Whistler waves and electron deficit in the solar wind: Insights from Particle-In-Cell simulations

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Abstract: In-situ observations of the solar wind reveal that the electron velocity distribution function (VDF) is composed of a quasi-Maxwellian core, along with two more sparse components: the halo and the strahl. Recent measurements by Parker Solar Probe (PSP) and Solar Orbiter (SO) have identified an additional feature in the non-thermal VDF structure: the **deficit**—a depletion in the sunward region of the VDF, long predicted by exospheric models but only recently extensively observed. Using Particle-in-Cell simulations, we analyze electron VDFs that reproduce those typically observed in the inner heliosphere and explore the potential role of the electron deficit in triggering kinetic instabilities. Prior studies and in-situ data indicate that strahl electrons can drive oblique whistler waves unstable, leading to their scattering. This process enables suprathermal electrons to access phase-space regions that satisfy resonance conditions with parallel- propagating whistler waves. The suprathermal electrons lose kinetic energy, resulting in the generation of unstable waves. The sunward side of the VDF, initially depleted of electrons, is gradually filled, as this wave-particle interaction process, triggered by the depletion itself, takes place. Our results are validated against current PSP and SO observations. Specifically, the study provides insights into the origins of the frequently observed parallel anti-sunward whistler waves in the heliosphere, their correlation with electron-deficit distributions, and a non-collisional process regulating heat flux.

The origins of the Sunward electron deficit

The Sunward electron deficit [**Berčič et al, 2020; Halekas et al, 2020**] is a consequence of heliospheric electron circulation in the presence of an eletrostatic potential $e\phi$, **Fig. 1**.

