Penetration Electric Fields: Meaning, Nature, Importance and Complexities

Dibyendu Chakrabarty
Physical Research Laboratory, India

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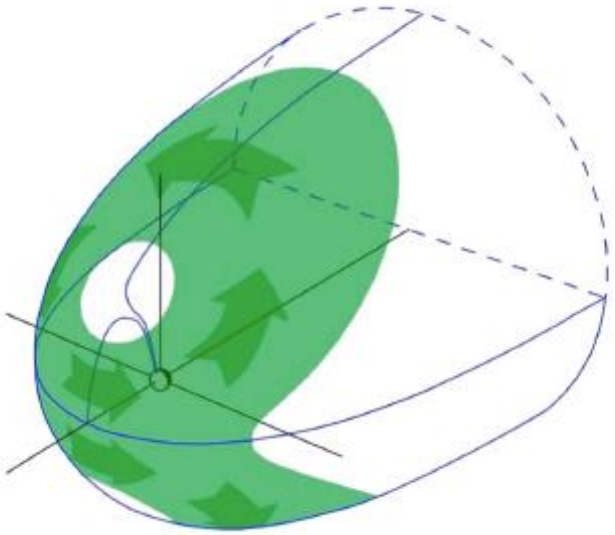
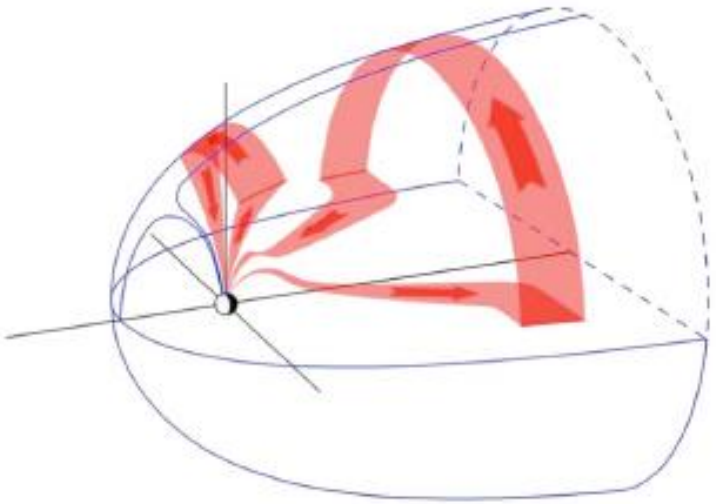
Meaning

Enhancements in solar wind dynamic pressure

- Compression of dayside magnetosphere by solar wind ram pressure => changes in the Chapman-Ferraro current => Changes in R1 FAC



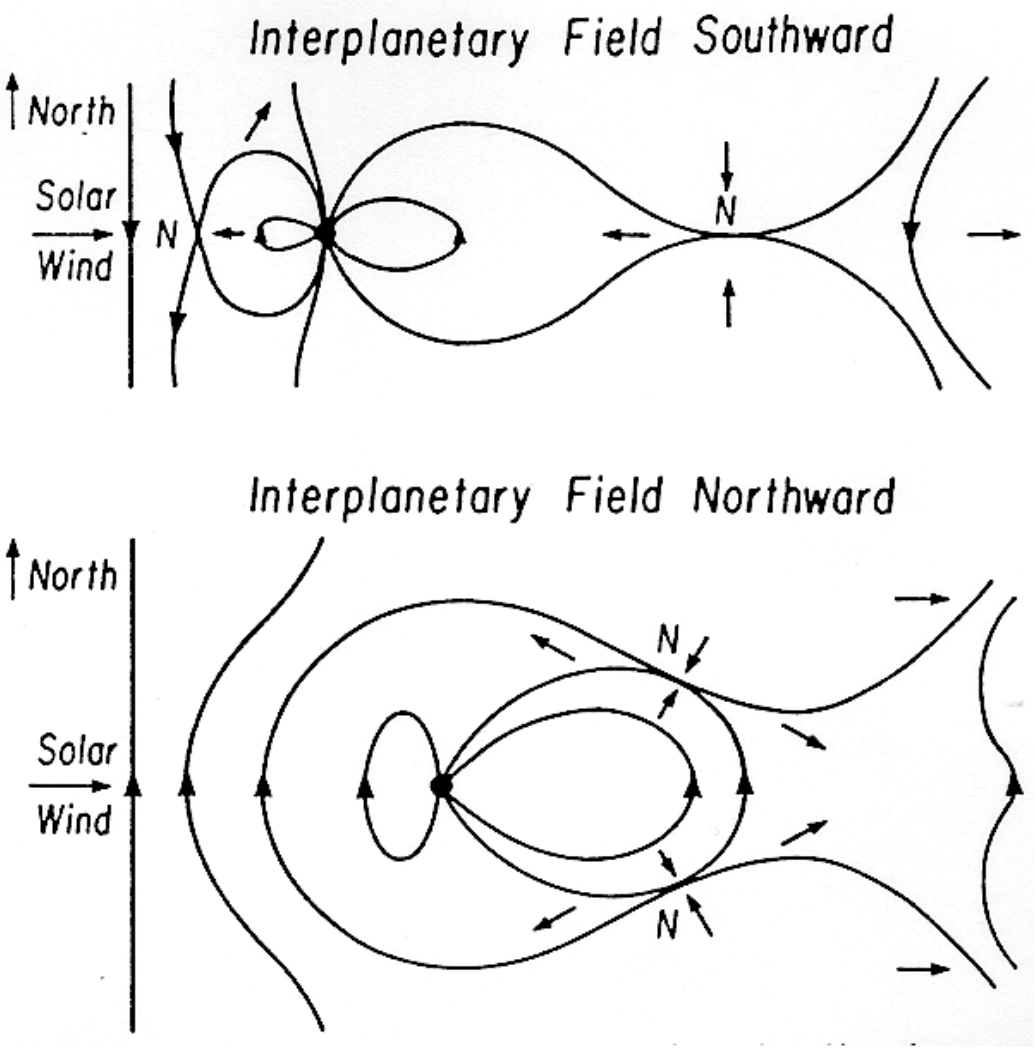
Chapman-Ferraro Current



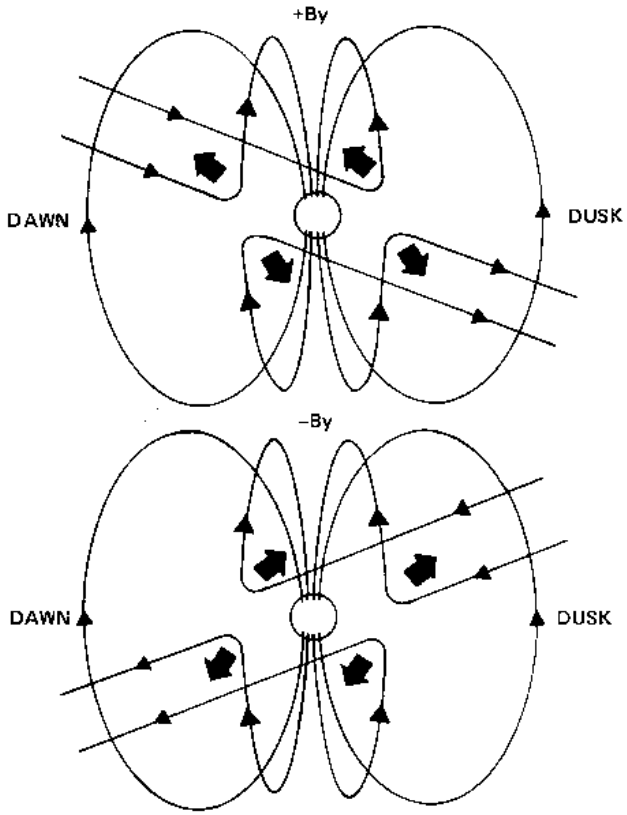
R1 FAC or Region 1 Field Aligned Current

Ganushkina et al., RG, 2018

IMF Bz turning southward, northward and changes in IMF By
= > Changes in R1 FAC



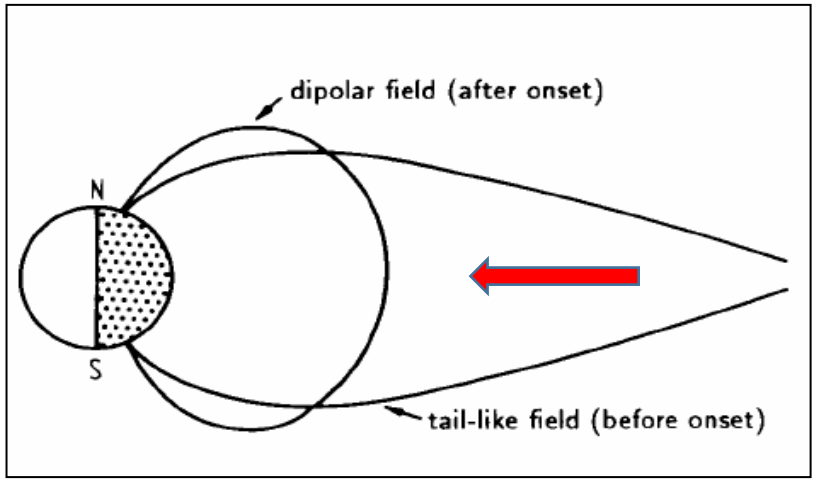
Russell et al., 1995

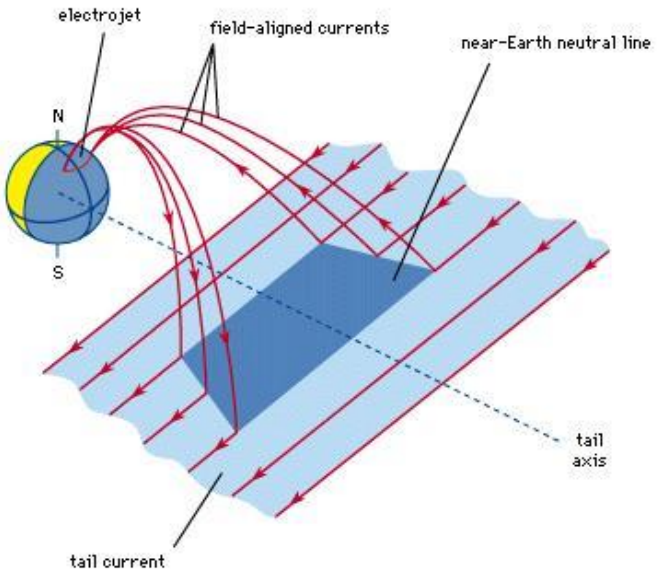


Kivelson and Russell, 1995

Magnetospheric Substorm => Generation of FAC in space

- Stored energy in the night side magnetotail is released.
- Reversal in the polarity of IMF Bz (or IEFy), enhancements in solar wind ram pressure, magnetospheric plasma instability processes can trigger substorm.





In Substorm Current Wedge model, tail current collapses and gets diverted to auroral ionosphere through **Field Aligned current**.

FACs seems to be important for penetration electric field

- Therefore, it appears that **Field Aligned Currents (FACs)** have important roles to play in communicating solar wind/magnetospheric electric field disturbances to polar ionosphere and eventually to equatorial ionosphere (**electric field penetration**).

- The exact phenomenology in each type of penetration E-field is not fully apparent till date.

