Ion Cyclotron Waves in the Solar Wind from 0.3 to 1 AU

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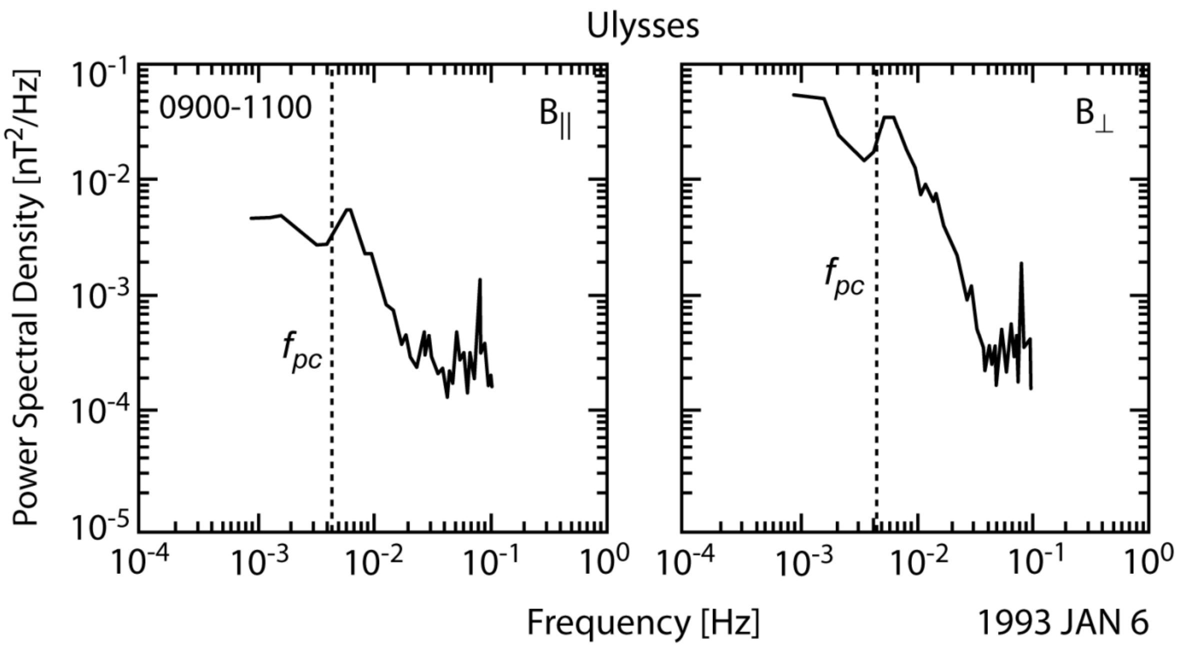
Waves Generated by Pickup Ions

- When the IMF and solar wind velocity are perpendicular, pickup ions can be accelerated by the $-\boldsymbol{V}\times\boldsymbol{B}$ electric field and form a ring beam distribution in velocity space, which is unstable to the generation of the ion cyclotron waves (ICWs).
  - These waves are **left-hand (LH)** polarized and near the ion cyclotron frequency in the **plasma frame**. These waves can propagate both directions along IMF, but they will all be carried outward by the super-Alfvénic solar wind. Hence, they can appear **either LH or right-hand (RH) polarized in the s/c frame**.
- When the IMF is more aligned with the flow, the pickup ions have a large parallel drift velocity relative to the solar wind and will generate waves that are **RH polarized in the plasma frame and propagating toward the Sun**. Because the spacecraft is essentially in the frame moving with the pickup ion beam, the waves **appear LH polarized in the s/c frame**.