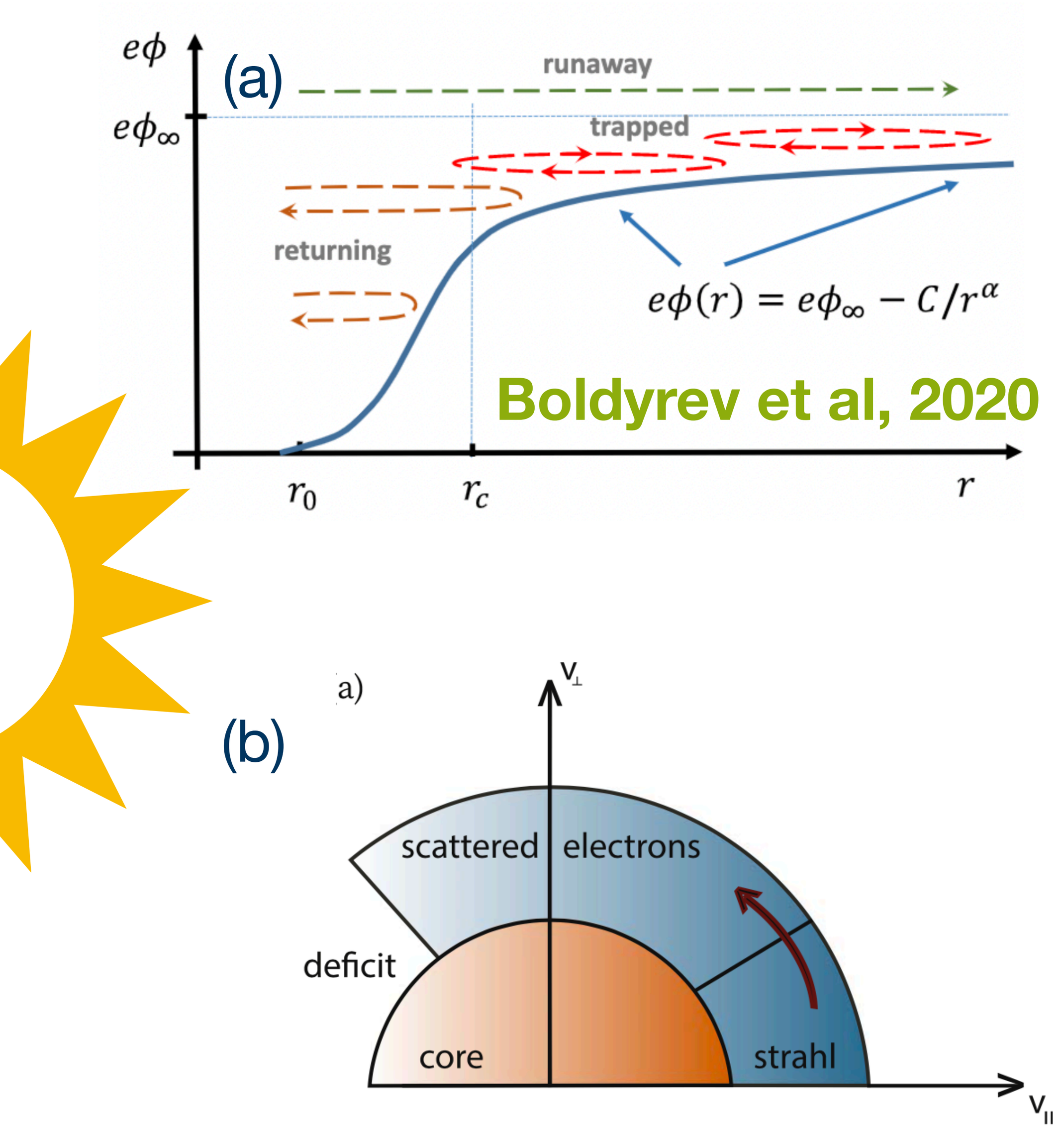


Fig. 1: heliospheric electron circulation (a) and electron Velocity Distribution Function, eVDF (b): *trapped* and *returning* electrons form the **core**, *runaway* electrons the **strahl**. The whistler heat flux instability scatters strahl electrons into the **halo** [**Micera et al, 2020 & 2021**]: a Sunward **deficit** is formed.

We model the electron deficit via 2D fully kinetic Particle-In-Cell simulations, run with the iPic3D code [**Markidis et al, 2010**]. The eVDF is initialised as a