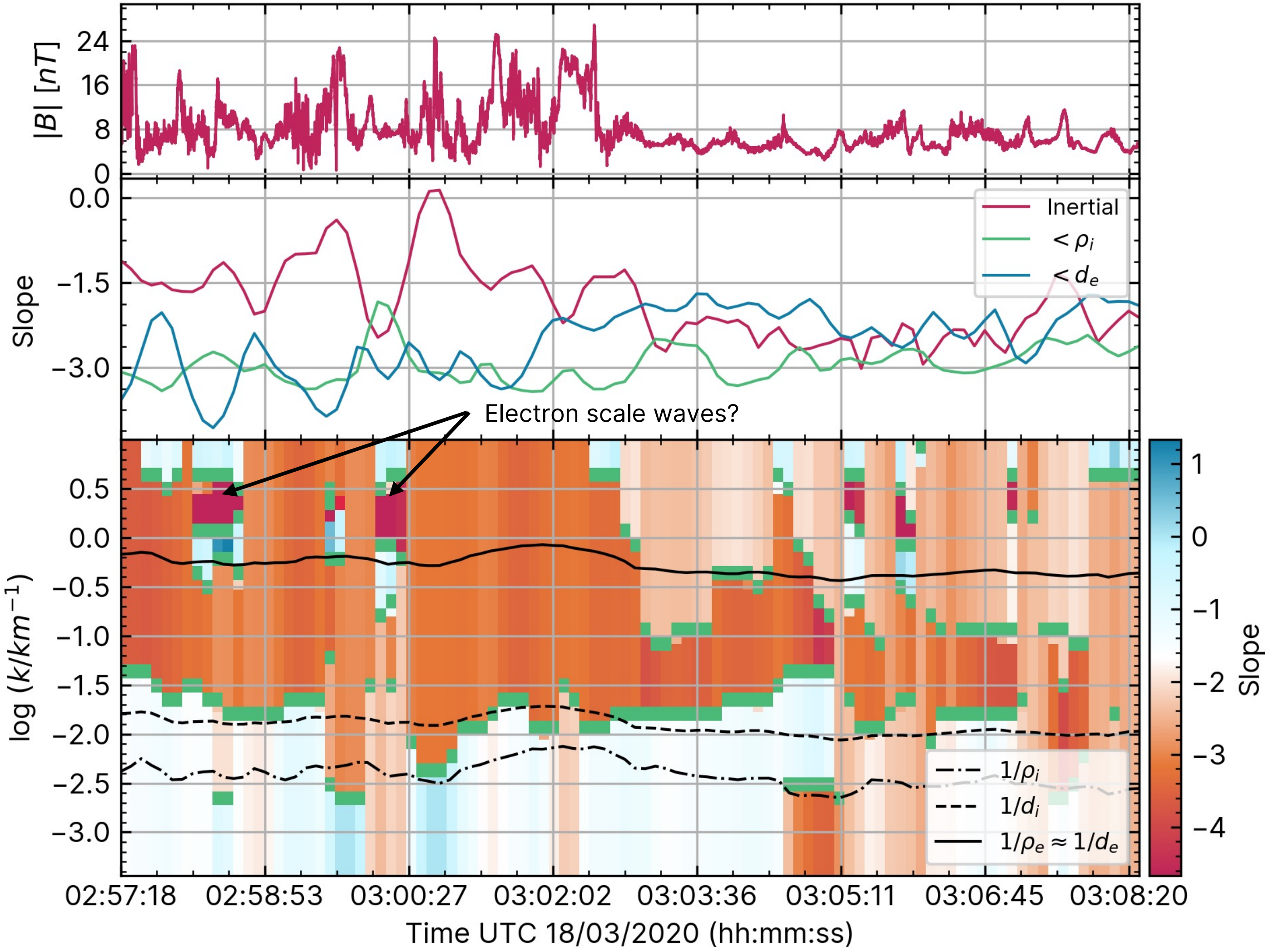

Fig. 4 *Top:* Magnetic field. Shock at about 03:02:30. *Middle:* Slope for inertial, ion and electron ranges, as calculated by method A. Inertial range slope flattens across the shock. Ion slope does not change significantly. Electron range slope becomes steeper. *Bottom:* Time dependence of best fit power laws to magnetic spectrum identified by method B (MARS). Green pixels indicate a change in power law. Colour represents power law index. Blue is shallower, white is centred on -5/3, and red is steeper. As plasma enters shock transition region, the distinction between electron and ion ranges is lost.

