Kappa distributions in solar wind and magnetospheric plasmas

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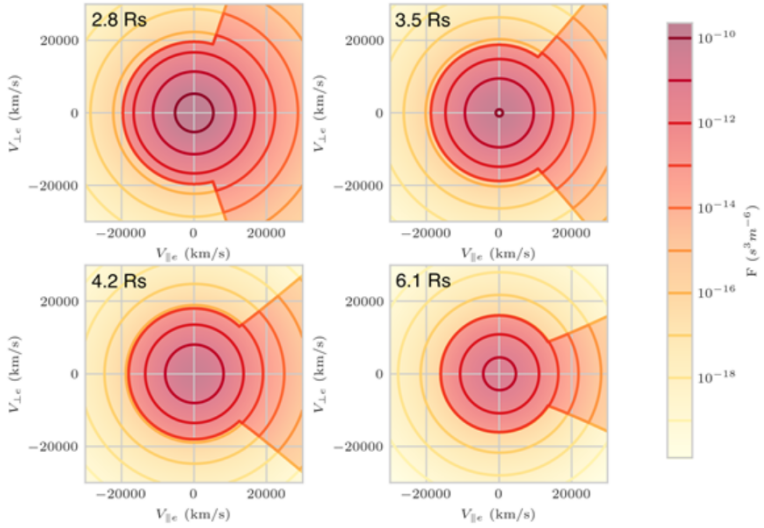
Kappa distributions are observed in many space plasmas, from the solar wind to planetary magnetospheres, including in the plasmasphere of the Earth and giant planets. We made fits with kappa functions of observed particle velocity distributions to determine the importance of the suprathermal tails at different distances [1]. Recent observations of Parker Solar Probe close to the Sun have shown diffusion of the strahl electrons into the halo population and a clear deficit of particles in the antisunward direction. Kinetic models determine the importance consequences of such suprathermal particles on the anisotropy, temperature, and heat flux profiles [2]. To study the emergence of suprathermal tails in the electron velocity distribution functions, kinetic three-dimensional simulations have been developed that include large-scale turbulent forcing. The results suggest a Kappa tail origin due to the interplay between turbulence and firehose instability. Our work bridges plasma observations and theoretical models with the goal to provide a unified, fully kinetic framework that captures the coupled effects of expansion, diffusion, turbulence-driven heating, and kinetic instabilities.

Kinetic models are not limited to the solar wind but apply also to the polar wind and plasmasphere of the Earth and other planets. The exceptional recent solar eruptions that generated geomagnetic superstorms gave nice opportunities to compare the observations with the results of the kinetic models during very disturbed periods. The plasmapause was exceptionally close to the Earth during such superstorms, in excellent agreement with the 3D dynamic model of the plasmasphere based on Kappa distributions [3]. The plasmasphere plays an important role in the loss of energetic radiation belt particles that led to unprecedented four electron belts observed during more than one month after Mother's Day event in May 2024 [4].



References:

[1] Pierrard V., Péters de Bonhome M., Halekas J., Audoor C., Whittlesey P. and Livi R., Exospheric Solar Wind Model Based on Regularized Kappa Distributions for the Electrons Constrained by Parker Solar Probe Observations, Plasma, 6, 518–540, 2023, https://doi.org/10.3390/plasma6030036

[2] Péters de Bonhome M., Pierrard V., Bacchini F., A Kinetic Model of the Solar Wind Acceleration Driven by Velocity Space Diffusion and the Ambipolar Electric Potential, Astronomy and Astrophysics, 697, A104, 2025, https://doi.org/10.1051/0004-6361/202554250

[3] Pierrard, V., Verhulst, T.G.W., Chevalier, J.-M., Bergeot, N., Winant, A. Effects of the Geomagnetic Superstorms of 10–11 May 2024 and 7–11 October 2024 on the Ionosphere and Plasmasphere, Atmosphere 2025, 16, 299, https://doi.org/10.3390/atmos16030299

[4] Pierrard V., A. Winant, Atmospheric loss of energetic electrons and protons from the radiation belts after the exceptional injection of the 11 May 2024 superstorm leading to four electron belts, Atmosphere, 17, 324, 1-24, 16 March 2026, https://doi.org/10.3390/atmos17030324