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

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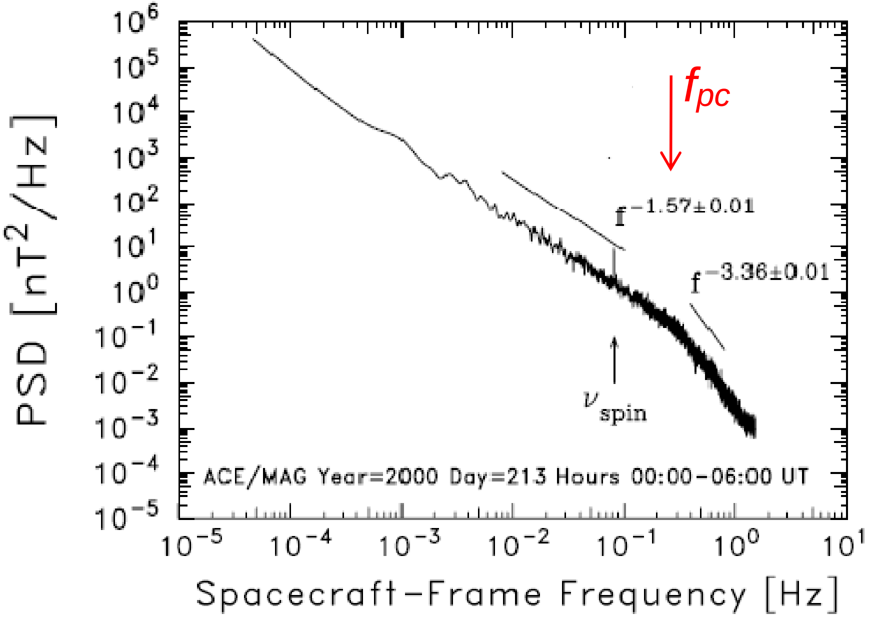
Introduction - I

- Ion cyclotron waves (ICWs): left-hand circularly polarized waves below the proton gyro-frequency (f_{pc})
  - In contrast, Alfvén waves are linearly polarized waves at frequencies well below the ion gyro-frequencies
- ICWs have been observed in a variety of space environments, including upstream of and within planetary magnetospheres
- ICWs are often generated by pick-up ions, which are accelerated by the electric field of a magnetized plasma flowing through a neutral gas

- Both remote sensing and *in situ* measurements show evidence for the absorption of fluctuating fields at the f_{pc} in turbulent cascades
- Very little evidence for the **resonant excitation** of solar wind ICWs has been previously reported

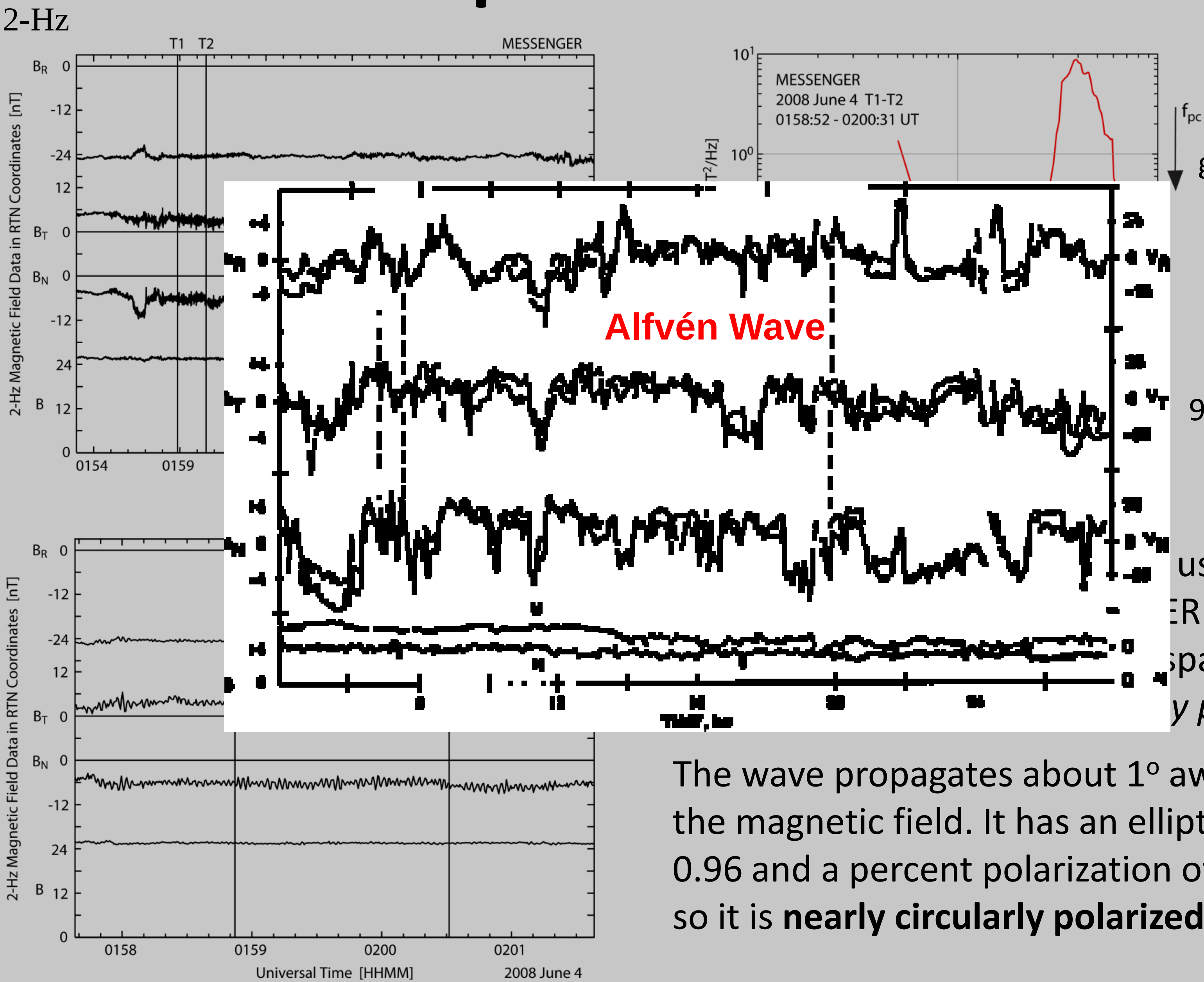


(after Hamilton *et al*. JGR 2008)

Introduction - II

- Here we show direct evidence of the existence of strong narrow-band ICWs at 0.3, 0.7, and 1 AU, and also compare their properties quantitatively, using high-resolution magnetometer data
- The study is confined around solar minimum, and no shocks occurred within our time windows. In addition, we undertake the survey as far from any planet or comet as possible, and consider a wide range of solar ecliptic longitude, and avoid the interstellar Helium focusing cone
- ICW criteria we used: (1) transverse power is dominant, (2) |ellipticity| > 0.7, (3) polarization rate > 70%
- For the wave events meeting the above criteria, we examine if the long axis of the perturbation ellipse is perpendicular to the plane of magnetic field ***B*** & wave propagation direction ***k***, to see if the wave is **intrinsically LH waves in the plasma frame** (Stix, 1962; Blanco-Cano, 1995)
- We find the majority (over 90%) of the waves have their long axes within 10° of perpendicular to both ***B*** and ***k***. We exclude waves which do not satisfy this criterion. The remaining waves should be ICWs

