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Impact of evolving turbulence on the diffusion coefficients of wave-electron interactions associated with whistler waves

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The solar wind electron velocity distribution function (eVDF) deviates significantly from thermal equilibrium throughout the heliosphere. The kinetic properties of solar wind electrons are fully described by an eVDF evolving with heliocentric distance. This evolution results from a delicate balance between competing mechanisms. Wave-particle interactions driven by whistler waves significantly regulate suprathermal electron transport in the solar wind. However, previous numerical models based on simplified spectral assumptions fail to reproduce observational features of the radial evolution of suprathermal electrons.

To resolve this, following the quasi-linear kinetic theory proposed by Steinacker & Miller (1992) [1], we extend the derivation of the diffusion coefficients for the transport of suprathermal electrons in the solar wind as used in previous works, retaining a completely general form of the magnetic energy spectral density of whistler waves. Using the turbulence model of Zank et al. (1996) [2] and a dimensional analysis method [3], we obtain an expression for the magnetic energy spectral density of whistler waves that evolves with heliocentric distance, rather than assuming a fixed simple power-law spectrum. The obtained magnetic energy spectral density is determined by the background magnetic field and the magnetic fluctuations at the resonant wavenumber of the whistler waves, which is more sophisticated than the previously used power law spectra. The radial evolution of turbulence-mediated diffusion coefficients is examined systematically through comparison with previous power-law-based coefficients.

Our results demonstrate that the turbulence-mediated coefficients decrease more slowly with heliocentric distance from 0.1 au, being approximately one order of magnitude stronger than the power-law-based coefficients in the range of 0.2 ~ 2 au. This in part is due to the dynamical generation of turbulence in the solar wind by various processes and the subsequent cascade of magnetic energy to small scales. This enhancement might help address the drawbacks in previous simulations of suprathermal electron transport in the solar wind, particularly the low numbers of halo electrons propagating in a sunward direction at larger heliocentric distance. Additionally, we find that the spectral index of the dissipation range must exceed 2 to maintain physical consistency between the two coefficients. These findings provide critical insights into turbulence-regulated suprathermal electron transport, directly affecting heat flux dynamics and the strahl-to-halo transition mechanism in the solar wind.

References

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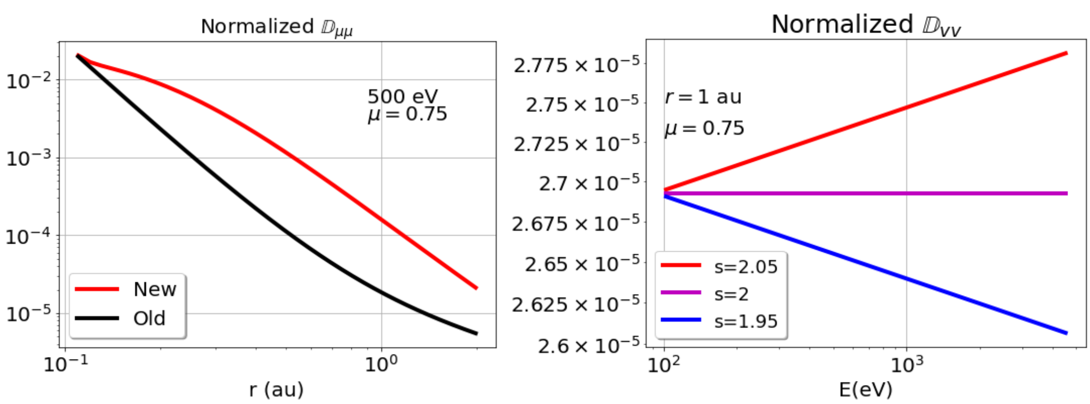

Figure 1. (Left) Comparison of turbulence-mediated and power-law-based diffusion coefficients as a function of distance from 0.1 to 2 au for strahl electrons (5×10^2 eV, μ= 0.75). Red curves are turbulence-mediated coefficients, while black curves are the power-law-based diffusion coefficients. **(Right)** Comparison of the normalized D_{vv} of turbulence-mediated diffusion coefficients as a function of electron kinetic energy from ~ 0.1 keV to ~ 4 keV with different spectral indices s. The red, magenta, and blue curves represent spectral indices s = 2.05, 2, and 1.95, respectively.