Determining the Magnetospheric Convection Electric Field from Lunar Shadowing

M. O. Fillingim (matt@ssl.berkeley.edu) and J. S. Halekas
Space Sciences Laboratory, University of California, Berkeley

PAST:

Apollo 15 & 16 Particles and Fields Subsatellites (PFS 1 & 2)

- First spacecraft to use **lunar shadowing** to determine the magnetospheric convection electric field [e.g., *Anderson*, 1970; *Chase et al.*, 1974; *McCoy et al.*, 1975; 1976; *Lin et al.*, 1977]

- Measured **omni-directional** electron flux at 0.5, 2, 6, & 14 keV
- Orbit inclination: PFS 1: ~ 28°; PFS 2: ~ 10° (nearly equatorial)
- Operational life: PFS 1: Aug. 1971 – Feb. 1972 (TM failure)
  PFS 2: Apr. 1972 – May 1972
  (Total of 8 magnetotail passes)

Summary of Results

- Observed range of convection electric field, **E**: < 0.02 – 2 mV/m
  Median of ~ **0.15 mV/m** in the dawn-dusk direction
- Corresponding convection velocity, V_D: < 5 – 190 km/s
  Median of ~ **15 km/s** toward the neutral sheet

Methodology

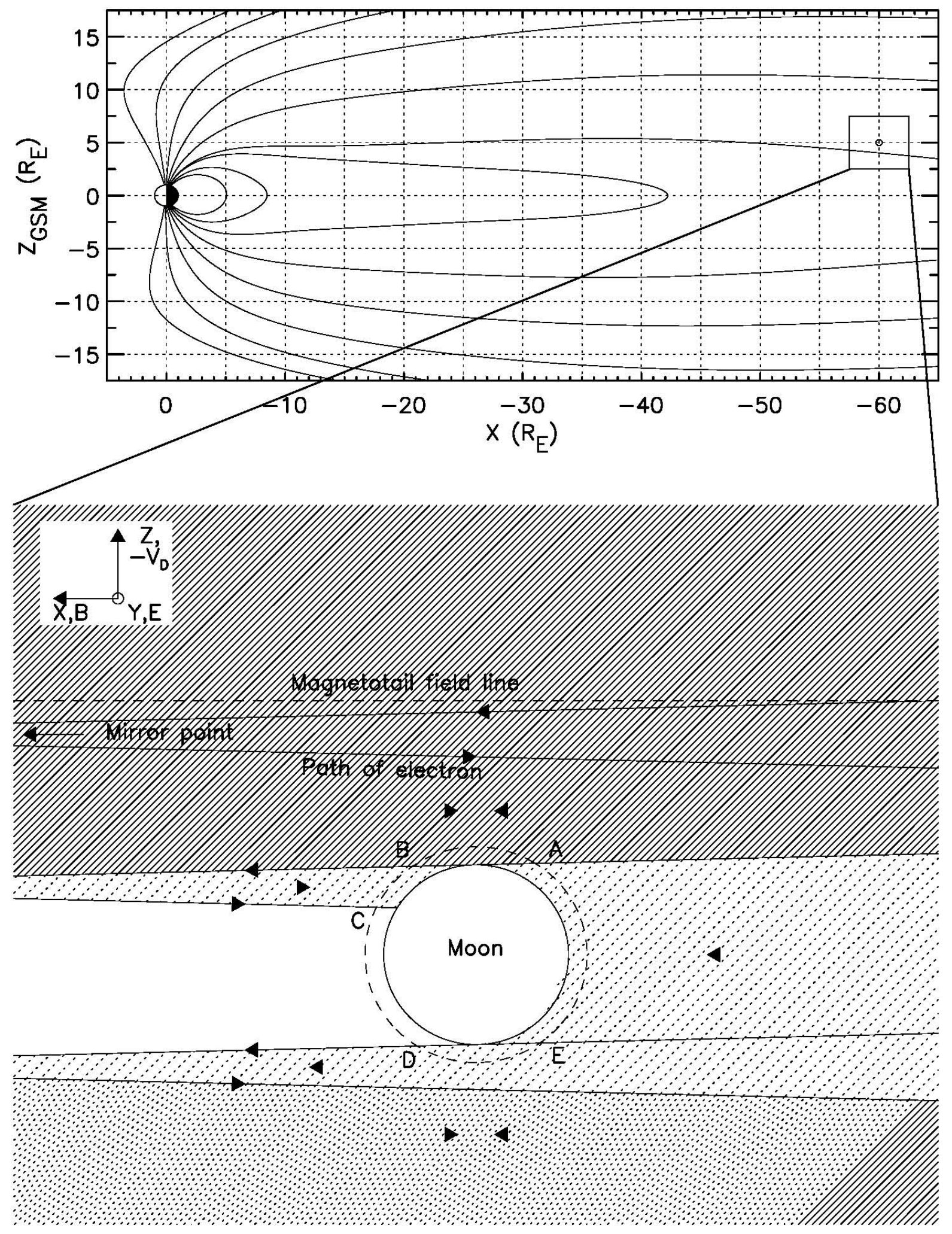
- In the high latitude magnetotail, solar wind electrons travel Earthward on open field lines