An Example of ICWs at 0.3 AU



Proton gyro-frequency

9-band average

using

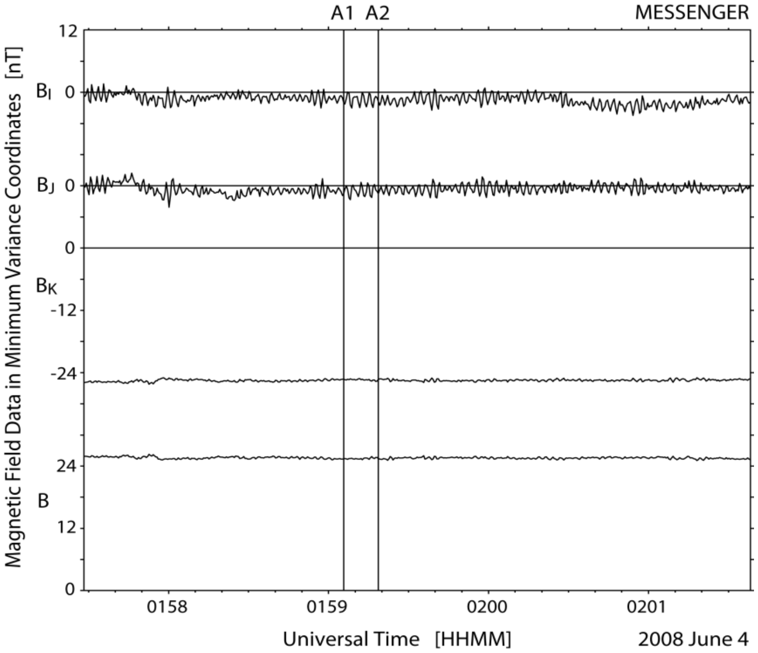
ER (2008).

spacecraft

y planet.

The wave propagates about 1° away from the magnetic field. It has an ellipticity of 0.96 and a percent polarization of 98%, so it is **nearly circularly polarized**.

The ICW Example in Minimum Variance Coordinates



Minimum Variance Coordinates

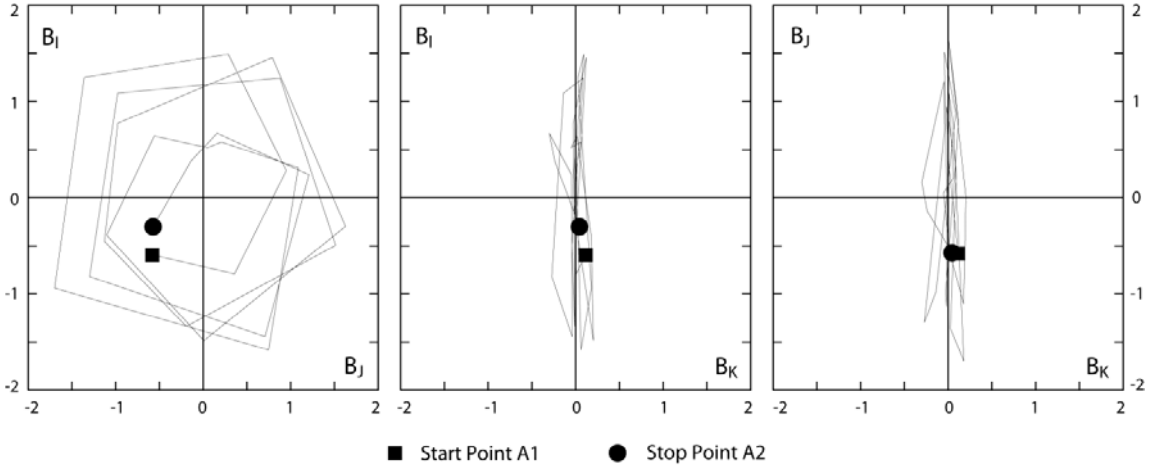
I: -0.151 **R**, 0.289 **T**, 0.945 **N**