- **We will take the simplest scenario that we understand best, i.e. when IMF Bz is southward.**

Interplanetary Electric Field (IEF) from Interplanetary Magnetic field (IMF)

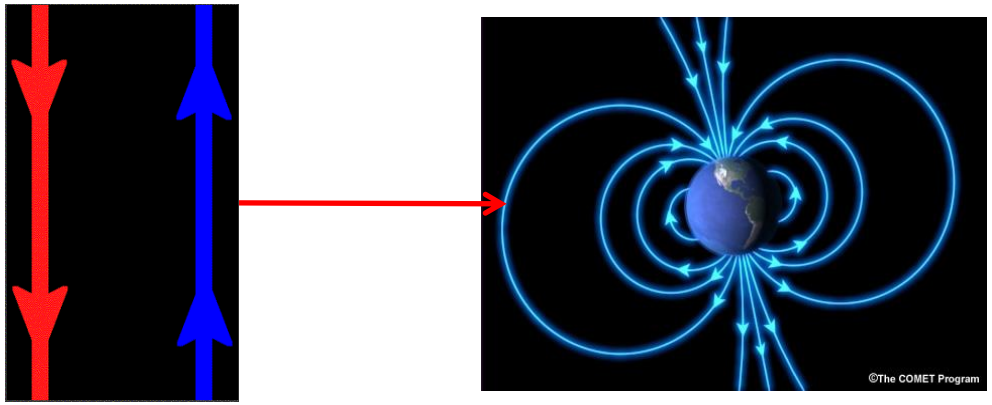
- Magnetic field is "Frozen-in" solar wind plasma: **B** goes where the plasma goes
- No electric field in solar wind frame, Electric field exists in the Earth frame

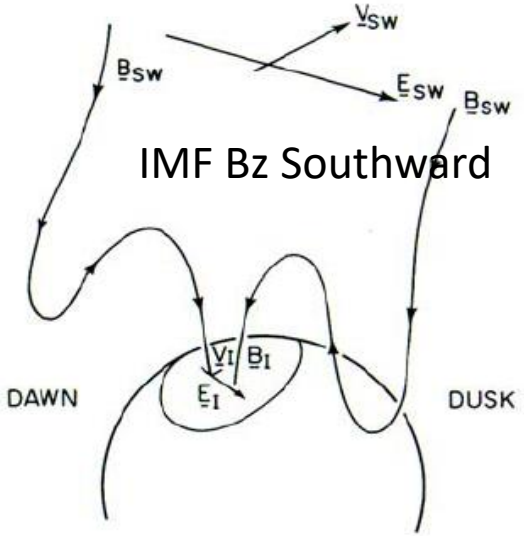
$$\mathbf{E' = E + V \times B = 0}$$

$$\mathbf{IEF\ or\ E_{SW} = -V_{SW} \times B_{SW}}$$

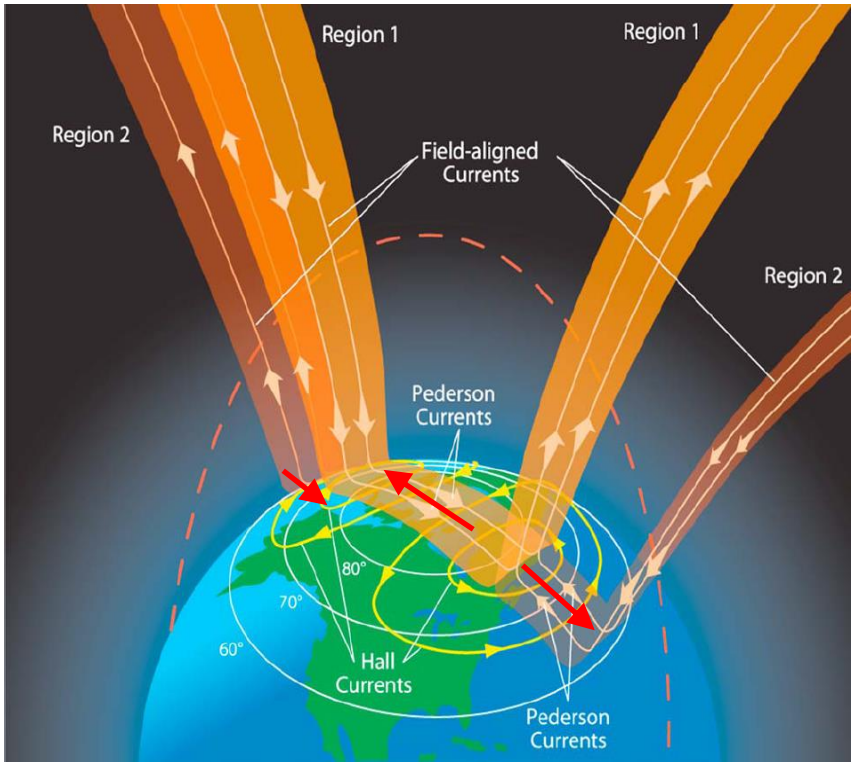
E' => Solar wind frame
E => Earth frame

- **IMF Bz southward component is equivalent to IEFy (east-west component)**
- **This is why ionospheric east-west component of E-field over low latitude is the most vulnerable.**
- **East-west E-field changes plasma transport and causes irregularities.**





Penetration Electric field: Competition between R1 and R2 FAC



Le et al., JGR, 2010 modified

- Response in R1 FAC nearly instantaneous
- R2 FAC takes some time to develop or decay

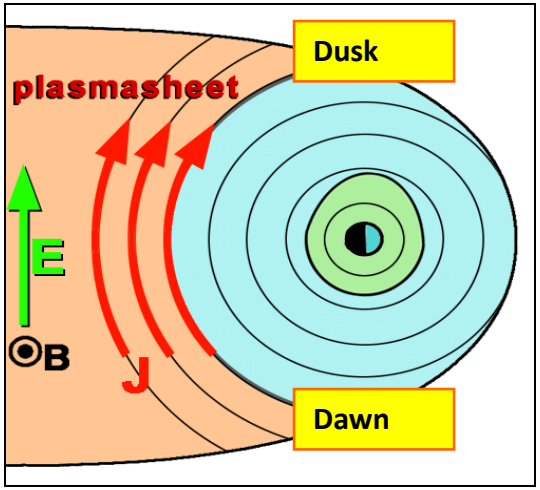
- IMF Bz turns southward

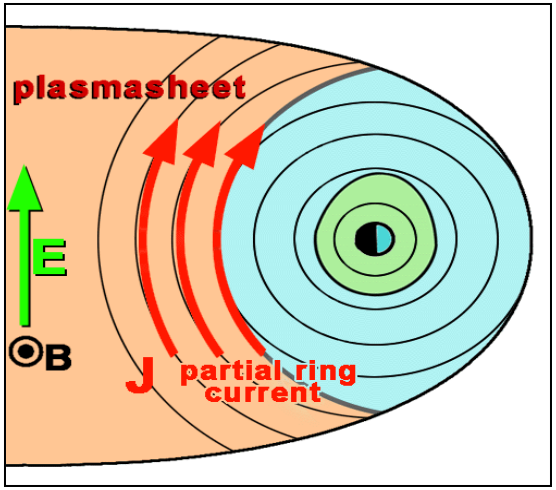
R1 FAC > R2FAC => Under-shielding/Prompt penetration

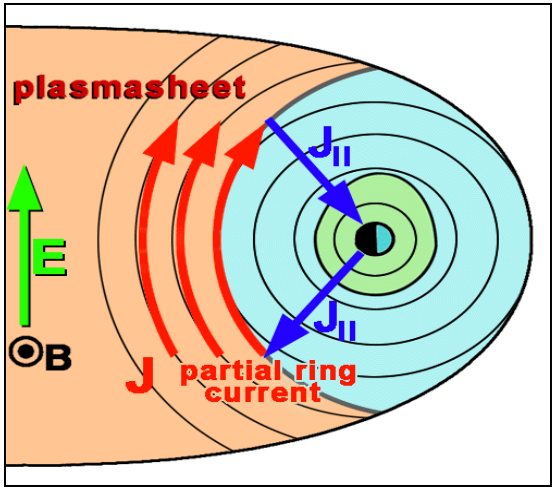
- IMF Bz turns northward after being southward for some time

R2 FAC > R1 FAC => Overshielding

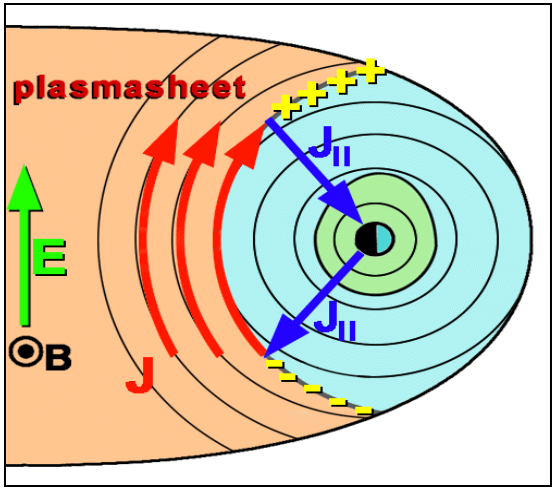
Electric field perspective

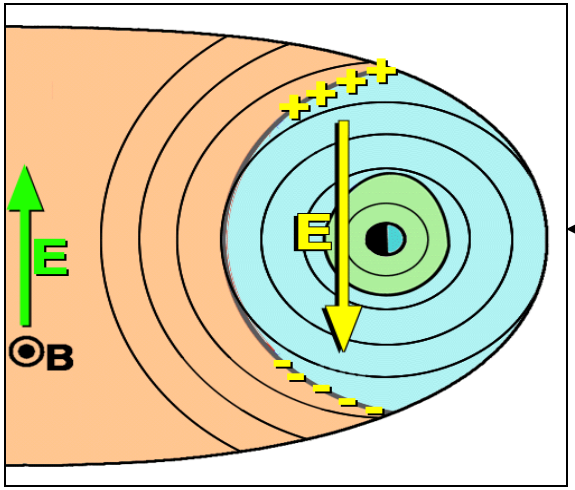






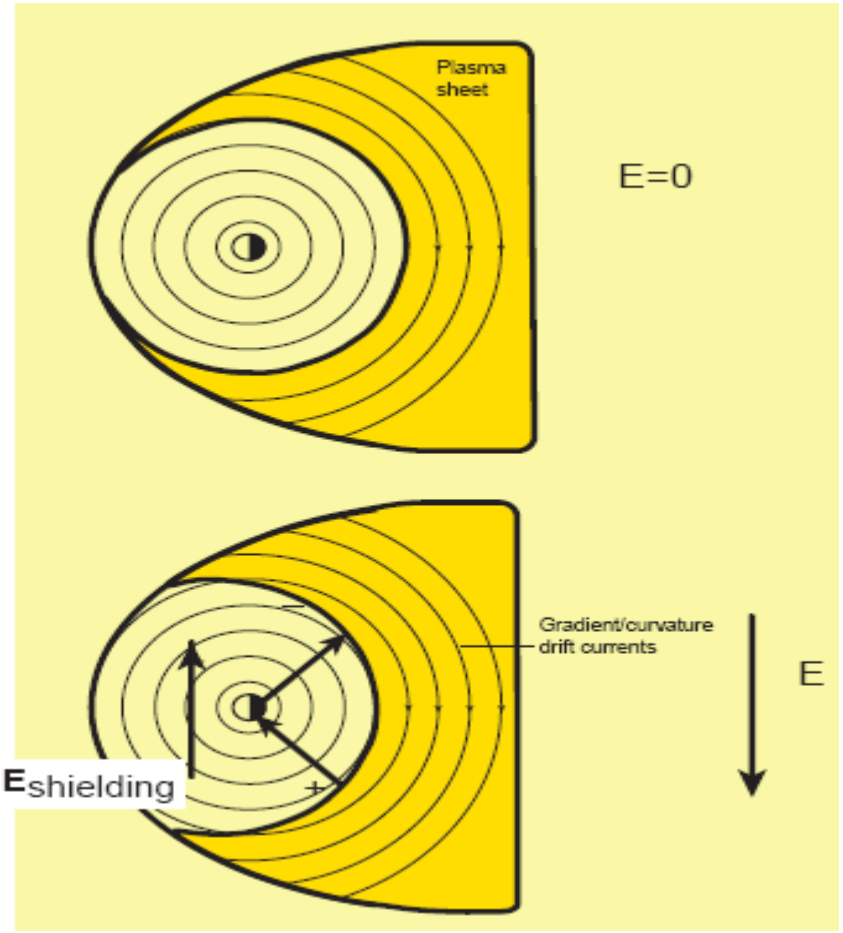
How is the effect of IEF shielded?