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4. COMPARISON TO V_X Time series data (e.g. Fig. 4) is not always the most accurate representation of how near or far the spacecraft is from the shock, due to non-stationarities or motion of the shock. Therefore, we consider another proxy for distance through the transition region, v_x (GSE). As plasma encounters the shock, v_x increases ($|v_x|$ decreases), therefore each panel of Fig. 5 can be read left-right as a transition from solar wind to shock transition region.

We find that the slope decreases in the inertial range when crossing the shock, in the ion range there is no significant change, while the electron range shows a decreasing spectral index. This is the same result as shown by method A & B above.

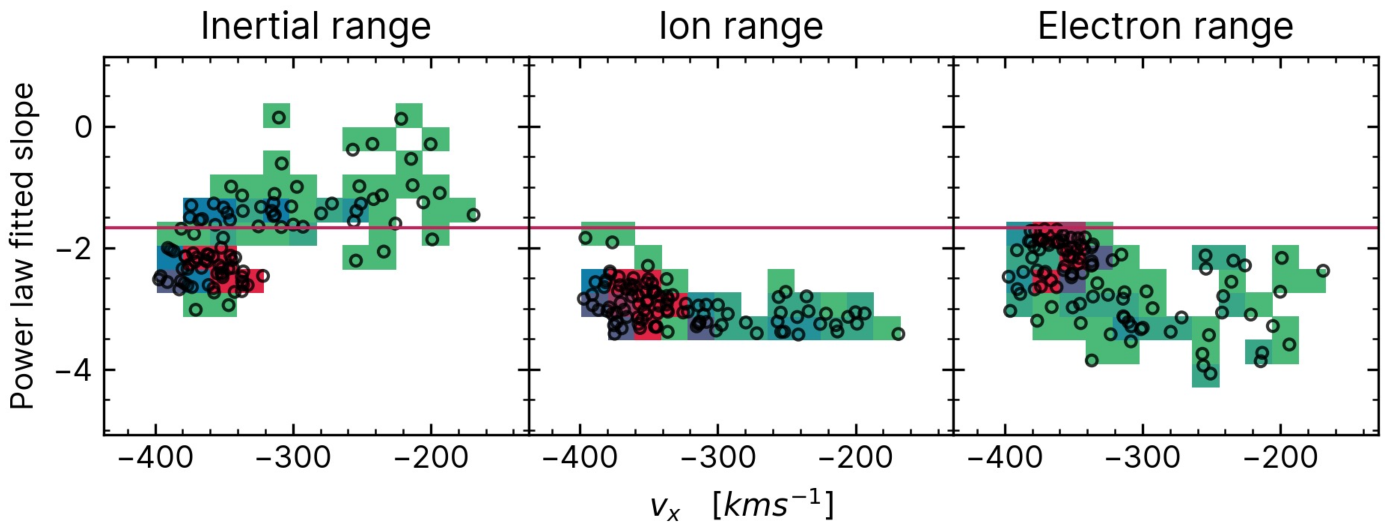

Fig. 5 Plot of power law index (calculated using method A) against v_x for the three ranges. 2D histogram (colour) is also shown. Slope decreases in inertial range, remains mostly unchanged in ion range and decreases in the electron range. A -5/3 slope is drawn in red.

5. CONCLUSION Across a quasi-parallel bow shock, the magnetic spectrum displays a power law that becomes shallower at the inertial scale, steeper at the electron scale and does not significantly change at ion scales. The electron scale slope steepens to become approximately equal to the ion slope such that the distinction between them is lost.

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