J: -0.162 **R**, -0.951 **T**, 0.265 **N**

K: 0.975 **R**, -0.113 **T**, 0.191 **N**

B: -0.961 **R**, 0.129 **T**, -0.241 **N**

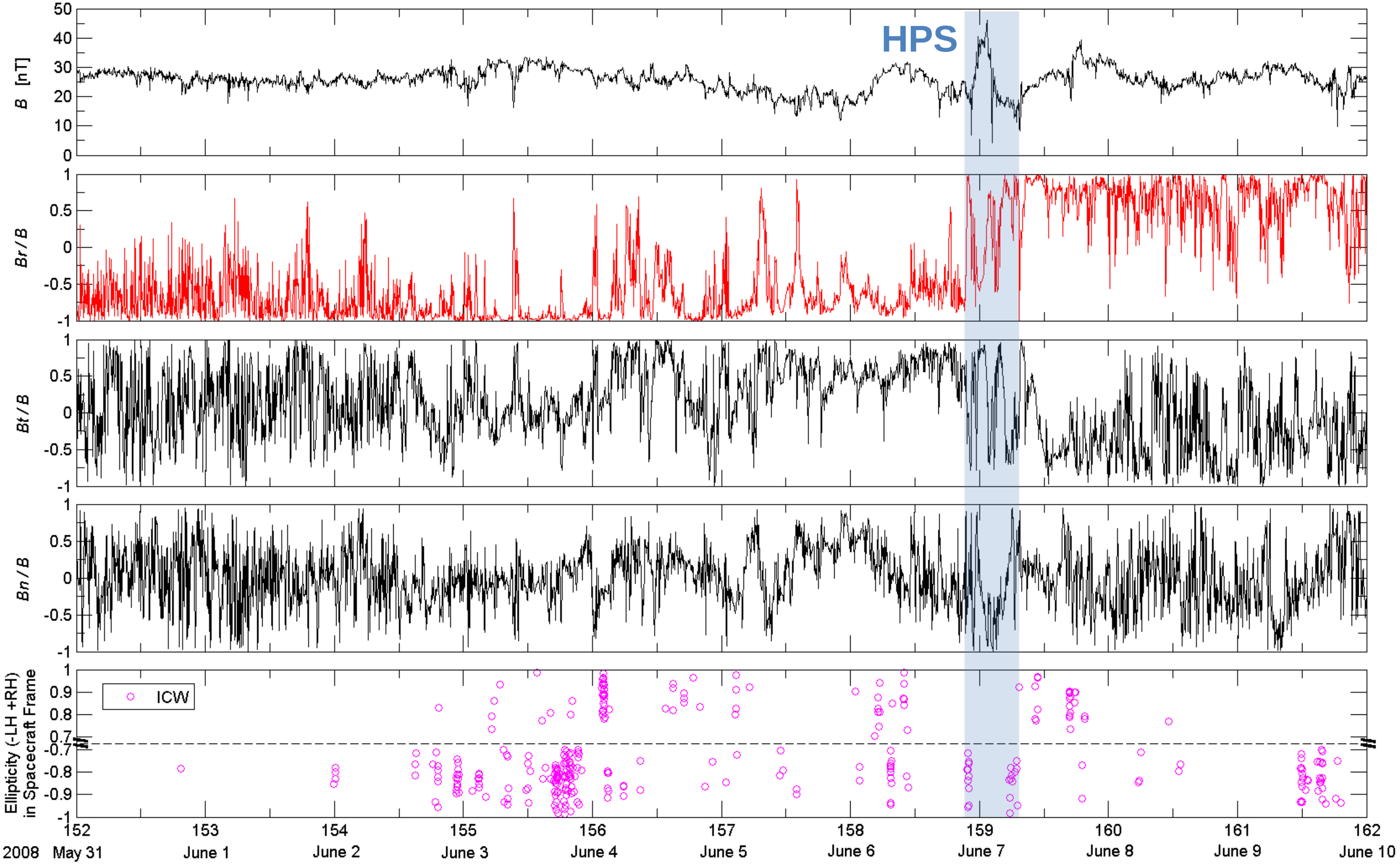
K is nearly anti-parallel to **B**



Hodogram for A1-A2: RH circular wave in s/c frame

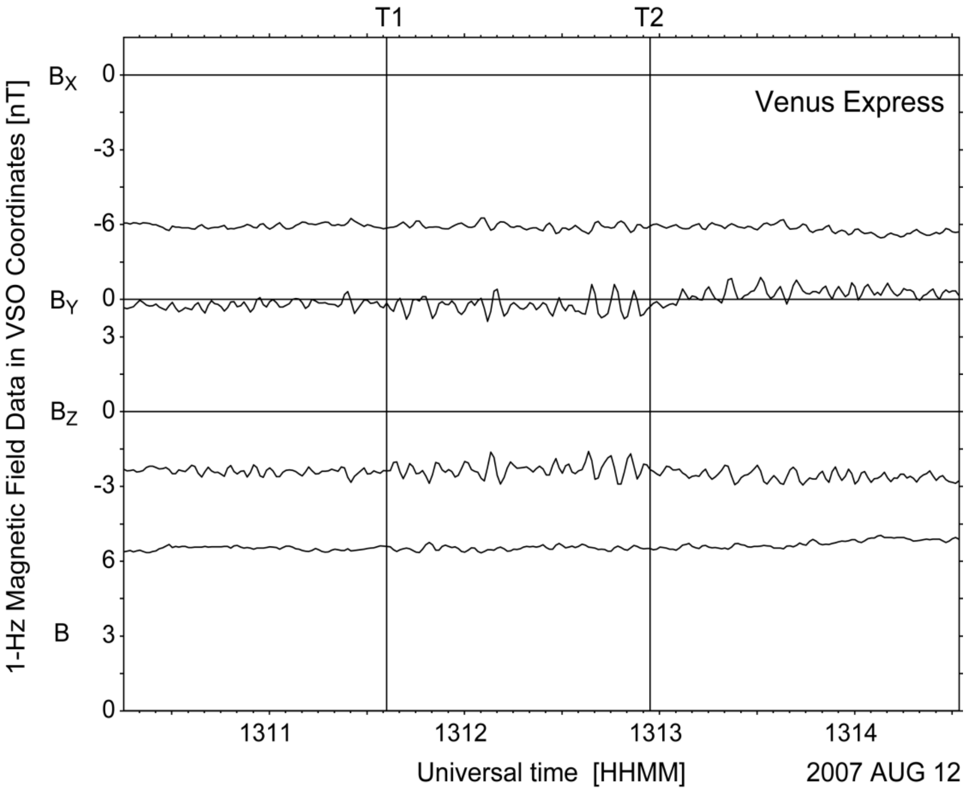
Observations of ICWs by MESSENGER: 2008 May 31 – June 9

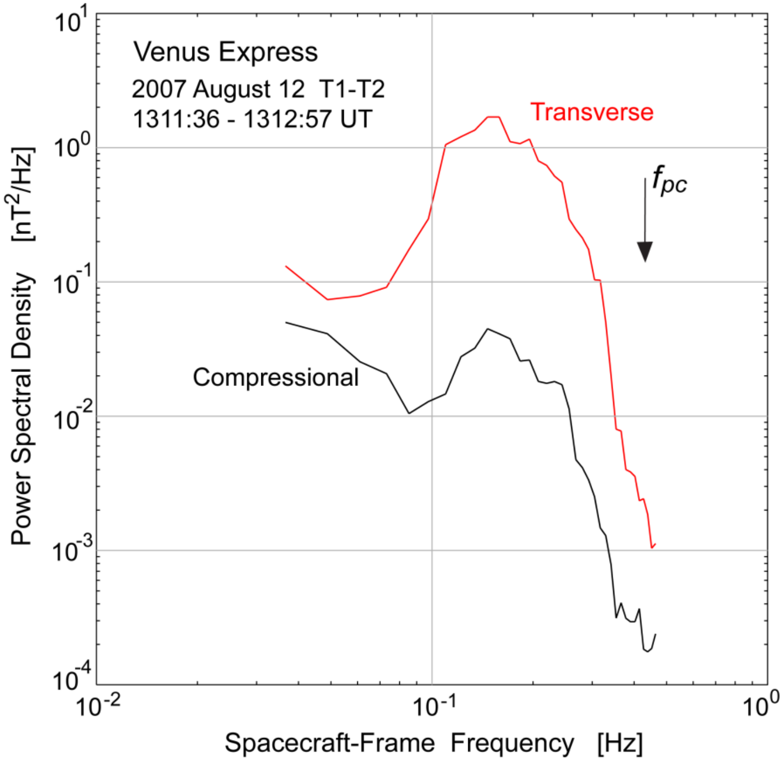
0.98% of the time



An Example of ICWs at 0.7 AU

1-Hz



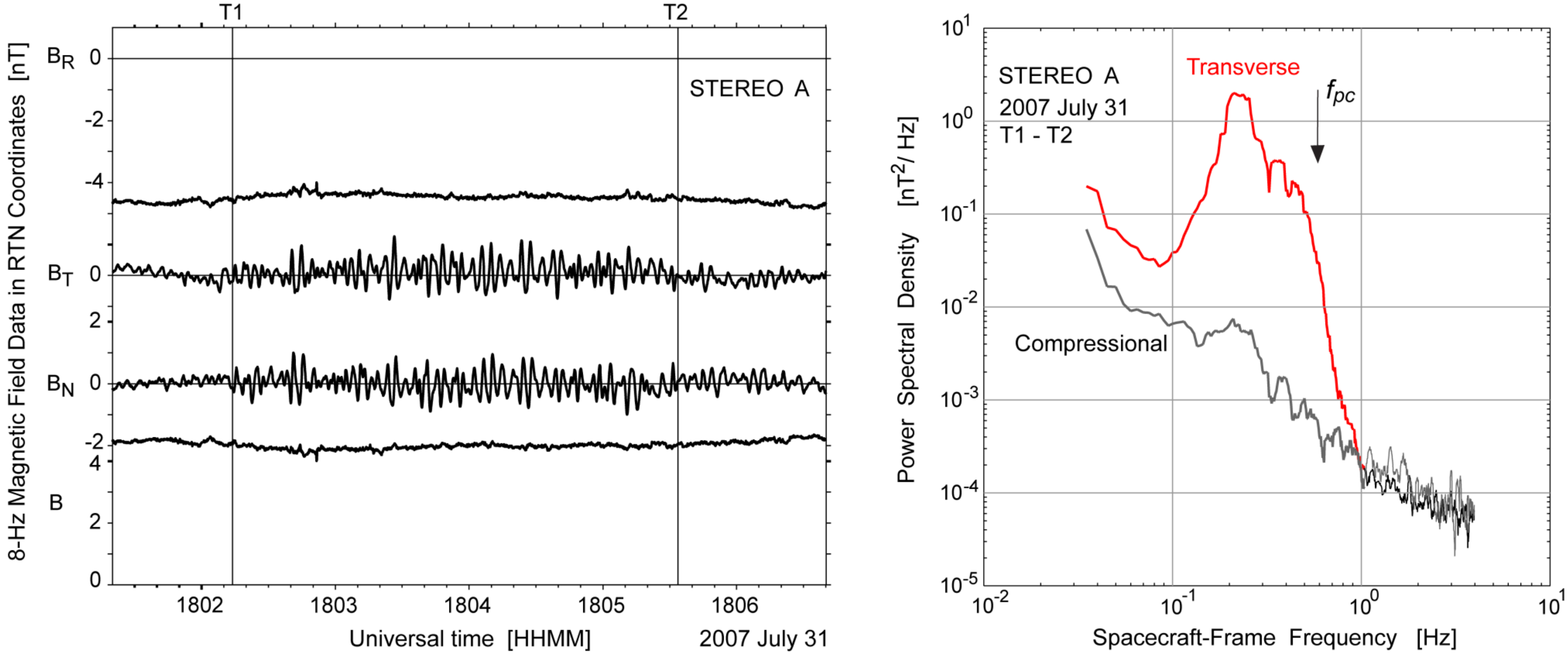


5-band average

- We use 1-Hz Venus Express (VEX) magnetic field data, covering ±**2 hours of the apocenter**, *i.e.*, the region **at least 11.5 Venus radii away from Venus**
- Within the interval T1-T2, the transverse power dominates. The wave has an ellipticity of 0.95 and a percent polarization of 97.3%

