Velocity-space structure and differential heating of ions in solar-wind turbulence

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The solar wind exhibits broadband turbulence and strongly non-Maxwellian ion velocity distribution functions (VDFs), including temperature anisotropies, beams, and more complex velocity-space structures. Although these phenomena are often studied separately, they must arise from the same underlying dynamics. The key question is how the turbulent cascade at large scales connects to the kinetic processes that shape ion distributions at small scales. In this talk, I use analytical theory and state-of-the-art numerical simulations to argue that a consistent picture emerges once the large-scale turbulence imbalance (cross-helicity) is treated as a controlling parameter of the cascade. In low- plasmas, sufficiently large imbalance throttles the cascade near ion-Larmor scales via the helicity barrier effect, limiting energy transfer to electron scales and driving the self-generation of high-frequency ion-scale fluctuations. These fluctuations include both kinetic-Alfvén and proton-cyclotron–like modes, which interact resonantly with particles and drive departures from Maxwellian equilibrium in a way that is strongly dependent upon imbalance. Within this framework, structured ion VDFs arise directly from the turbulent dynamics. Protons develop beams and anisotropies associated with Landau and cyclotron resonances, while alpha particles and heavier ions exhibit enhanced perpendicular heating and characteristic arc-like features in velocity space. The degree of heating and the morphology of the VDFs are strongly species-dependent, exhibiting nontrivial dependences on mass-to-charge ratio that are consistent with trends inferred from in situ measurements of the fast solar wind. At the same time, the cascade develops a steepened transition range and a modified spectral break at ion scales, again consistent with solar-wind observations. These spectral properties and velocity-space structures therefore arise from a single, imbalance-controlled cascade dynamics. The resulting picture is that differential ion heating and velocity-space structure are direct consequences of how imbalanced turbulence regulates the emergence of proton-cyclotron waves and the partitioning of energy across species. In this way, ion VDFs provide one of the most direct diagnostics of turbulent dynamics in the solar wind.