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Theory and hybrid simulations of the radial evolution of the solar wind turbulence

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Solar wind turbulence in the inner heliosphere is believed to evolve in the radial direction away from the Sun driven by various nonlinear processes. When a perturbative treatment is applicable, plasma fluctuations evolve along the dispersion relations while the frequencies deviate from the normal-mode frequency by exciting non-normal modes or sideband waves. Direct numerical simulations of magnetized plasma at the scale of ion gyro-radius or smaller using the hybrid code AIKEF show smooth transitions and evolutions into nonlinear stage with sideband wave excitations. The evolution profile of linear and nonlinear modes as well as the intrinsic nature of wave vector anisotropy can be unambiguously classified according to the values of ion plasma beta. By using a mapping based on a one-dimensional solar wind expansion model, the resulting ion kinetic scale turbulence is related to the solar distance from the Sun. We find that the relevant normal modes such as ion cyclotron and Bernstein mode will occur first at radial distance of about 0.2-0.3 AU, i.e. near the Mercury orbit. Furthermore, a radial dependence of the wave-vector anisotropy is obtained. The predominance of the filament structures highlights the strong impact of Alfvénic waves.