Ion cyclotron waves in the solar wind: indications of source ion distributions

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1. Abstract

Electromagnetic waves near the proton cyclotron frequency are frequently observed in the solar wind at a wide range of heliocentric distances. These so-called ion cyclotron waves play important roles in transferring energies and mediating the level of temperature anisotropy of ions. The wave-particle interaction in this frequency range is of high interest to solar wind turbulence studies, because the ion kinetic scale lies in the transition from the inertial range to the sub-ion dissipation range. The recent studies of Parker Solar Probe (PSP) data and hybrid modeling as well as the Magnetospheric Multiscale (MMS) data suggest ion beams appear to be an important source for generating these circularly polarized and field-aligned propagating waves. STEREO and WIND observations, both far away from the Earth bow shock to exclude it from being the source, provide a large sample set to investigate the wave properties statistically. This presentation shows case studies with MMS data to investigate the possible source ion distributions for these waves and the statistical studies with datasets in the solar wind to examine their statistical properties.

2. Introduction

Electromagnetic ion cyclotron waves (ICWs) were first detected in the solar wind by STEREO far away from any planetary or cometary sources [Jian et al., 2009]. Figure 1 show an example of an ICW observed by STEREO-A spacecraft on July 31, 2007, when the spacecraft was at 0.96 AU and 13° away from the Earth. The left panel shows a sinusoidal wave form lasting more than 3 min, and the right panel shows significant enhancement near 0.3 Hz in the transverse power, which is also much stronger than the compressional power. In the spacecraft frame, the wave frequency at the peak transverse power is observed above the local proton gyro-frequency (fpc) of 0.076 Hz but actually below the Doppler-shifted fpc as 0.57 Hz as marked in Figure 1. Generally, these waves have nearly field-aligned propagation, left-handed (LH) or (RH) right-handed circular polarization (as shown in Figure 2), and frequencies (in local plasma frame) below the proton gyro-frequency.

From STERERO data, the majority of the waves are observed far away from any planets and when there are no ICMEs, shocks, flares, and solar energetic particle events, excluding them be the sources of these waves. In addition, there is little correlation between the wave occurrence rate and the flux of interstellar pickup He+ and Ne+ [Jian et al., 2009; 2014]. However, the wave occurrence rate is enhanced when the solar wind magnetic field is in nearly radial geometry. Using multi-spacecraft observations (MESSENGER, VEX and STEREO) at 0.3, 0.7, and 1 AU, Figure 3 shows that the wave power and wave frequencies in both spacecraft frame and plasma frame slightly decrease heliocentric distances. The more recent observations from Parker Solar Probe and Solar Orbiter detect these waves as far as 0.1 AU with more frequent occurrences. Since ICW are observed ubiquitously in the space plasma environment, it is important to understand the wave characteristics, their generation mechanism and their role in energy transferring or mediating the temperature anisotropy between ion species.

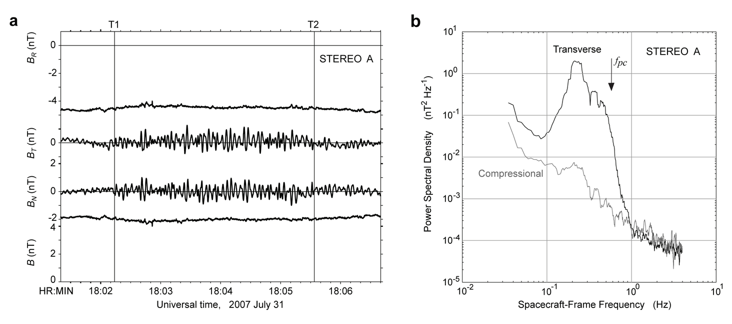

Figure 1. An example of the time series and power spectra of ICWs observed by STEREO [Jian et al., 2009].