Waves Generated by Parallel Pickup of Interstellar Hydrogen near 5 AU



Adapted from *Murphy et al.* (1995)

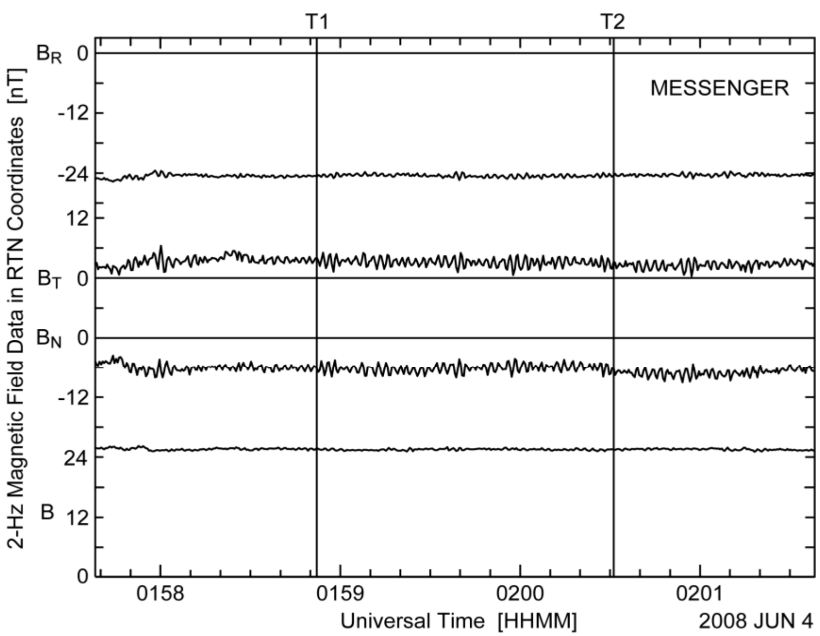
- LH in the spacecraft frame and a lower cutoff in the wave spectra at the local proton cyclotron frequency (f_{pc})
- *Murphy et al.* (1995) found only 31 wave events over 640 days. The event typically lasted one or more hours

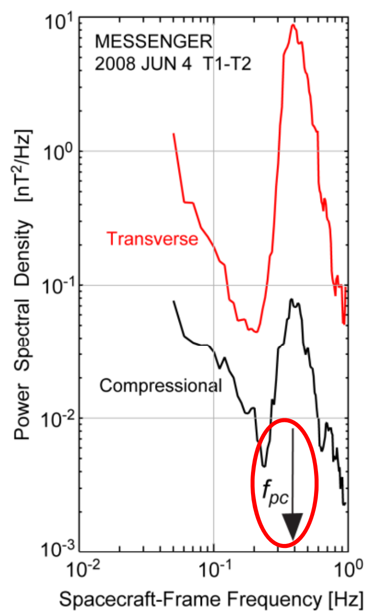
ICW Criteria and An Example at 0.3 AU

Criteria

- i) Transverse power is dominant
- ii) |ellipticity| > 0.7
- iii) Percent polarization (signal-to-noise ratio) > 70%

> 90% of the waves: long axis of its perturbation ellipse within 10^{o} of the direction perp. to both ***B*** and ***k***, *i.e.*, the ***B***-***k*** plane