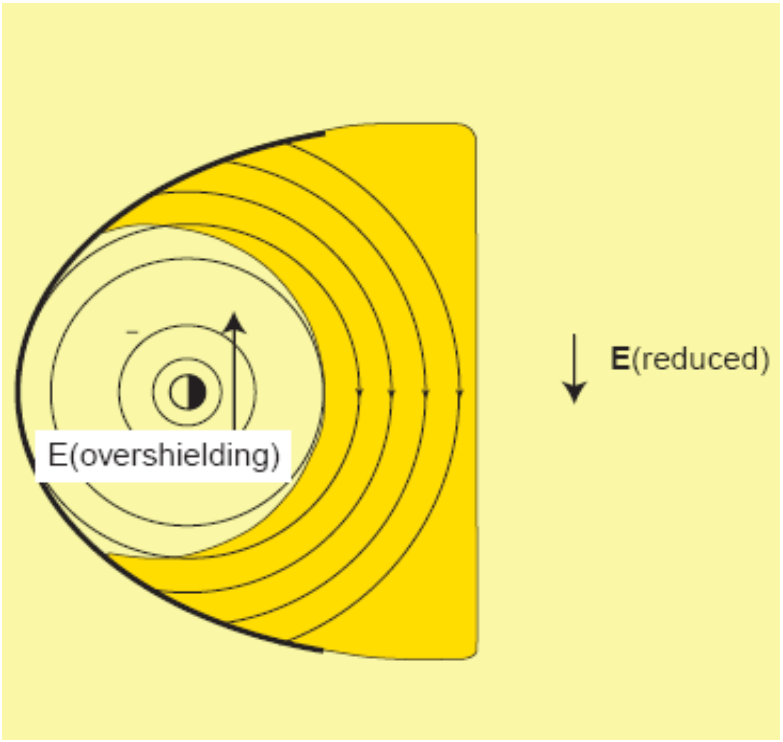


Goldstein, 2002

Undershielding (prompt penetration) and overshielding Electric field perspective



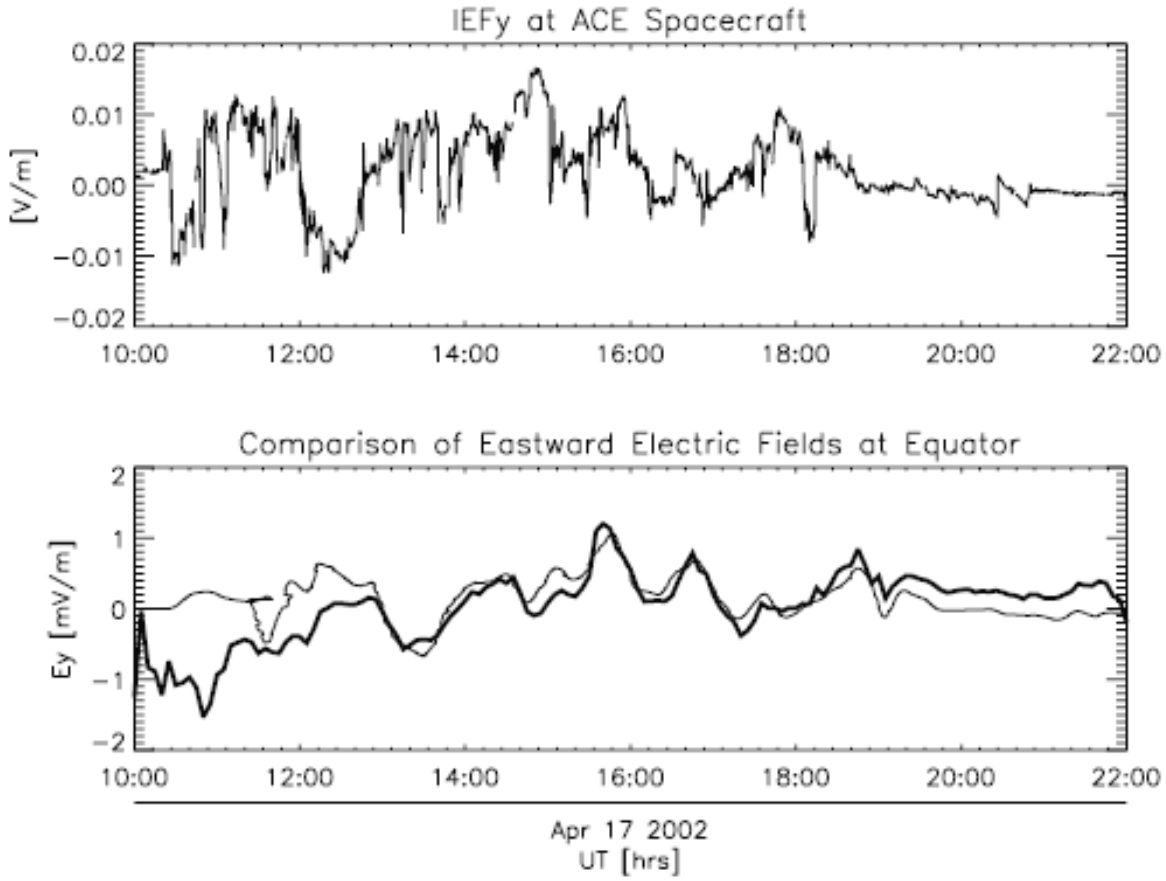
Wolf, 2002



- If the shielding layer is configured to shield the inner magnetosphere from a strong convection field, and that convection field suddenly increases, due to a southward turning of the IMF, the result will be a partial **E** field (dawn to dusk) in the inner magnetosphere, until the shielding layer readjusts.
- If IMF turns northward (convection decreases, there is suddenly a reversed (dusk to dawn) E-field temporarily.

Penetration electric field: Definition and examples

When the electric field of solar wind or magnetospheric origin penetrates from high latitude to low latitude ionosphere despite closed magnetic field configuration, it is known as penetration electric field.



Kelley et al., GRL, 2003

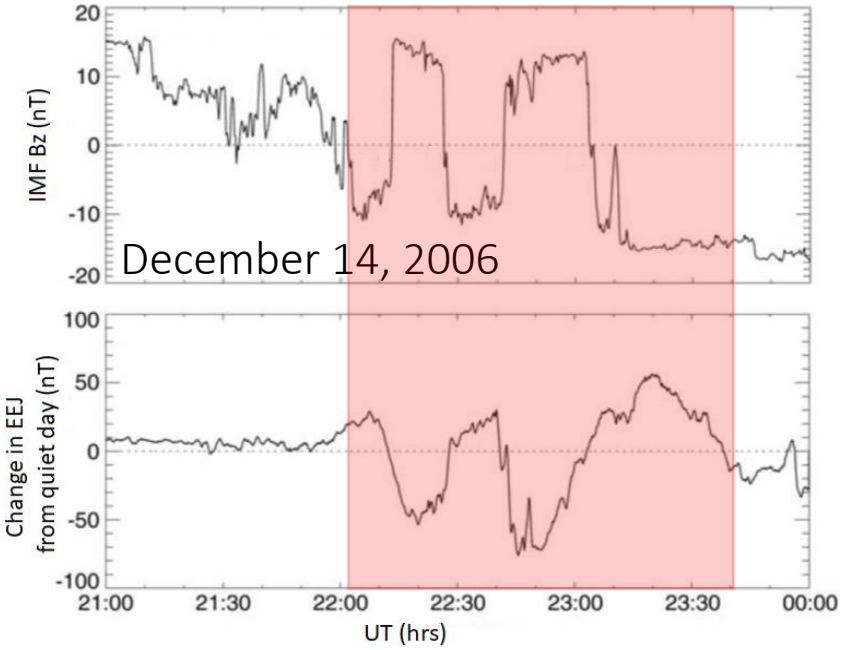
The dawn-dusk component of the filtered IEFy measured by the ACE spacecraft (bold line) scaled-down by a factor of 15 (thin line).