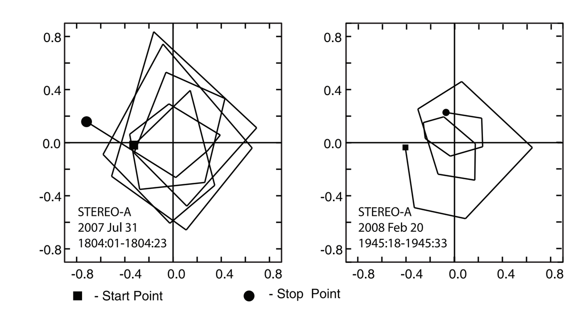

Figure 2. Hodograms of LH and RH waves. The background magnetic field points out of the board.

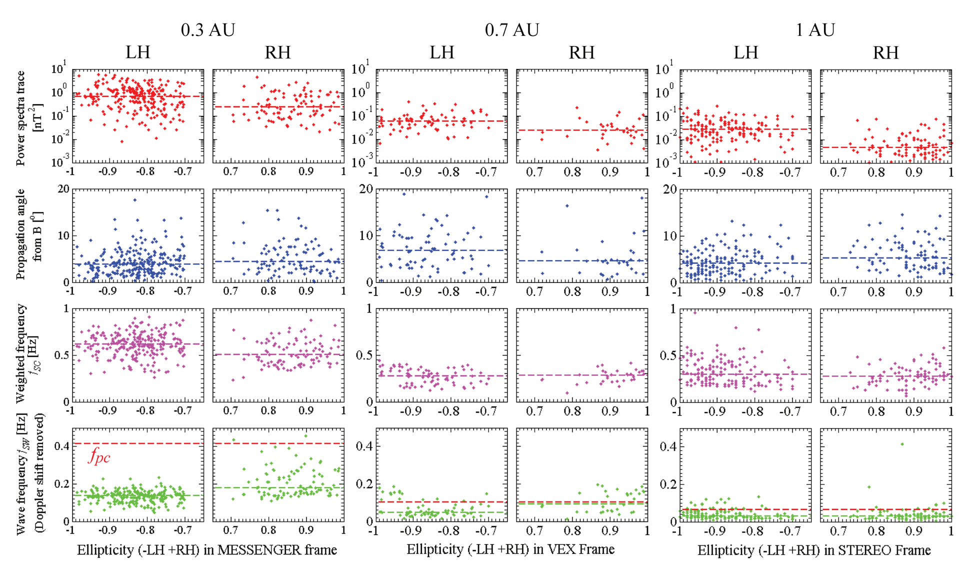

Figure 3. Variation of ICW properties over three heliocentric distances. All events are selected with the same criteria in Jian et al. [2009]. The dashed line in each panel indicates the corresponding median value except for the red line in the bottom panels marking local fpc. [Wei et al., 2016]

3. Possible mechanisms for wave generation

To examine the wave generation due to local instabilities, and Gary et al. [2016] and Jian et al. [2016] conducted case studies with WIND data. They found over half of the events with wave properties in agreement with the unstable mode predicted from dispersion analysis, that is the LH waves are generated by ion components with temperature anisotropies (i.e. ion cyclotron instability) while the RH waves are generated by ion component with relative flows (i.e. magnetosonic instability). However, the Doppler shift from plasma frame to s/c frame is large enough to reverse the handness of the waves, so actually the LH and RH waves observed in the s/c frame can be due to either of the two types of instabilities.

The more recent PSP observations suggest ICWs are often associated with proton or alpha beams [Verniero et al. 2020; Ofman et al. 2022]. The MMS observations in the "pristine" solar wind near the apogee shows ICWs associated with sunward ion beams (Figure 4). We can use such events for studying the wave generation mechanisms, but to perform statistical analysis we need to use observations far away from the Earth bow shock to exclude it from being the source (such as STEREO and WIND).

Figure 5 shows a simulated dispersion relation from Ofman et al. 2017, for wave generation due to an alpha particle beam in the solar wind using a 2.5D hybrid model. They found the RH magnetosonic mode grows first, which then perpendicularly heats the background ions and leads to the growth of LH ion cyclotron instability.