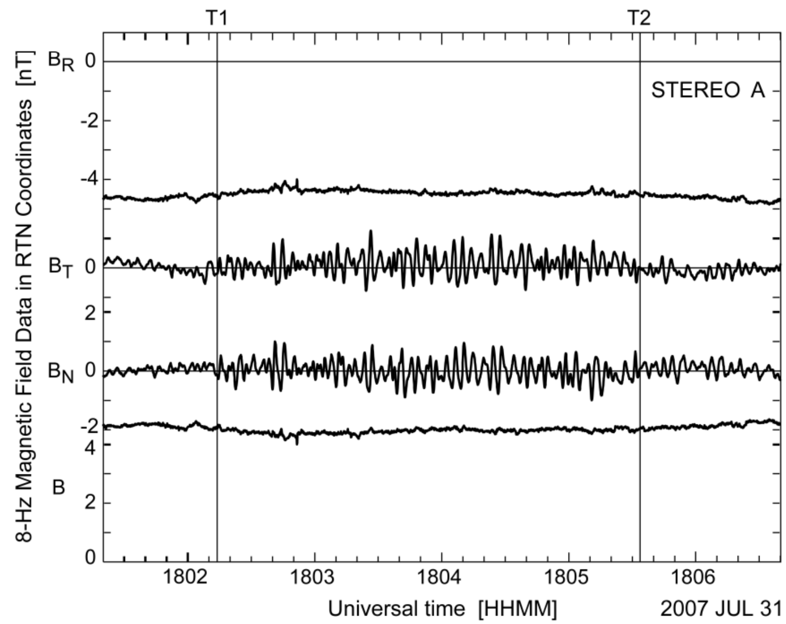
9-band Average

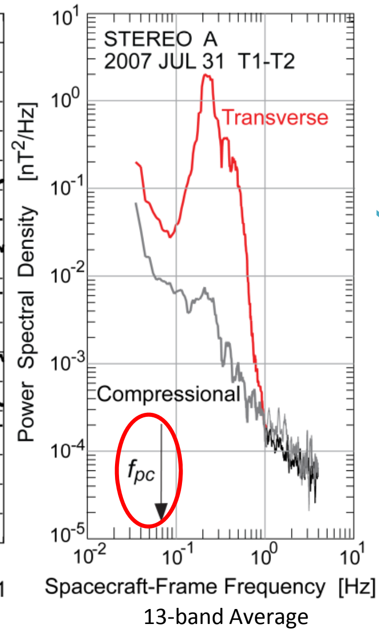
0.3 AU

Ellipticity in s/c frame: 0.96
98% polarized
Propagating 1^{o} away from ***B***

(*Jian et al.*, submitted, 2010)

Examples of ICWs at 1 AU

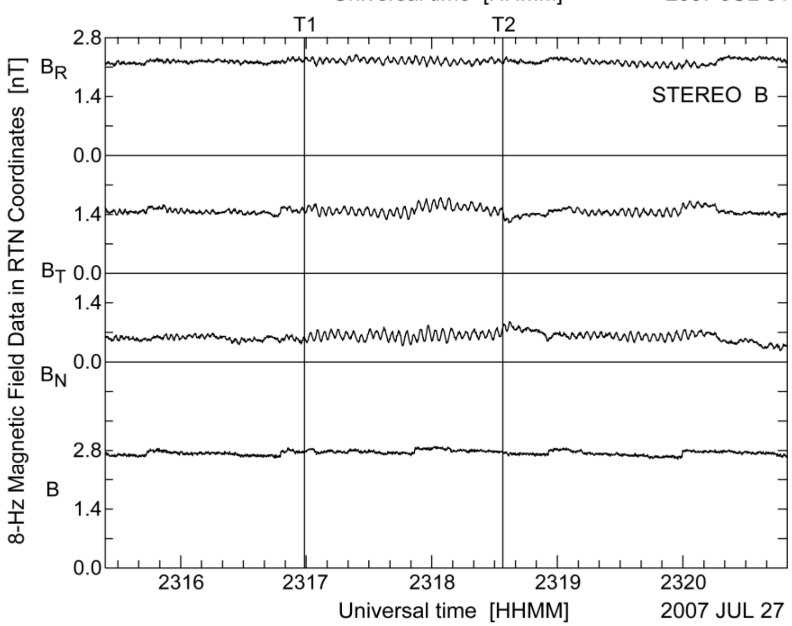


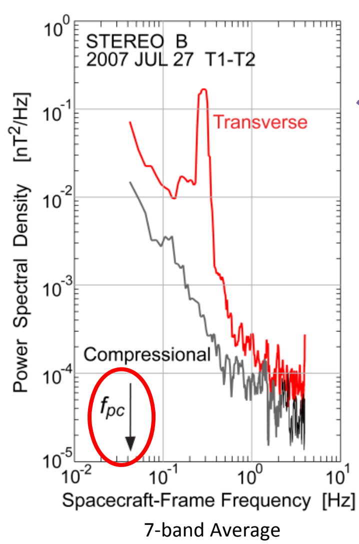


STEREO A and B are far away from any planet.