- The solid body of the Moon acts as a particle absorber creating a lunar shadow in the Earthward electron flux

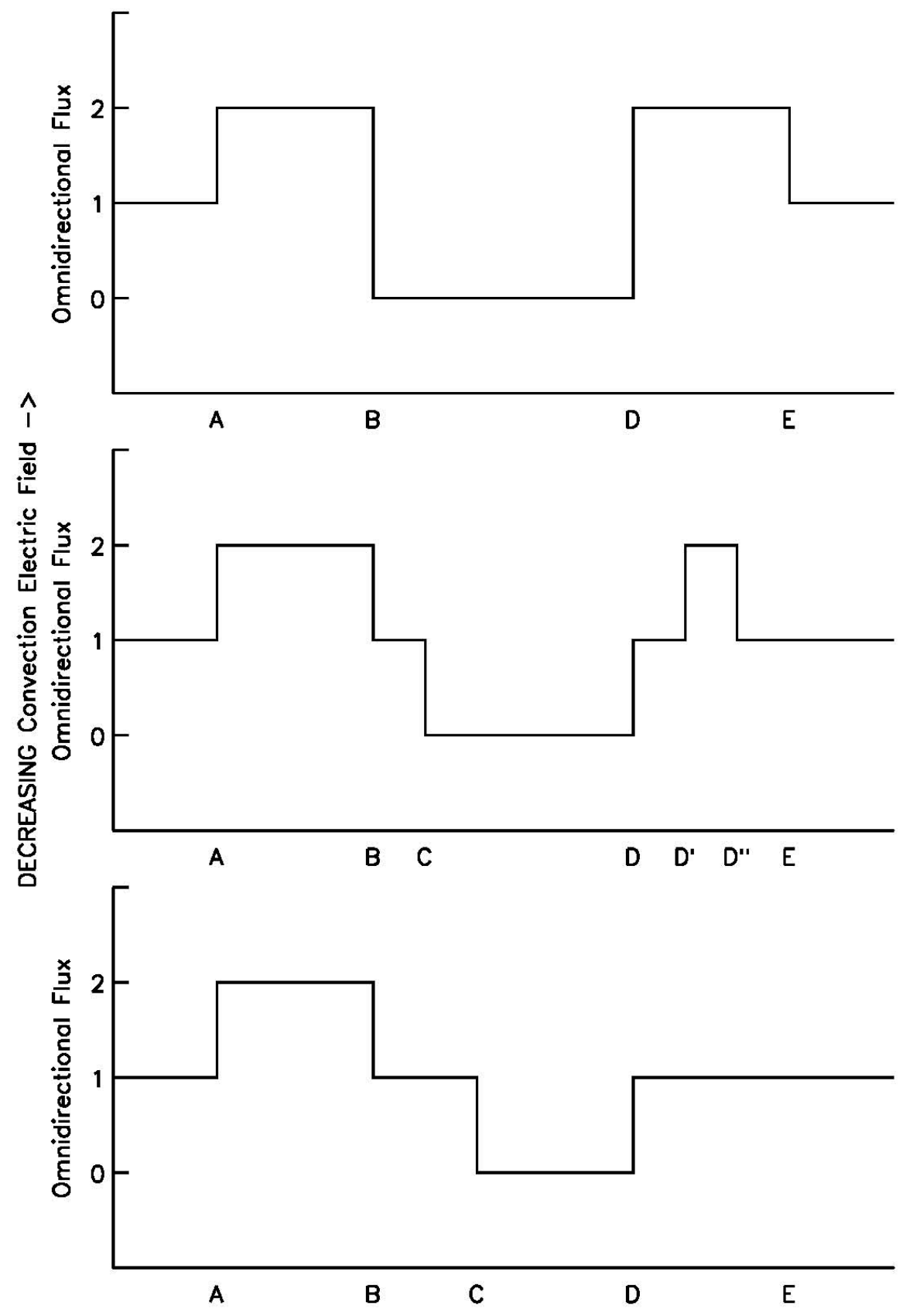
- Electrons just outside the lunar shadow mirror near Earth and return to the vicinity of the Moon deflected by the magnetospheric cross tail convection electric field

