Plasma Waves Near the Electron Cyclotron Frequency in the Near Sun Solar Wind: Wave Mode Identification and Driving Instabilities

2021 EGU meeting
ST1.4 - Latest results from Parker Solar Probe

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This work is under review in Astronomy & Astrophysics

Between Switchbacks

Switchbacks

- localized reversals of radial **B**
- Perhaps the most unexpected large-scale solar wind feature < 55 Rs ?

In this talk, I will do something extremely controversial with regard to switchbacks:

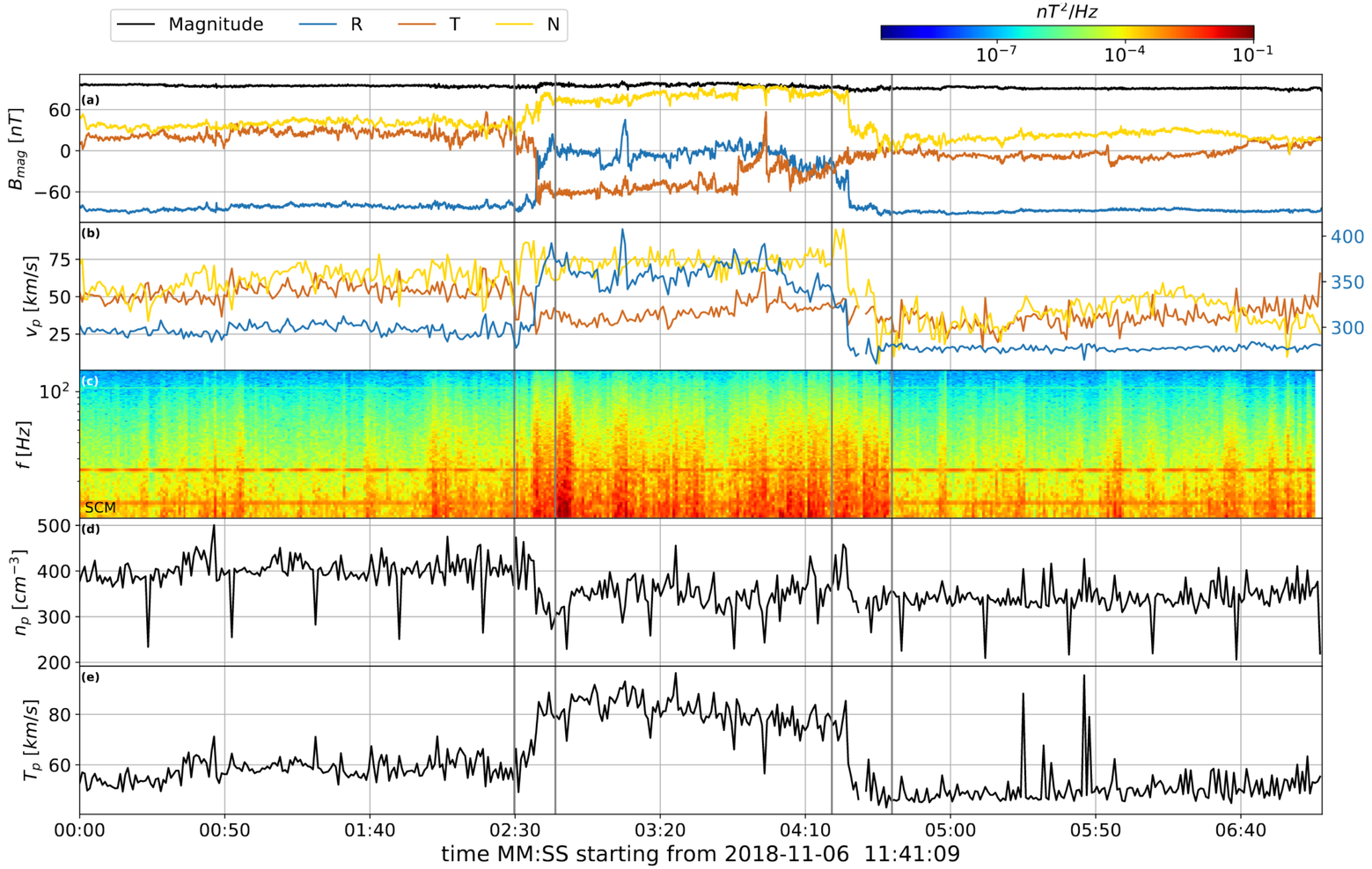


Fig. 3. Switchback example. **a** MAG magnetic field data, **b** Proton velocity, **c** Trace Spectrogram from the SCM waveform, **d** Proton density, **e** Proton temperature. Leading and trailing edges, respectively, are located between the first and second pairs of vertical lines.

Larosa+ 2021

Between Switchbacks

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- localized reversals of radial **B**
- Perhaps the most unexpected large-scale solar wind feature < 55 Rs ?

In this talk, I will do something extremely controversial with regard to switchbacks:

I will not talk about them!