An Example of ICWs at 1 AU

8-Hz

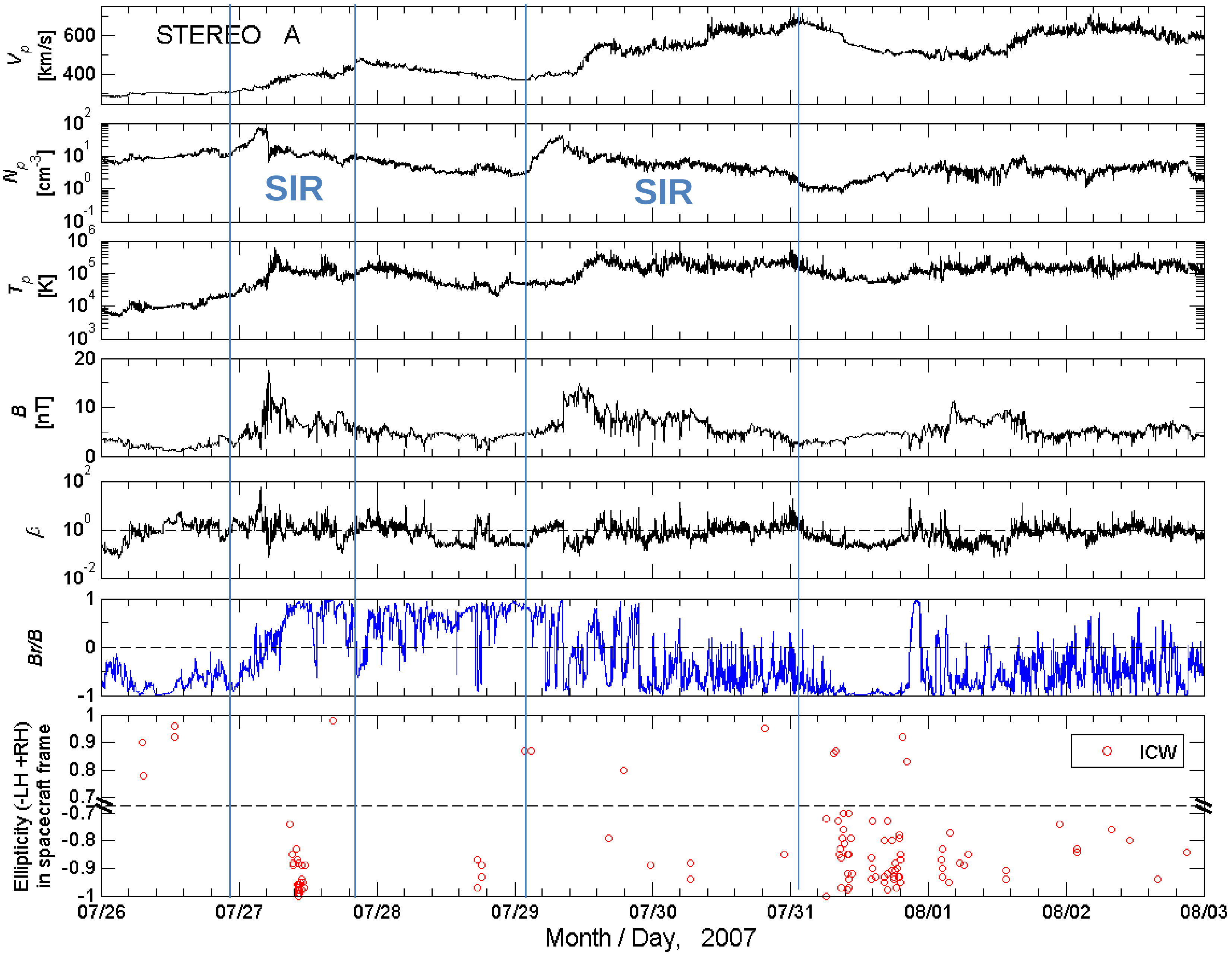


(Jian *et al*., ApJ 2009)

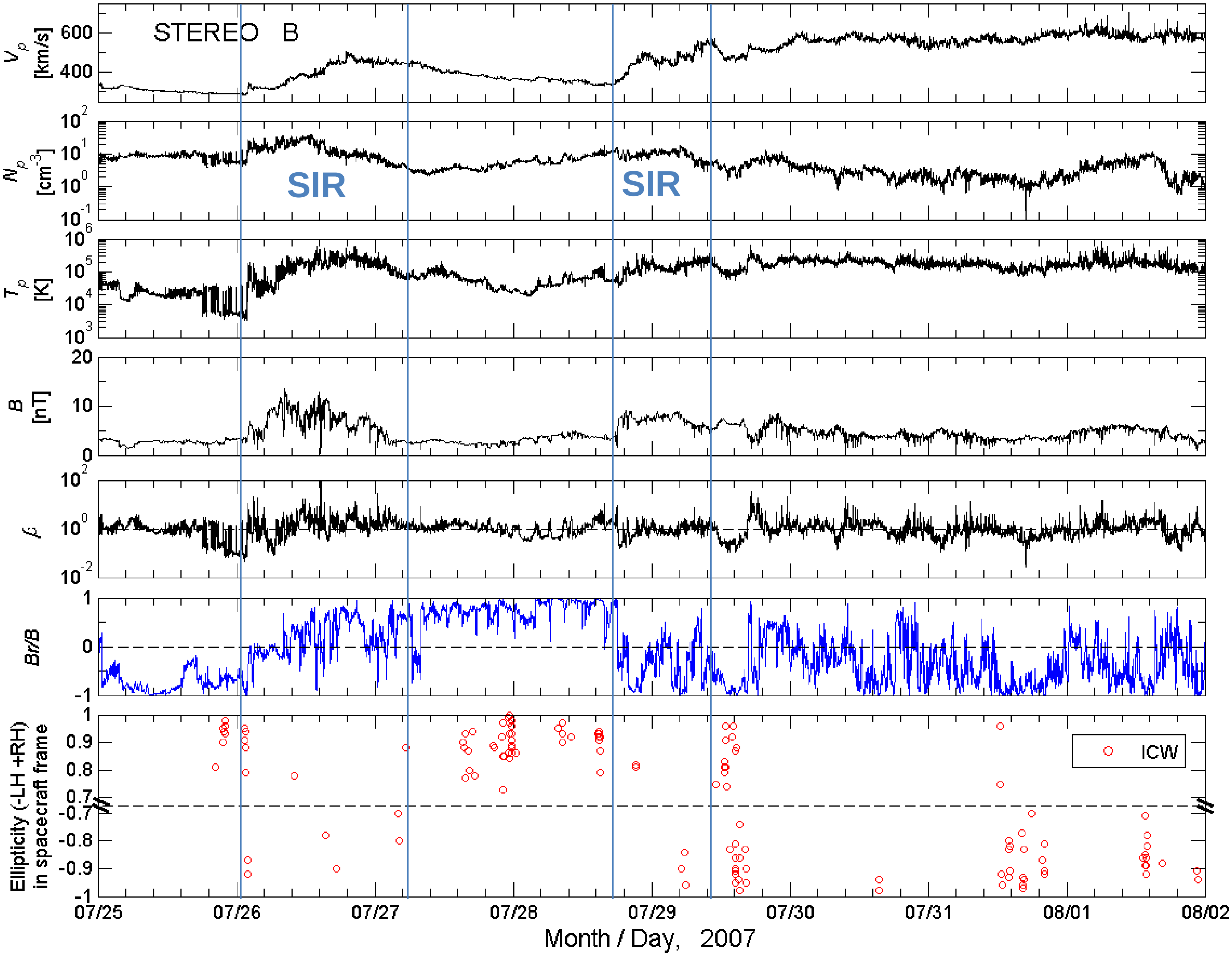
13-band average

- STEREO A/B are far away from any planet. Surrounding the shown 5.5-min interval, there are many ICW packets. They are well above the strength of other natural signals and the instrument noise level
- Within the interval T1-T2, the wave has an ellipticity of -0.95 and a percent polarization of 95.2%. The propagation angle from ***B*** is 1.2^o
- Electric field data are dominated by electrostatic signals at these frequencies