- By measuring this displacement of mirrored electrons (the distance from B to C), the electric field can be determined

Lunar shadowing is the most **sensitive** technique to measure weak electric fields (< 0.1 mV/m) in the **low-density** magnetotail



Ideal Omni-directional Flux Profiles



FUTURE:

Future Work:

- Determine **E** for 18 months of data
  - LP spent ~ 1 week/month in the magnetotail
  - ~ ½ of that time in the lobe (other ½ in the plasma sheet)
  - 2 hour orbital period

  → **> 700 orbits**

- More rigorous determination of t_m → particle tracking
  Track particles using semi-empirical magnetic field model
  (e.g., T96 or your favorite model)

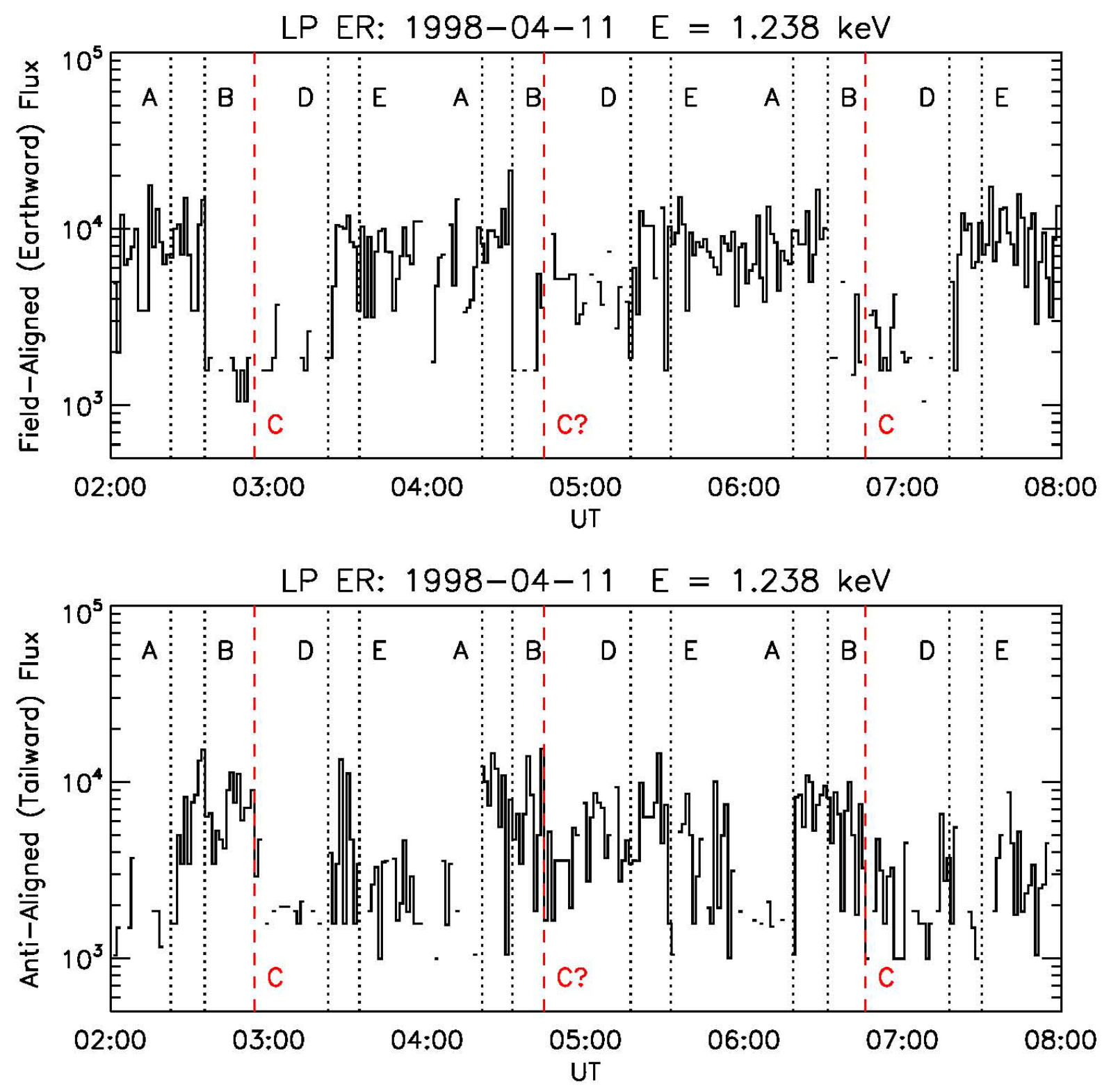
- Correlate with solar wind and IMF conditions
  How does solar wind influence **E**?

