Spacecraft Separation Studies: Two Examples

1. Multiple-point observations of EMIC waves by Cluster and Double Star/TC1 [*Zhang et al.*, 2010, JGR]
2. Derivation of wave parameters, e.g., wavelength, wave vector **k**, propagation velocity, and normal angle, from simultaneous wave measurements on the four Cluster spacecraft.

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Collaborators:

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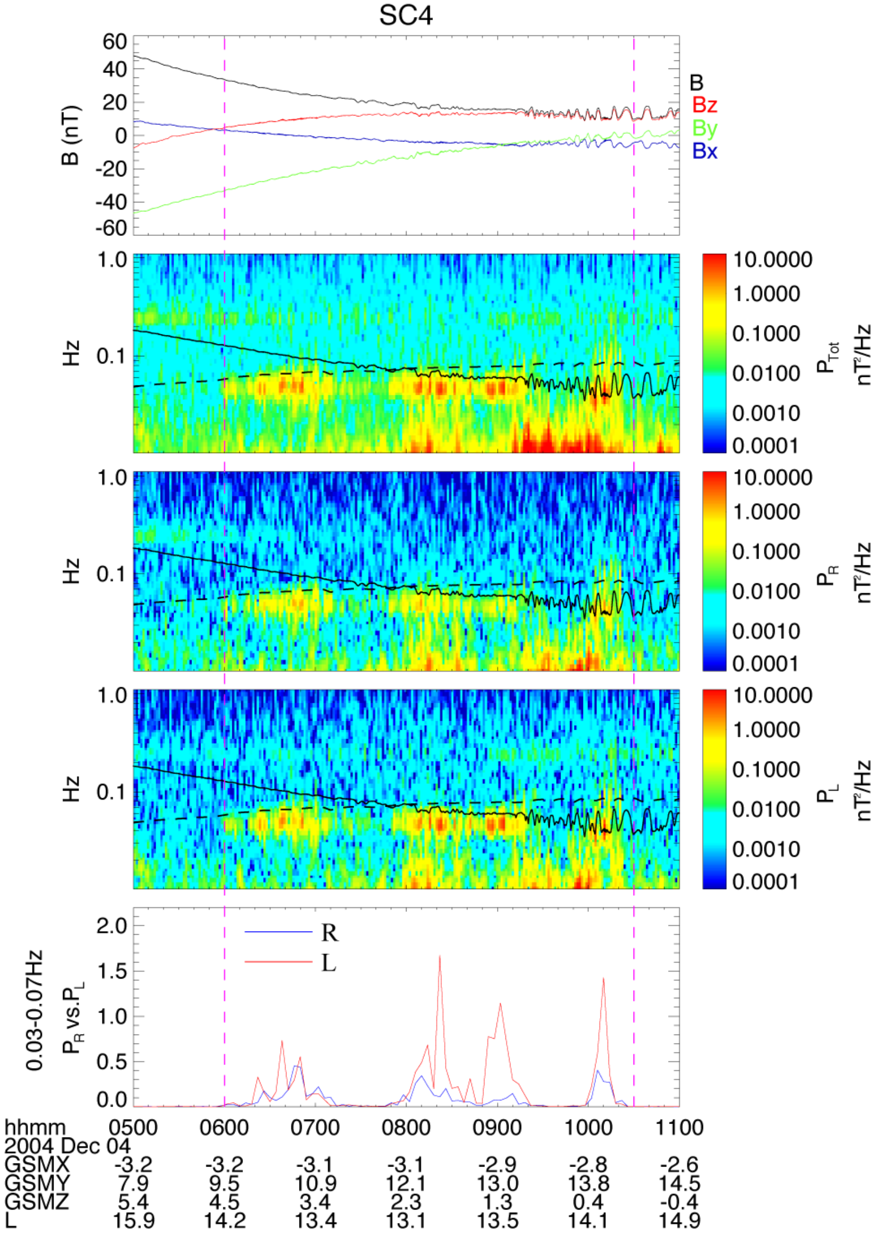
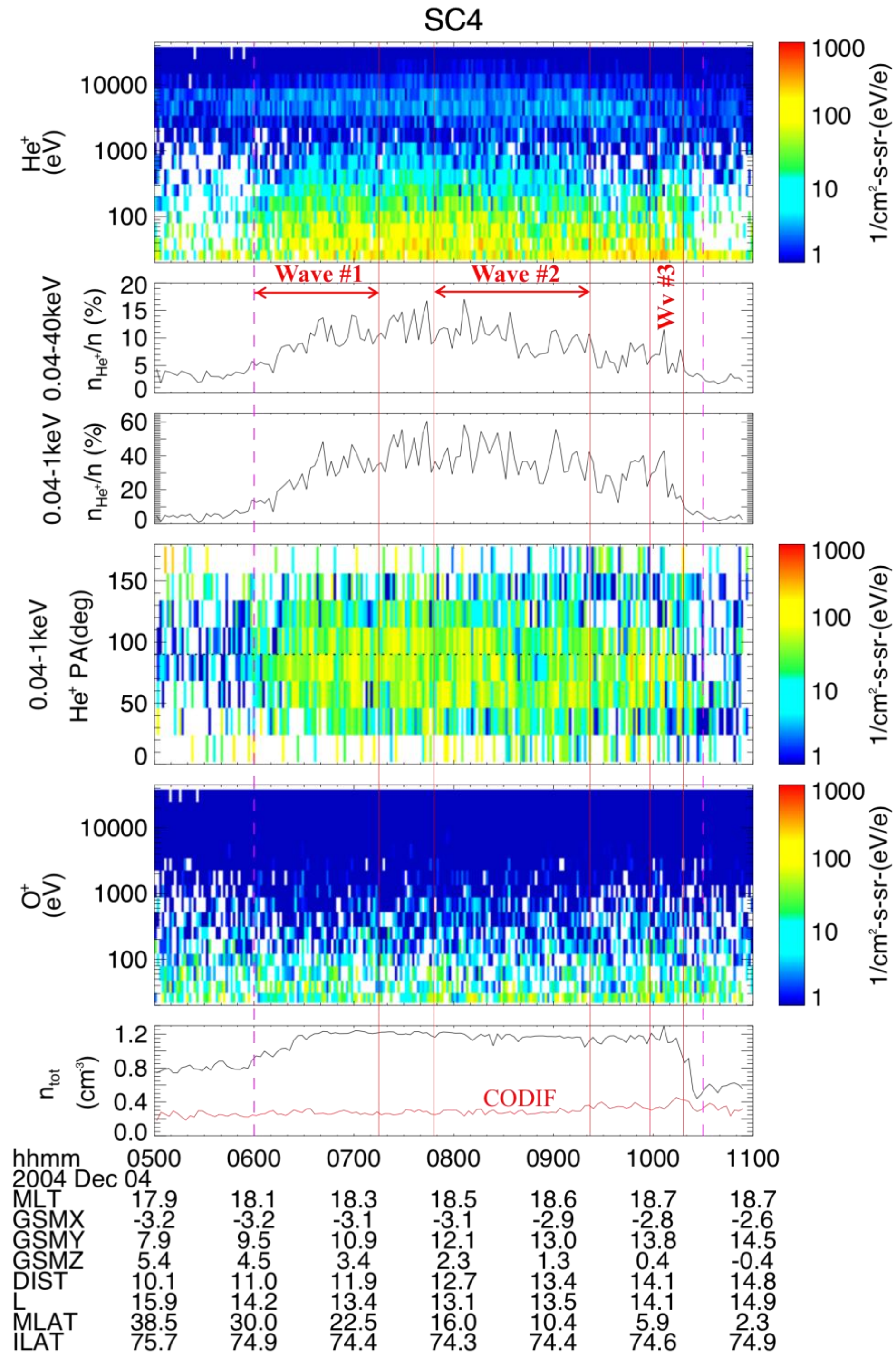
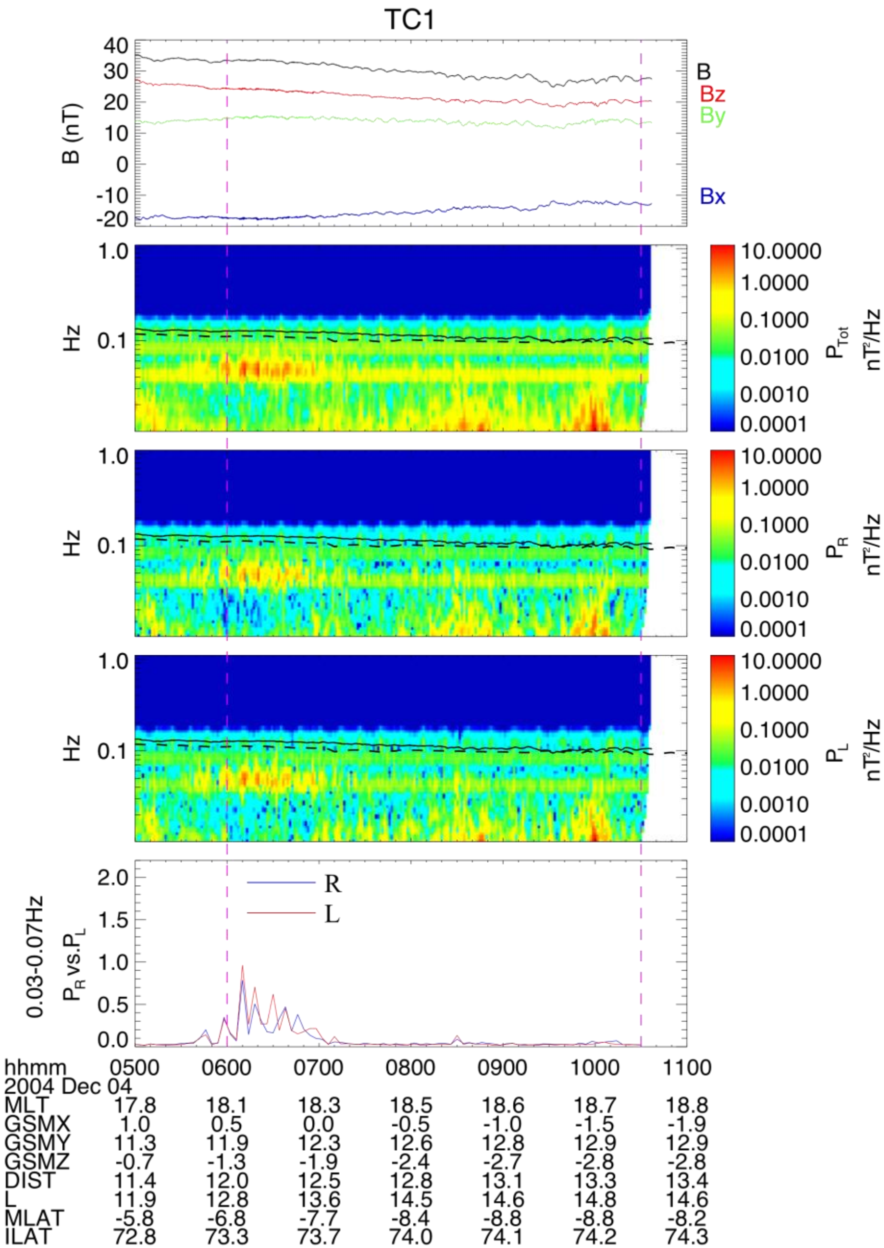
Multiple-point observations of EMIC waves by Cluster and Double Star/TC1

