9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Direct Evidence of Nonlinear Cyclotron Resonance in the Solar Wind

Jing-Huan Li[1], Yuri V. Khotyaintsev[1], Daniel B. Graham[1], Philippe Louarn[2]
[1] Swedish Institute of Space Physics, Uppsala,
[2] Institut de Recherche en Astrophysique et Planétologie, CNES-CNRS, Universite Toulouse III
e-mail (speaker): jinghuan.li@irfu.se

Cyclotron resonance is a fundamental mechanism underlying a wide range of plasma energization phenomena, including solar wind heating, a long-standing problem traditionally addressed within the quasi-linear framework. However, the prevalence of large-amplitude, coherent waves in the solar wind suggests that nonlinear resonance also contributes significantly to energy transfer and dissipation. Despite this, direct observational evidence remains scarce due to the limited resolution of in-situ particle measurements.

We utilize the high-resolution Solar Orbiter measurements to investigate the nonlinear interactions between ion-cyclotron waves (ICWs) and solar wind protons. The observations reveal that the proton core and beam are phase-bunched by left-hand and right-hand polarized waves, respectively. Such bunching provides direct evidence for the nonlinear cyclotron resonance in the solar wind. Subsequently, we use the resonant velocities to identify the wave modes and determine the wave properties in the plasma frame. With the aid of the Doppler-shifted dispersion relations, we identify the left-hand and right-hand waves as outward- and inward-propagating ICWs, respectively. These counter-propagating ICWs, likely excited by temperature anisotropies, can trap protons and drive nonlinear growth, reaching a large amplitude ~1nT. The ion concentration perpendicular to the wave electric field indicates the marginal stability of ICWs. As a result, ICWs can remain stable while being convected by the fast solar wind, explaining their ubiquitous detection by various spacecraft over a broad range of heliocentric distances. The wave properties derived above allow us to construct phase-space trajectories of nonlinearly resonant protons, which closely align with the phase-space density (PSD) contours in the $v_\parallel - v_\perp$ plane. Thus, the observed signatures are consistent with the waves scattering the particles to form plateau distributions via nonlinear interactions, which are traditionally interpreted as a signature of quasi-linear relaxation.

References

[1] Kitamura, Naritoshi, et al. "Direct measurements of two-way wave-particle energy transfer in a collisionless space plasma." Science 361.6406 (2018): 1000-1003.
[2] Liu, Z-Y., et al. "Simultaneous macroscale and microscale wave–ion interaction in near-earth space plasmas." Nature Communications 13.1 (2022): 5593.
[3] Li, Jing-Huan, et al. "Direct observations of cross-scale wave-particle energy transfer in space plasmas." Science Advances 11.6 (2025): eadr8227.

Figure 1

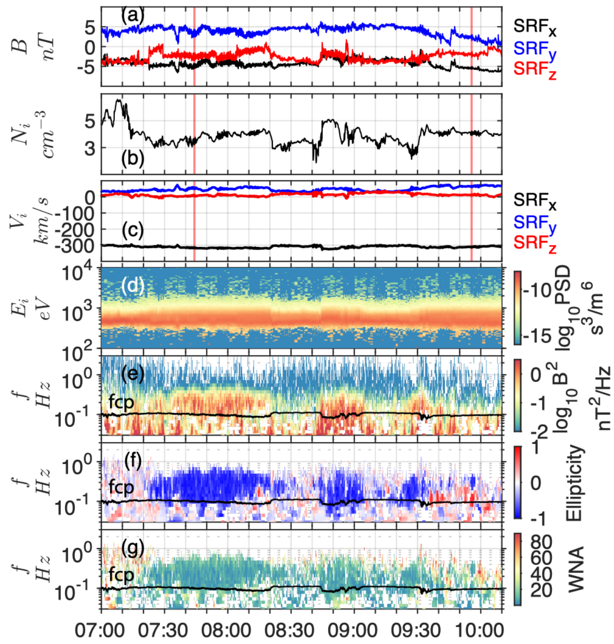

Figure 2