PRESENT:

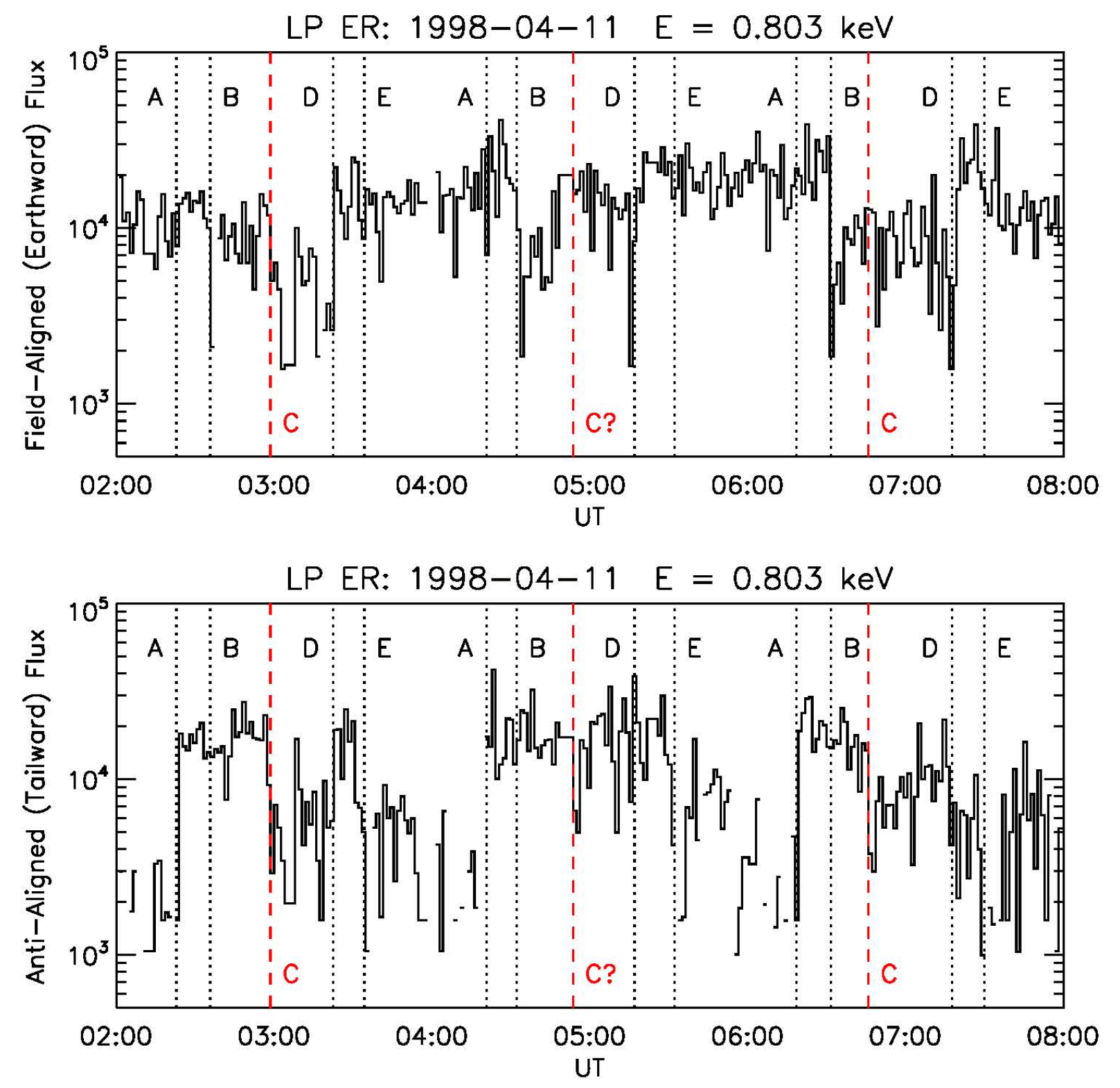
Lunar Prospector Electron Reflectometer (ER)

- Measured 3D electron distributions
- Energy range: ~10 eV – 20 keV (ΔE/E ~ 38%)
- Time resolution: 2.5 sec integration time; 80 sec cadence
- Angular resolution: up to 22.5° X 22.5° in equatorial bins
- Orbit inclination: 90° (polar orbit)
- Operational life: Jan. 1998 – July 1999
  (18 magnetotail passes – more than doubles the amount of data from PFS 1 & 2)