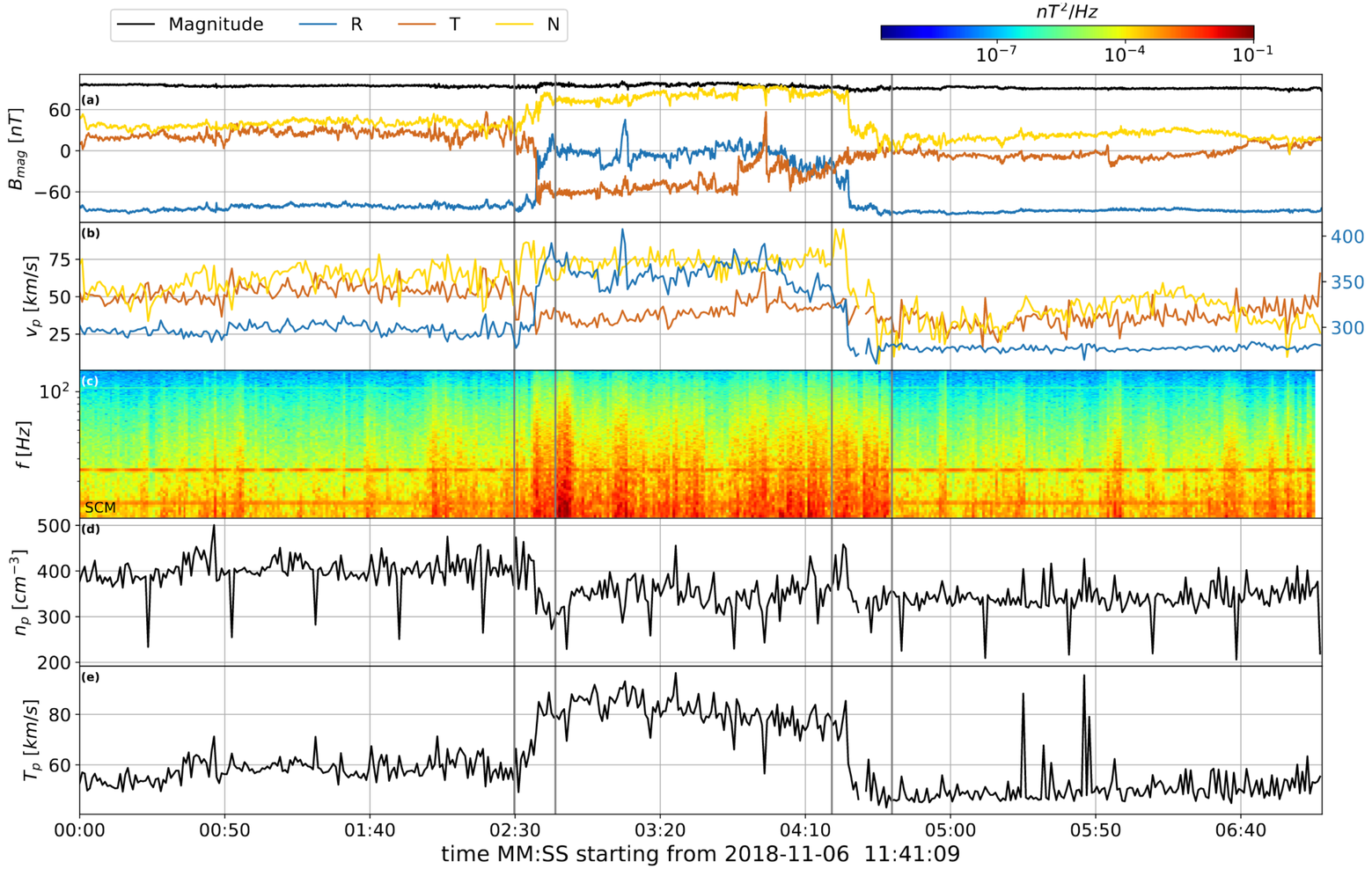


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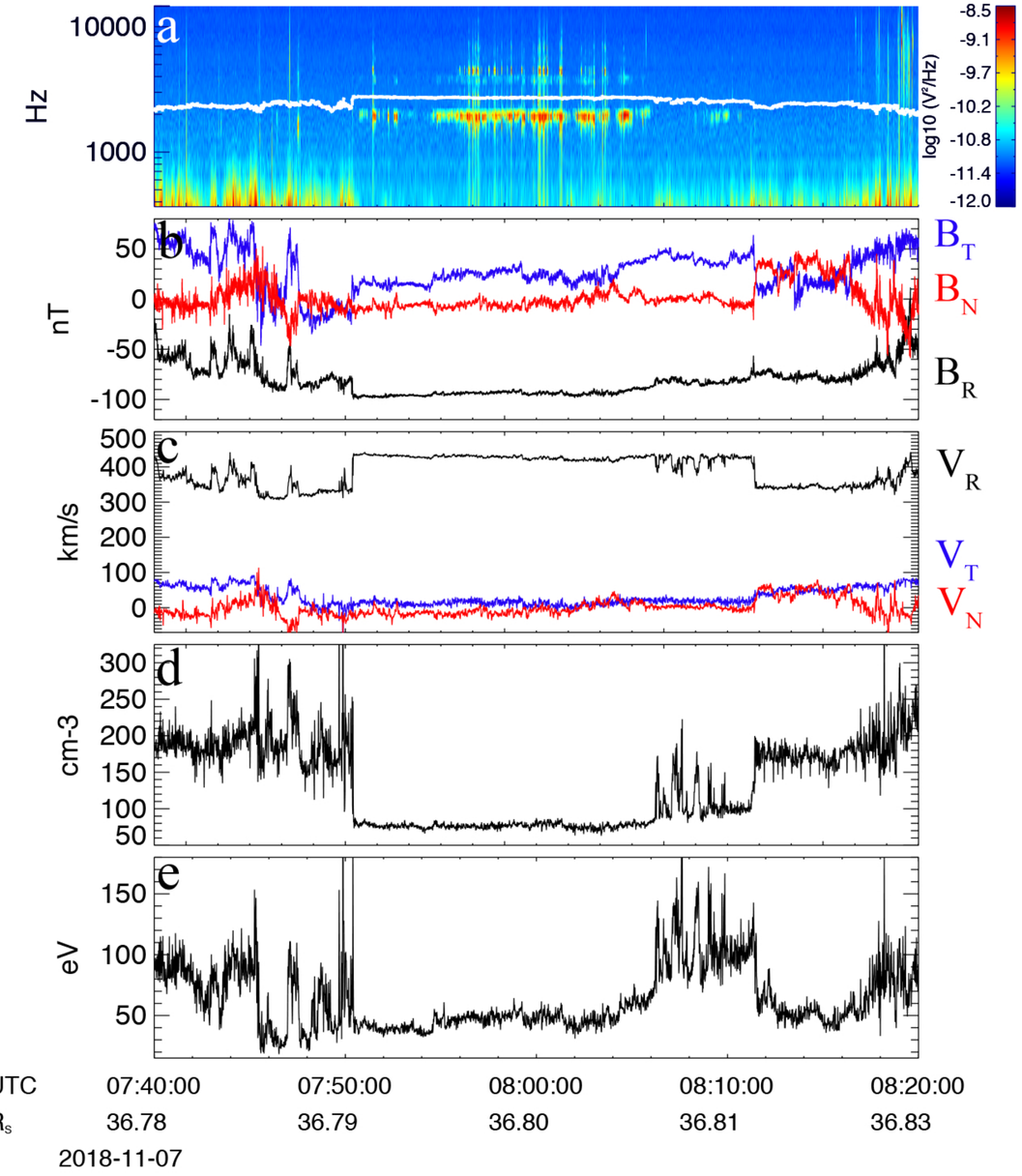
The Quiescent Solar Wind