Ellipticity in s/c frame: -0.95
95% polarized
Propagating 1° away from ***B***

(*Jian et al.*, ApJ 2009)

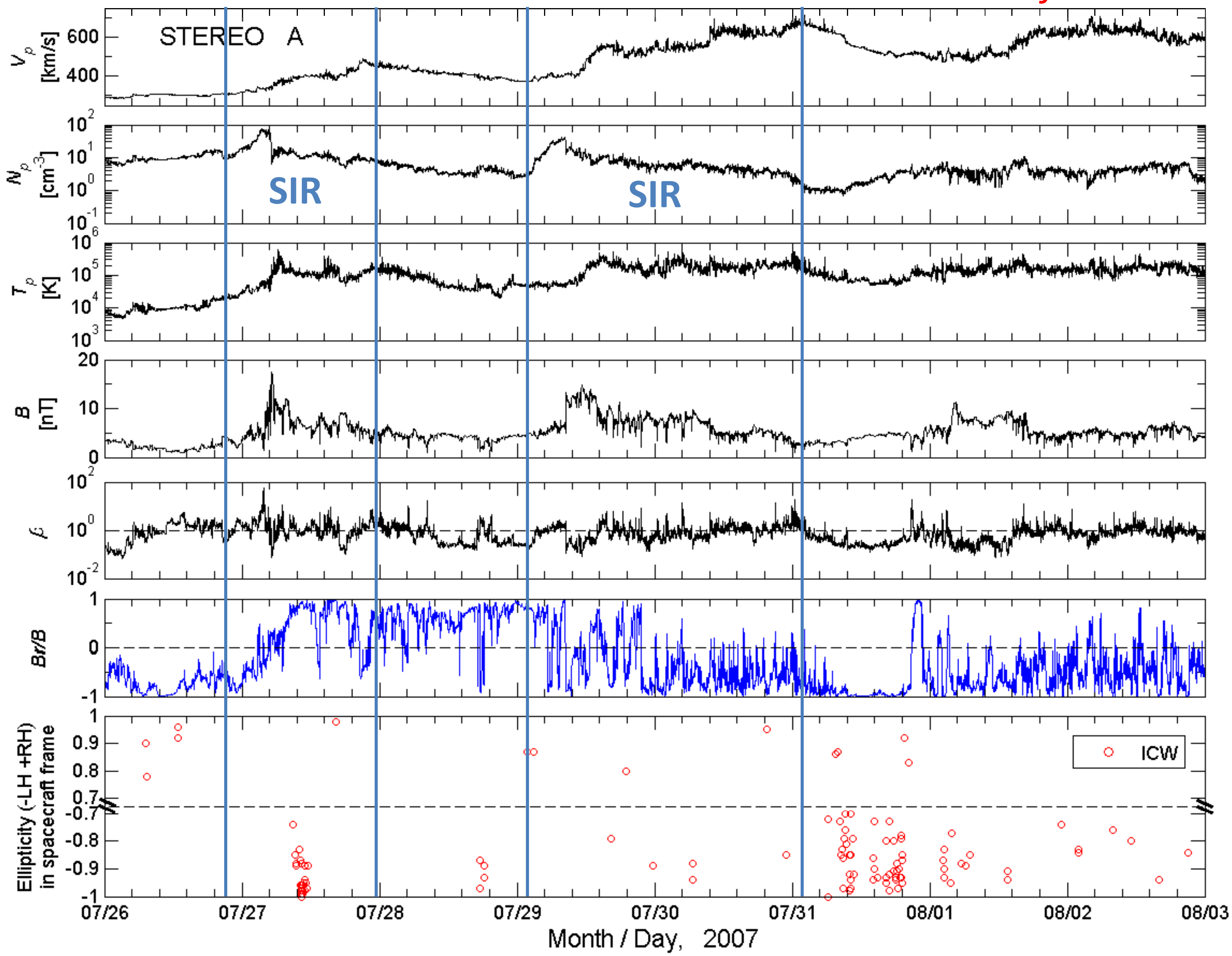