Increased energy, angular, and temporal resolutions of ER should allow us to determine the convection electric field from **lunar shadowing** with greater **sensitivity** and **accuracy**

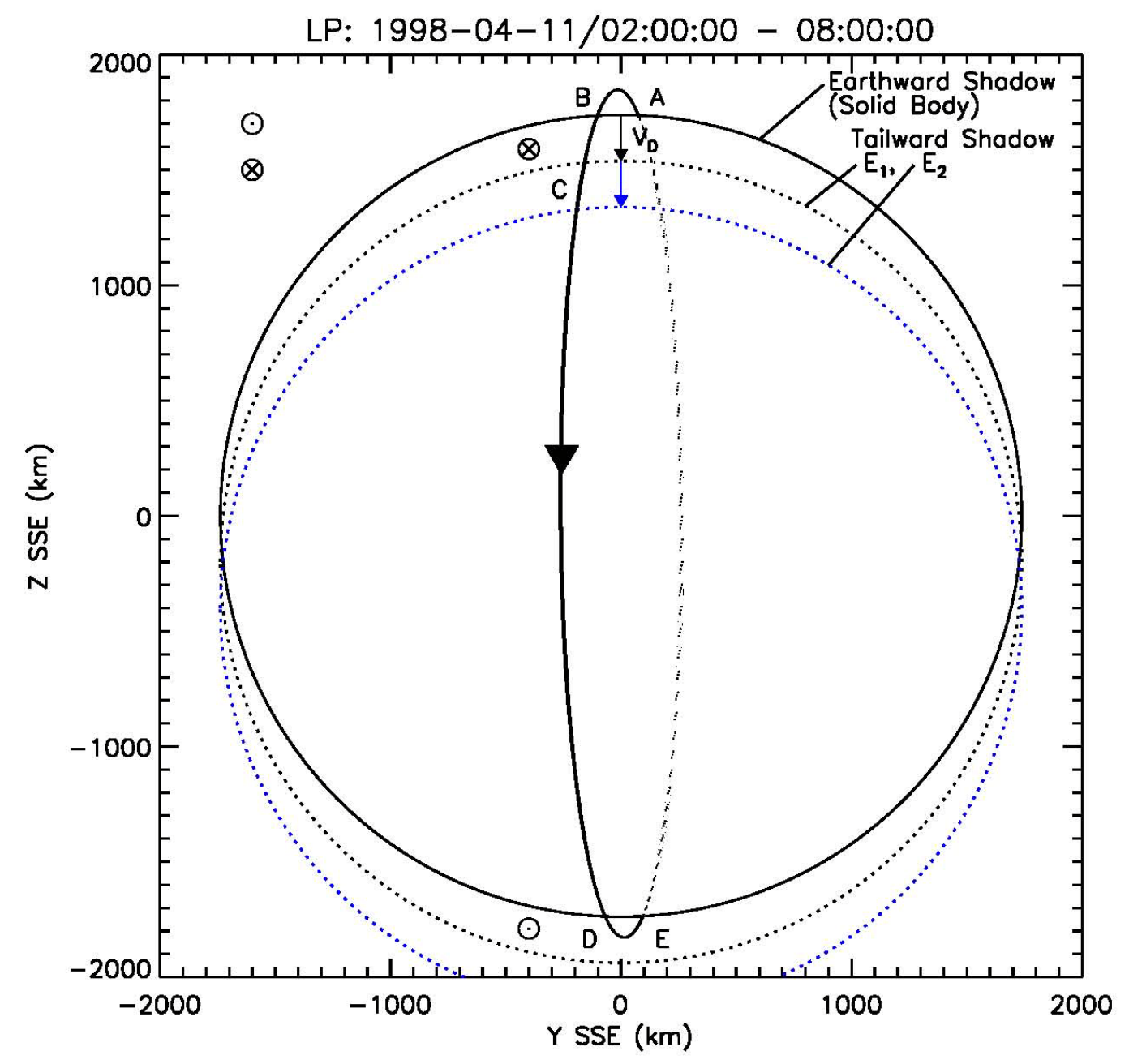


Shadow 1: $\Delta t_{B-C}^{1.2\ keV}$: 1130 ± 80 s
$\Delta z_{B-C}^{1.2\ keV}$: 1260 ± 130 km
Shadow 2: $\Delta t_{B-C}^{1.2\ keV}$: 723 ± 80 s
$\Delta z_{B-C}^{1.2\ keV}$: 635 ± 130 km
Shadow 3: $\Delta t_{B-C}^{1.2\ keV}$: 858 ± 80 s
$\Delta z_{B-C}^{1.2\ keV}$: 945 ± 130 km