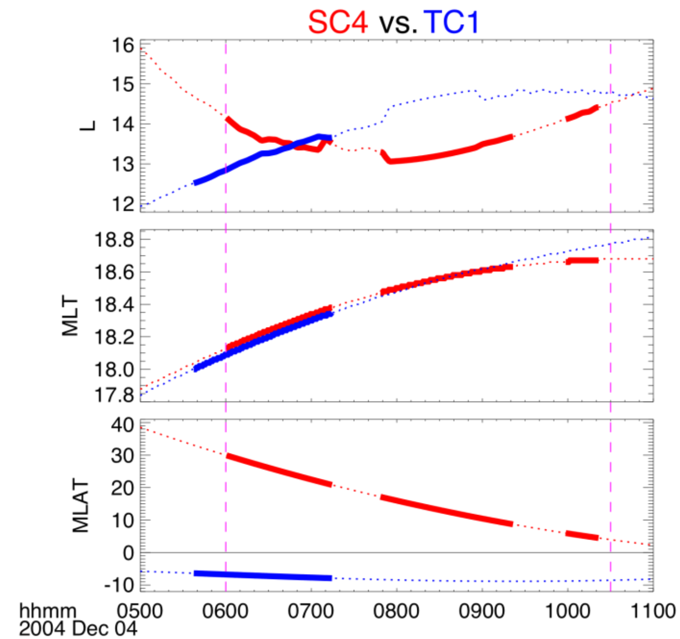
EMIC waves & associated plasma conditions @ 4 Dec. 2004

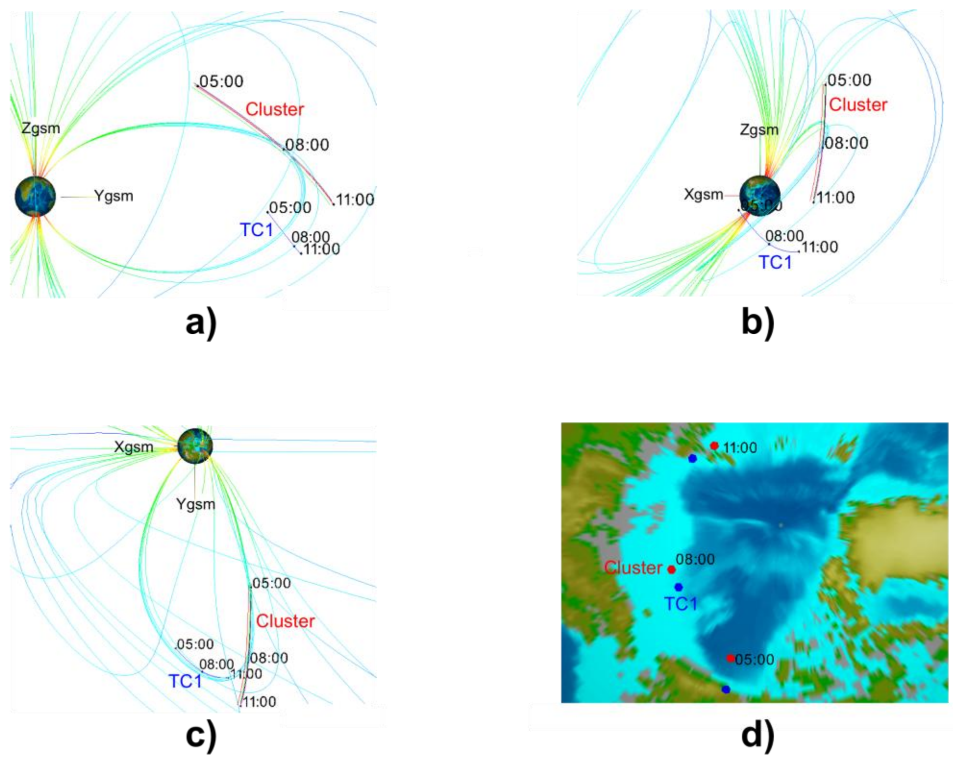




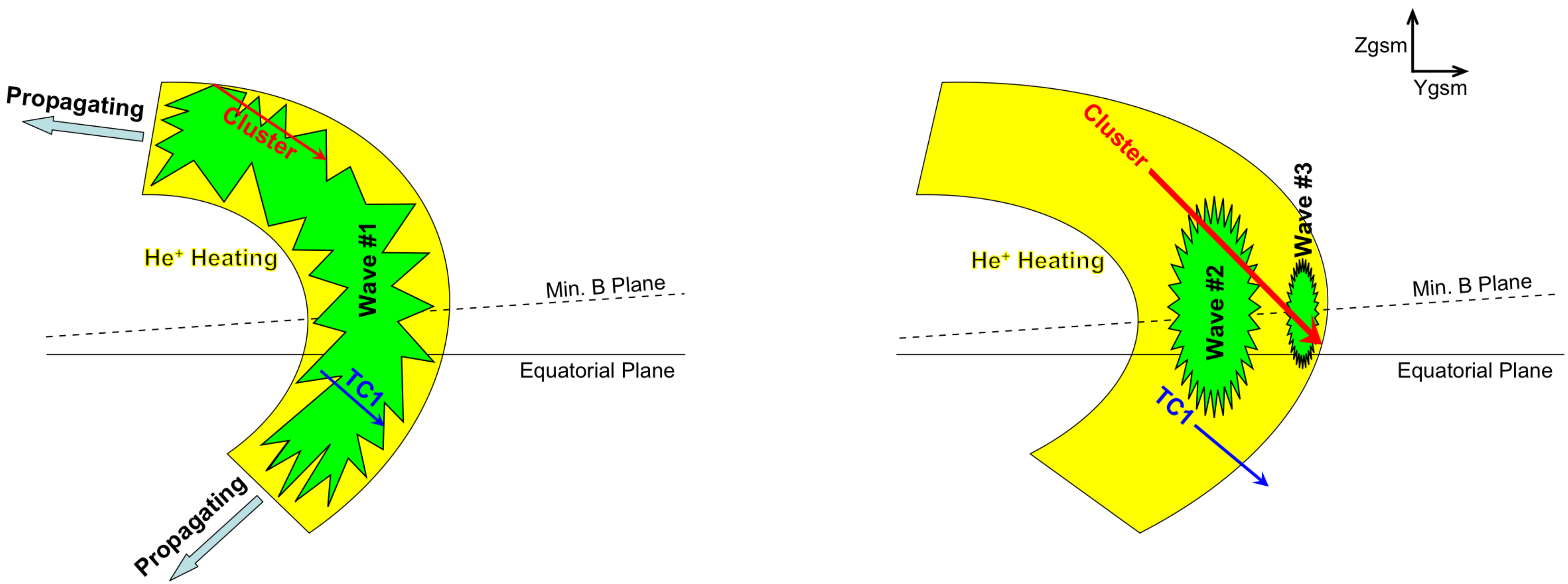
EMIC wave observed by TC1 @ 4 Dec. 2004







He^+ heating process in the GSM Y-Z plane.