Ellipticity in s/c frame: 0.96
99% polarized
Propagating 2° away from ***B***

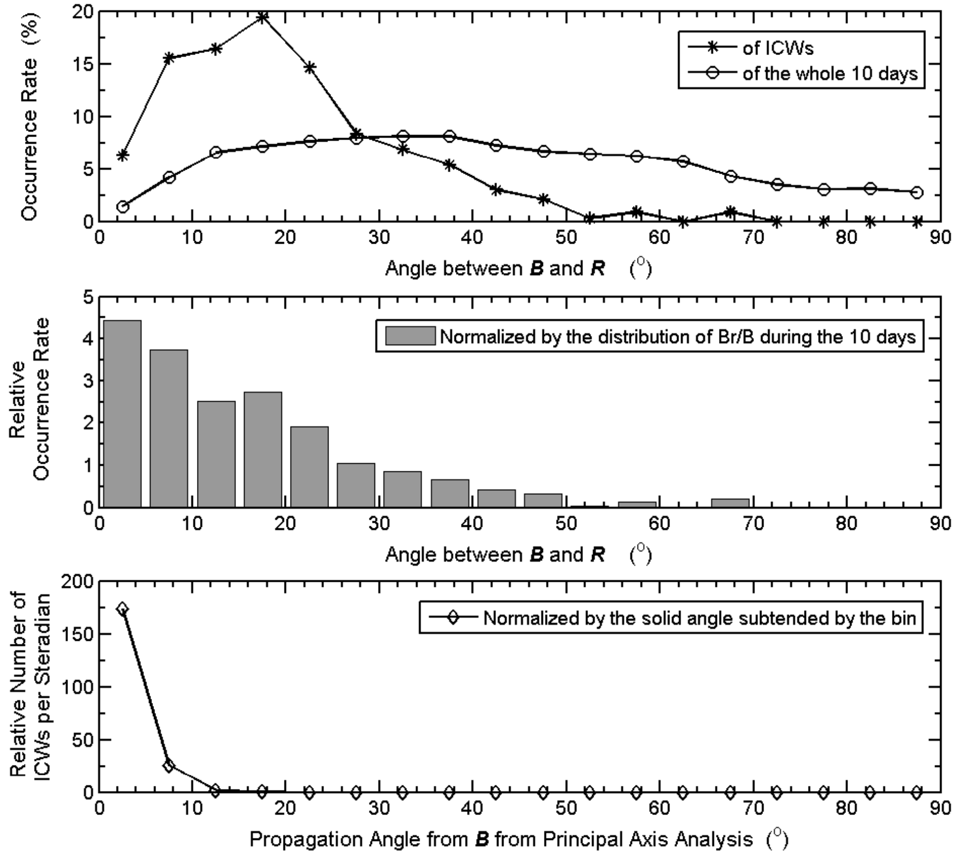
8-Day Survey of ICWs near 1 AU Using STEREO A