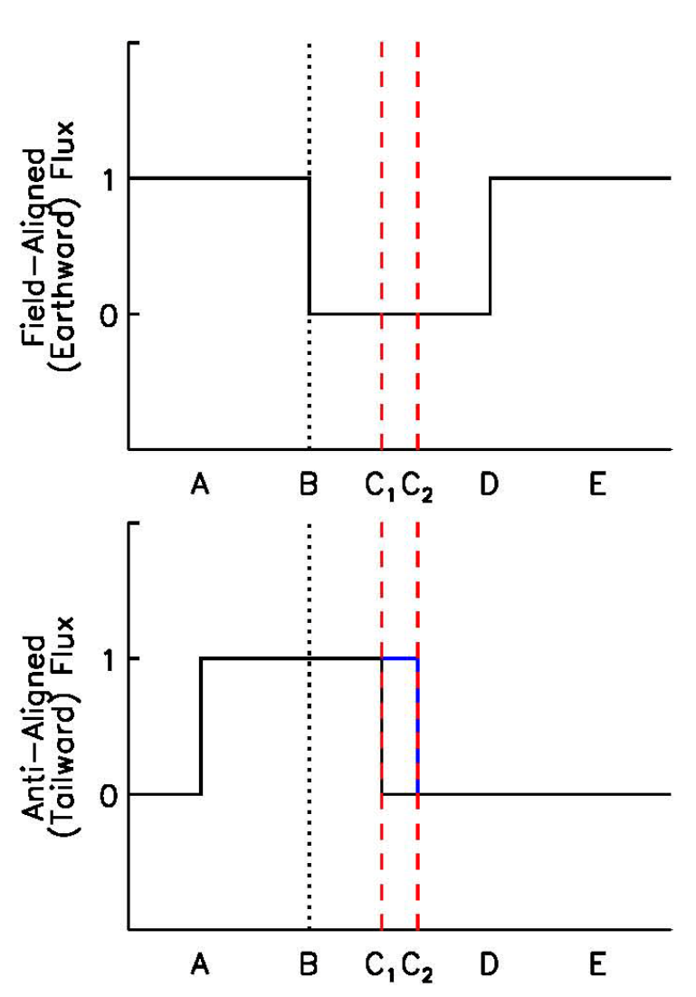


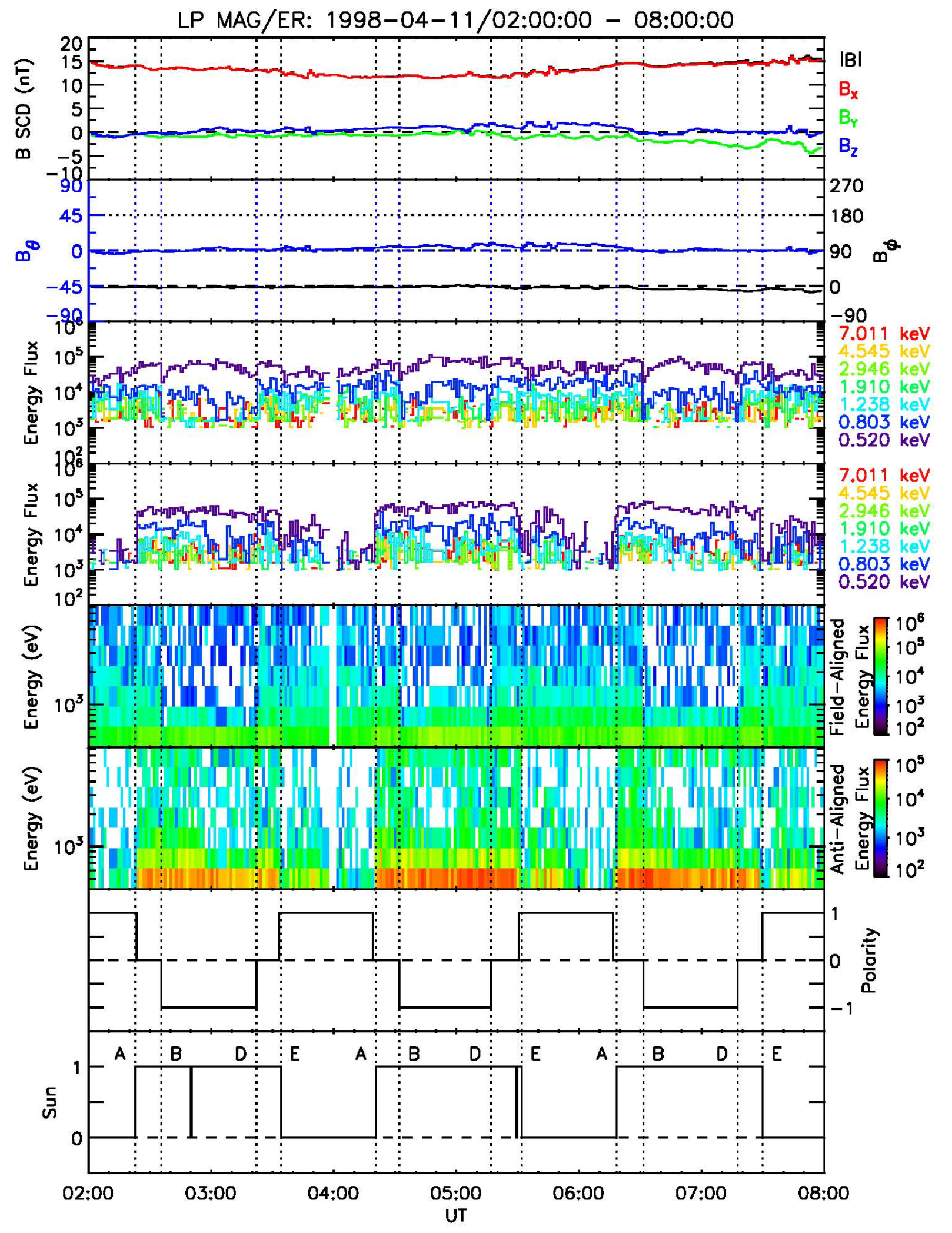
Shadow 1: $\Delta t_{B-C}^{0.8\ keV}$: 1372 ± 80 s
$\Delta z_{B-C}^{0.8\ keV}$: 1646 ± 130 km
Shadow 2: $\Delta t_{B-C}^{0.8\ keV}$: 1286 ± 80 s
$\Delta z_{B-C}^{0.8\ keV}$: 1426 ± 130 km
Shadow 3: $\Delta t_{B-C}^{0.8\ keV}$: 858 ± 80 s
$\Delta z_{B-C}^{0.8\ keV}$: 945 ± 130 km