15:1 => Ratio of magnetospheric size to length of dayside reconnection line

Penetration efficiency: 6-7%

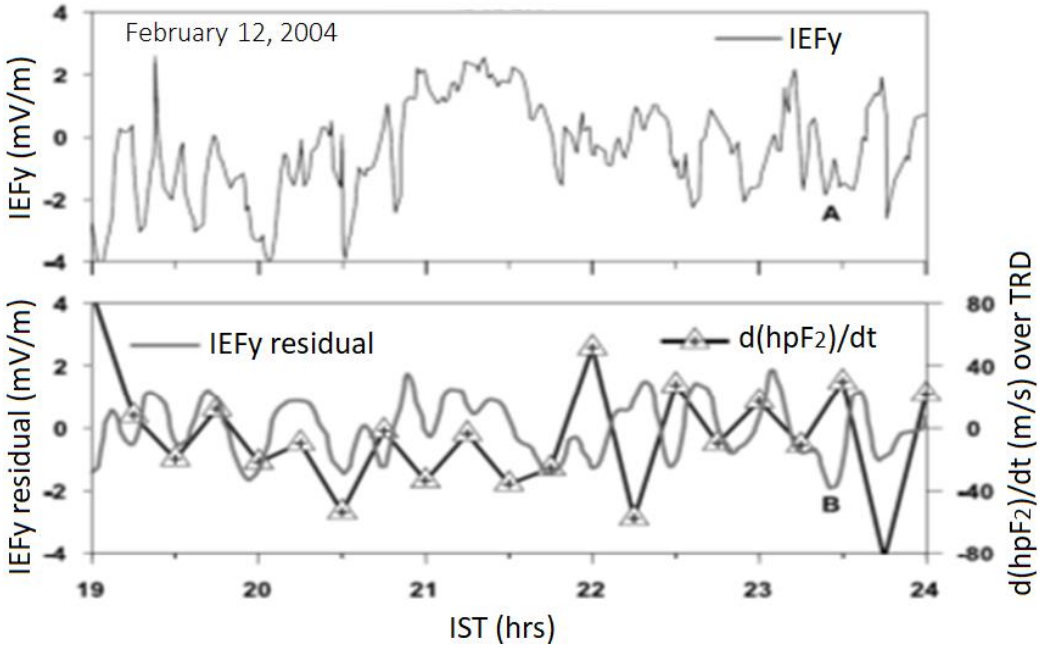
Penetration electric field: Examples

Effects of PP/OS on EEJ



Kikuchi et al., JGR, 2010

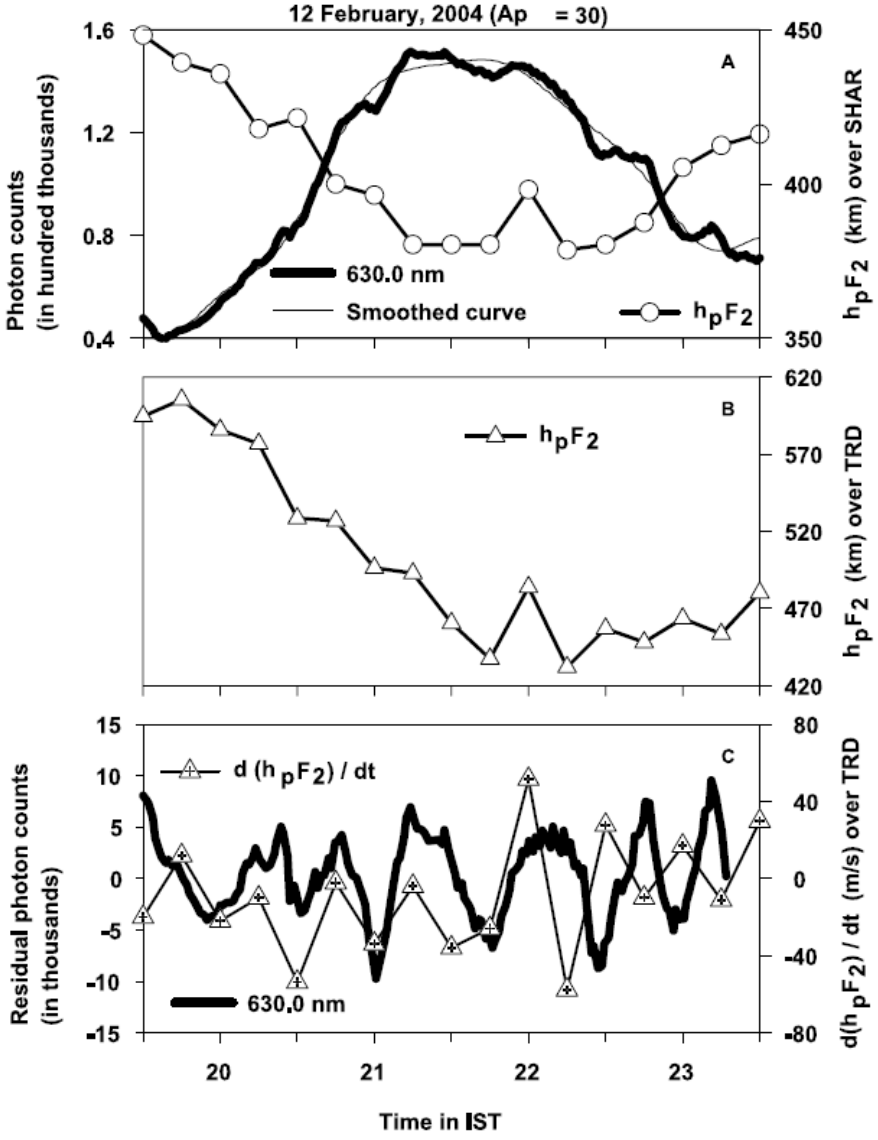
Effects of PP/OS on F-layer movement

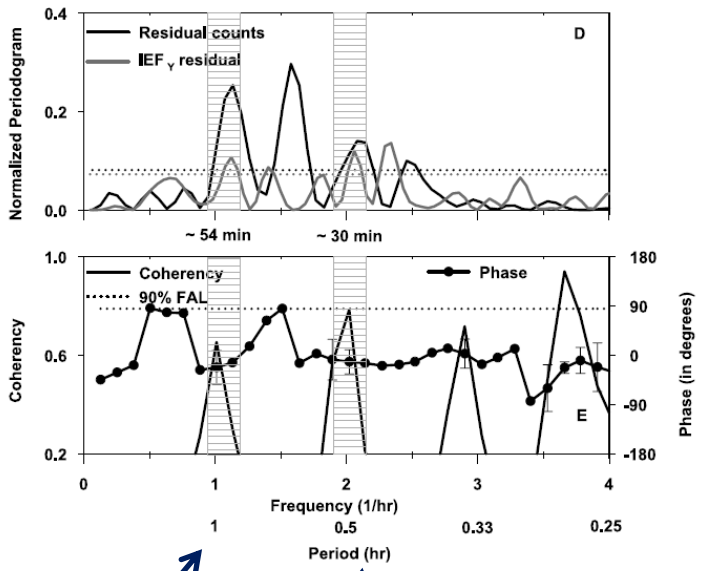


Chakrabarty et al., JGR, 2005

Penetration electric field: Examples

Effects of PP on OI 630.0 nm airglow emission



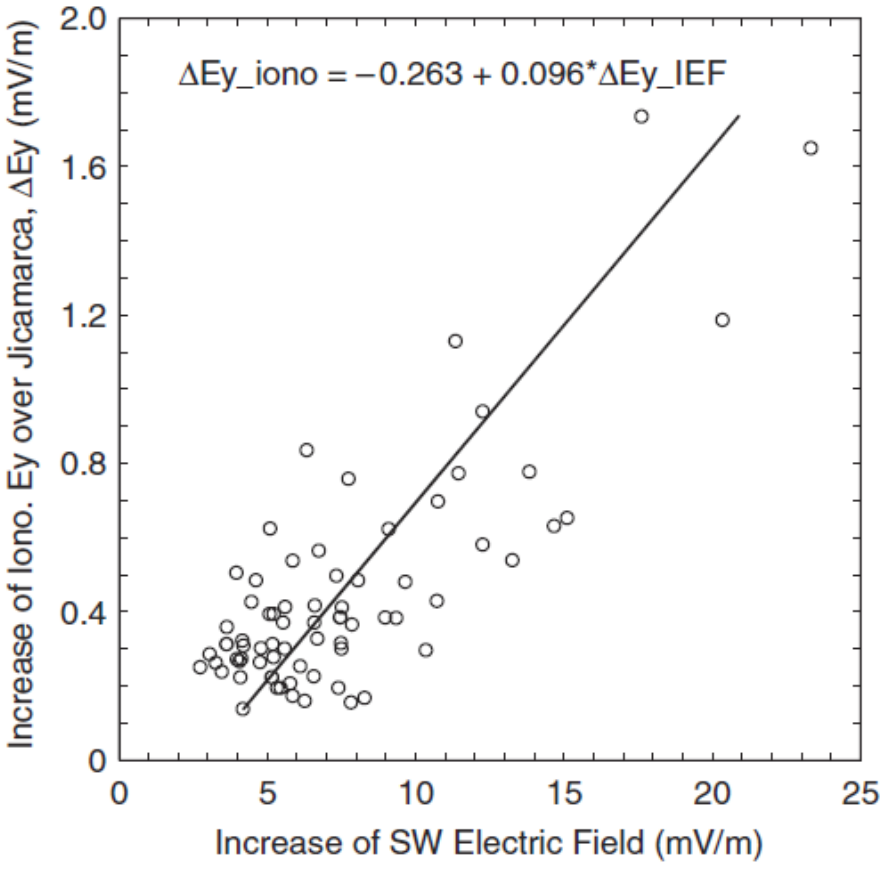


1.0 hr and 0.5 hr periodic components in IEF affect the 630.0 nm airglow emission

Chakrabarty et al., JGR, 2005

Nature

Penetration efficiency: Magnitude of penetration E field



Huang et al., JASTP, 2007

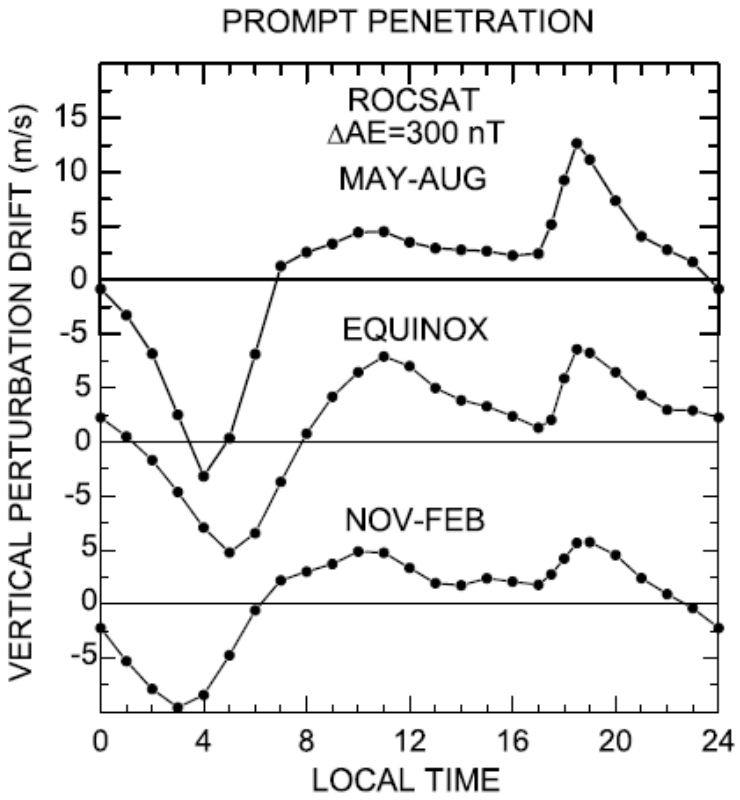
Kelley et al. (2003) – 6.6% (Jicamarca observations)

Burke (2007) – 11.6 (Using Volland-Stern model, Theoretical)

Huang et al. (2007) – 9.6% (Jicamarca observations)

There are occasions when larger penetration efficiencies (Hui et al., JGR, 2017; Rout et al., JGR, 2019) are seen. However, those events need more attention regarding added effects of substorms – complexity

Polarity of penetration E-field

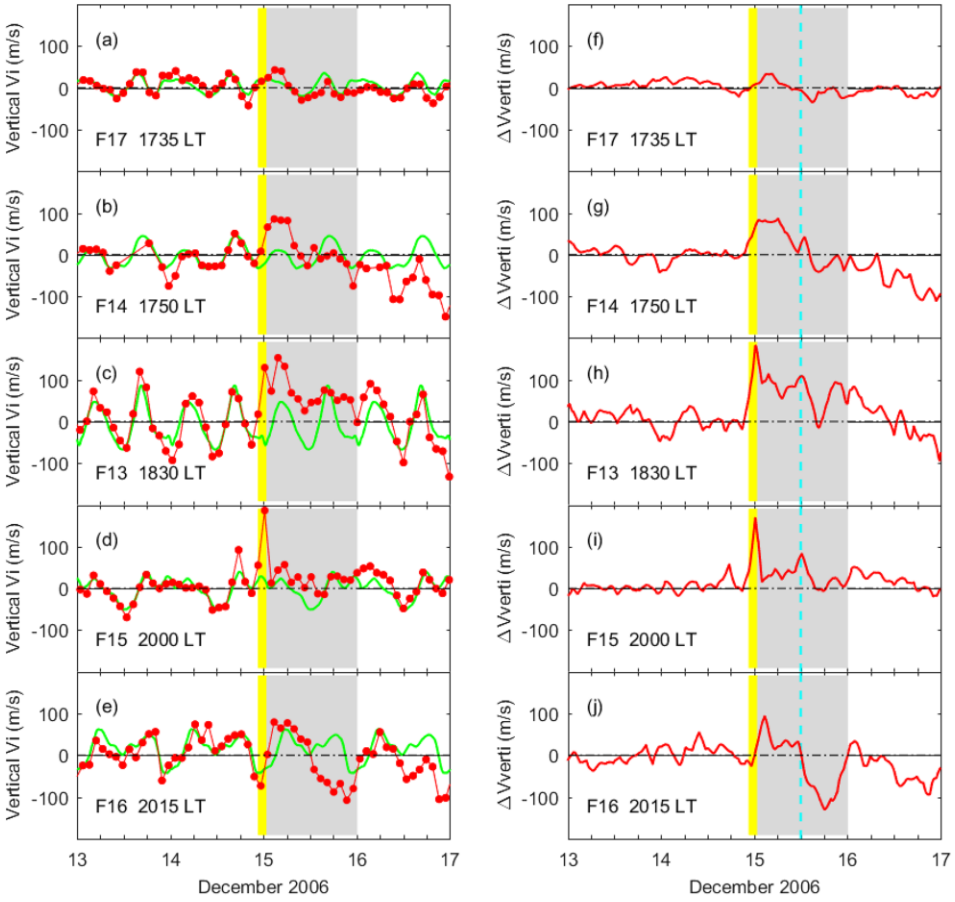


Fejer et al., GRL, 2008

On many occasions, we do see anomalous polarities! Roles of IMF By (Chakrabarty et al., 2017) is important but less studied - complexity

Time constant of shielding

- LT (or conductivity) dependent (Jaggi and Wolf, 1973) – 3 min on the nightside and 5 hr on the dayside .
- 3-5 hrs (Earle and Kelley, 1987), 3 hr (Nicolls et al., 2007), 2 hr (Manoj et al., 2008)
- Theoretical studies ~ 30 min (Senior and Blanc, 1984)
- Even during sustained southward IMF Bz condition, the shielding does not develop on many occasions (e.g. Huang et al., 2007). Why?



Huang, JGR, 2019

Critical question:

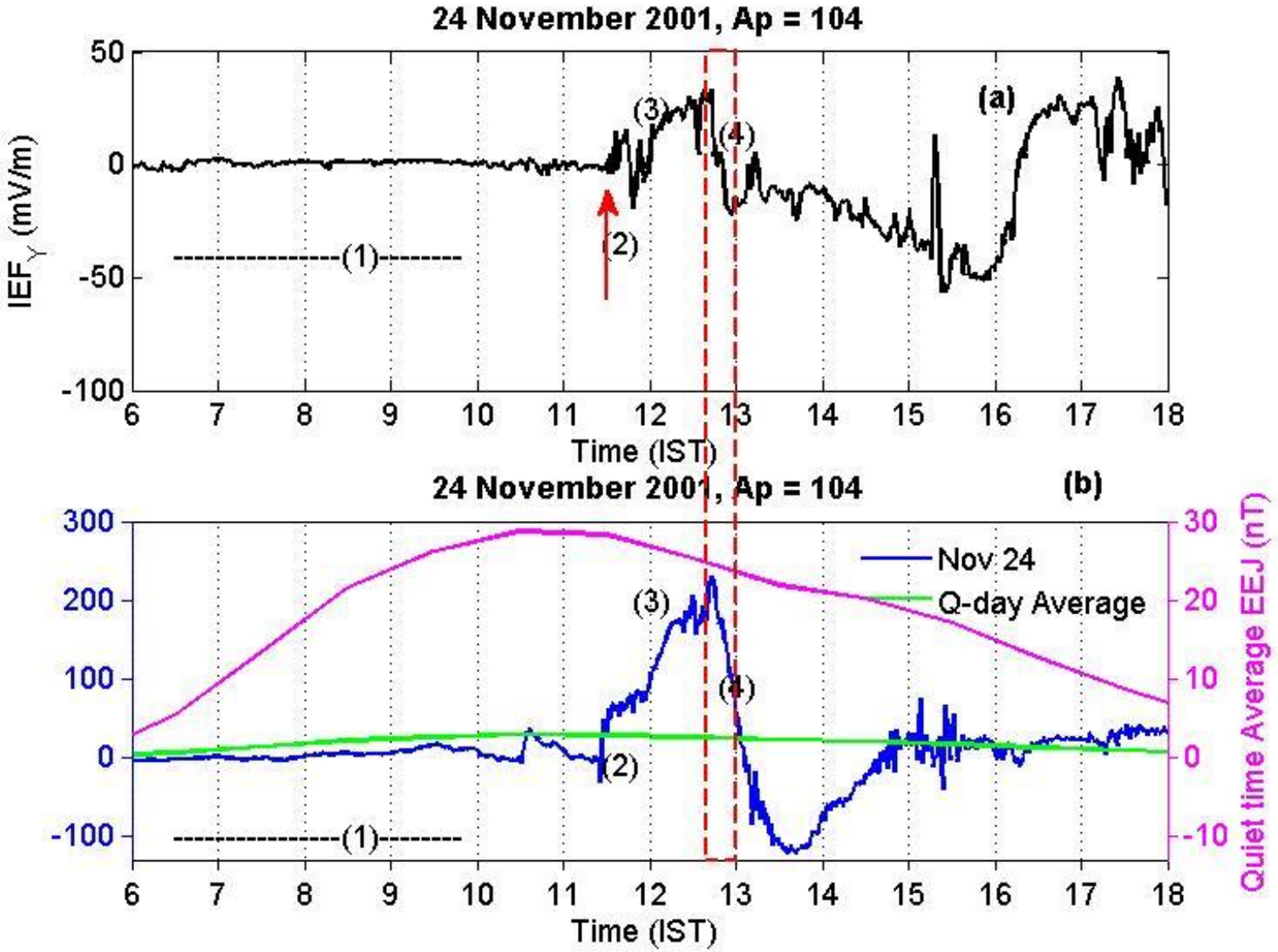
5 DMSP satellites

Penetration E-field for 11 hrs.

