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Turbulence in the Solar Wind: Theory, Simulations, and Comparisons with Observations[1]

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In situ measurements of the solar wind uniquely enable detailed comparison of turbulence in an astrophysical environment with theory and simulations. We present an analytical cascade model that follows the nonlinear flow of turbulent energy from the large driving scales in the MHD regime to the dissipative scales in the weakly collisional kinetic regime. For a large inertial range, scaling arguments suggest the turbulence remains low frequency, $\omega \ll \Omega_i$, due to the anisotropy of the MHD cascade, $k_\parallel \ll k_\perp$. Such low-frequency, anisotropic turbulence is optimally described by gyrokinetics. In this limit, the MHD Alfvén wave cascade transitions to a kinetic Alfvén wave cascade at the scale of the ion Larmor radius. Analytical cascade model results, nonlinear gyrokinetic simulations, and observational evidence support this claim, eroding the case for the importance of the ion cyclotron resonance in causing the break and steeper dissipation range of the turbulent magnetic energy spectrum in the solar wind. The analytical cascade model predicts that one expects an exponential cut-off in the energy spectrum above the spectral break, but that instrumental sensitivity limitations lend the dissipation range a power-law appearance. The observed variation of dissipation range slopes is naturally explained by the varying effectiveness of Landau damping as the plasma parameters change. Conditions under which the cyclotron resonance may play a role are identified. Nonlinear gyrokinetic simulations of solar wind turbulence support the predictions of the analytical model, producing magnetic and electric field fluctuation spectra that are consistent with satellite measurements.

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