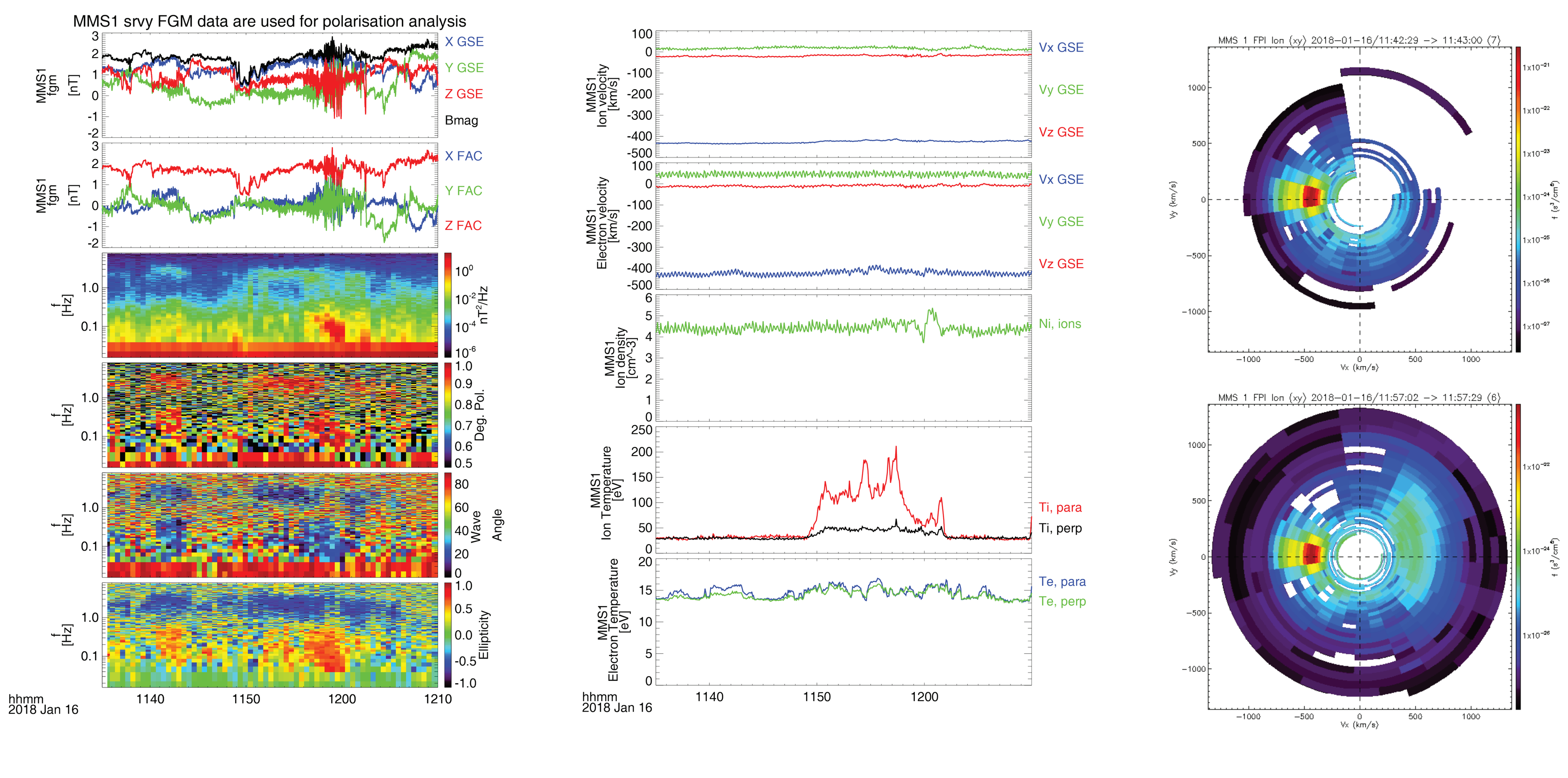

Figure 4. (left) magnetic field and wave properties; (middle) plasma velocity and temperature; (right) ion distributions in the xy-plane of GSE coordinates for two time slots during the wave interval when there are both LH and RH waves.