How well- delineated are the other effects like disturbance dynamo, substorms etc.?

Importance

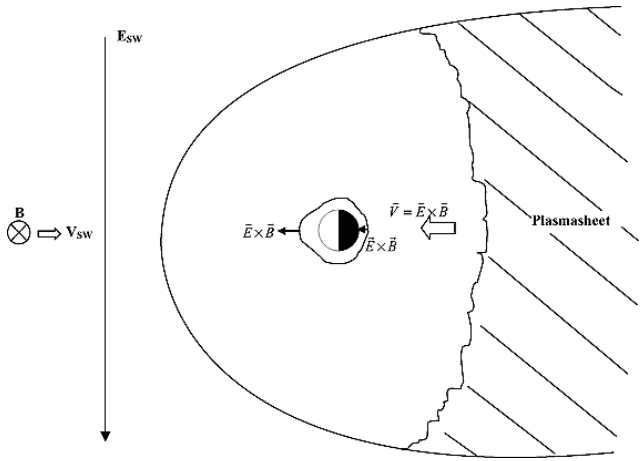
Super-enhanced EEJ current



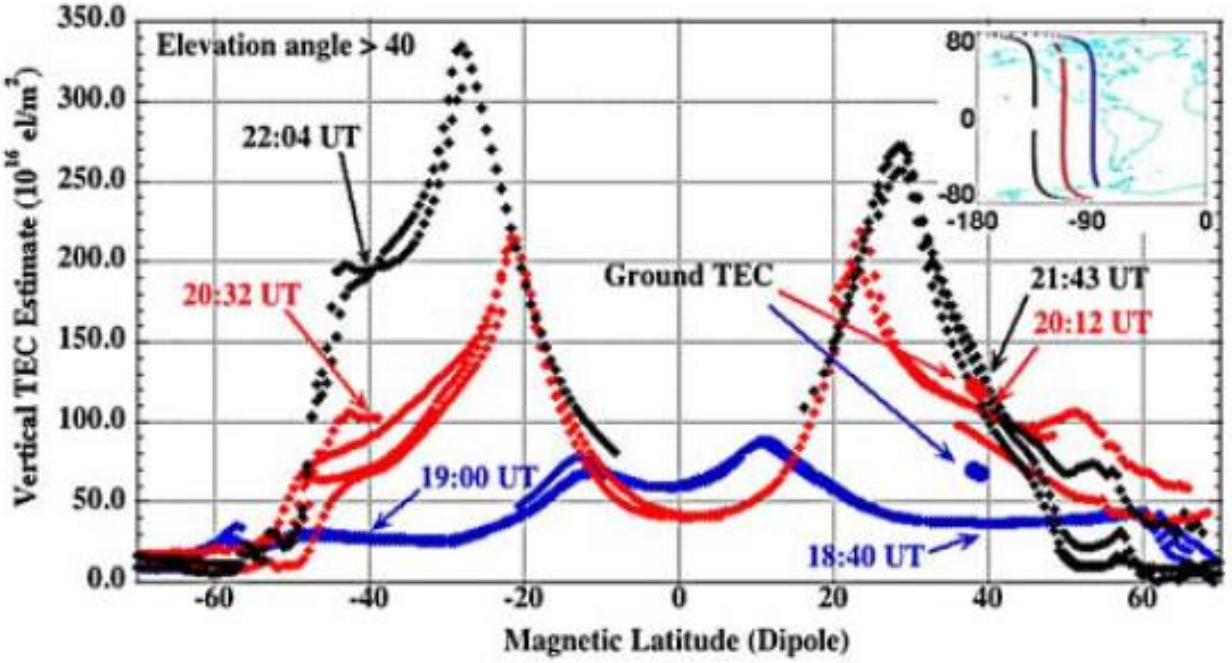
Simi et al., JGR, 2012

F-region Super-fountain

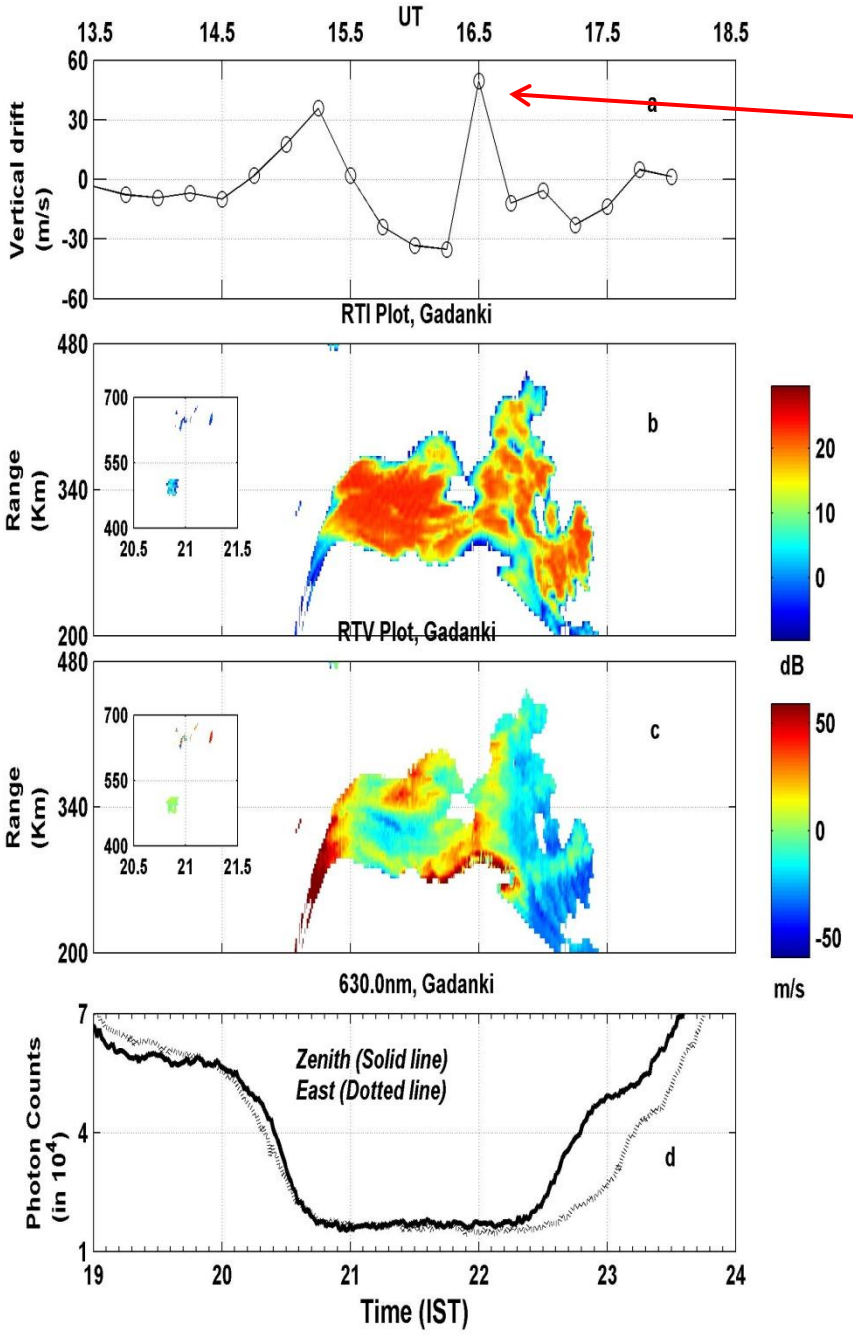
Tsurutani et al., 2004

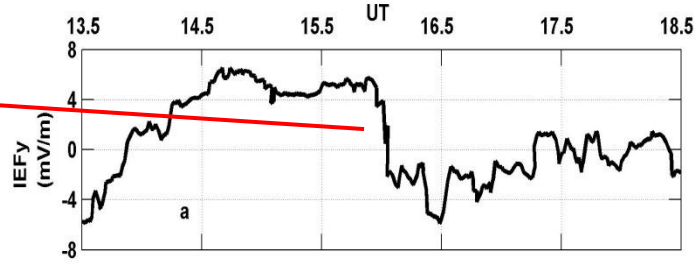


Manucci et al., GRL, 2005



F-region Plasma irregularities





Linear analysis

$$\gamma = \frac{1}{L}\left[\frac{g}{\nu_{in}} + \frac{E_x}{B}\right]$$

1930 IST

Linear growth rate ~ -0.3×10^{-4} s^{-1}

2030 IST

Linear growth rate ~ 1.95×10^{-3} s^{-1}

and growth time ~ 9 minutes

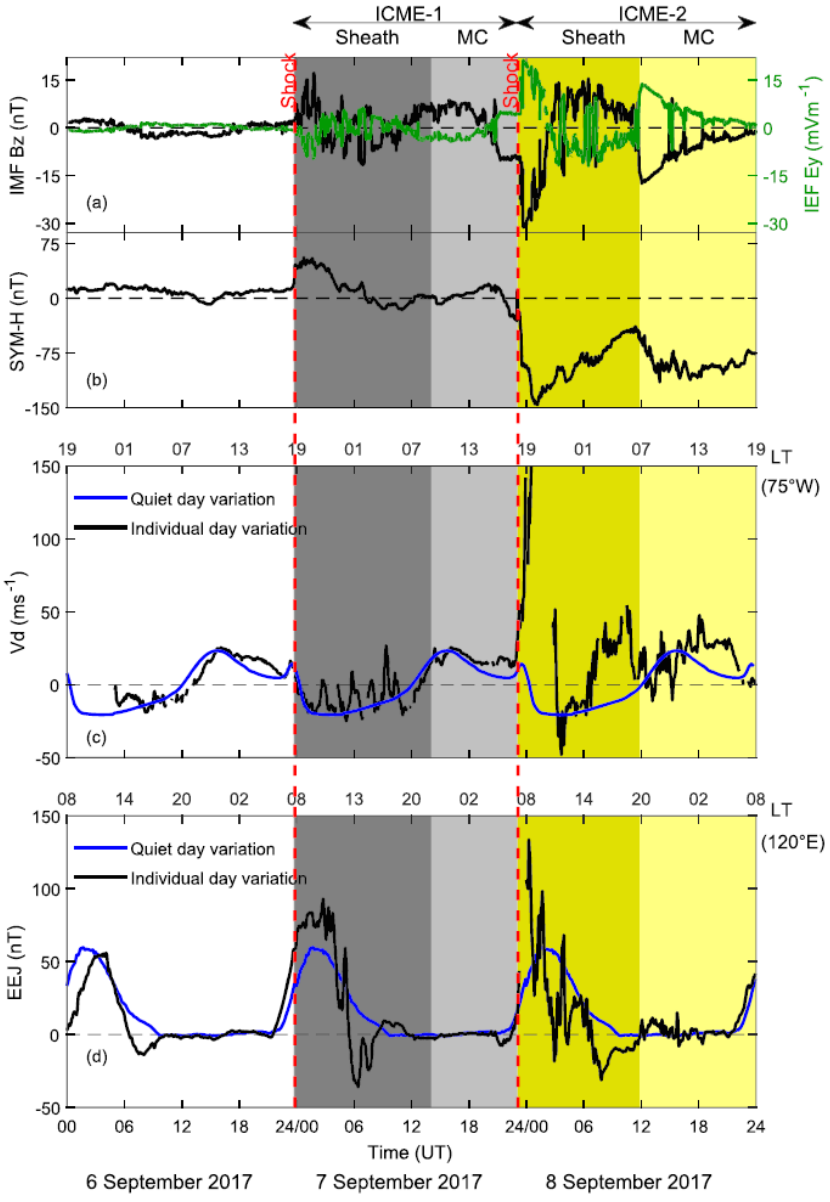
Penetration E-field triggers plasma irregularity