Quiescent wind regions show:

- ~10x lower turbulent amplitudes (Dudok de Wit+ 2020)
- Lower-frequency turbulent break point (Dudok de Wit+ 2020)
- Magnetic field closely aligned with the Parker Spiral (Malaspina+ 2020)
- Stronger / narrower electron strahl (e- that escape the corona)

Quiescent wind regions contain:

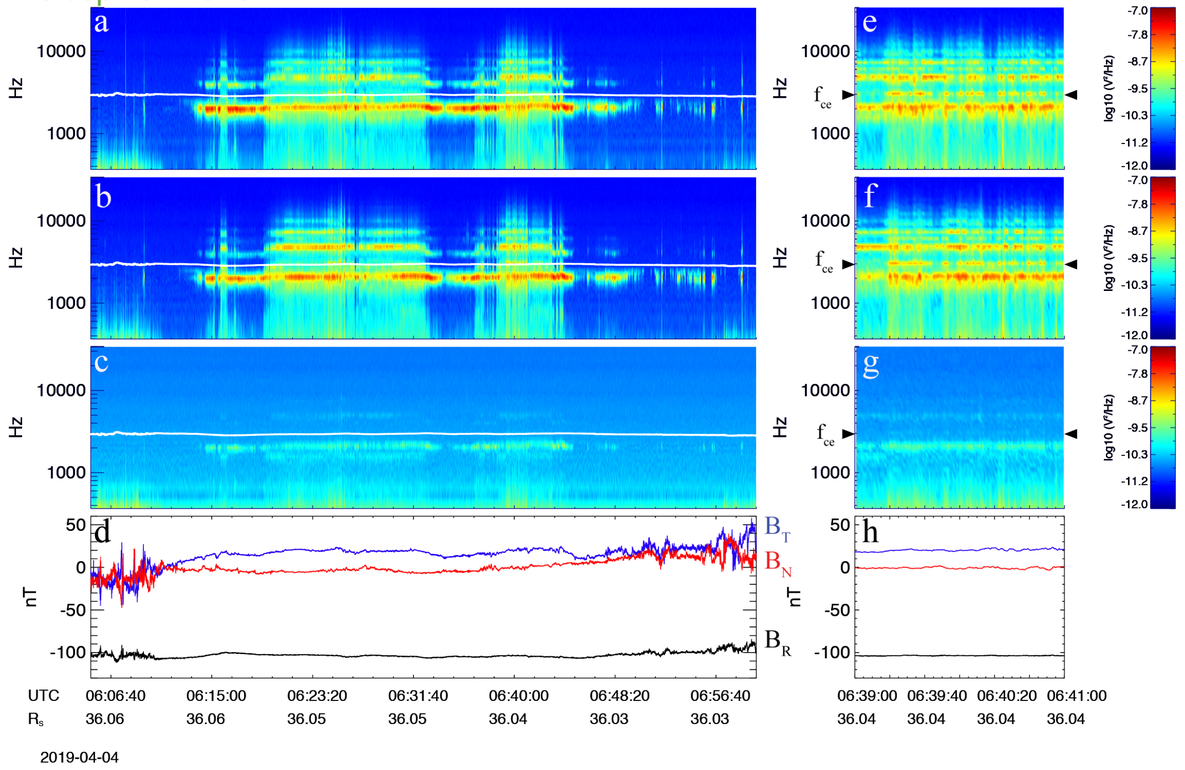
- The solar wind least evolved from coronal conditions
- Intense plasma wave activity near electron cyclotron frequency (fce)



Malaspina+ 2020

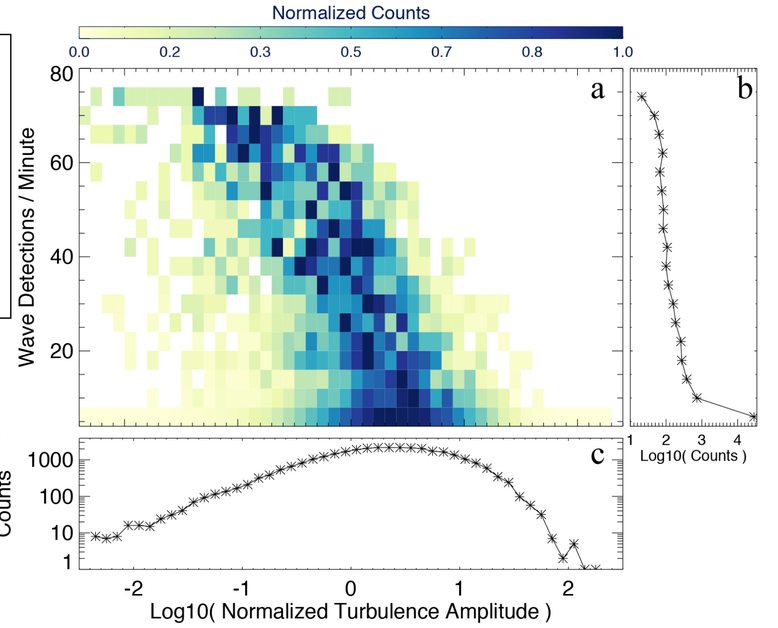
Near-fce Waves in the Quiescent Near-Sun Solar Wind