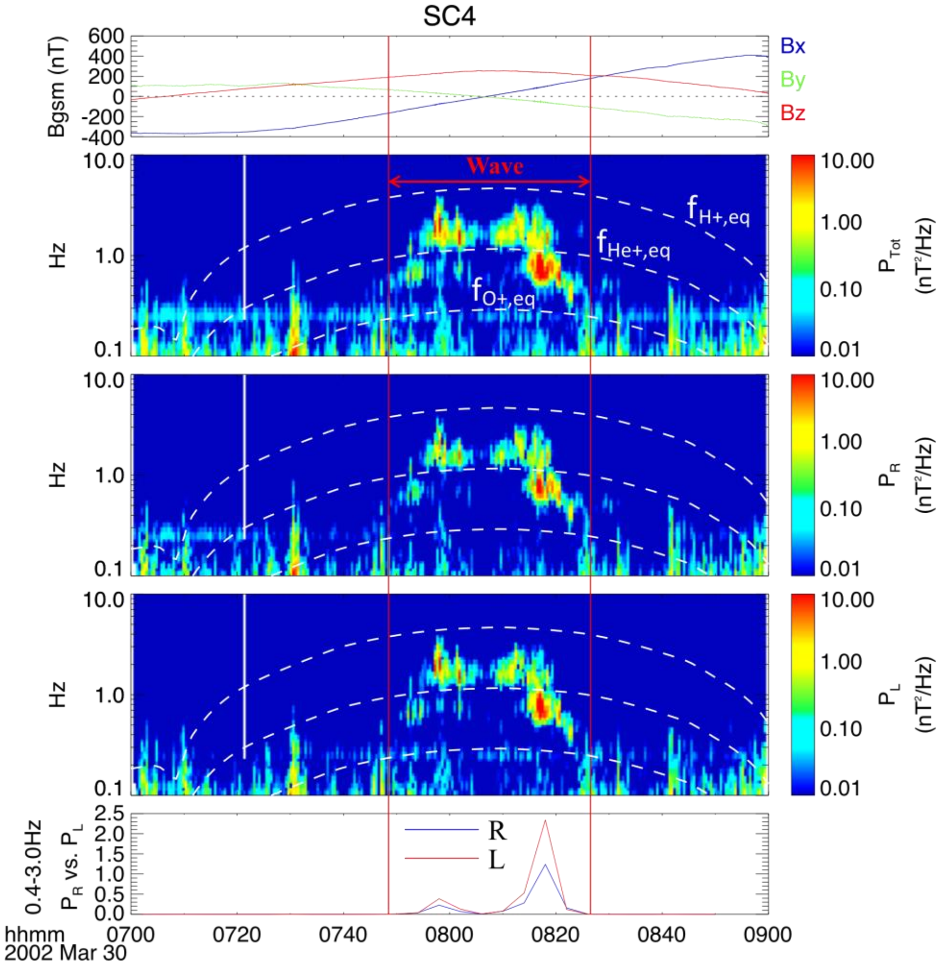
(a) 0600 – 0715 UT **(b) 0715 – 1030 UT**

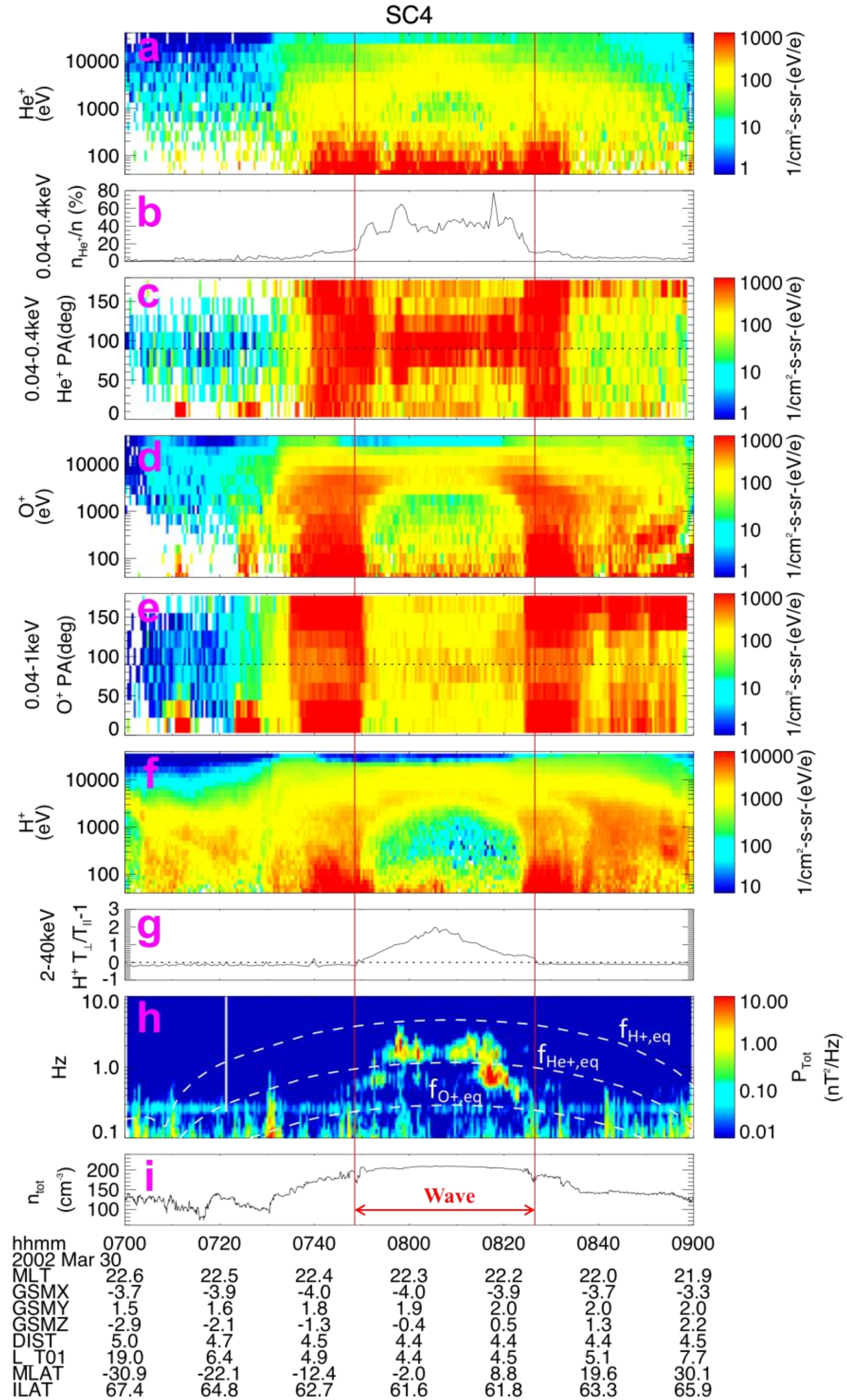
Use data from 4 Cluster S/C to obtain wave parameters, such as wavelength, wave vector k, phase speed, and normal angle?