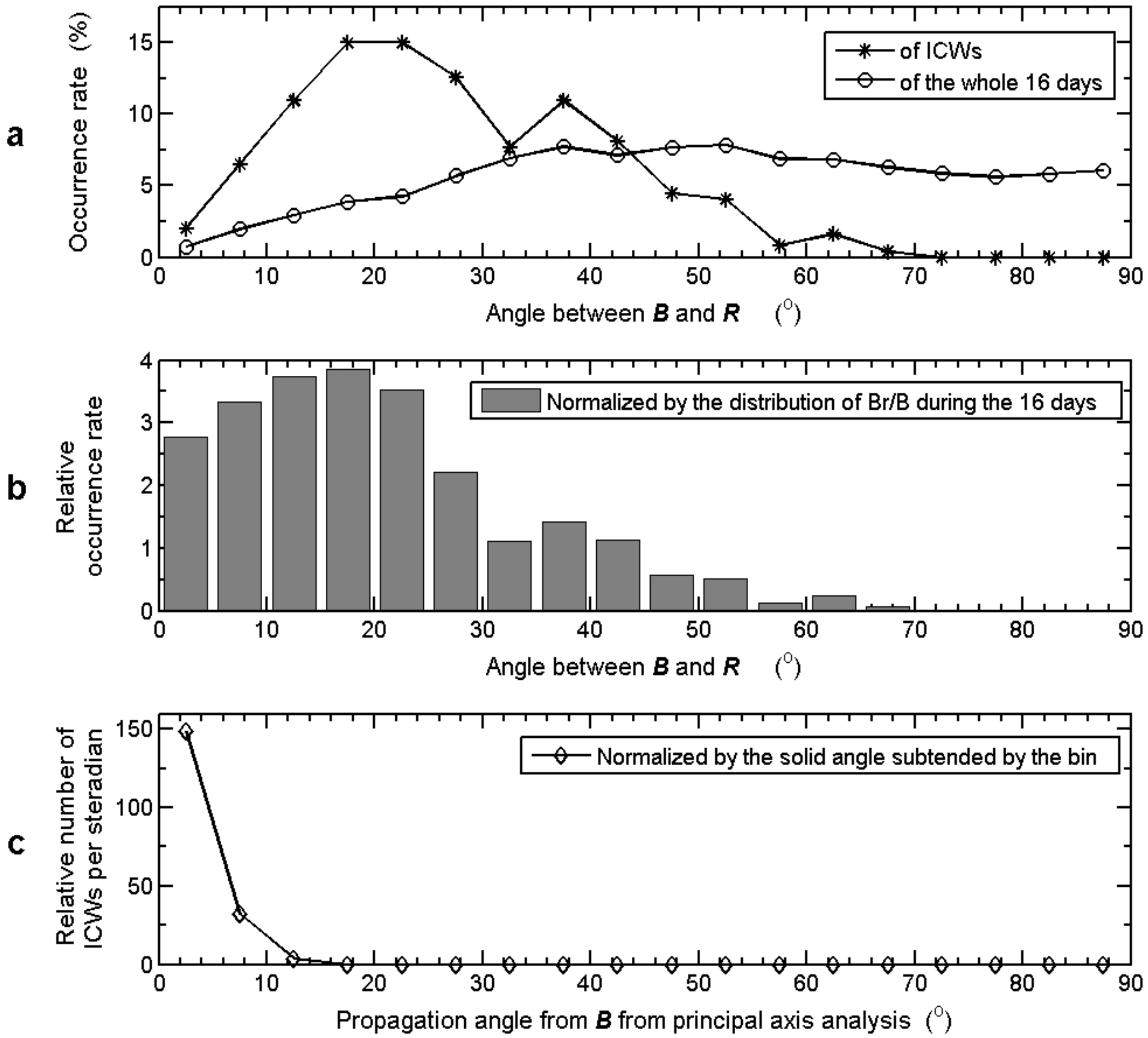
8-Day Survey of ICWs Using STEREO A



8-Day Survey of ICWs Using STEREO B



Angular Distribution of ICWs at 1 AU



246 wave events

Waves appear more often when field is more radial than the general condition

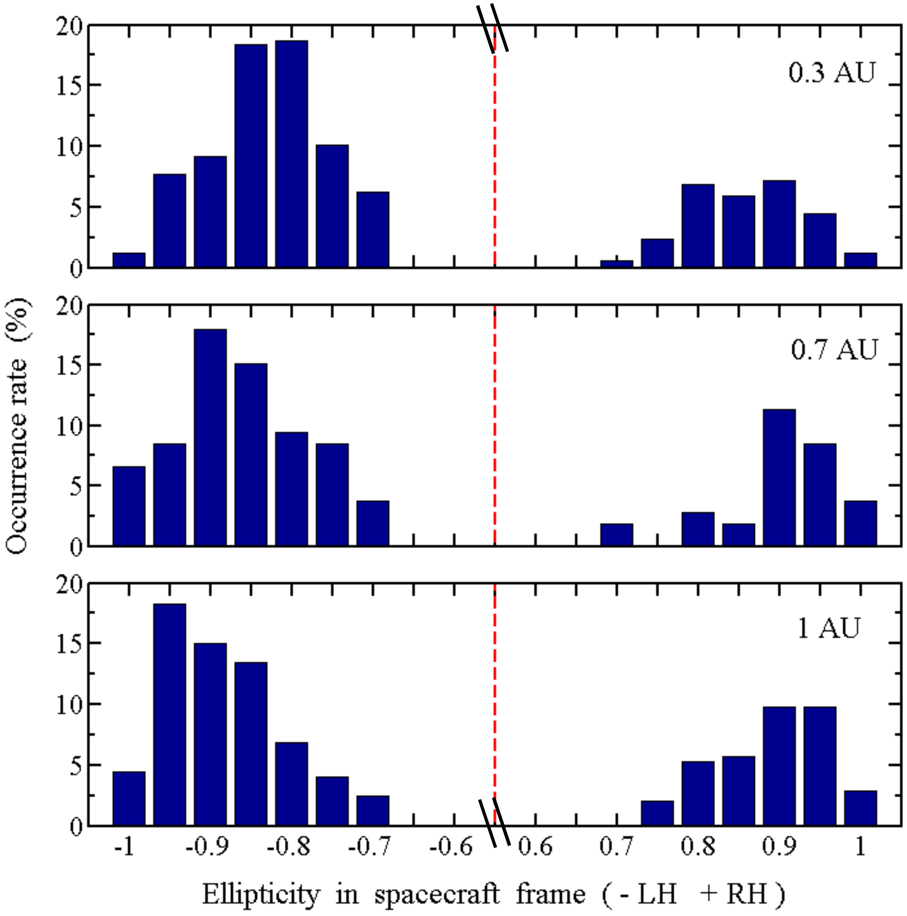
Waves propagate mostly along the field direction

(Jian *et al*., ApJ 2009)