Causes resurrection of plume structure during pre-midnight hours

Airglow variations at two directions remove the space-time ambiguity

Chakrabarty et al., JGR, 2006

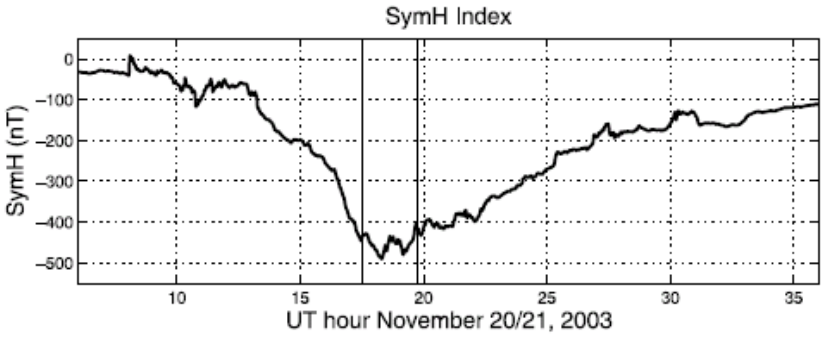
Extreme vertical drift over Jicamarca

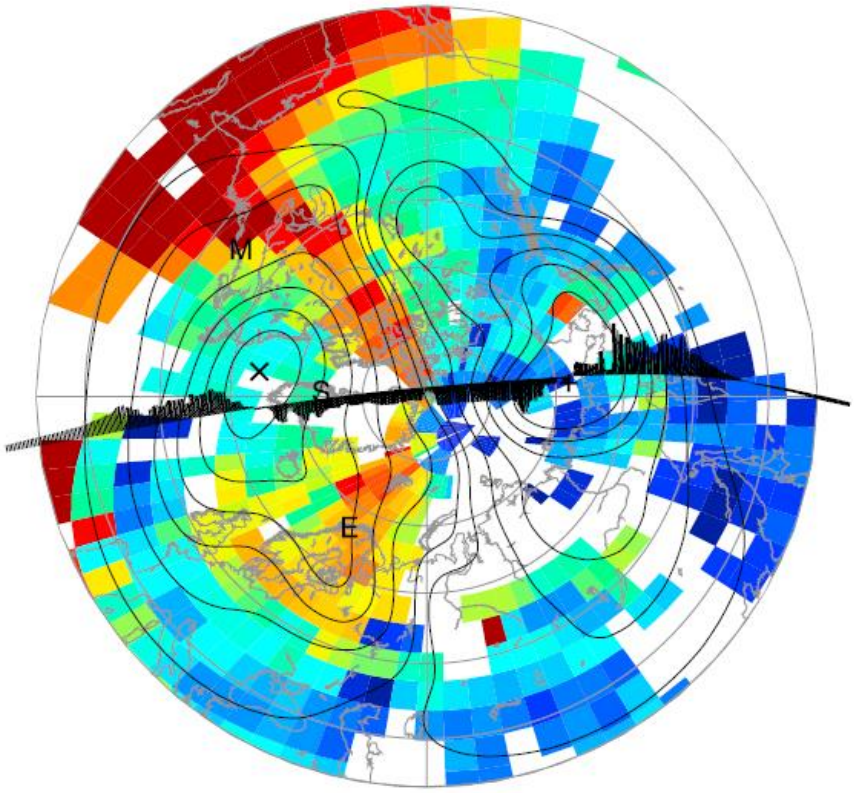


Rout et al., JGR, 2019

- One of the highest vertical drift recorded by Jicarmarca ISR.
- It is shown that with only penetration electric field and without substorm contribution, this much vertical drift is not possible.

Storm enhanced density (SED) over mid-high latitudes





Foster et al., JGR, 2005

Associated with the large-scale enhancement of the ionospheric convection electric field during disturbed geomagnetic conditions, solar-produced F-region ionospheric plasma is transported sunward from mid and low latitudes in the afternoon sector.

As a result, a latitudinally narrow region of storm-enhanced plasma density (SED) and increased total electron content (TEC) is carried toward higher latitudes in the noon sector.

The SED/TEC plumes identified at low altitudes map closely to plasmaspheric drainage plumes.

Complexities

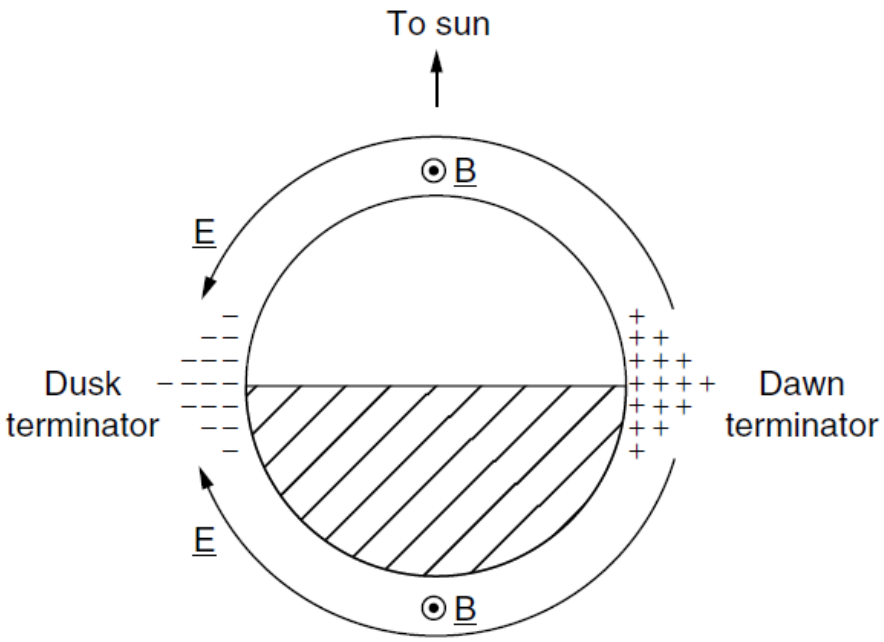
IMF By

Electric field in ionosphere is electrostatic in nature (E field is conservative or “irrotational”)

Maxwell’s equation

$$\nabla \times \mathbf{E} = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{l} = 0$$

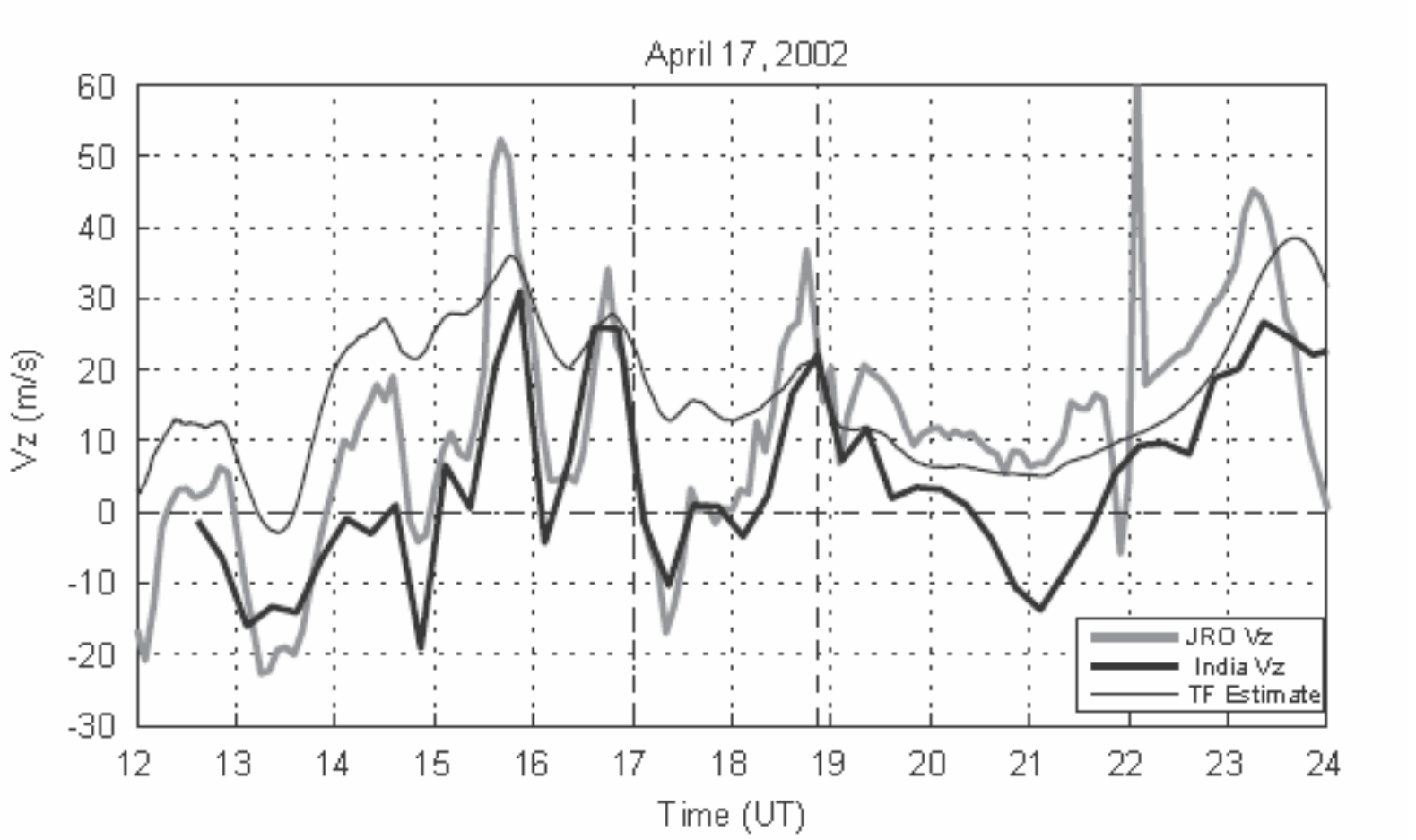


Kelley, 1989

Day and nightside ionospheric electric fields have opposite polarities.