modified drifting Maxwellian in a background magnetic field, with parallel electron and ion beta $\beta_{e\parallel} = 1.5$ and $\beta_i = 1.7$, realistic mass ratio $m_r = 1836$ and an electron drift that ensures the zero current condition.

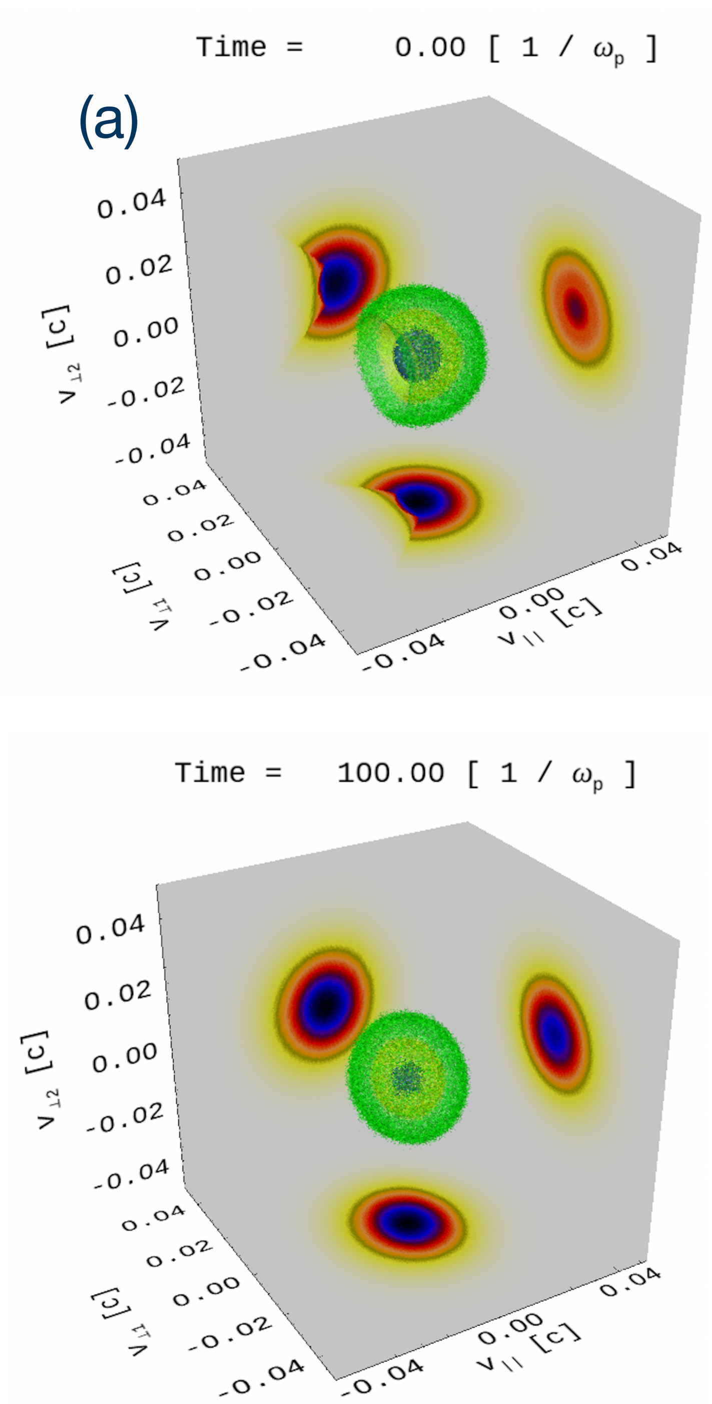
Micera, A., Verscharen, D., Coburn, J. T., & Innocenti, M. E. (2025). Quasi-parallel Antisunward-propagating Whistler Waves Associated with the Electron Deficit in the Near-Sun Solar Wind: Particle-in-cell Simulation. *The Astrophysical Journal*, *979*(2), 226