Malaspina+ 2020

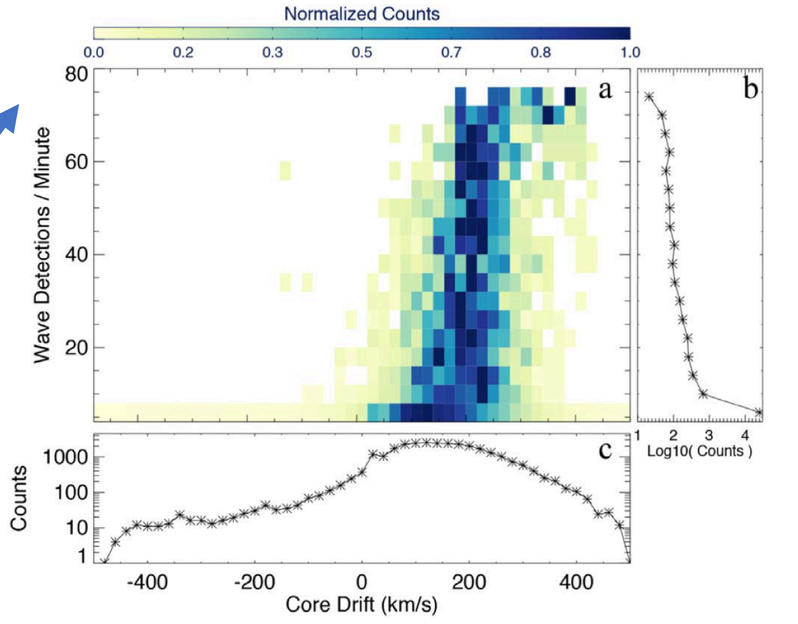


What drives these waves?

How do they impact solar wind evolution?



Malaspina+ 2020



Intense plasma wave activity near electron cyclotron frequency (fce)

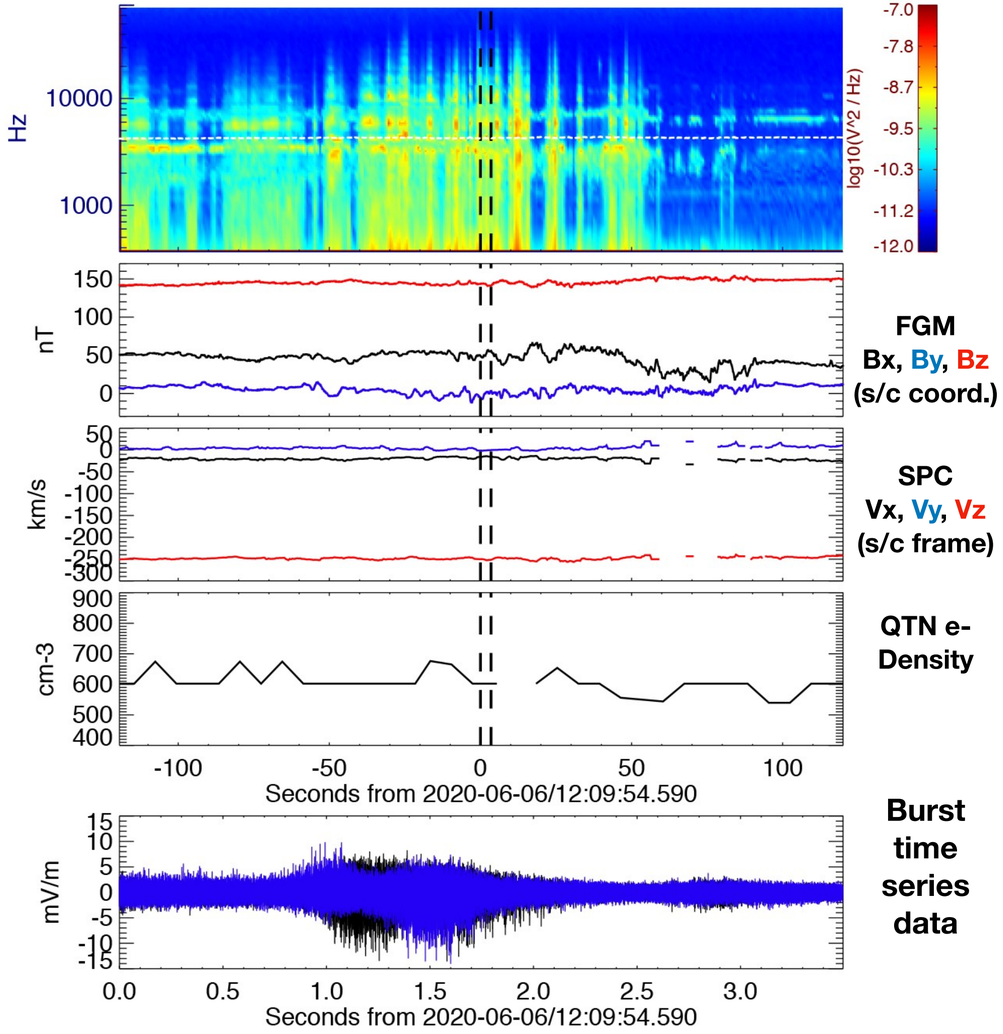
- Common in quiescent field regions
- long-lasting (min to hours)
- only appear < 55 Rs
- Electrostatic (to SCM limit)
- Peaks < fce