Vertical drifts over Jicamarca (Peru) and Thumba (nearly antipodal points) are anti-correlated

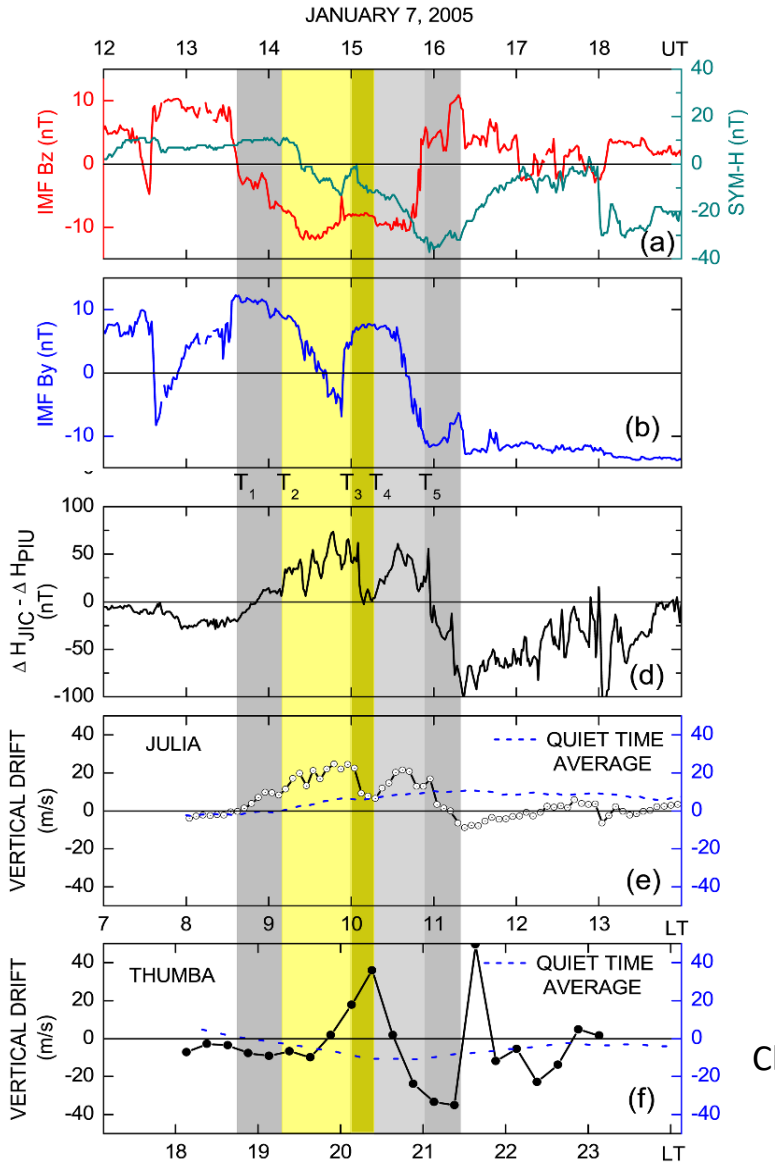
Consistent with curl-free condition of ionospheric electric field



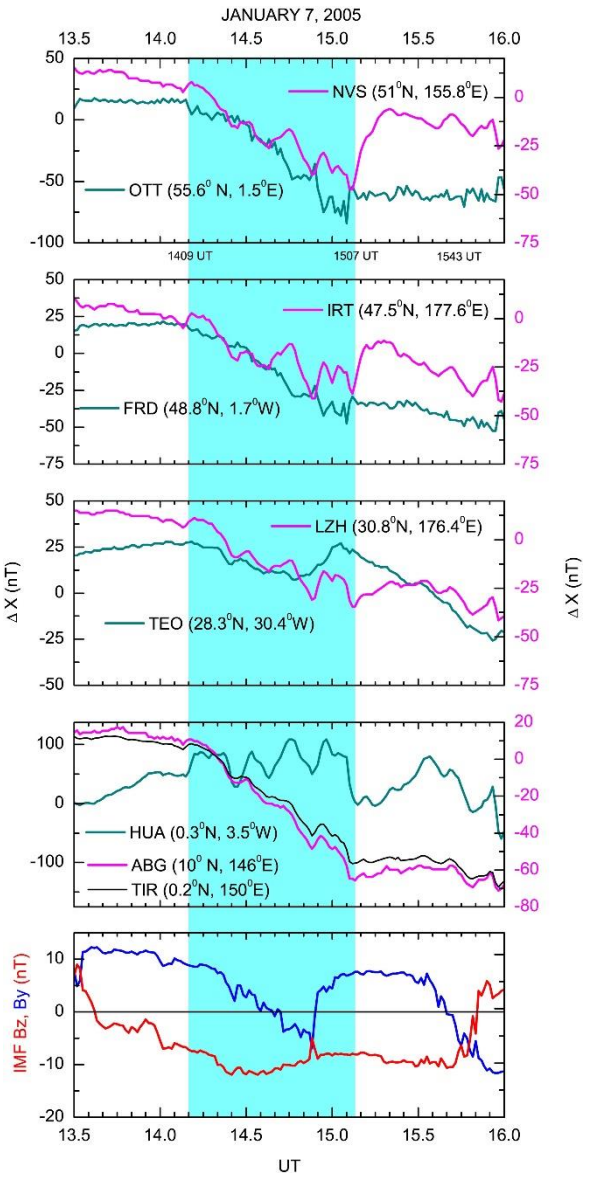
Negative of (India Vz) is plotted here

Kelley et al., 2007

- $\nabla \times \boldsymbol{E} = \boldsymbol{0}$ opposite changes in E field expected at antipodal points.
- Under influence of IMF By, similar polarities are observed during post-sunset hours

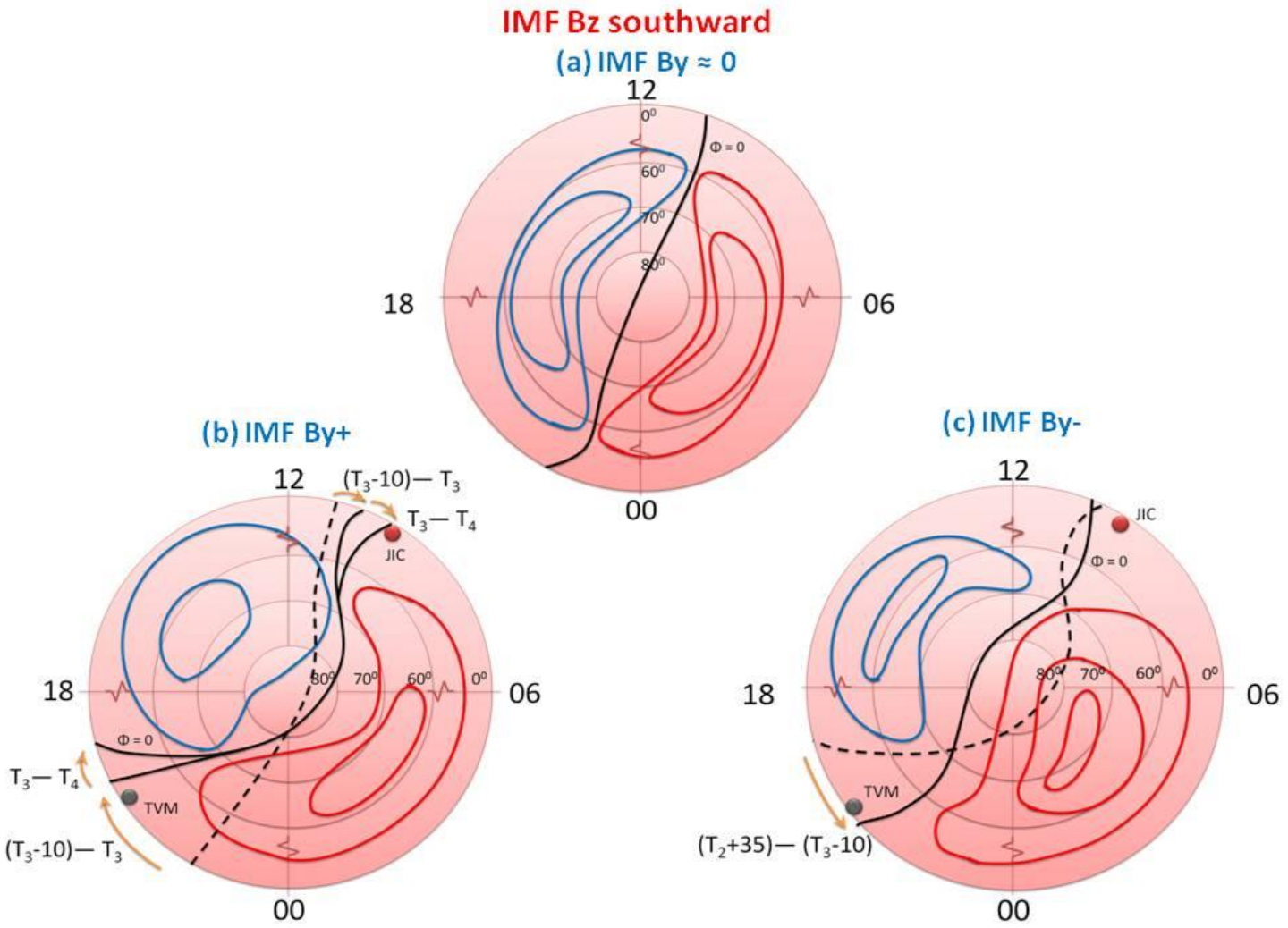


Chakrabarty et al., JGR, 2017



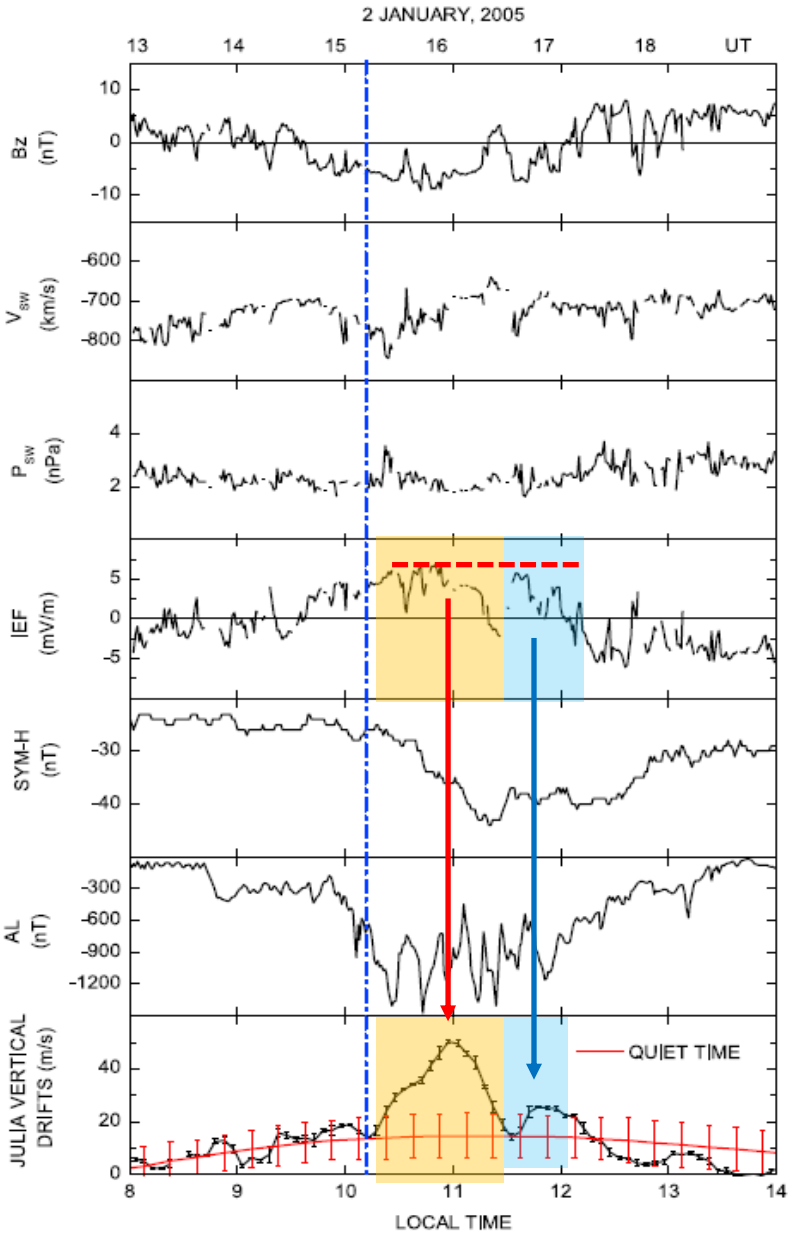
Proposed mechanism: Both Thumba and Jicamarca are coming under the same DP2 cell under the influence of IMF By

As far as E-field is concerned, it's still daytime over Thumba!