PIC simulations of the electron deficit instability

Electrons are initialised as a modified drifting Maxwellian, removing from the distribution electrons with velocities

$$v_\parallel > -p\sqrt{(v_{\perp 1}^2 + v_{\perp 2}^2)}, \text{ with } p = 1,$$

A parallel instability is observed, which fills the deficit, **Fig. 2**.



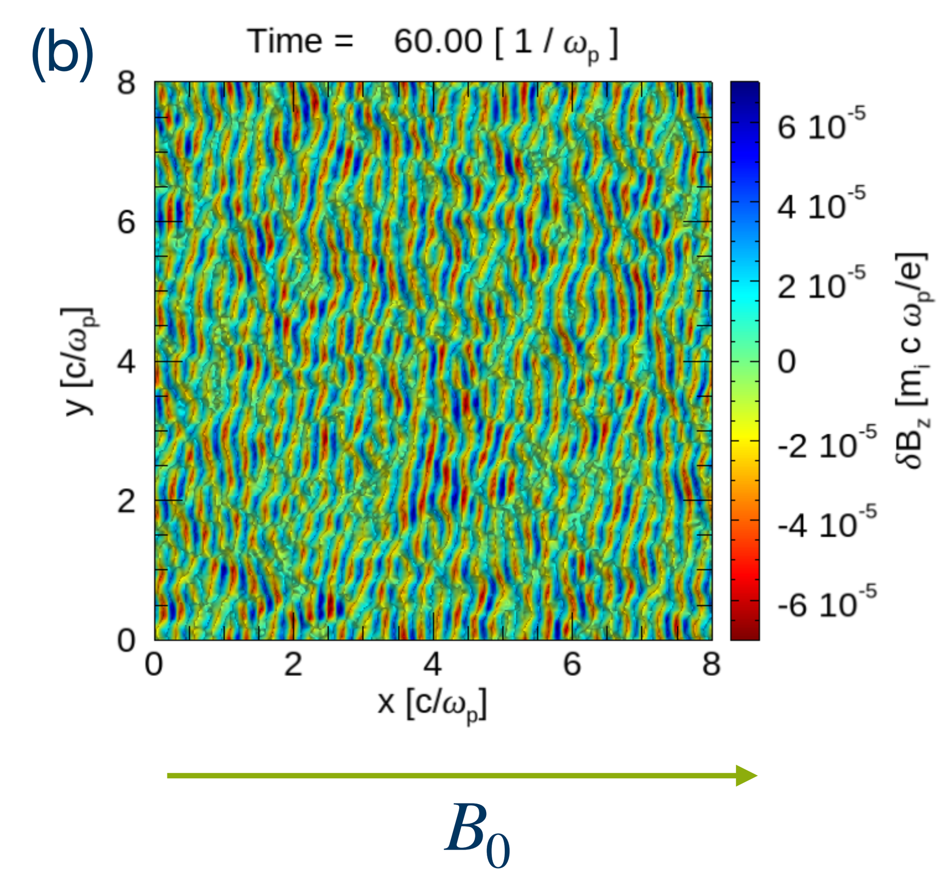


Fig. 2: (a) eVDF evolution: the electron deficit is partially filled by electron scattering due to an ensuing parallel instability (panel b)

The instability propagates in the parallel anti-Sunward direction, has dispersion relation in the $k_\parallel$ *vs* ω_r plane compatible with the whistler dispersion relation and is right hand polarised, **Fig. 3**

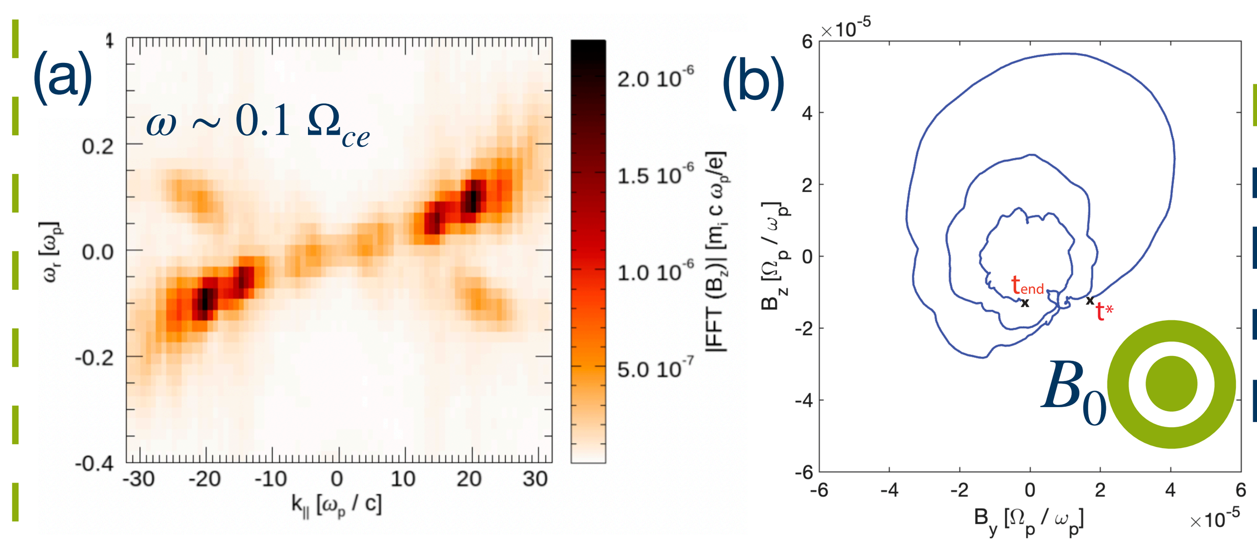


Fig. 3: (a) dispersion relation and (b) hodogram, showing right hand, RH, polarization

This matches Solar Orbiter, SO, observations of the whistler deficit instability, **Fig. 4, Berčič et al, 2021**