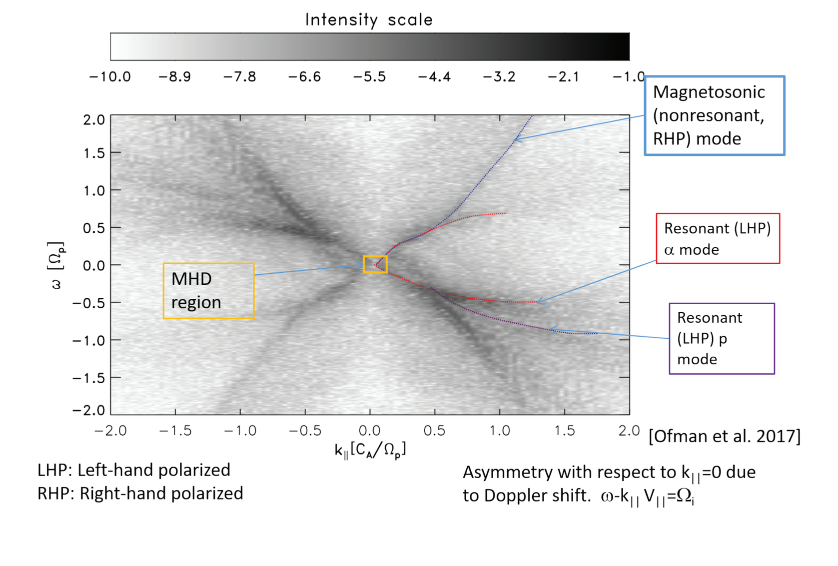

Figure 5. A 2.5D hybrid simulation result for dispersion relation due to an alpha particle beam. [Ofman et al., 2017].

4. Statistical studies

The STEREO observations are far away from the Earth bow shock to exclude it from being the source, and they provide a large sample set to investigate the wave properties statistically. We perform statistical studies of the wave properties versus the IMF cone angle for the event list of 2008 in Jian et al., [2014] and our newly obtained event list from 2018/10/16 to 2020/12/31 (shown in Figure 6 and 7).

Although we did not find correlation of wave occurrence with the period when STEREO passing the interstellar pickup ion focusing cone for the 2008 event list, we need to check if our new event lists have any correlation too. Figure 8 and 9 shows the monthly wave occurrence time from the STEREO and WIND data from 2018/10/16 to 2020/12/31. The red bars indicate the periods s/c passing the focusing cone and we do not see enhance wave occurrence except in the STEREO data in 2019/03. The reason for no consistent correlation could be due to the sources of the waves include both ion beams from the Sun and the interstellar pickup ions.

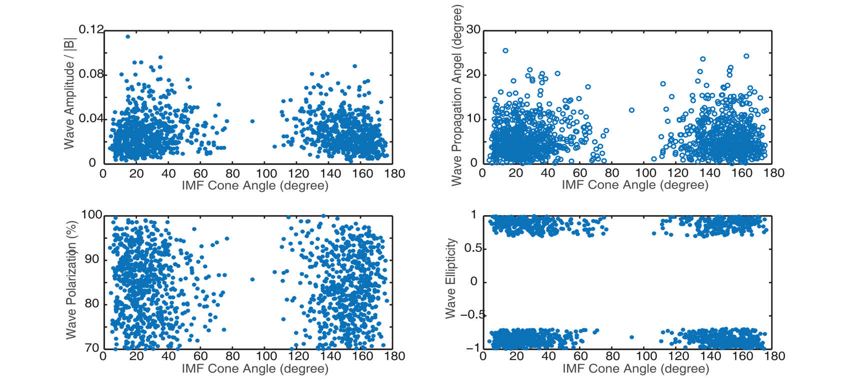

Figure 6. Wave amplitude normalized by the field strength, wave propagation angle, percent polarization, and wave ellipticity versus the IMF cone angle which is the angle between the magnetic field vector and the Sun-spacecraft line, for STEREO 2008 event list.