Chakrabarty et al., JGR Space Physics , 2017

Substorm

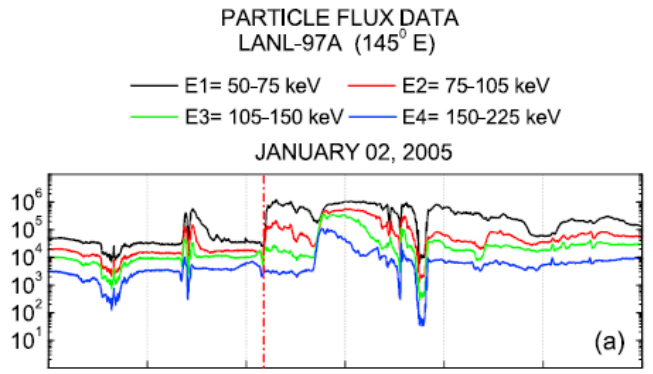


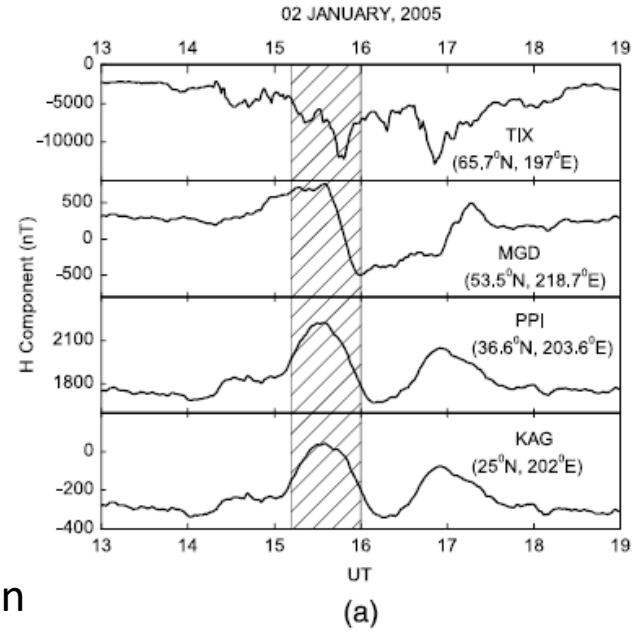
Southward IMF Bz

+ IEFy

Increase in Ionospheric Ey

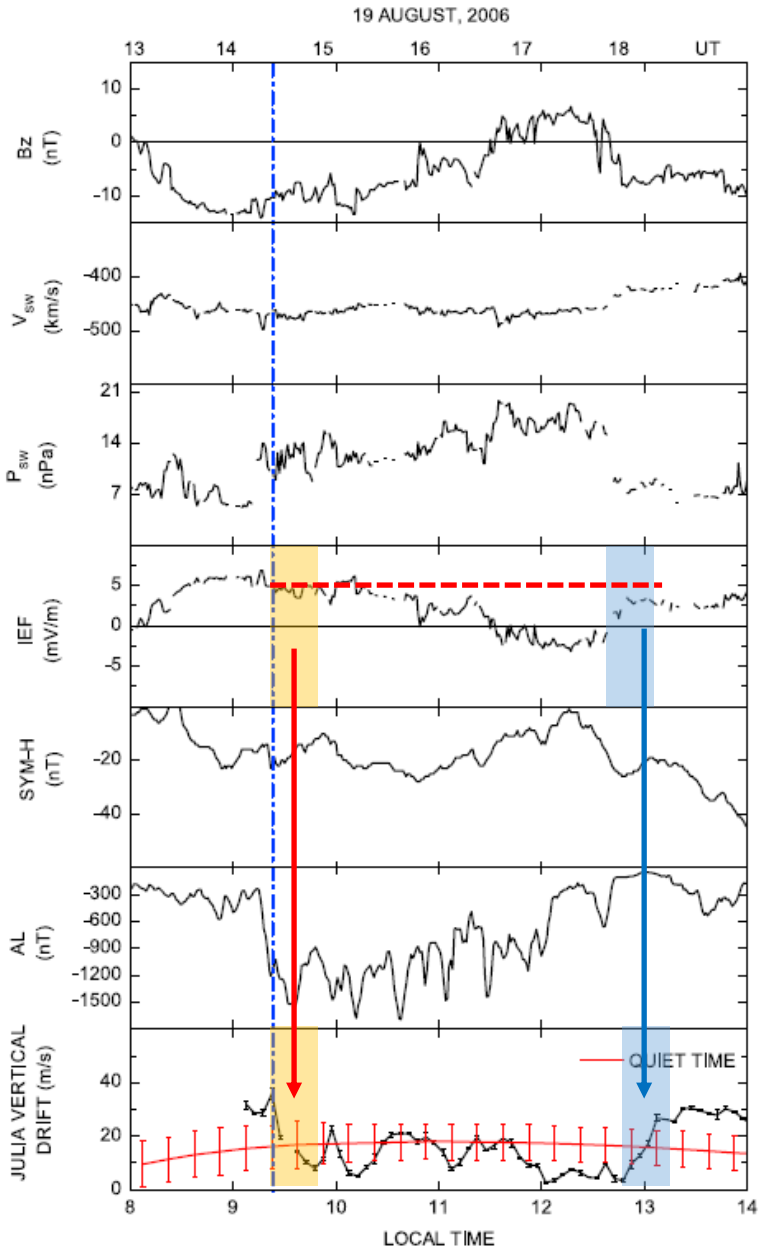
Storm and substorm acting in tandem





Hui et al., JGR, 2017

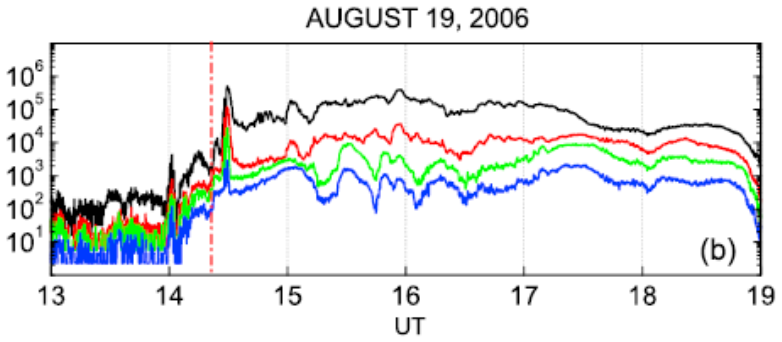
Storm and substorm acting in opposition

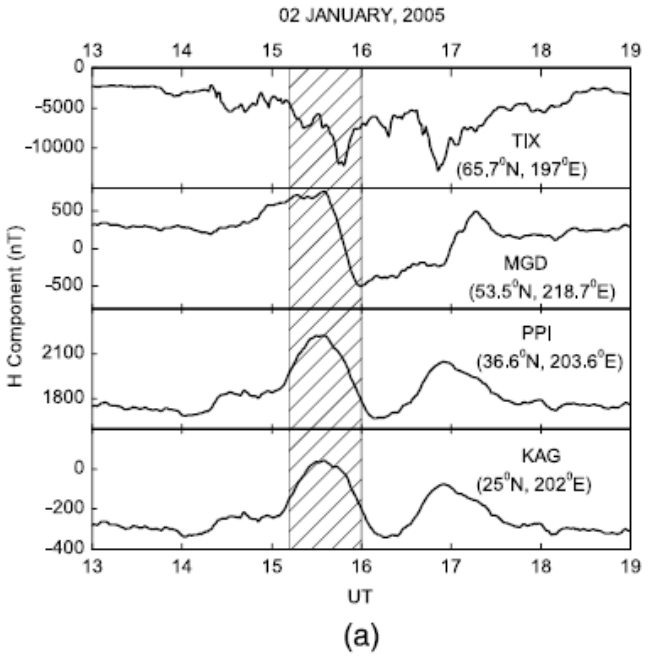


Southward IMF Bz

+IEFy

Decrease in Ionospheric Ey





Hui et al., JGR, 2017

Estimated contributions due to Substorms

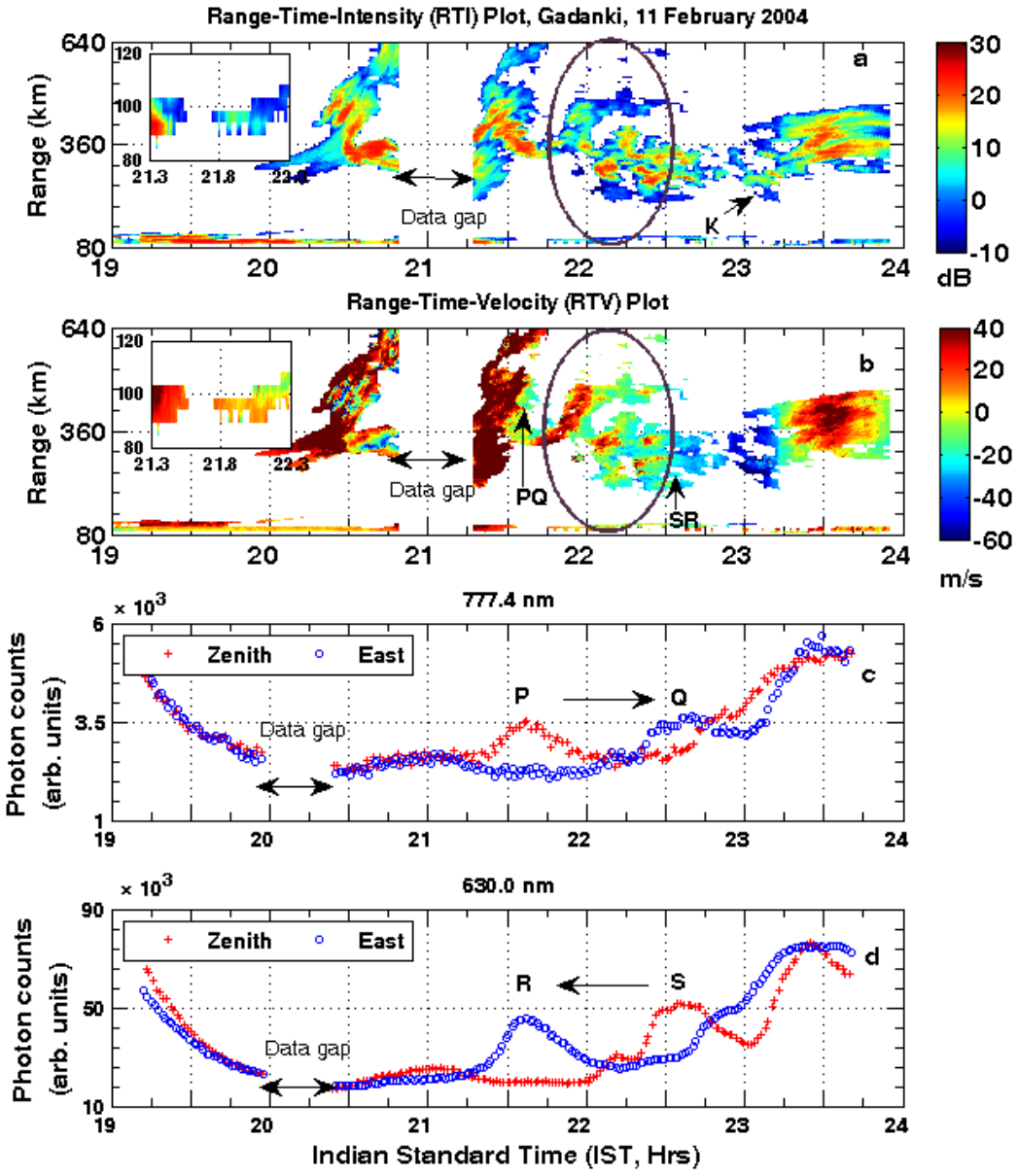
Table 1. A Comparison of Different Model and Measured Electric Fields Over Jicamarca During the Two Events Brings Out the Competitive Contributions of Substorms[a]

	Quiet Time Field [*Hui and Fejer*, 2015] (mV/m)	Max Storm Contribution [IEFy/10] (mV/m)	Measured Field From JULIA (mV/m)	Min Range of Substorm Contribution (mV/m)	Comments
2 January 2005					
1100 LT	0.36 ± 0.21	0.37	1.24	0.3–0.7	Substorm contribution could be underestimated due to DD which is of the order of a few m/s
1155 LT	0.35 ± 0.21	0.4	0.62		substorm absent
19 August 2006					
0920 LT	0.27 ± 0.16	0.5	0.9		Substorm absent
0945 LT	0.32 ± 0.16	0.5	0.2	−0.46 to −0.8	Westward electric field due to substorm

[a]Note that the errors in JULIA radar measurements are 1 order less than the 1 σ values of climatological drifts and thus not shown in the table.

Hui et al., JGR, 2017

Perturbations in Vertical E-field ?



C-shaped plasma irregularity structure

Airglow variations suggest shear in the zonal plasma flow

Penetration E-field present at this time

Vertical penetration E-field?

Sekar et al., JASTP, 2012

Poorly understood problems for low latitudes

- Unexpected penetration E-field polarities – **role of IMF By** (e.g. Kelley et al., GRL, 2003; Chakrabarty et al., JGR, 2017)
- Modulation of magnitude as well as polarity - **substorm induced penetration electric field** (e.g. Chakrabarty et al., GRL, 2008; Hui et al., JGR, 2016; Rout et al., JGR, 2019)
- Competition between disturbance dynamo and penetration E-field (Huang, JGR, 2019)
- Effects of penetration electric field on the **vertical E-field component**? (e.g. Sekar et al., JASTP, 2013)
- Penetration E-field due to changes in dynamic pressure (SSC) has been reported. However, effects of **changes in solar wind density ALONE** during northward IMF Bz are not well understood (e.g. Rout et al., JGR, 2016).

Thank you.