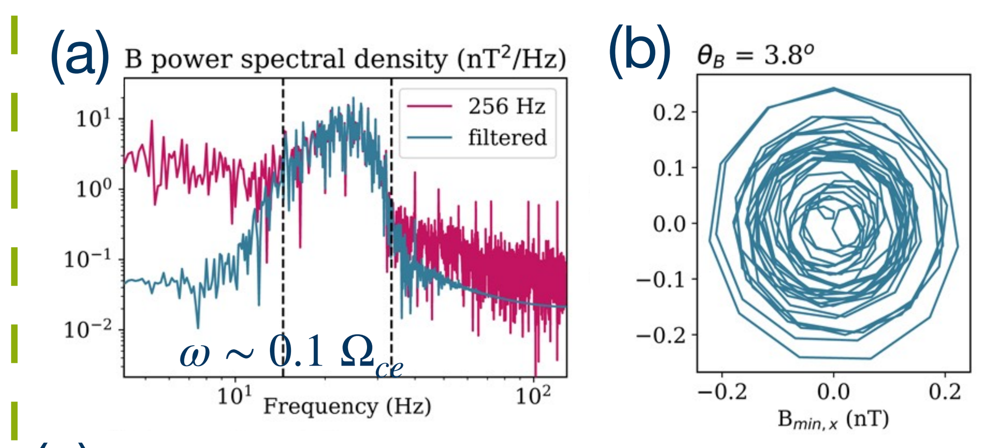
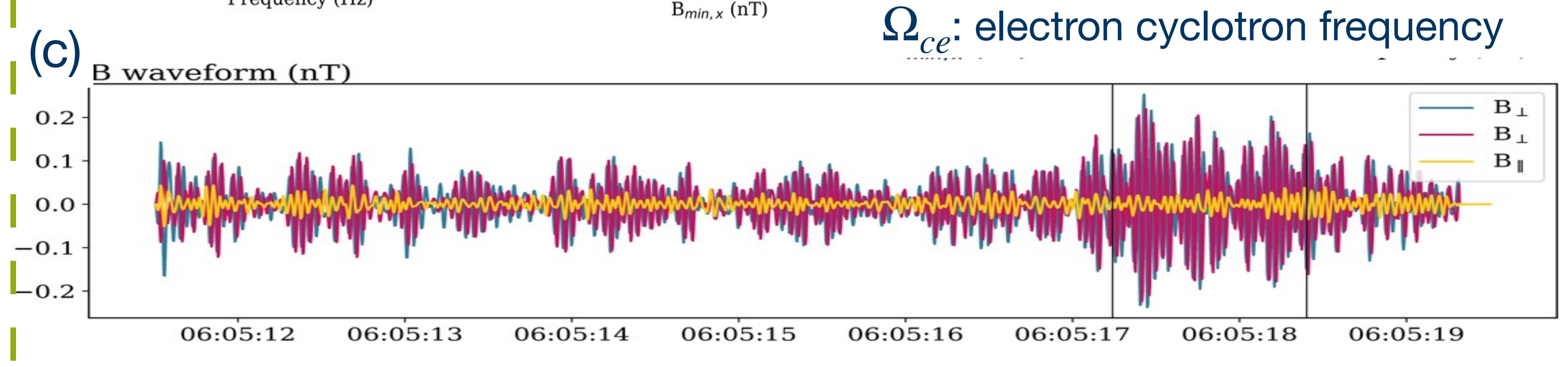


Fig. 4: SO observations: a) power spectral density, b) RH polarization, c) parallel propagation

Ω_{ce}: electron cyclotron frequency



Conclusions: our work proposes a possible origin mechanism for **parallel-propagating, anti-Sunward whistler waves** in the solar wind, with characteristics compatible with what reported in Solar Orbiter observations by **Bercic et al, 2021**. The waves are originated by the Sunward electron deficit [**Halekas et al, 2020; Bercic et al, 2020**], in turn a consequence of global electron dynamics [**Boldyrev et al, 2020; Micera et al, 2020, 2021**]. During the evolution of the instability, the deficit is partially filled, and the (anti-Sunward) heat flux is reduced

References: Berčič, L. et al. 2020, ApJ, 892, 88; Berčič, L. et al. 2021, A&A, 656, A31; Boldyrev, S. et al. 2020, PNAS, 117, 9232; Halekas, J. S. et al. 2020, ApJS, 246, 22; Markidis, S. et al. 2010, Math. Comput. Simul., 80, 1509; Micera, A. et al. 2020, ApJL, 903, L23; Micera, A. et al. 2021, ApJ, 919, 42