Comparison of Wave Parameters: 0.3, 0.7, and 1 AU

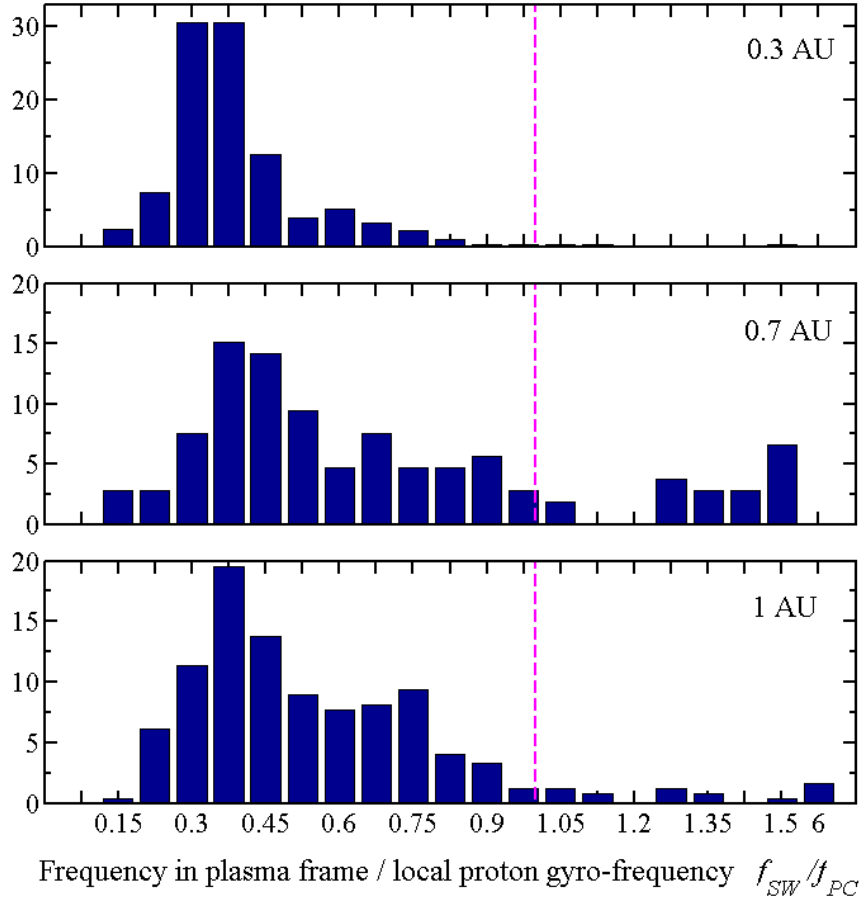
LH vs. RH in S/C Frame

LH (~ 70%) RH

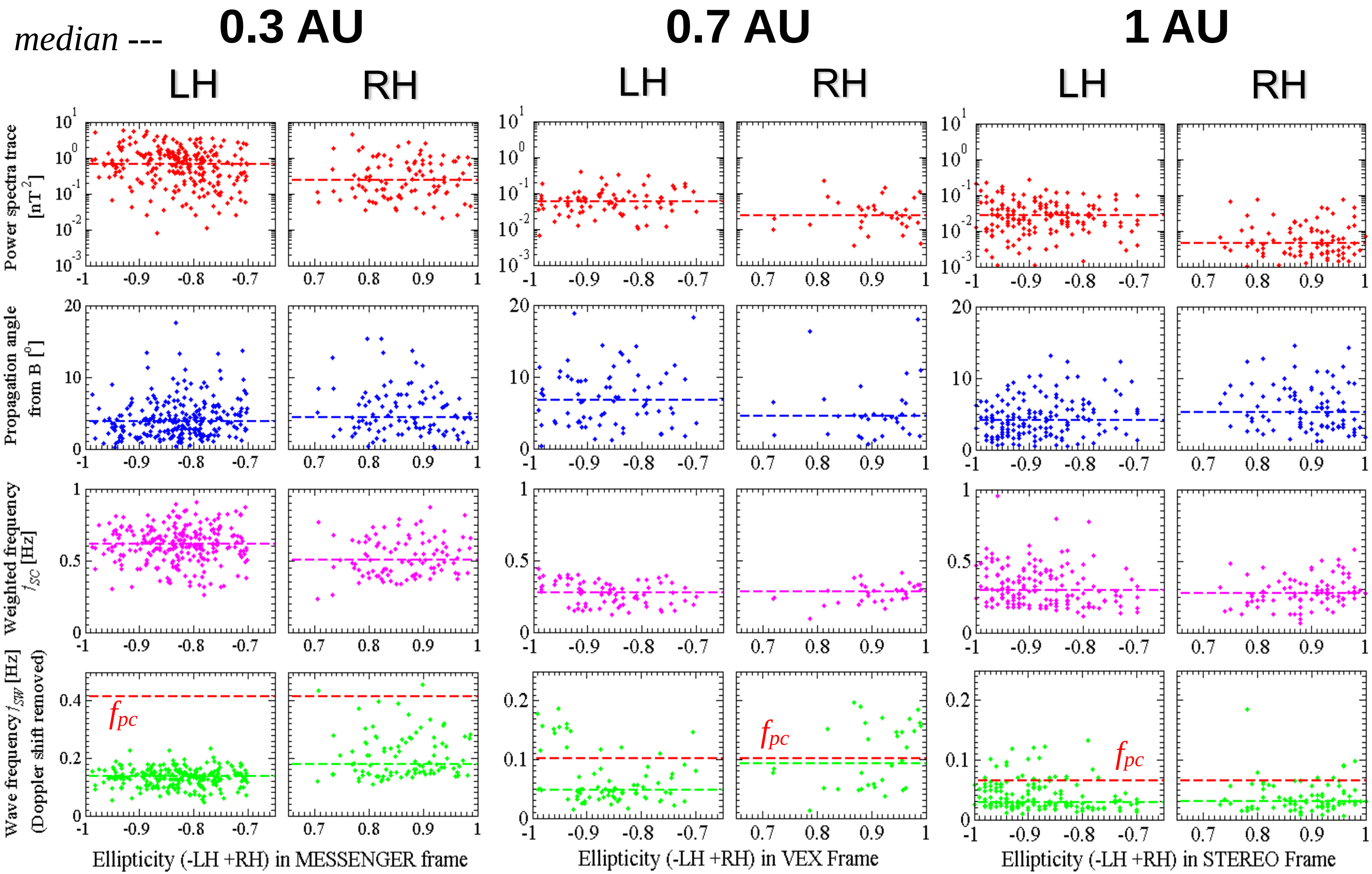


f_{sw}/f_{pc}

in Plasma Frame



Comparison of the Properties of LH and RH Waves in Spacecraft Frame



Radial Variation of ICW Parameters

MESSENGER
Venus Express
STEREO A/B

Heliocentric distance	**0.3 AU**	**0.7 AU**	**1 AU**
Occurrence rate [/day]	*33.7*	*28.9*	*15.4*
ICW duration / total time [%]	*0.94*	*1.79*	*1.18*
Angle between B and R [º]	18.2	26.7	25.1
Angle between K and R [º]			
Propagation angle from B [º]			
Absolute value of ellipticity			
% Polarization			
Power spectra trace [nT^2]			
$(dB)^2 \times r$ [nT^2m]	0.160	0.031	0.016
Compressional Ratio	0.010	0.001	0.013
Weighted frequency f_{SC} in s/c frame [Hz]	0.59	0.28	0.28
Wave frequency f_{SW} [Hz] (Doppler shift removed)	0.144	0.052	0.030
Local field B [nT]	27.1	6.7	4.3
Duration [second]	21.0	59.0	51.5

Conservation of Poynting flux

$$dB \times E \times r^2 = \text{constant}$$

$$\rightarrow (dB)^2 V_A r^2 = \text{constant}$$

$$\rightarrow (dB)^2 B n^{-1/2} r^2 = \text{constant}$$

$$\rightarrow (dB)^2 r = \text{constant}$$

fewer waves at a greater distance

longer duration for each event

– more radial than Parker spiral

agating

larized

Poynting flux
= constant
but it decreases significantly

decreases, consistent with ICWs being continuously absorbed by local plasma as they approach local f_{pc}

short time scale, explaining why the ICWs cannot be detected using spectrum analysis over long intervals

ICW Properties: 1976 vs. 2008

Spacecraft Time period Solar cycle phase	**Helios 1** **1976 Mar 25 – 31** **Solar Min 20/21**	**MESSENGER** **2008 May 31 – June 9** **Solar Min 23/24**
Local field B [nT]	37.6	27.1
Occurrence rate [/day]	44.0	33.7
Power spectra trace [nT^2]	1.120	0.532
Weighted frequency f_{SC} in s/c frame [Hz]	0.87	0.59
Wave frequency f_{SW} [Hz] (Doppler shift removed)	0.186	0.144