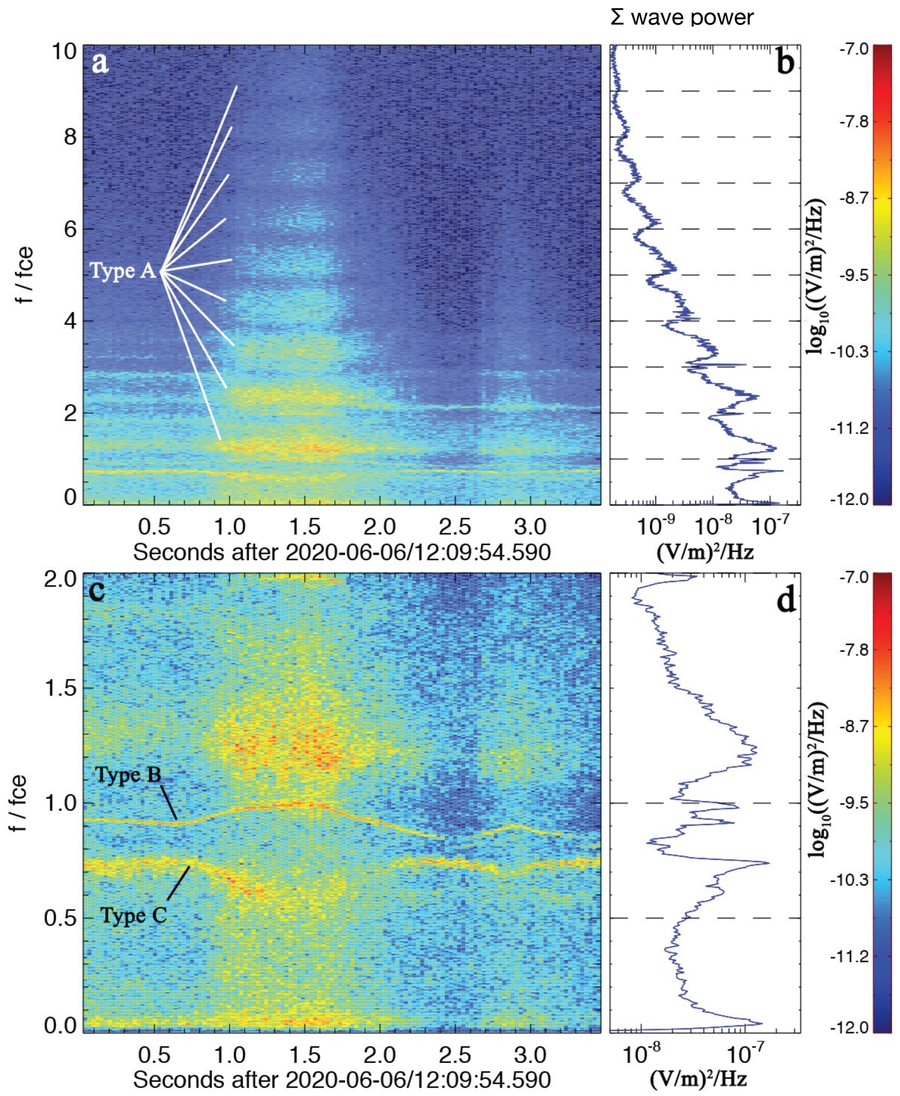
- Harmonic structure > fce
- Distinct background **B**
  - Near-Parker spiral
  - Small **B** fluctuations
- Appear with strong e- core drift

Burst Mode Observations

For burst interval:
λ_D ~ 1.8 m
ρ_e ~ 98 m
f_{ce} ~ 4,200 Hz
f_{pe} / f_{ce} ~ 52

~3.5 s @ 150 kS/s burst capture





Three wave types

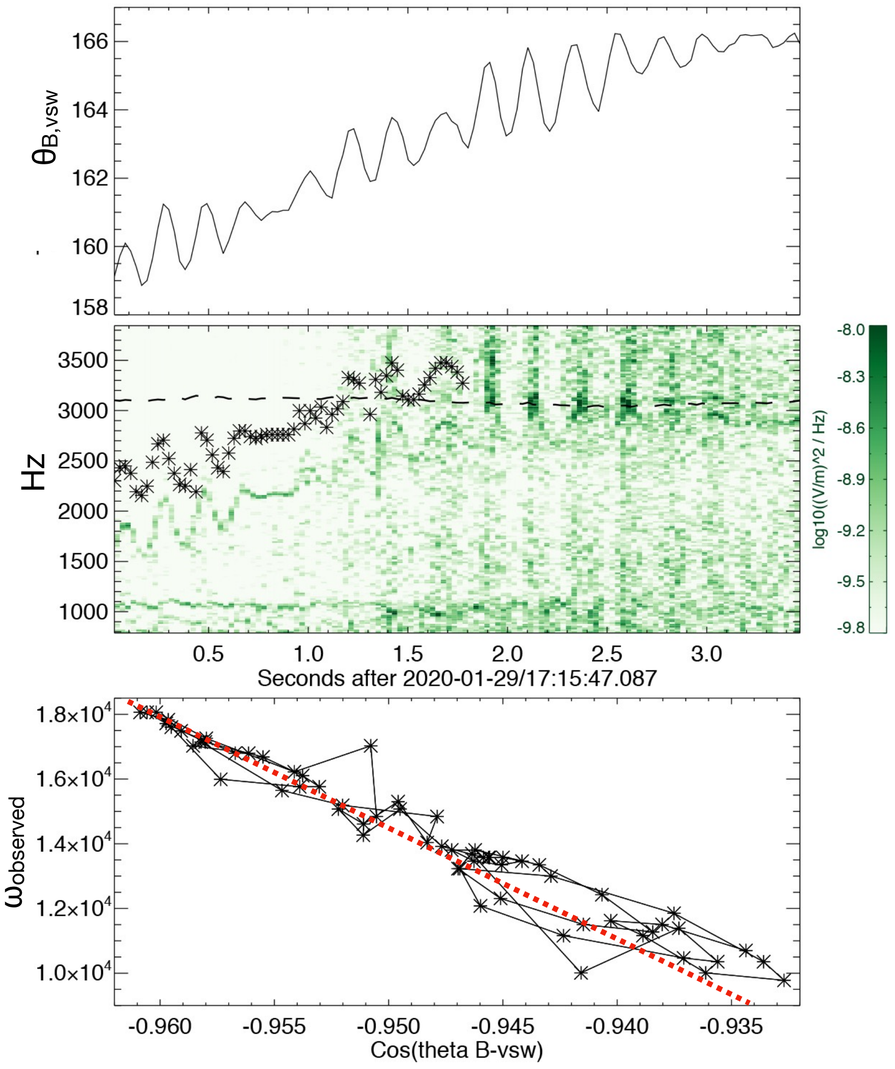
Type A
e- Bernstein waves (ECH)
Non-integer near-fce harmonics
f > fce
(only prior obs. in solar wind w/ s/c Barium release or at shocks)

Type B
Near-fce very narrow band
df ~ 130 Hz
df / f ~ 3%

Type C
Near-fce/2 narrow band
df ~ 360 Hz
df / f ~ 12%

What wave modes are types B and C?
How do they interact with solar wind e-?