Orbit Configuration



Ideal Flux Profiles





Panels 1 & 2: Magnetic field
Magnetic field magnitude is stable and magnetic field direction is Earthward
→ Northern lobe

Panels 3 – 6: Electron flux
Field-aligned (pitch angle ≤ 60°) & anti-aligned (pitch angle ≥ 120°) directional fluxes

- ≤ 500 eV: solar photon contamination in anti-aligned direction
- ≥ 2keV: low particle counts

Panels 7 & 8: LP orbit
Is LP magnetically connected to the Moon?
|Polarity| = 1, yes; = 0, no
Does LP see the Sun? = 1, yes; = 0, no

3 lunar orbits (A to E) → 3 **shadow** events

For the following computations, only use **0.8** and **1.2 keV** energy channels

Results

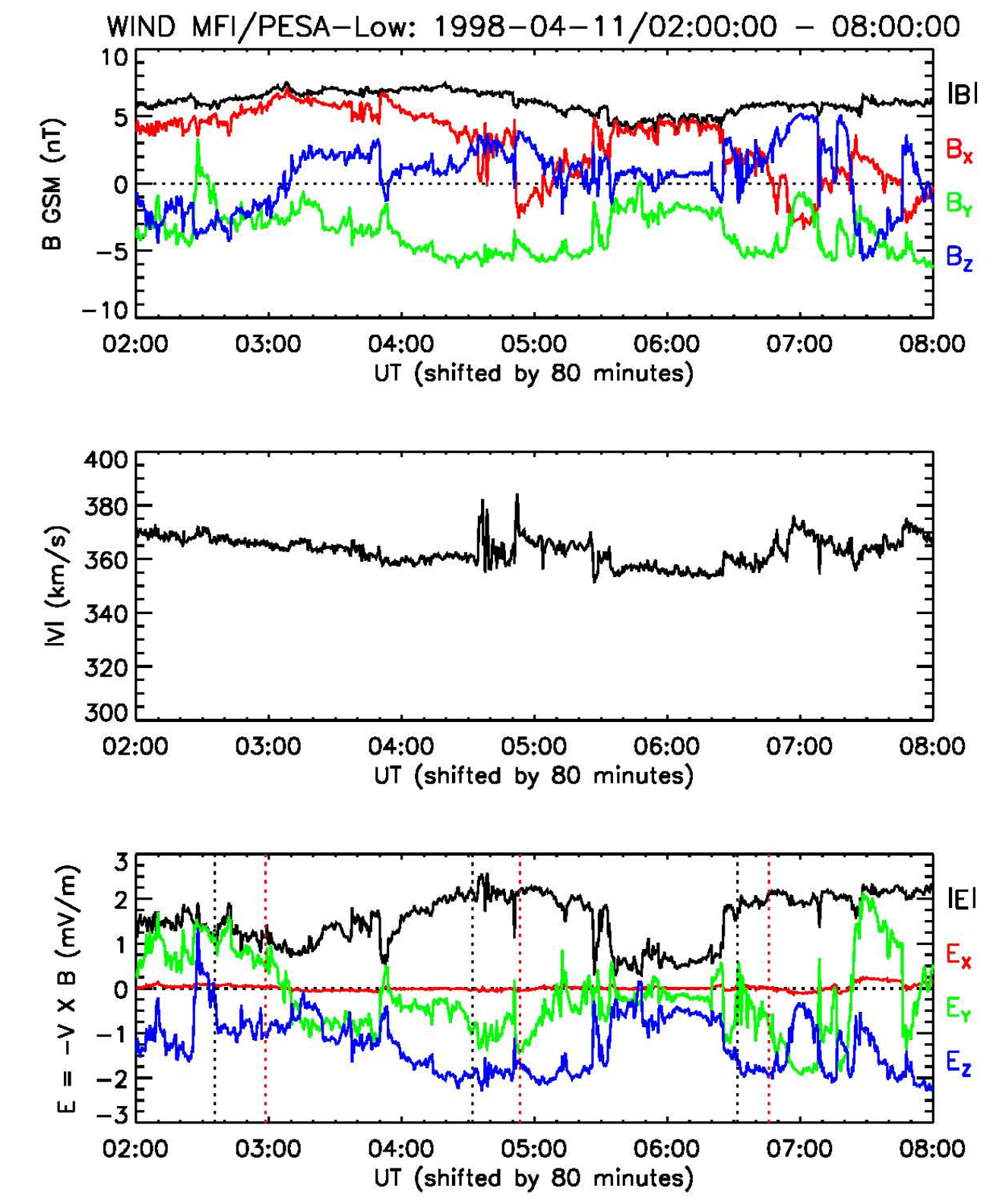
The displacement, **Z**, is the product of the convection velocity, $\mathbf{V_D}$, and the round-trip travel time of the mirrored electrons, t_m:

$$\mathbf{Z} = \mathbf{V_D} \cdot t_m = (\mathbf{E} \times \mathbf{B})/B^2 \cdot t_m;$$
$$\mathbf{E} = -(\mathbf{Z} \times \mathbf{B})/t_m$$

where t_m [s] = $d/v_e \approx 120\ R_E \cdot 6378$ km/R_E/(18800 km/s · $\sqrt{(E\ [keV])}$)
(for a more rigorous treatment of t_m, see *McCoy et al.* [1975])