1.45% of the time



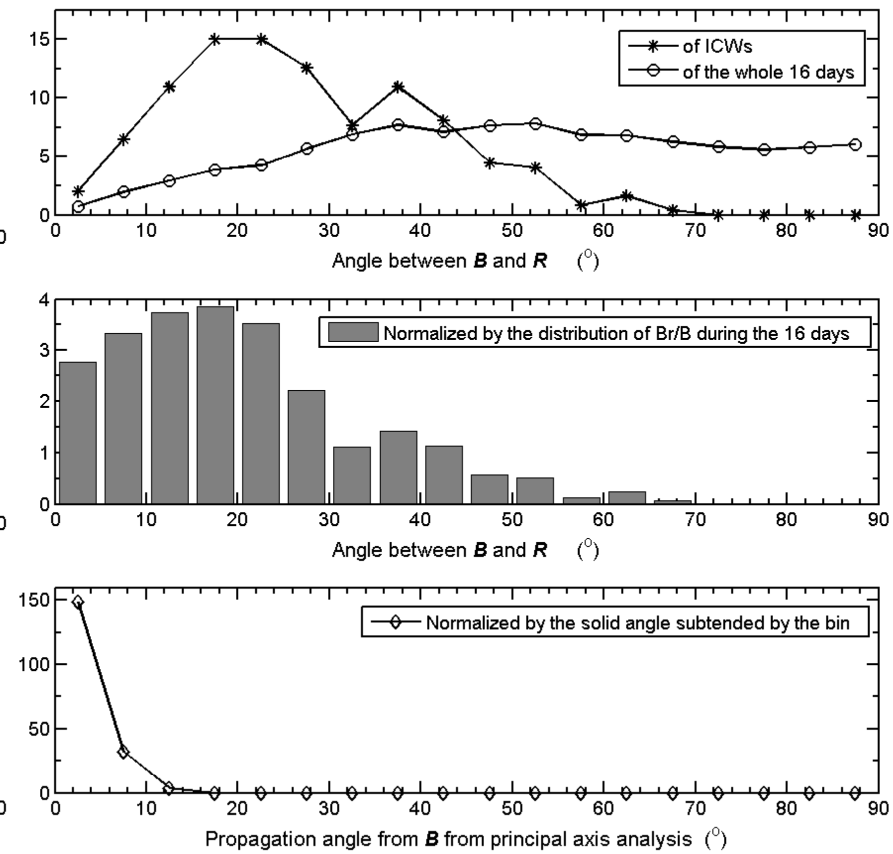
Angular Distribution of ICWs

0.3 AU



(*Jian et al.*, submitted, 2010)

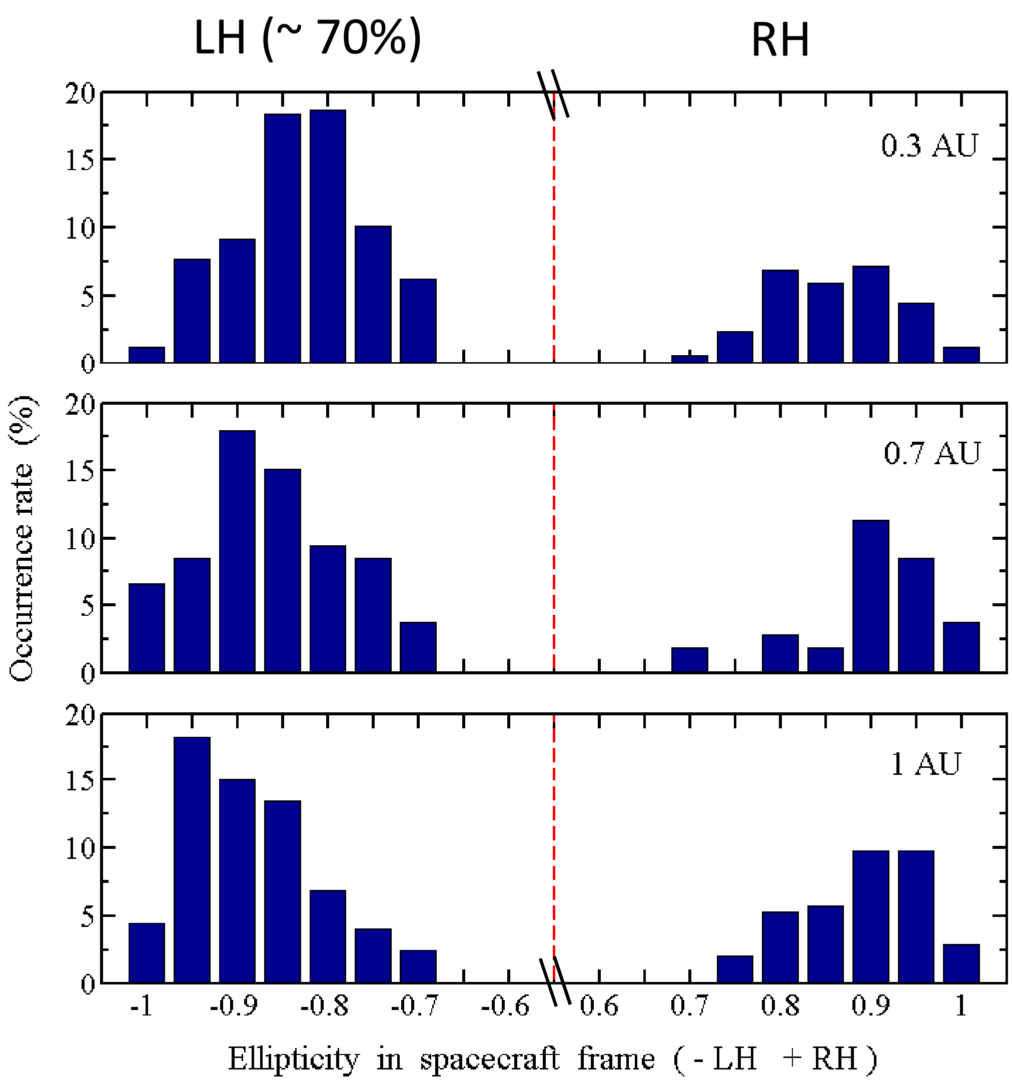
1 AU



(*Jian et al.*, 2009)