Burst Mode Observations



Type B wave frequency varies strongly with $\theta_{B,vsw}$

Could be Doppler shift

$\omega_{observed} = \mathbf{k} \cdot \mathbf{V}sw + \omega_{real}$

$\omega_{observed} = |k\ Vsw|\ \cos(\theta_{k,vsw}) + \omega_{real}$

Redefine:

y = m * x + b

$\omega_{observed} = (k\ Vsw) * \cos(\theta_{k,vsw}) + \omega_{real}$

We know: Vsw, $\omega_{observed}$

We want: ω_{real}, $\vec{k}$

Procedure:

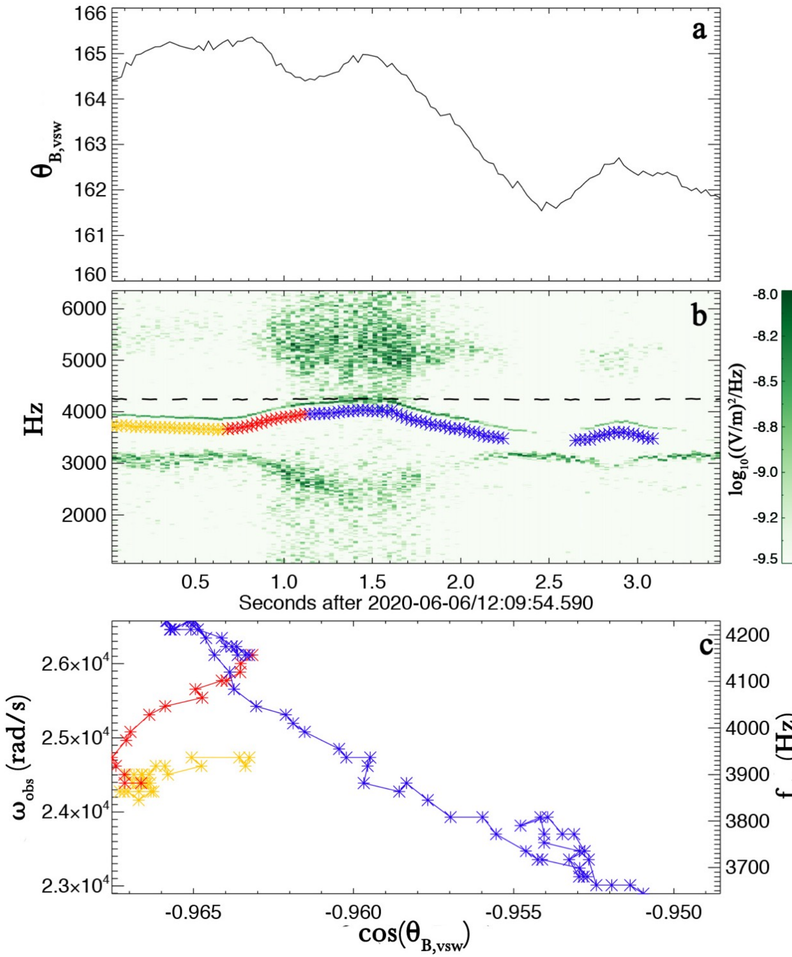
- Rotate into
  - **B**, (**B** x **V**sw), (**B** x **V**sw)x**B** coordinates
- calculate $\cos(\theta_{k,vsw})$ for $\hat{k}$ test vector
- Plot **x** ($\cos(\theta_{k,vsw})$) vs. **y** ($\omega_{observed}$)
- Move test $\hat{k}$ all over 4π sky

For each $\hat{k}$, fit points of :