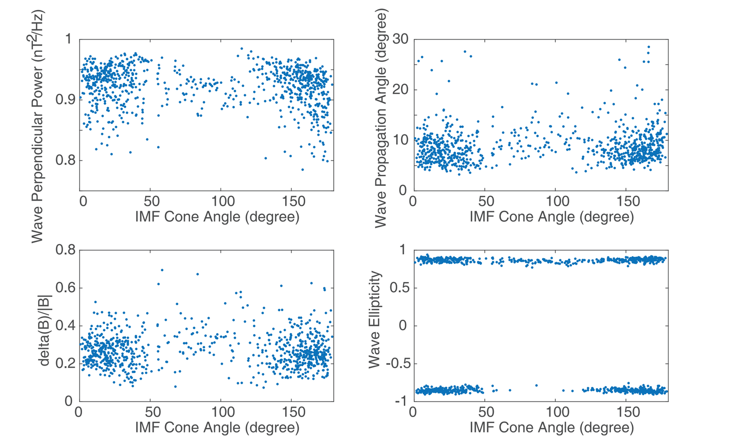

Figure 7. Wave perpendicular power and normalized perpendicular amplitude normalized, wave propagation angle, percent polarization, and wave ellipticity versus the IMF cone angle for STEREO 2018-2020 event list.

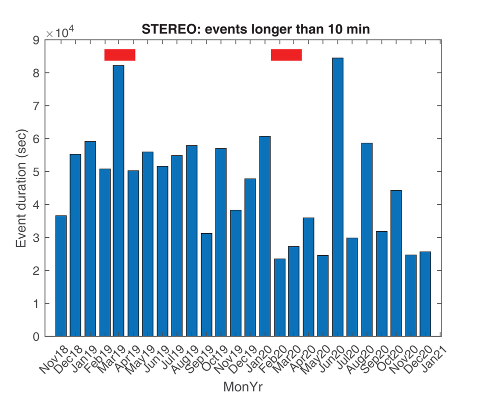

Figure 8. Montly wave occurence time for STEREO 2018-2020 event list. The top red bars mark when the spacecraft passing the instellar pickup ion focusing cone.

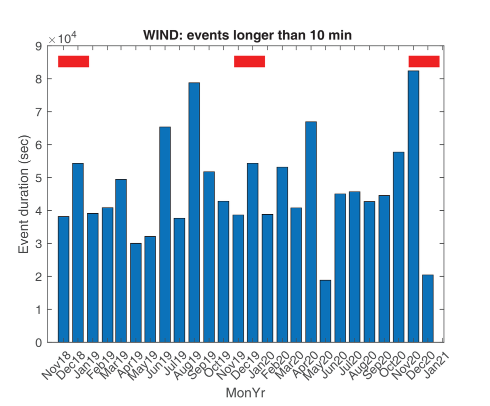

Figure 9. Montly wave occurence time for WIND 2018-2020 event list. The top red bars mark when the spacecraft passing the instellar pickup ion focusing cone.

5. Beam velocity estimation for the STEREO events

To investigate the wave generation due to temperature anisotropy, Omidi et al., [2014a&b] perform hybrid simulations under a wide range of plasma conditions relevant to the corona and solar wind for uniform and non-uniform magnetic field background, and Wei et al., [2016] examined the cases with LH and RH waves simultaneously to calculate the Doppler shift and the locations of the source region. In this poster we investigate an alternative wave generation mechanism, i.e. due to relative drift between ion species. We make assumptions for waves being generated near the s/c by proton beams for calculating the beam velocity (Figure 10). In the frame moving with the ion beam, the wave is left-handed and near the ion gyro-frequency. The wave k vector can be nearly parallel or anti-parallel to the beam velocity, leading to Doppler shift of the wave frequency in the s/c frame up or down.