Popular Techniques for Wave Vector (k) Determination

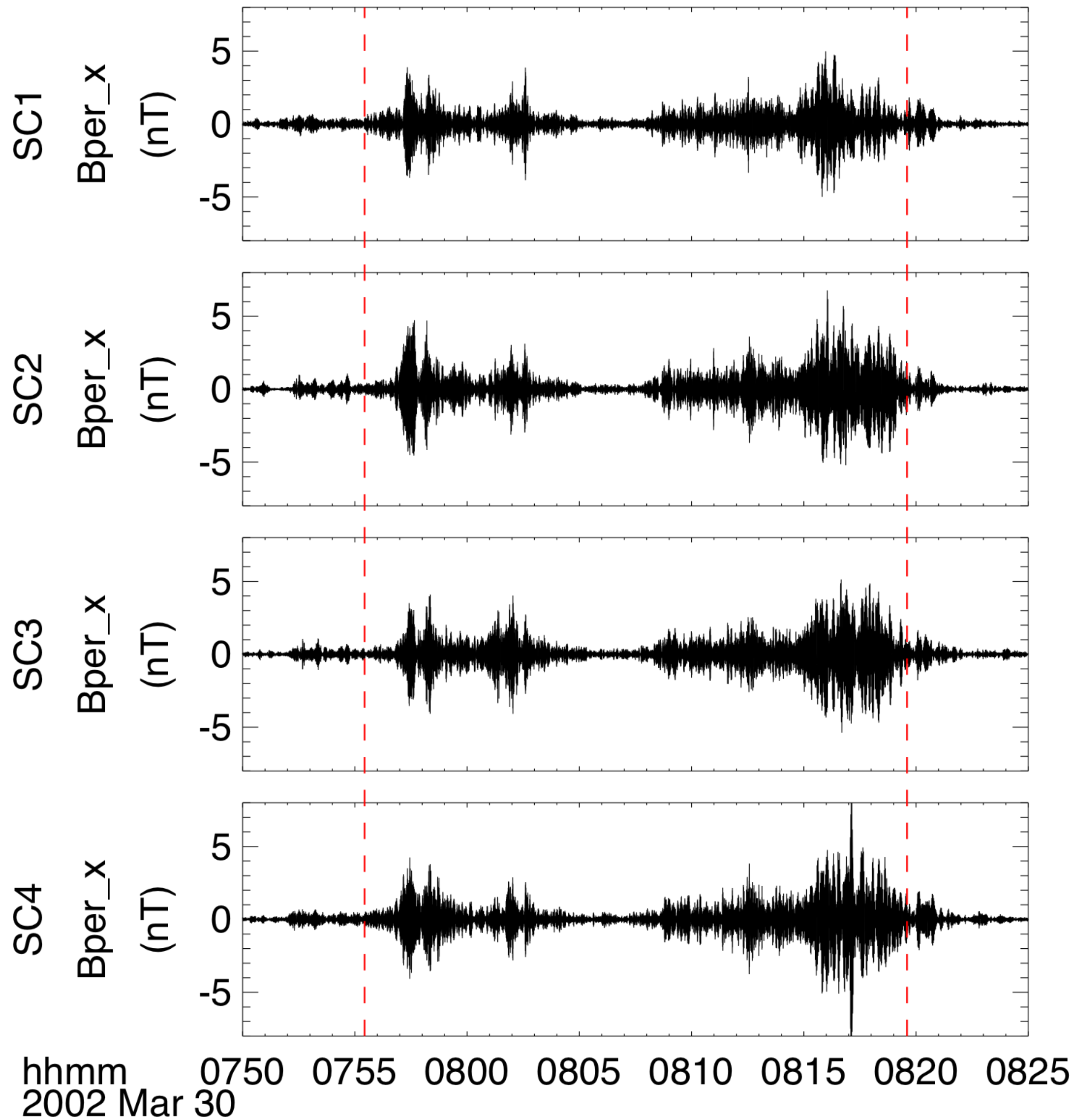
- Phase-differencing [*Balikhin & Gedalin*, 1993; *Dudok de Wit et al.*, 1995]
  - The projection of **k** along the s/c separation vector at a given frequency is calculated by determining the phase difference of the waves observed by different pairs of s/c.
  - Successfully applied for dual s/c [e.g., *Balikhin et al.*, 1997]
- Minimum Variance Analysis (MVA) [Sonnerup & Cahill, 1967]
  - The eigenvector for the smallest eigenvalue of the covariance matrix of magnetic field measurements is computed to obtain the direction of **k**.
  - **k** direction can be determined from a single s/c, but a large error is expected for linearly polarized waves.
  - Cluster as a wave telescope [e.g., *Neubauer & Glassmeier*, 1990; *Pincon & Lefeuvre*, 1991; *Motschmann et al.*, 1996; *Glassmeier et al.*, 2001]

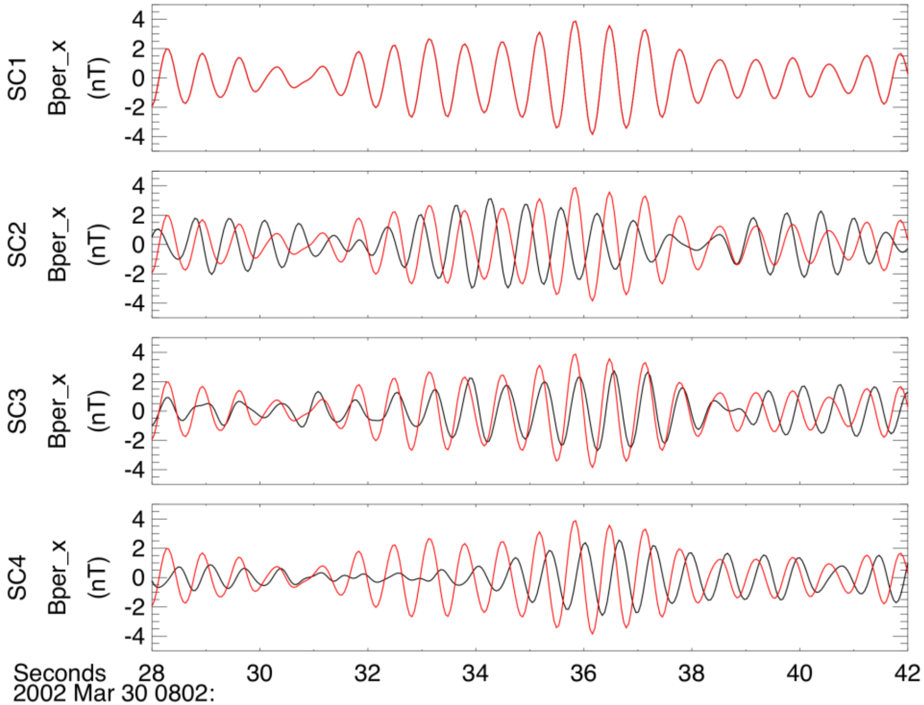
EMIC wave & associated plasma conditions @ 30 Mar. 2002