We assume $\mathbf{Z} = \Delta z_{B-C}$; i.e., $\mathbf{V_D} = -V_{DZ}$, and $\mathbf{E} = E_Y$ (dawn-dusk)
→ **lower limit of E**

$E_1^{1.2\ keV}$ = 0.44 ± 0.05 mV/m $E_1^{0.8\ keV}$ = 0.48 ± 0.04 mV/m
→ consistent!
$E_2^{1.2\ keV}$ = 0.22 ± 0.05 mV/m $E_2^{0.8\ keV}$ = 0.41 ± 0.04 mV/m
→ inconsistent!
$E_3^{1.2\ keV}$ = 0.33 ± 0.05 mV/m $E_3^{0.8\ keV}$ = 0.27 ± 0.04 mV/m
→ consistent!



Solar Wind Conditions

- Wind was located about 225 R_E upstream
- **B**, **V**, & **E** time-shifted to 60 R_E downtail
- B_X mostly > 0
- $B_Y \sim E_Z$ mostly < 0
- $B_Z \sim -E_Y$ weak, variable but no more variable during 2nd shadow (inconsistent **E**) than during 3rd shadow (consistent **E**) (?)

FUTURE (CONT'D):

Future Mission Planning:

- Address Problems with ER data
  - Need better solar photon rejection
  - Also need high geometric factor since density is low

- Increase sensitivity (reduce uncertainty)
  → Increase data sampling cadence
  Currently 80 s cadence → ± ~ 0.05 mV/m uncertainty

- Currently only measure component of $\mathbf{V_D}$ parallel to orbit plane
  → **E** perpendicular to orbit plane
  In order to completely constrain $\mathbf{V_D}$ (hence, **E**, assuming $E_{//} = 0$), requires **2 spacecraft**