y = $\omega_{observed}$ vs. x = $\cos(\theta_{k,vsw})$

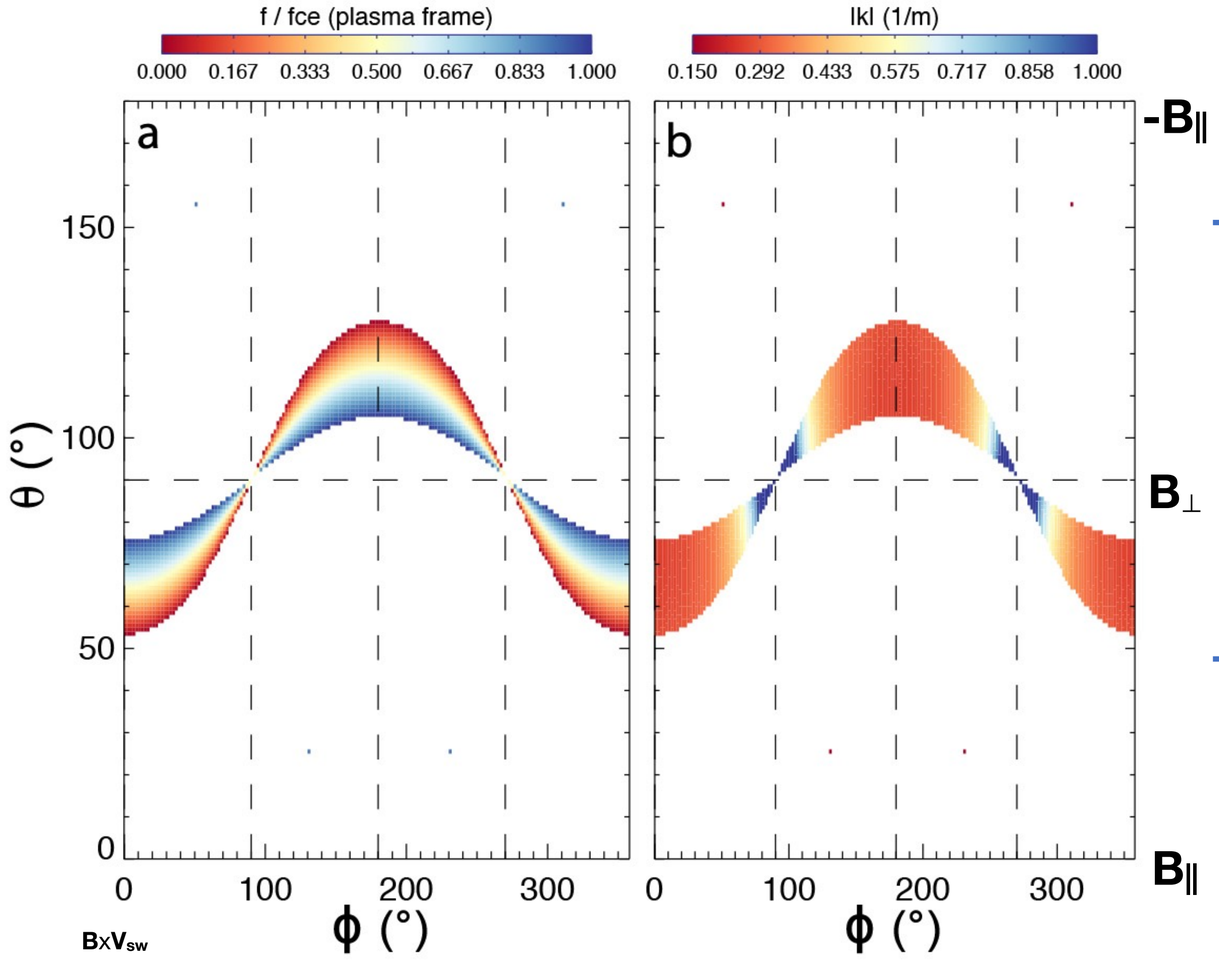
(slope) m = |k| |Vsw|

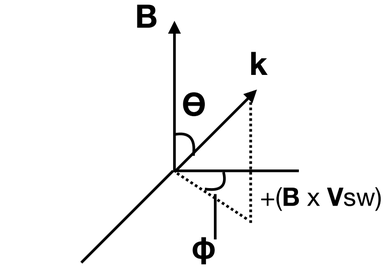
(offset) b = ω_{real}



Fits for each test $\hat{k}$ produce solutions for |k|, ω_{real}

Burst Mode Observations - Wave Vector





Coordinate system

Solutions for 0 < f < fce considered

Type B Wave character:

0 < f < fce (likely ~fce)

0.15 < |k| (1/m) < 0.3

$\theta_{k,B}$ ~ 110° or 70°

If Landau Resonant

$\omega_{real} = \mathbf{v} \cdot \mathbf{k}$

$v_{||} = \omega_{real} / k \cos(\theta_{k,B})$

$v_{\perp} = \omega_{real} / k \sin(\theta_{k,B})$

(0.19 eV) < $v_{||}$ < (0.75 eV)

(0.0025 eV) < $v_{\perp}$ < (0.10 eV)

Instability exists in cold e- core

Te ~ 35 eV

Possible if strong strahl current offsets sunward e- core (?)

If Cyclotron Resonant

(f_{real} ~ 0.98 fce)

$v_{||} = (\omega_{real} - N\,\omega_{ce}) / k_{||}$

$v_{||} = (\omega_{real} - N\,\omega_{ce}) / |k| \cos(\theta_{k,B})$

N = +1	$7x10^{-5}$	< $v_{||}$	$3x10^{-4}$
N = +2	0.2 eV	< $v_{||}$	0.8 eV
N = -1	0.74 eV	< $v_{||}$	3.0 eV
N = -2	1.7 eV	< $v_{||}$	6.7 eV