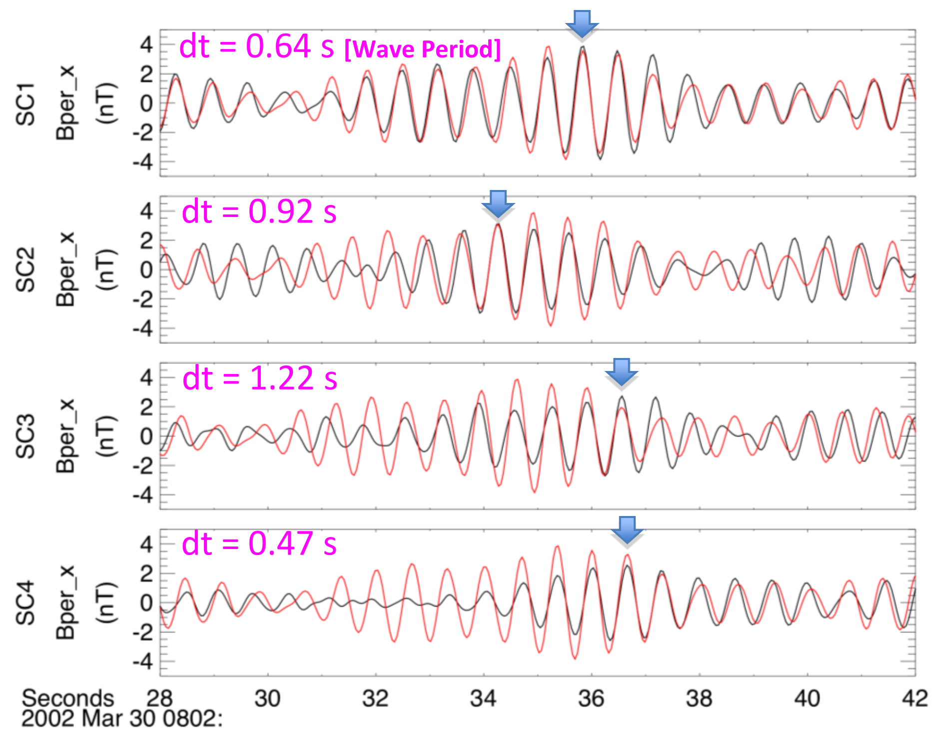


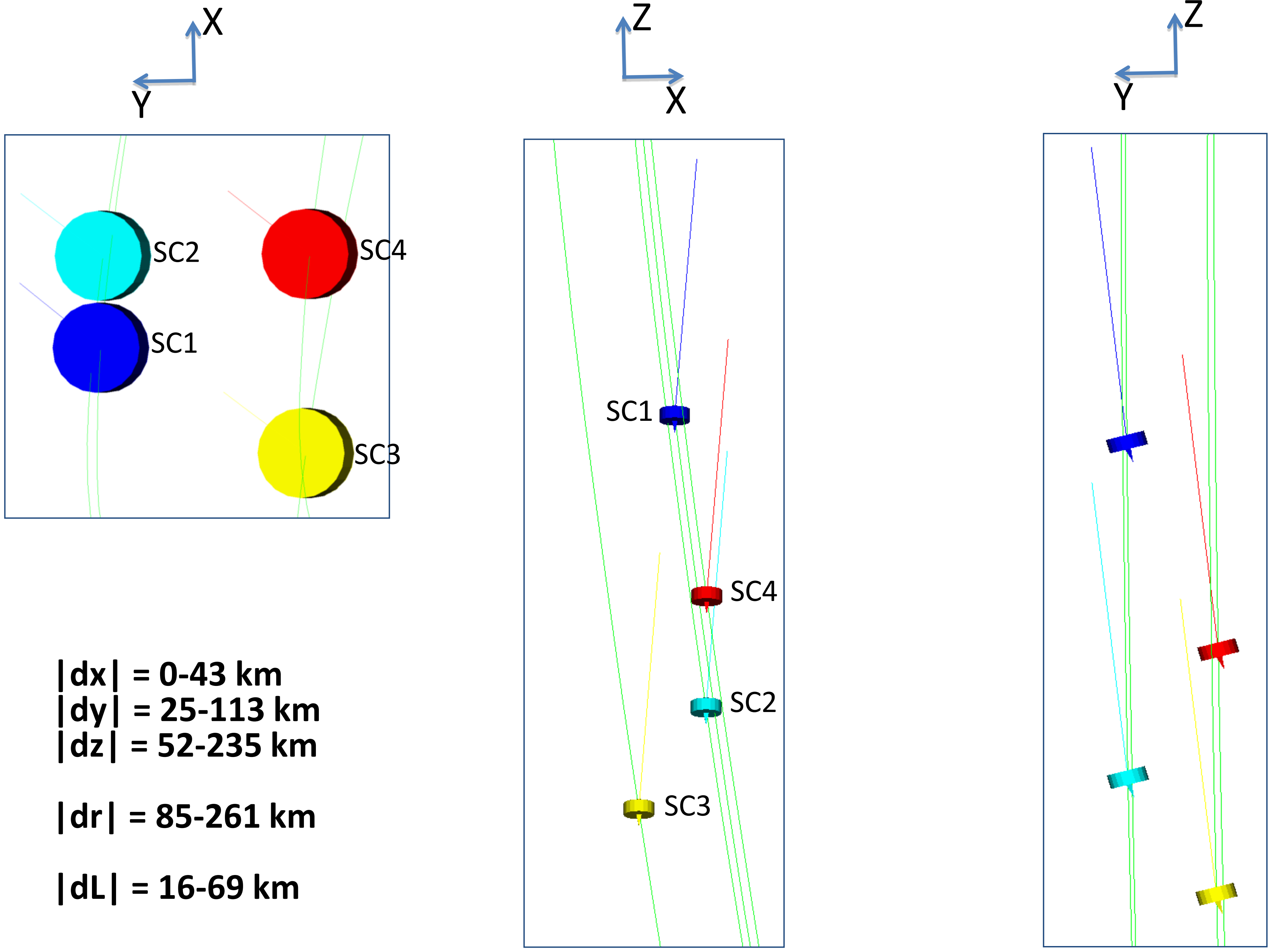
Waveforms @ 4 Cluster S/C





Waveforms on each S/C (in black) overplotted with time-shifted waveforms on SC1 (in red).




X
Y
Z
X
Z
Y
SC2
SC4
SC1
SC3
SC1
SC4
SC2
SC3
|dx| = 0-43 km
|dy| = 25-113 km
|dz| = 52-235 km
|dr| = 85-261 km
|dL| = 16-69 km

Find V_p

- 3 equations for 3 unknowns ($\mathbf{V_p}$):

$$\mathbf{S}_{12} \cdot \frac{\mathbf{V}_p}{V_p^2} = dt_{12}$$

$$\mathbf{S}_{13} \cdot \frac{\mathbf{V}_p}{V_p^2} = dt_{13}$$

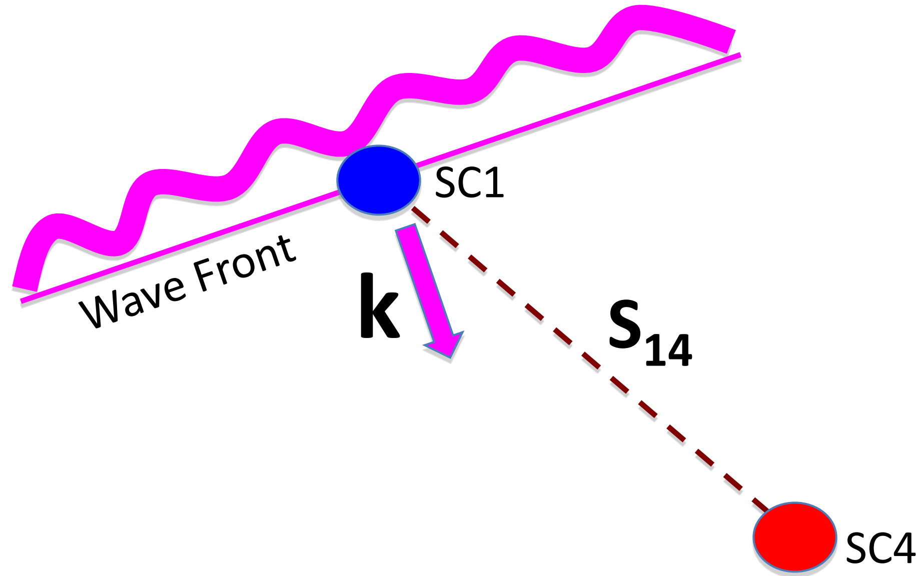
$$\mathbf{S}_{14} \cdot \frac{\mathbf{V}_p}{V_p^2} = dt_{14}$$

- Solution:

$$\mathbf{A} \bullet \mathbf{X} = \mathbf{b}$$

$$\Rightarrow \mathbf{X} = \mathbf{A}^{-1} \bullet \mathbf{b}$$

$$\Rightarrow \mathbf{V}_p = \frac{\mathbf{X}}{X^2}$$



(Note: SC2 and SC3 not shown)

Assumptions

- It’s a plane wave.
- The turbulent field is supposed to be stationary in time and homogeneous in space.
- Wave source region is at Zgsm = 0. So, the wave first reaches SC1(t0), then SC4 (t0+0.47s+n1*T), next SC2 (t0+0.92s+n2*T), and last SC3 (t0+1.22s+n3*T), where n1, n2, and n3 = 0, 1, 2, 3, ….
- Wave amplitude can change when the wave arrives at each S/C; only local peak Bper_x lined up (See the “timing” slide).
- Doppler shift (due to plasma *and S/C* motion) is negligible.

Key Wave Parameters @ ~0802:33 UT

- Wave Period: T = 0.65 s
- Wave Frequency: f = 1/T = 1.54 Hz
- Propagation Velocity:
  - $\mathbf{V_p}$ = (76.4, -46.5, -109.9) km/s in GSM
  - $|\mathbf{V_p}|$ = 141.6 km/s
  - $\mathbf{n\_V_p}$ = (0.54, -0.32, -0.78) in GSM [Normal unit vector of the wave plane]
- Wavelength: $\lambda = (\mathbf{S}_{12} g \mathbf{n\_V}_p) \times \frac{T}{1.12} = 92.1(km)$
- Wave Vector **k**: $k = \frac{2\pi}{\lambda} = 0.068(km^{-1}); \mathbf{k} = k\mathbf{n\_V}_p$
- Phase Speed: $V_p = \frac{\omega}{k} = \frac{\lambda}{T} = 141.6(km/s)$
- Angle between **k** and **B** field: $\theta = \cos^{-1}(\mathbf{n\_V}_p g \frac{\mathbf{B}}{B}) = 148.6°$