- $f_{s/c} = f_{beam} + \vec{k} \cdot \frac{\vec{V}_{beam}}{2pi} = f_{beam}[1 + \frac{V_{beam}}{\frac{2pi * f_{beam}}{k}} \hat{k} \cdot \hat{V}_{beam}]$
- If $\frac{f_{beam}}{2pi*k} = V_{phase} \approx V\_Alfven$, and $f_{beam} = f_{gyro}, \hat{V}_{beam} \approx \hat{b}$ (field-aligned beam)
- Then, $f_{s/c} = f_{gyro}\left[1 + \frac{V_{beam}}{V_A}\left(\hat{k} \cdot \hat{b}\right)\right]$
- Taken signs of LH and RH polarizations' in to the equation,

$$V_{beam} = \left[\frac{-sign(ellipticity) * f_{\frac{s}{c}}}{f_{gyro}} - 1\right] * \frac{V_A}{|\hat{k} \cdot \hat{b}|}]$$

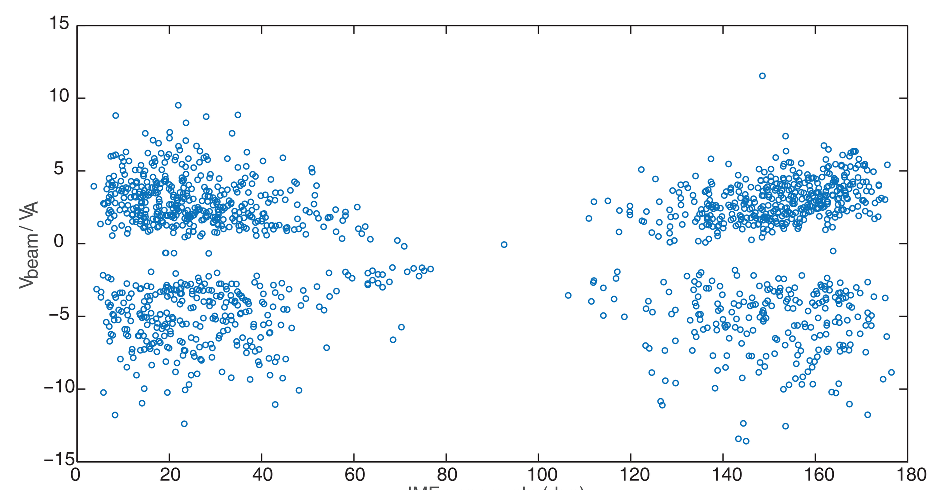

Figure 10. The calculated beam velocity normalized by local Alfven speed versus the IMF cone angle. Note the sign of the beam velocity is mostly dependent on whether the wave vector is parallel or antiparallel to the beam velocity.

6. Summary

ICWs have been observed extensively from 0.1 to beyond 1 AU by multiple missions. Both ion cyclotron instability due to ions with temperature anisotropy and magnetosonic instability due to relative drift between ion species are possible to generate the wave properties as observed. A rough estimate of ion beam velocity agrees with the generation mechanism of source ions with super-Alfvenic relative drift. We will perform hybrid simulations to obtain quantitative analysis of wave properties due to different types of instability, which could help distinguish the waves from different sources and thus enable us to use the wave properties to investigate their sources.

Statistical studies are performed to event list found in STEREO and WIND data from 2018/10/16 to 2020/12/31. We will examine the PSP data for the same period to compare the wave properties at different heliocentric distances. For these new event lists, we still do not find consistent correlation of wave occurrence with the interstellar pickup ion focusing cone.