- Waves appear more often when the IMF is more radial than the general condition
- Waves propagate mostly along the field direction

Distribution of LH vs. RH in S/C Frame



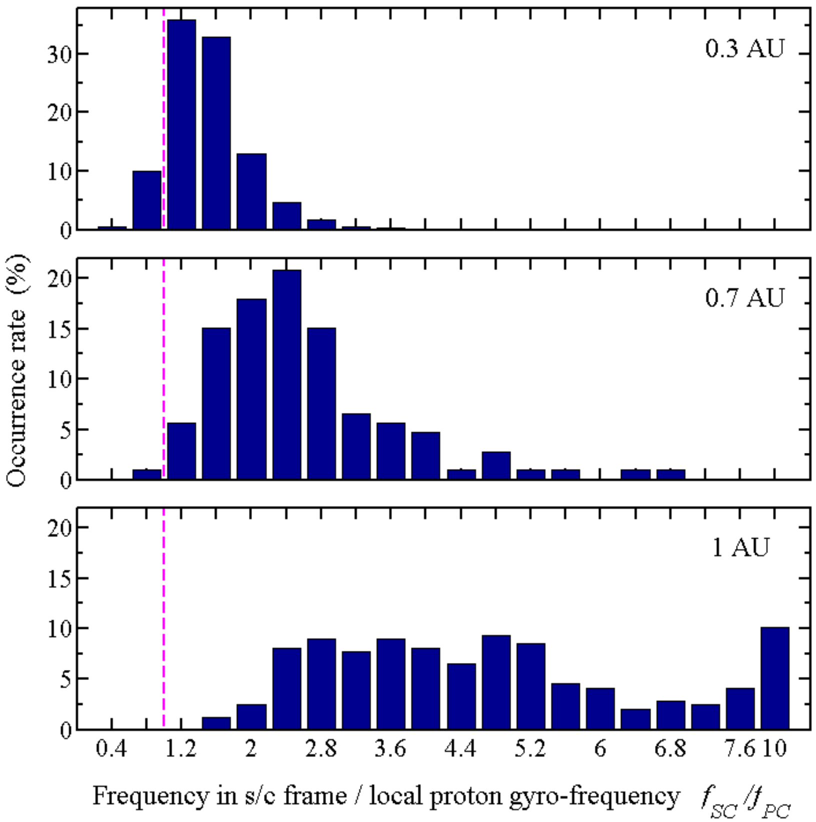
- Because all the waves are intrinsically LH in plasma frame, the RH waves in s/c frame should be due to **inward propagation with respect to the solar wind**
- Both the inward and outward propagating ICWs can be carried out by the super-Alfvénic solar wind
- We use the Doppler shift relation to get f_{sw} from f_{sc}