Backup Slides

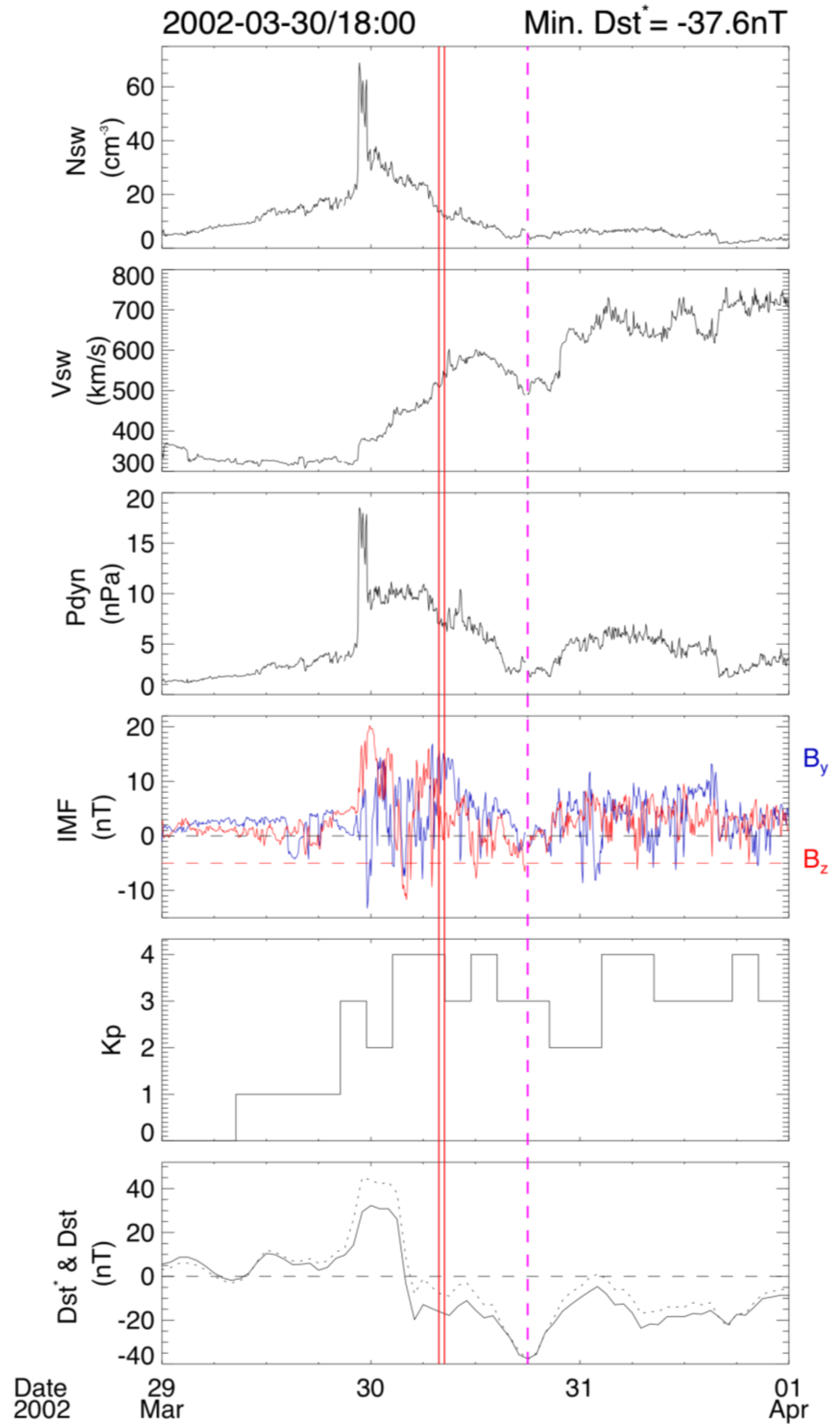
Solar Wind Plasma/IMF & Geomagnetic Indices

- Max. Nsw(cm-3) = 68.98 (BAD data?)
- Max. Vsw(cm/s) = 755.6
- Max. Pdyn(nPa) = 18.53
- Max. IMFBy_gsm(nT) = 16.92
- MIN. IMFBy_gsm(nT) = -13.30
- Max. |IMFBy_gsm|(nT) = 16.92
- Min. IMFBz_gsm(nT) = -11.75

- Max. Kp = 4

- Min. Dst(nT) = -38
- T_Dstmin= 2002-03-30/18:00:00

- Min. Dst*(nT) = -37.58
- T_Dstmin* = 2002-03-30/18:00:00



Cluster Location & Speed @ 2002-03-30/08:02:30

EPH_SC1_GSM_XYZ: (-3.97263, 1.91540, -0.26651) Re
EPH_SC1_GSM_R: 4.41833 Re

EPH_SC1_GSM_Vxyz: (0.40666, 0.50550, 4.64733) km/s
EPH_SC1_GSM_V: 4.69240 km/s

EPH_SC2_GSM_XYZ: (-3.96946, 1.91528, -0.29637) Re
EPH_SC2_GSM_R: 4.41733 Re

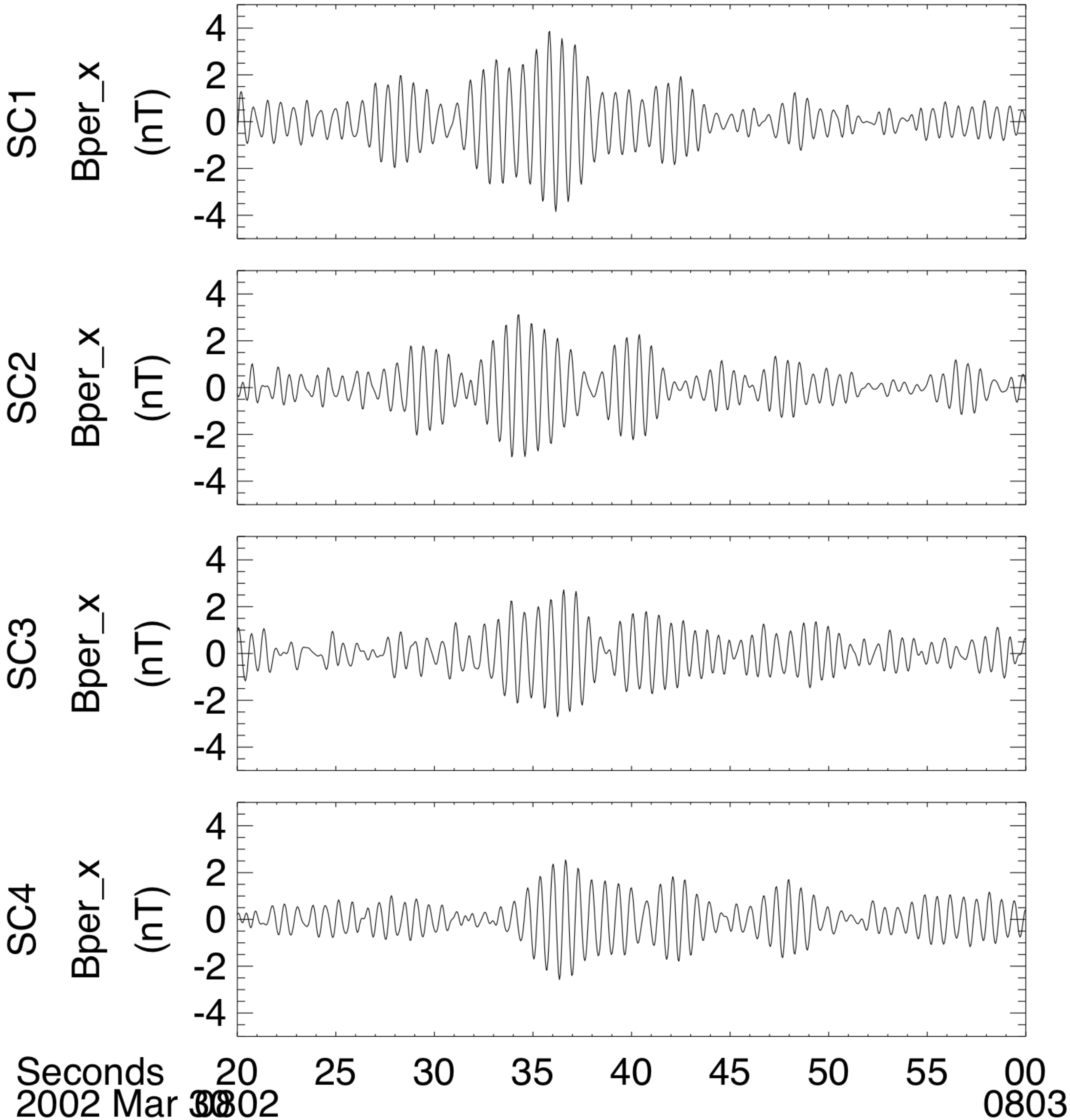
EPH_SC2_GSM_Vxyz: (0.39117, 0.51165, 4.64850) km/s
EPH_SC2_GSM_V: 4.69290 km/s