More than 300 wave events at each s/c

Comparing with Helios 1 observations in 1976, the ICW wave power and frequencies observed by MESSENGER in 2008 are smaller. This is probably due to the weaker IMF of this solar minimum

Elimination of Several Generation Mechanisms

- The ICWs in the solar wind are **ubiquitous** in the inner heliosphere. They exist in regions far away from any planetary and cometary influence

- **No shocks** occurred within our observation window

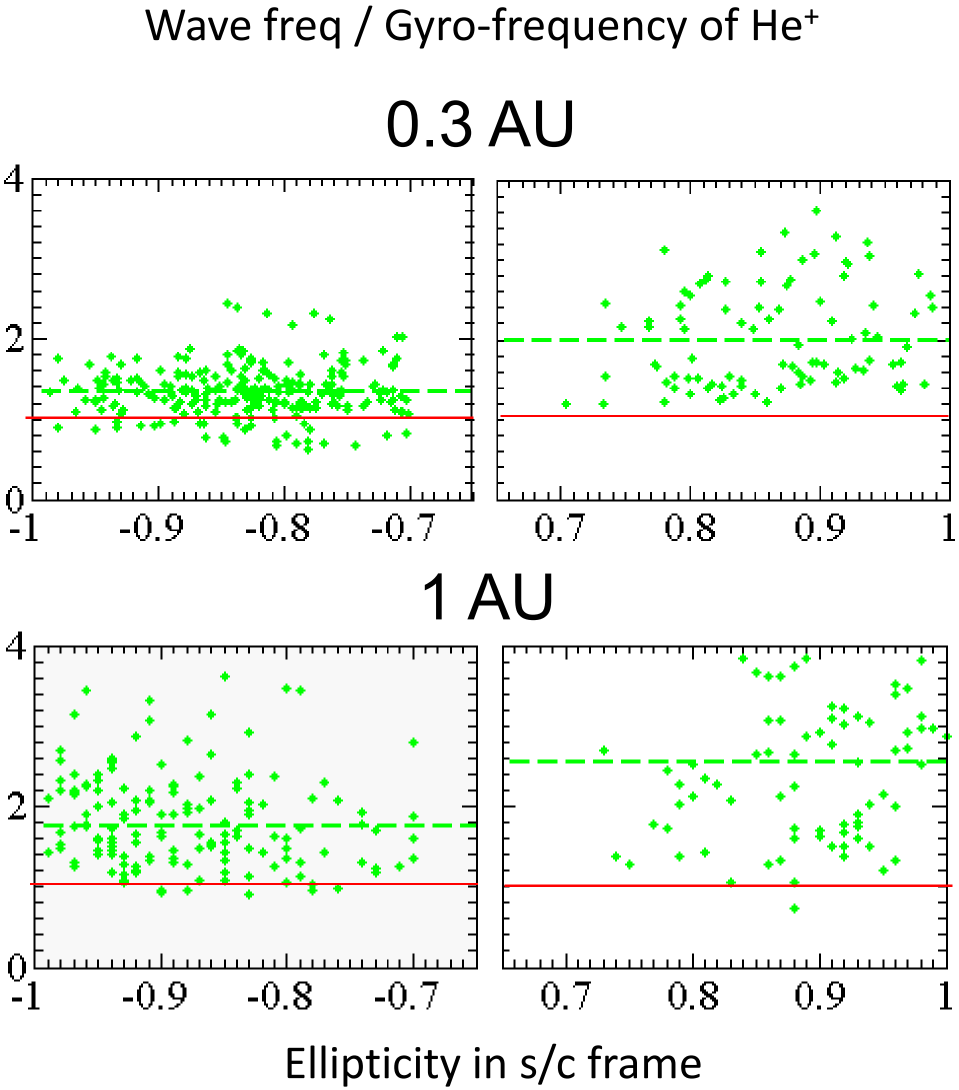
- The field direction is close to the solar wind velocity, and the wave frequency in the s/c frame is higher than the local f_{pc}, so the waves are **not locally generated by pickup ions**

➔ **The ICWs must be generated at a location closer to the Sun than the s/c**

Closer-to-Sun Generation Scenario

- There are multiple sources of neutral particles in the inner heliosphere. These neutral particles can be ionized and accelerated, forming ring beams, which would be unstable to the generation of ICWs

- The ICWs have a frequency range of 0.2 – 0.9 local f_{pc}, but mostly around 0.3 – 0.4 local f_{pc}, *i.e.*, close to the He$^+$ gyro-frequency in the plasma frame



Possible Association with Pickup He^+?

Pro

- Assuming the f_{sw} (0.144 Hz) is constant from the generation region to 0.3 AU, for He^+, the field in the generation region should be about 40 nT
- The ICW travel time from the 40-nT region to 0.3 AU (B = 27 nT) is shorter than the ICWs' damping time in the case of parallel-to-B propagation (thousands of ion cyclotron periods)

Con

- Some ICWs have ***multiple peaks*** in the power spectra

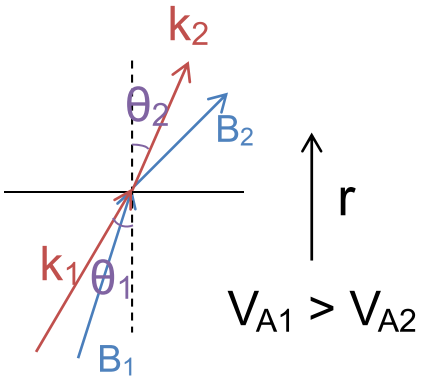
Questions

- Is the He^+ density high enough to create so many ICWs? Can its radial variation explain the significant decrease of the wave power?
- Why do not we see many newly generated ICWs at large B-R angle?
- The B-R angle is often small where we see ICWs. How much can the B-R angle change within the ICW travel distance, which is shorter than 0.1 AU?

Note: Focusing cone is not obvious within 1 AU

Propagation Scenario of the ICWs in the Solar Wind

- After the ICWs are generated, they can propagate either inward or outward along the magnetic field. However, they will both be carried out by the super-Alfvénic solar wind. As they convect outward, much of the ICW energy has damped and the energy remaining may be ***only a very small remnant***
- The appearance of LH and RH waves in the s/c frame should be due to outward and inward propagation. The **lower power and smaller occurrence rate of RH waves** are consistent with longer travel time and greater damping experienced by these inward-propagating waves.
- The enhanced occurrence rate of ICWs when the IMF is more radial is likely due to **minimal damping associated with parallel-to-B propagation** since the wave normal angle is constantly being pulled toward the radial direction by refraction



Summary and Conclusions

- Strong narrow-band ICWs are detected **extensively and discretely** from at least 0.3 to 1 AU in the solar wind, far away from the influence of any planet. They are strongest when the field is more radial than the nominal Parker spiral. They propagate close to the magnetic field direction, and are below the local f_{pc} and close to the He^+ gyro-frequencies in the plasma frame

- The waves are both LH and RH in the s/c frame, but are intrinsically LH in the plasma frame. The comparison of the LH and RH waves in the s/c frame, and the radial variation of the frequency and wave power of the ICWs, is consistent with our closer-to-Sun generation and outward propagation scenario