$$f_{sw} = f_{sc} - \frac{\boldsymbol{k} \cdot \boldsymbol{V}_{sw}}{2\pi}$$

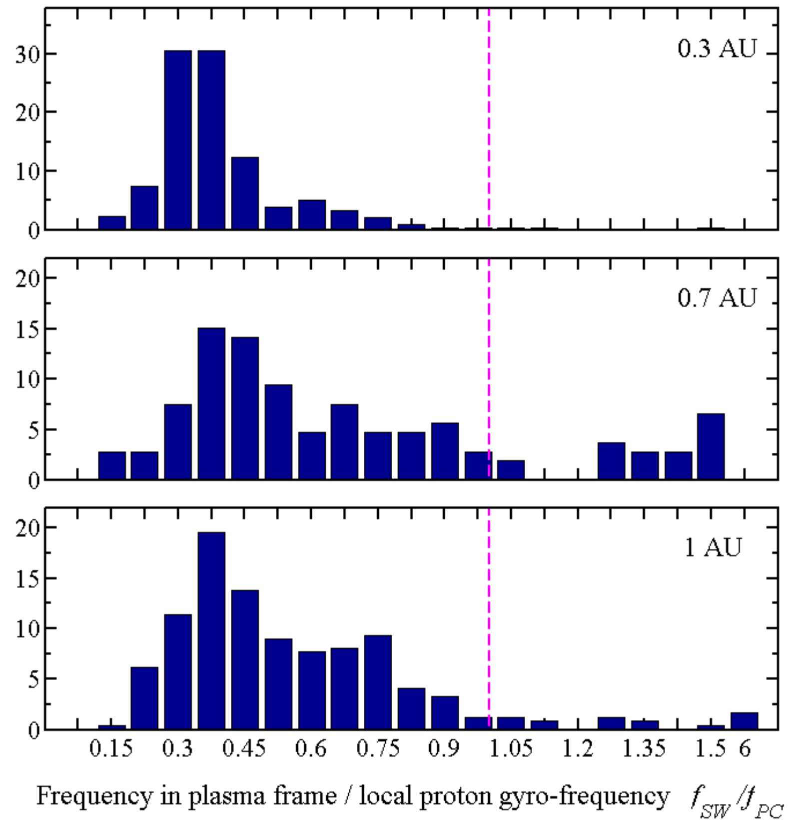
$$= f_{sc} \Big/ \left(1 + \frac{V_{sw}}{V_A} \hat{\boldsymbol{k}} \cdot \hat{\boldsymbol{V}}_{sw}\right)$$

Comparison with Local Proton Gyro-frequency: 0.3, 0.7, and 1 AU

f_{sc} / f_{pc}



f_{sw} / f_{pc}



$f_{sc} > f_{pc}$: the waves are not locally generated by pickup ions

$f_{sw} < f_{pc}$: consistent with the fact that the waves have not been resonantly damped by local protons yet

Radial Variation of ICW Parameters

Heliocentric distance	0.3 AU (MESSENGER)	0.7 AU (Venus Express)	1 AU (STEREO A/B)
Occurrence rate [/day]	*33.7*	*28.9*	*15.4*
Duration [second]	20.0	59.0	51.5
ICW duration / total time [%]	0.94	1.79	1.18
Angle between ***B*** and ***R*** [°]	18.2	26.7	25.1
Propagation angle from ***B*** [°]	4.0	5.3	4.5
Relative wave amplitude d*B*/*B*	0.028	0.032	0.03
Wave power $(dB)^2$ [nT^2]	0.532	0.044	0.016
$(dB)^2 \times r$ [$nT^2 AU$]	0.160	0.031	0.016
f_{sc} [Hz]	0.59	0.28	0.28
f_{sw} [Hz]	0.144	0.052	0.030

fewer waves at a greater distance

almost parallel propagating

Conservation of Poynting flux

$dB \times E \times r^2$ = constant

→ $(dB)^2 V_A r^2$ = constant

→ $(dB)^2 B n^{-1/2} r^2$ = constant

→ $(dB)^2 r$ = constant

Summary and Conclusions

- Strong narrow-band ICWs are detected **extensively and discretely** in the solar wind from 0.3 to 1 AU, over a wide range of solar ecliptic longitude. The waves are intrinsically LH in the plasma frame, but appear both LH and RH in the s/c frame, suggesting they were generated by **perpendicular pickup**.
- The waves are preferentially observed at small ***B***-***R*** angle, probably due to minimal damping associated with parallel-to-B propagation**.**
- The **lower power and smaller occurrence rate of RH waves** at all the three locations are consistent with the longer travel time and greater damping experienced by these inward-propagating waves. The decrease of wave power with heliocentric distance also supports this scenario.
- If the waves were generated in the same rest frame as the s/c, the initial frequency should be as the same as f_{sc} (0.59 Hz at 0.3 AU). So we can derive *B* at the generation region is about 38.7×m/q nT, where m/q is the mass-charge-ratio normalized by protons. If the ion is pickup He^{+}, *B* at the generation region would be about 155 nT, and the generation location would be 0.13 AU away from the Sun.