EPH_SC3_GSM_XYZ: (-3.97631, 1.90823, -0.30675) Re
EPH_SC3_GSM_R: 4.42114 Re

EPH_SC3_GSM_Vxyz: (0.38500, 0.51368, 4.64667) km/s
EPH_SC3_GSM_V: 4.69080 km/s

EPH_SC4_GSM_XYZ: (-3.96939, 1.90814, -0.28498) Re
EPH_SC4_GSM_R: 4.41341 Re

EPH_SC4_GSM_Vxyz: (0.39669, 0.50967, 4.65150) km/s
EPH_SC4_GSM_V: 4.69613 km/s


SC1 Bper_x (nT)
SC2 Bper_x (nT)
SC3 Bper_x (nT)
SC4 Bper_x (nT)
4
2
0
-2
-4
Seconds
20
25
30
35
40
45
50
55
00
2002 Mar 30 0802
0803

Other Relevant Wave Parameters (See a figure next page)

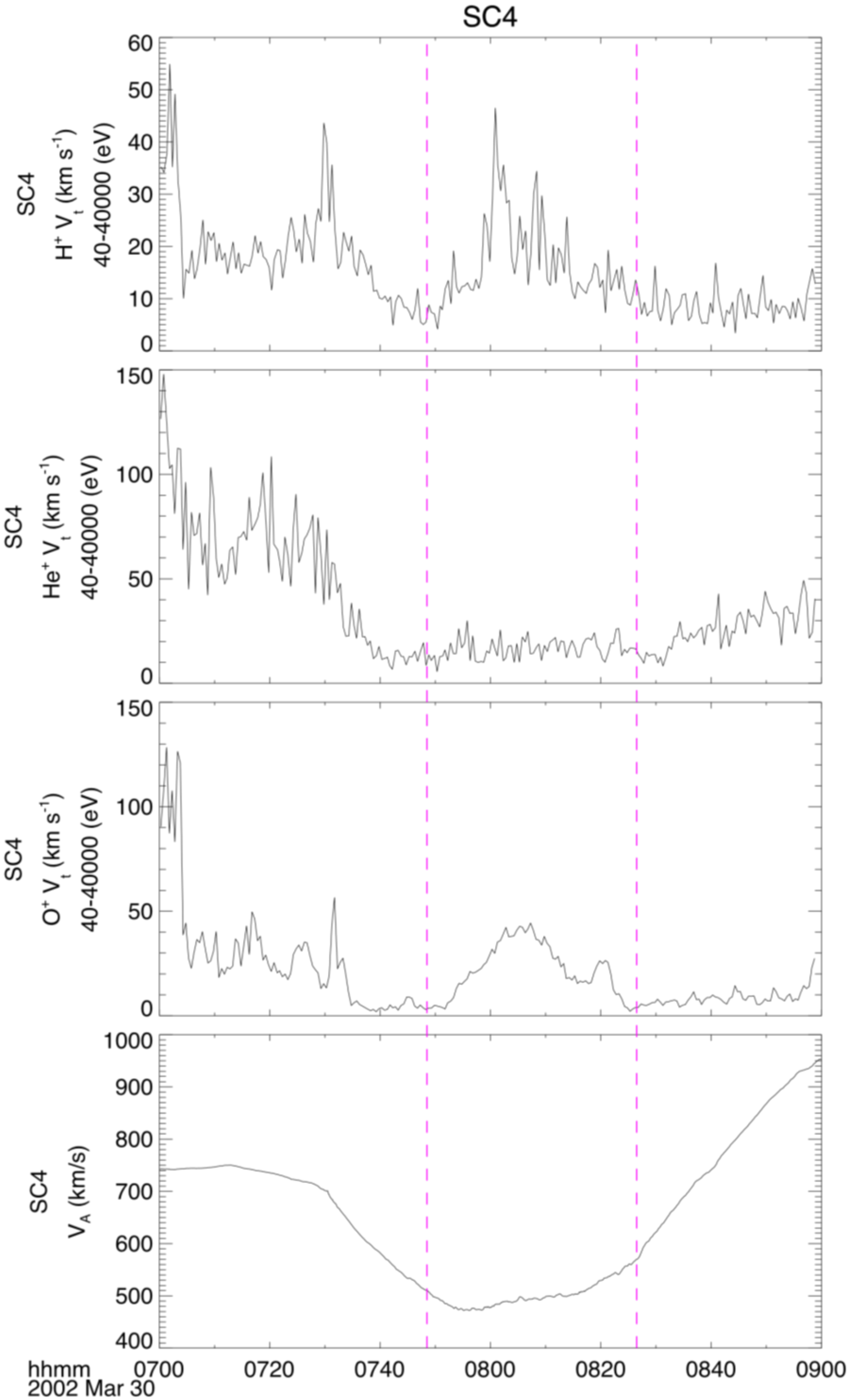
- Alfvén speed: V_A ($v_A = \frac{B}{\sqrt{\mu_0 \rho}}$): Avg. (Max., Min.) = 502.13 (570.05, 472.08) km/s

- Avg. (Max., Min.) Plasma bulk flow speed: V_{H+} = 16.61 (46.52, 4.16) km/s; V_{He+} = 16.59 (30.00, 5.56) km/s; V_{O+} = 22.00 (44.40, 2.13) km/s;

- Doppler drift (V_{plasma} [= Avg. V_{H+}] / Vph=16.61/ 181.78 = 9.14%): $\omega_{sc} = \omega_{plasma}(1+\frac{V_{plasma}}{V_{ph}}\cos\theta)$

Other Relevant Wave Parameters

Ion bulk speeds and Alfvén speed ➔



Resonant Energy

[*Kennel and Petschek*, 1966]

- Magnetic energy per particle,

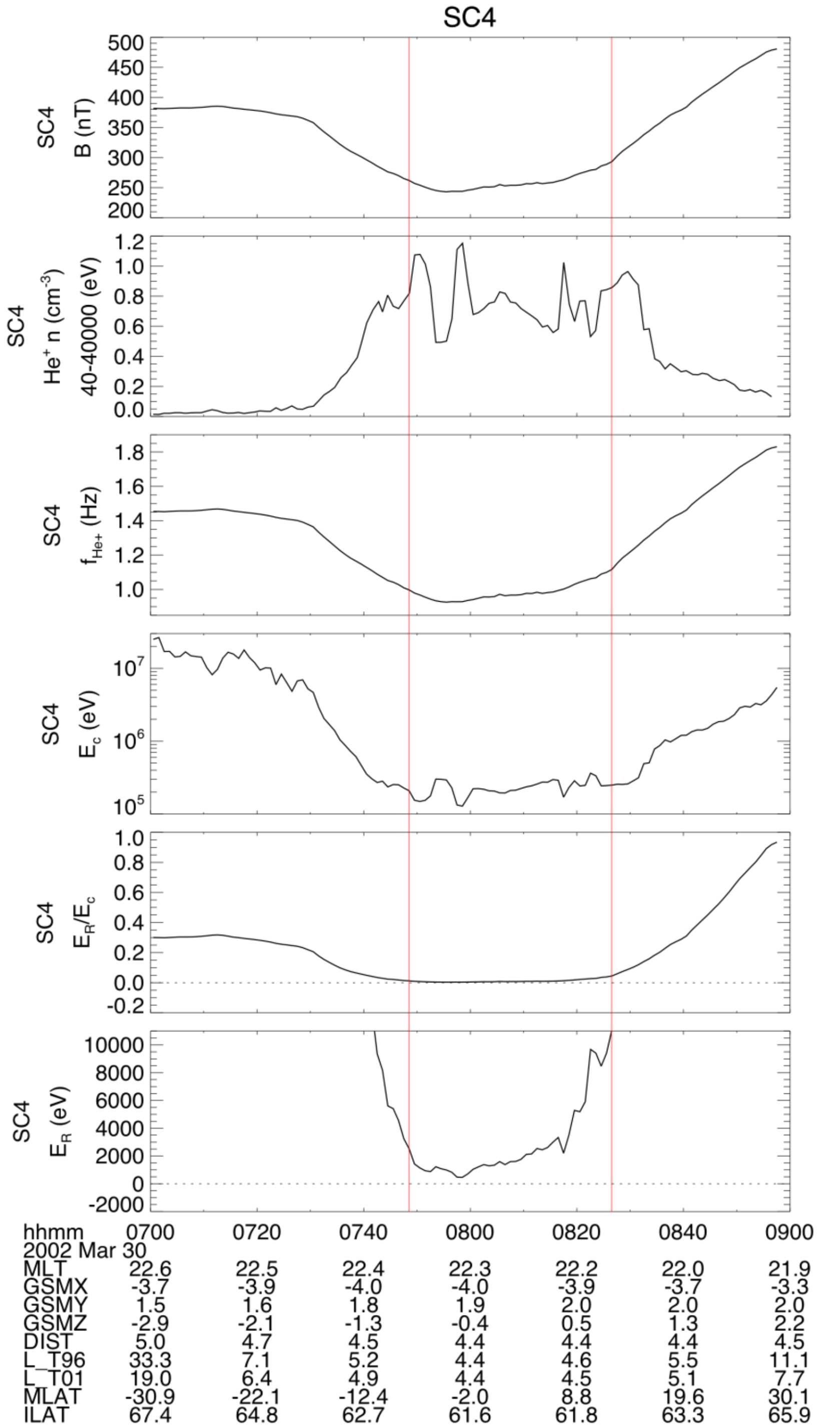
$$E_c = \frac{B^2}{2\mu_0 N},$$

which is a characteristic energy for cyclotron interactions.