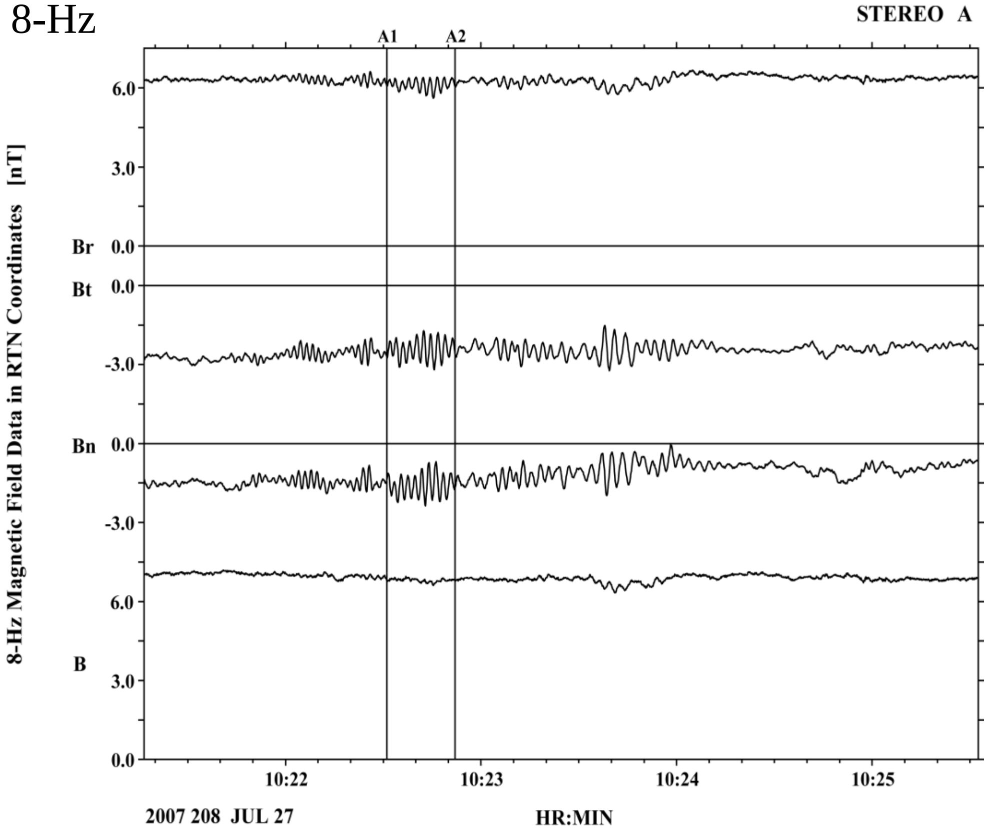
- As the ICWs approach local f_{pc} at a greater heliocentric distance, they can provide an energy source for extended solar wind heating

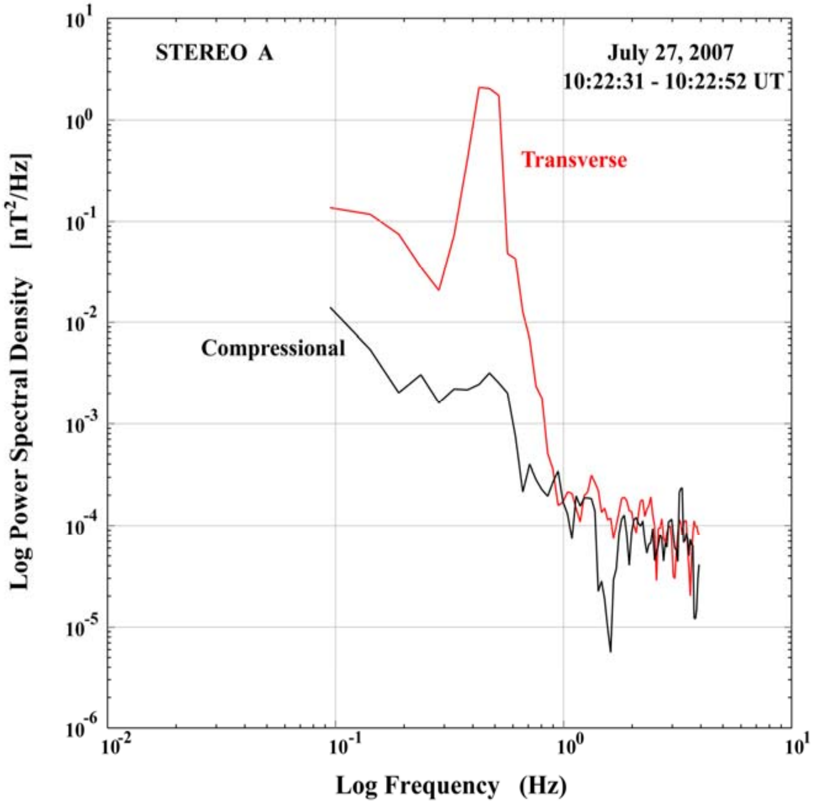
- A mission flying closer to the Sun should be able to see many more such ICWs with stronger wave power. More observations and coordinated models are needed to better understand these ICWs

Backup

Example of ICW at 1 AU

8-Hz





- STEREO A/B are far away from any planet. During the 4 minutes shown above, there are several wave packets. They are well above the strength of other natural signals and the instrument noise level

- Within the interval A1-A2, the wave has an ellipticity of -0.98 and a percent polarization of 99.9%

ICW Properties: 1976 vs. 2008

Spacecraft Time period Solar cycle phase	**Helios 1** **1976 Mar 25 – 31** **Solar Min 20/21**	**MESSENGER** **2008 May 31 – June 9** **Solar Min 23/24**
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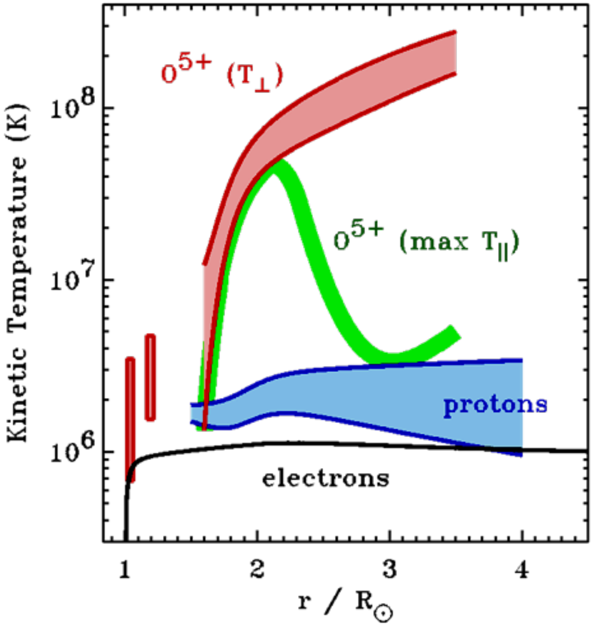
Wave frequency f_{SW} [Hz] (Doppler shift removed)	0.186	0.144
Angle between B and R [^{o}]	22.0	18.2
Angle between K and R [^{o}]	21.0	19.9
Propagation angle from B [^{o}]	7.2	4.0
Absolute value of ellipticity	0.87	0.83
% Polarization	92.5	93.1
Compressional Ratio	0.021	0.010
Duration [second]	23.5	21.0

Closer-to-Sun Generation Scenario

Highly Anisotropic
Heavy-Ion
Distributions



Strongly Mass-Dependent
Heating in the Corona

$$\left\{\begin{array}{ccc} T_{\text{ion}} \gg & T_p & > T_e \\ (T_{\text{ion}}/T_p) & > & (m_{\text{ion}}/m_p) \\ T_\perp & \gg & T_\parallel \\ u_{\text{ion}} & > & u_p \end{array}\right\}$$

(Cranmer, SPD, 2006)

- Alfvén waves in the lower solar atmosphere may provide sufficient energy flux to heat the corona, but they need an agent to convert their energy to a form that can heat the core proton efficiently and accelerate the solar wind

- One possible energy transfer is the production and subsequent damping of ICWs, which is supported by SOHO observations and coronal models

- The **electric field associated with the Alfvén wave fluctuations** could accelerate newly created ions into **ring beams**, and these ring beams would be unstable to the generation of ICWs that in turn damp and heat the solar wind when they interact with the solar wind ions