Observations of Ion-Scale Cyclotron Waves and Their Relationship with Non-thermal Ion Distributions in the Solar Wind

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Electromagnetic cyclotron waves (ECWs) near the proton cyclotron frequency \(f_{pc}\) and higher than Alfvén wave frequency

- Ion cyclotron waves (ICWs): left-hand (LH) polarized in plasma frame
- Magnetosonic waves: right-hand (RH) polarized in plasma frame

They are important because the absorption of fluctuating magnetic field energy starting at \(f_{pc}\) has been demonstrated extensively

Before PSP era, intermittent observations of such ECWs in quiet solar wind have been reported in Behannon (1976), Tsurutani et al. (1994), Jian et al. (2009, 2010, 2014), Boardsen et al. (2015), Wicks et al. (2016), etc.
Possible Wave Generation Due to Solar Wind Non-thermal Ion Instabilities

- Temperature anisotropies of protons and $\alpha$ particles as well as secondary component (beam) of protons and $\alpha$ particles are often observed in the solar wind.

- Temperature anisotropy
  - Ion $T_\perp > T_\parallel$ and low $\beta \rightarrow$ ion cyclotron anisotropy instability $\rightarrow$ LH ICWs
  - Ion $T_\parallel > T_\perp$ and high $\beta \rightarrow$ ion fire hose instability $\rightarrow$ RH magnetosonic waves

- Addition of a secondary ion population
  - Ion velocity distributions have a ring or ring-beam $\perp B$ $\rightarrow$ ion cyclotron ring instability $\rightarrow$ LH ICWs
  - Isotropic and cold ion beam $\rightarrow$ ion beam instability $\rightarrow$ RH magnetosonic waves

- Some studies (e.g., Gary et al. 2016, Jian et al. 2016) have used the observed ion velocity distribution to derive the growths of multiple types of instabilities, and check against the wave observations.

Gary et al. (2016)
ECW Studies in the PSP Era

- Bowen et al. (2020a) detected ECWs in 30-50% of radial field intervals during the first perihelion encounter of PSP.

- Using magnetic and electric field data from FIELDS, Bowen et al. (2020b) demonstrated most of the ECWs propagate away from the Sun.

- Verniero et al. (2020) showed several cases of the coexistence of ECWs and secondary proton beams using 3D VDFs of SPAN-Ion.

- Vech et al. (2021) suggested the energy transfer from fields to particles on ~Tpc is 3-6% of the electromagnetic energy flux, and the rate is consistent with the hypothesis that ICWs are locally generated in the solar wind.

- Using high-cadence magnetic field data from PSP (~ 20s⁻¹) and Wind (~ 11 s⁻¹), we identify the ECWs in 2018 Oct – 2020 December.

- The identification method is the same as used in Boardsen et al. (2015) for MESSENGER wave survey.

- Polarization analysis is performed on the averaged power spectral matrix following Arthur et al. (1976).

- **ECW criteria**: degree of polarization (DOP) >70%, |ellipticity| >0.65, wave normal angle (WNA) < 40°.

- Blobs need to include at least 100 pixels.
ECWs are detected **more often** in the inner heliosphere using PSP than at 1 AU using Wind data, consistent with higher rate of unstable solar wind (88% from Helios 1/2 vs. 54% at 1 AU) suggested by Klein et al. (2018, 2019)

- The long-duration radial IMF seems to appear **more often** at PSP than at 1 AU
Distribution of Ellipticity and Wave Normal Angle: PSP vs. Wind Surveys

**PSP**
- Ellipticity
- Wave Normal Angle

**Wind**
- Ellipticity
- Wave Normal Angle

Slightly larger WNA than PSP

Selected PSP ICW $\delta f - \delta t$ pixels
- npts = 3942419
- median = -0.702
- mean = -0.0431 ± 0.862

Selected WIND ICW $\delta f - \delta t$ pixels
- npts = 1089843
- median = 0.880
- mean = 0.272 ± 0.814
Radial Variation of ECW Properties

Selected PSP ICW $\delta f-\delta t$ pixels

Occurrence Count

Frequency in s/c Frame

Power Spectral Density

$f_{sc}$ Normalized by Local $f_{pc}$
Radial Variation of Ellipticity: LH vs. RH

0.1 AU
PSP_ellip 0.100 AU

0.3 AU
PSP_ellip 0.300 AU

0.5 AU
PSP_ellip 0.500 AU

0.7 AU

0.9 AU

1 AU by Wind
Radial Variation of Wave Power: LH vs. RH

0.1 AU

0.3 AU

0.5 AU

0.7 AU

0.9 AU

1 AU by Wind
Radial Variation of Wave Frequency in S/C Frame: LH vs. RH

0.1 AU

0.3 AU

0.5 AU

0.7 AU

0.9 AU

1 AU by Wind
Search for PSP-Earth
Conjunction Time

< 0.3 AU
Three Radial Conjunction Intervals

2019 April 7

2020 January 28

2020 June 15

OMNI

V_{SW}

PSP
Summary

- We have surveyed electromagnetic cyclotron waves (ECWs) in the ion kinetic scale using PSP and Wind magnetic field data in 2018 October – 2020 December.
- We find the ECW occurrence rate is higher in the inner heliosphere (~10-30%) than at 1 AU (typically 5%).
- LH waves are observed more often than RH waves close to the Sun, but slightly less often than RH waves as PSP travels further away from the Sun.
- The wave power of LH waves is always stronger than the RH waves throughout the inner heliosphere.
- The radial conjunction time periods between PSP and Earth around PSP’s perihelia are rare, and we plan to analyze the evolution of ECWs from PSP to 1 AU focusing on these intervals.
- We will conduct further coordinated analysis using electric field and plasma data from PSP to better understand the evolution of the LH vs. RH waves.