- Resonant energy,

$$E_R = E_c \frac{(1-\frac{\omega}{\Omega i})^3}{(\frac{\omega}{\Omega i})^2},$$

where ω is the wave frequency (=0.8 Hz; can affect the results significantly) and Ω_i is the local ion gyrofrequency.



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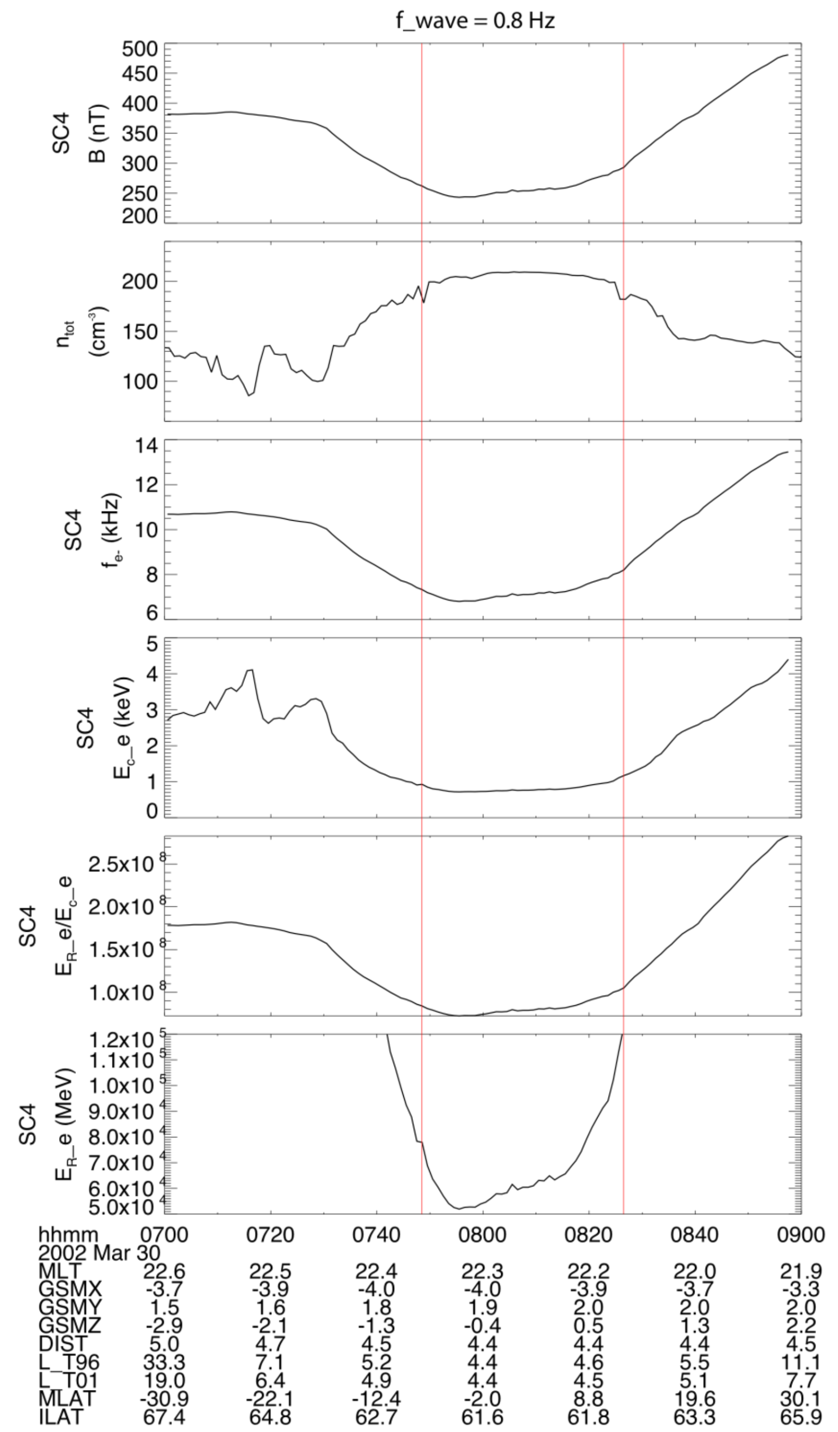

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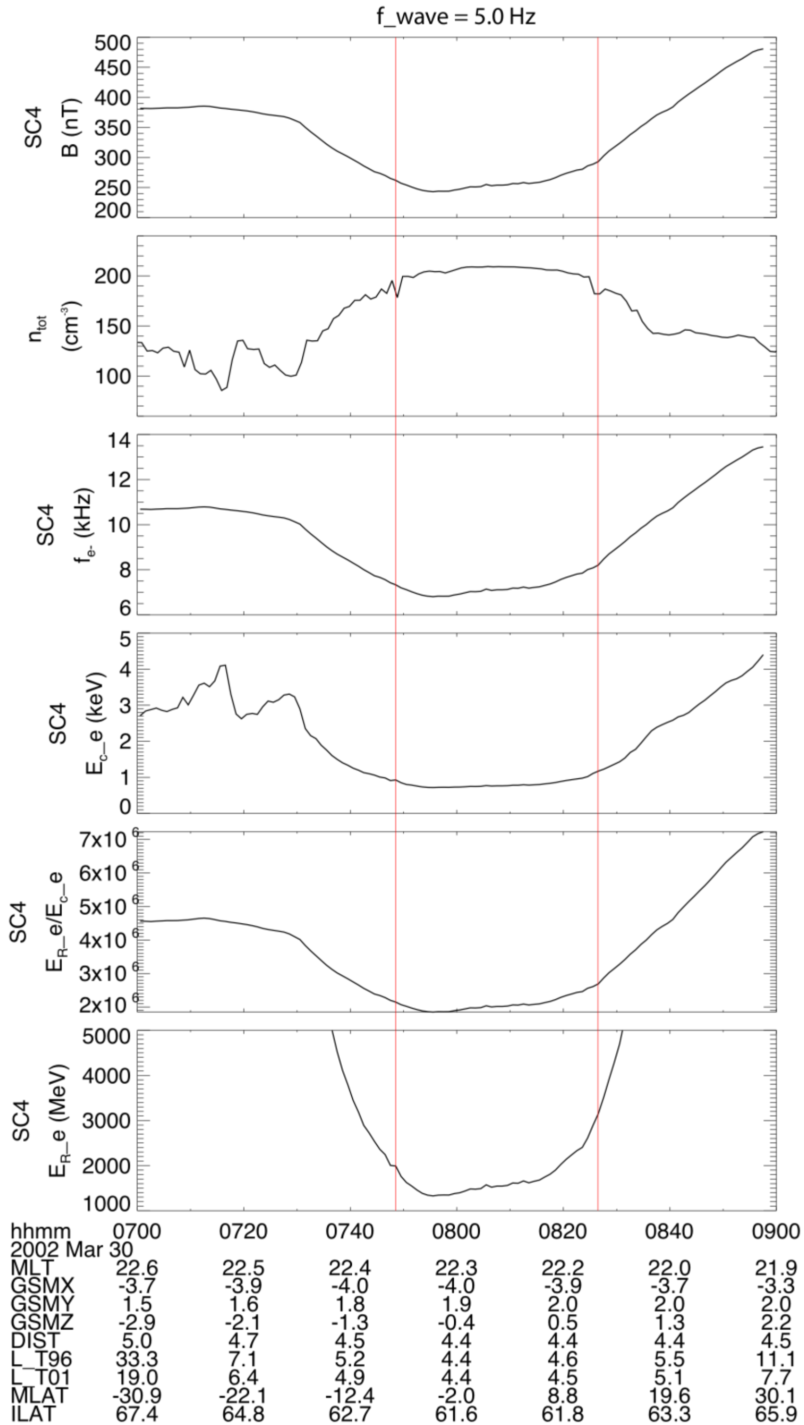
where ω is the wave frequency (=5.0 Hz; can affect the results significantly) and Ω_e is the local electron gyrofrequency.



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$$E_R = E_c \frac{\left(1-\frac{\omega}{\Omega i}\right)^3}{\left(\frac{\omega}{\Omega i}\right)^2},$$

where ω is the wave frequency (=1.0 Hz) and Ω_i is the equatorial (wrong?!) ion gyrofrequency.