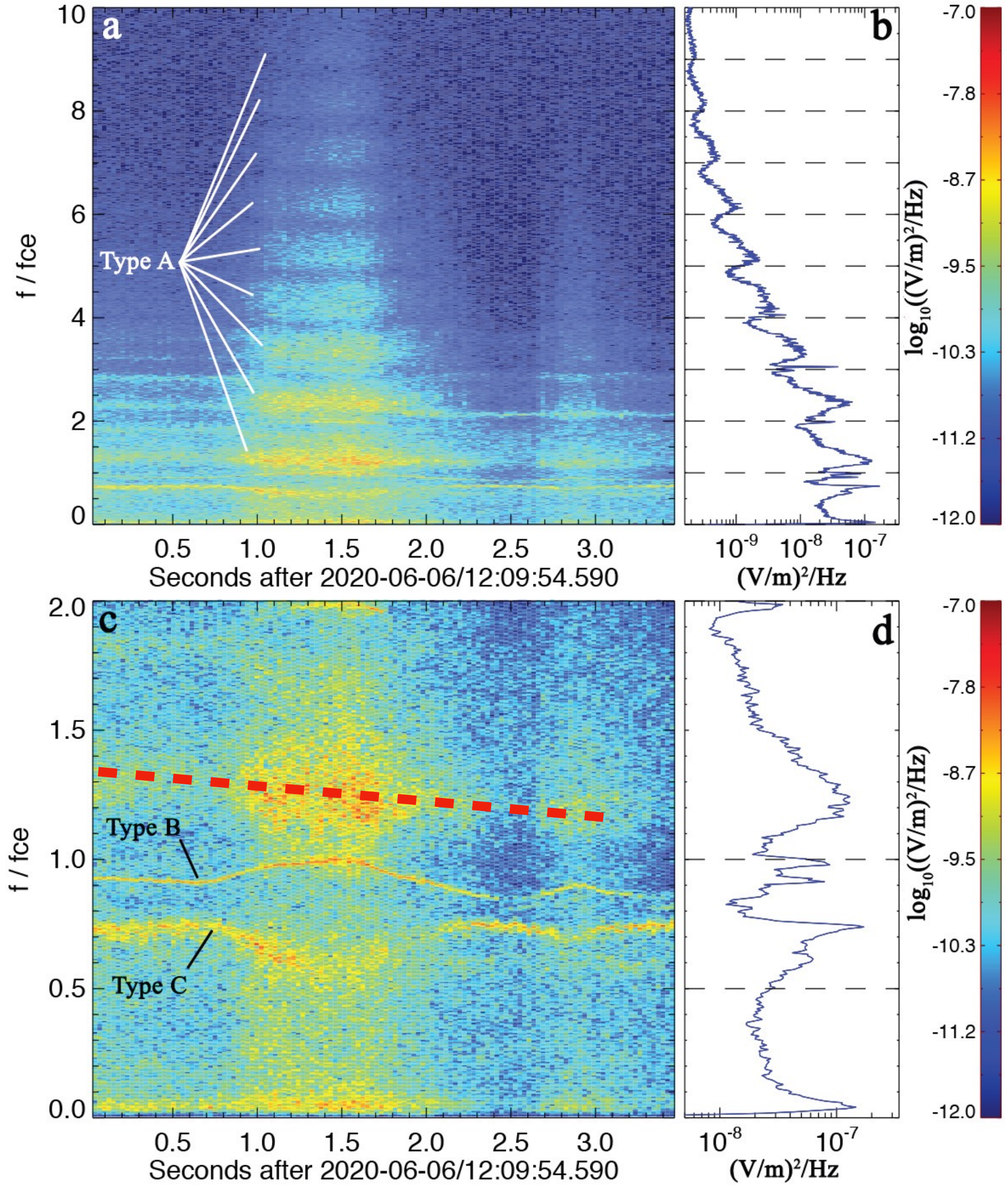
Instability still in cold e- core

Te ~ 35 eV

Anomalous cyclotron resonance with sunward e- ?

Possible if strong strahl current offsets sunward and anti-sunward e- core

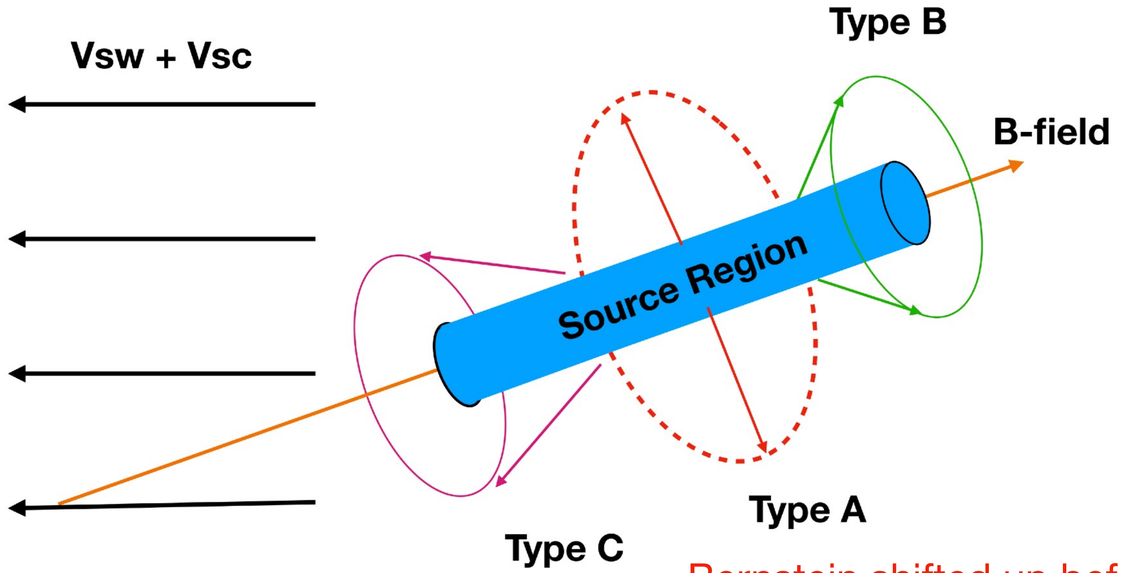
Source Region?



What if high amplitude e- Bernstein (Type A) region is a source region?

Source region ~cylindrical
for Doppler shifts to be consistent

Type B shifted down from fce
(so component of k and Vsw oppose: (**k** · **V**sw) < 0)



Bernstein shifted up before source,
shifted down after source
(**k** ⊥ **B**)

Type C shifted up from fce/2
(so component of k and Vsw align: (**k** · **V**sw) > 0)

Conclusions

Identified three wave modes near fce for near-Sun quiescent solar wind:

Type A: e- Bernstein (ECH) waves

Type B: Extremely narrowband, near fce (df/f ~3%)
- Doppler analysis:
  - f ~fce, |k| ~ 0.15 (1/m), $\theta_{k,B}$ ~ 70°
  - Resonant energies in cold e- core
    - Anomalous cyclotron possible
- Polarization Analysis
  - E ⊥ **B** (approximately)
  - **Right**-hand elliptically polarized

Type C: Moderately narrowband, near fce /2 (df/f ~ 12%)
- Doppler analysis:
- **k** opposes Type B **k**
- f ~fce, |k| ~ 0.08 (1/m), $\theta_{k,B}$ ~ 85°
- Resonant energies in cold e- core
- Polarization Analysis
  - E ⊥ **B** (approximately)
  - **Left**-hand elliptically polarized

All three: Source regions at broadband bursts (?)
- Type A strongest
- Type B, C **k** 'radiate' from source regions (?)
- Elongated source regions (?)

[1] The quiescent solar wind may give us our best look at the properties of the solar wind close to the corona.

[2] The quiescent solar wind has lots of interesting physics!
- plasma waves, turbulence
- current sheets, energetic particles

[3] Focused here on near-fce waves
- interact with cold plasma
- possibly related to strahl-driven e- core drift

[4] Open questions:
- What mode are Type B, Type C waves?
- What instability drives them?
- How do they evolve solar wind e- distributions?
- Are the e- Bernstein waves independent?
  - or a consequence of the near-fce waves?

[5] Publications:
Statistical analysis of near-fce waves:
Malaspina+ 2020 ApJ doi: https://doi.org/10.3847/1538-4365/ab4c3b

Burst analysis of near-fce waves:
Malaspina+ 2021 A&A (under review)

[6] Pursuing new lines of inquiry
- (bicoherence + secondary cold plasma instabilities)