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School on the Physics of Equatorial Atmosphere

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Solar-Terrestrial Disturbance Scenario: Magnetosphere, Ionosphere/Thermosphere

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Solar-Terrestrial Disturbance Scenario: Magnetosphere, Ionosphere/Thermosphere

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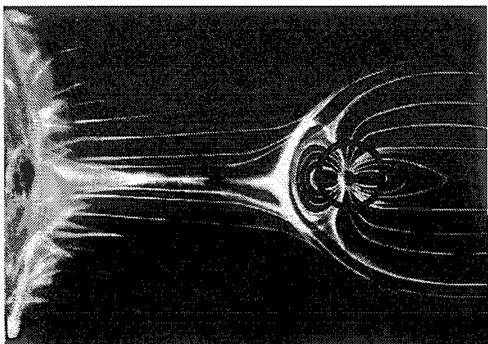
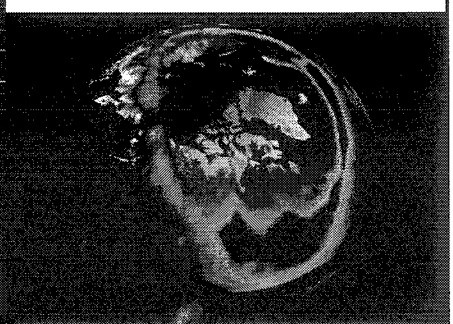
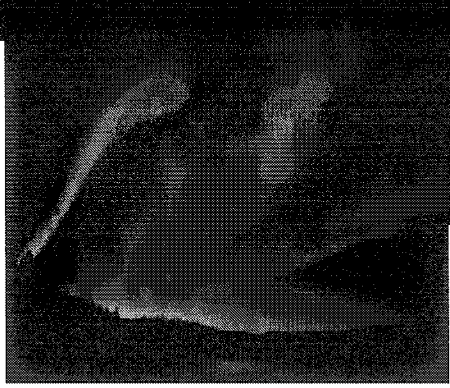


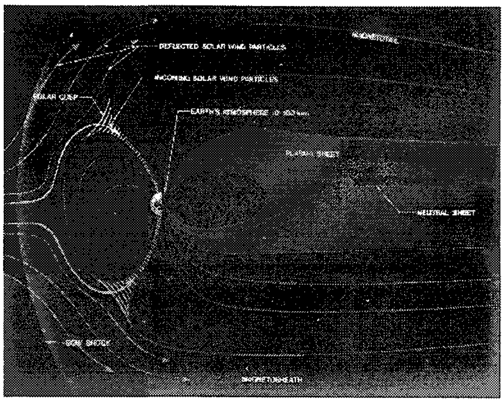
Geomagnetic disturbances are carried by the solar wind into the magnetosphere, and from the magnetosphere into the Earth's upper atmosphere...





... causing substantial changes which can be seen also from the ground.

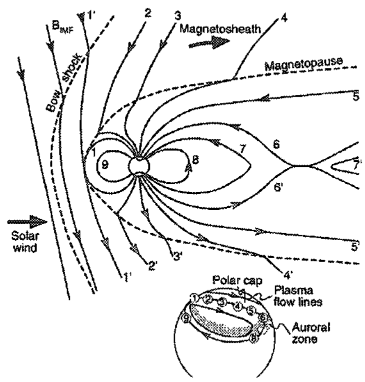
Plasma disturbances travel along the magnetic field lines into the Earth's upper atmosphere, so areas in which the magnetic field maps out into the magnetosphere are primarily affected:



Since magnetic field lines at low latitudes are closed, they are more shielded from the solar wind disturbances than regions of open field lines, which are found at higher latitudes. Therefore, the most prominent response to geomagnetic storms is observed at mid to high latitudes.

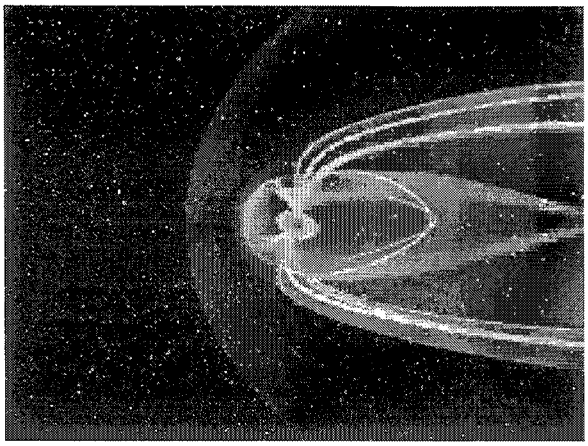
Changes of the high latitude convection field during a geomagnetic storm

- The solar wind causes convection of magnetic field lines:



- The observer on Earth experiences an **electric convection field** of:

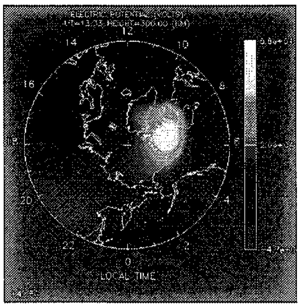
$$\vec{E}_c = \vec{u}_c \times \vec{B} \qquad u_c \ldots B \text{ drift velocity}$$



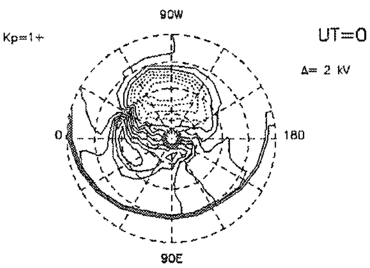
(animation)

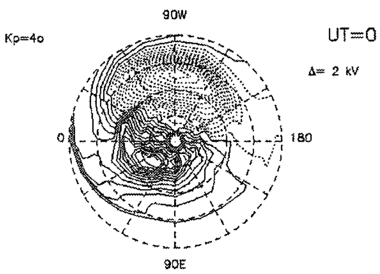
- The impact of a Coronal Mass Ejection (CME) leads to sudden changes in the solar wind dynamic pressure at the magnetopause, and thereby an enhancement of u_c and E_c

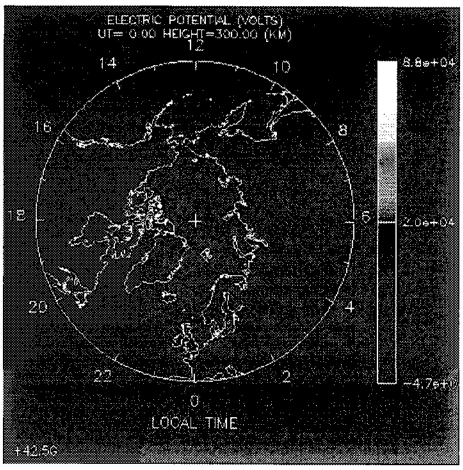
Cross-polar cap potential and Kp index



Kp	Potential	Power Input
1+	26 kV	5 GW
2+	36 kV	12 GW
3+	53 kV	29 GW
4o	57 kV	45 GW
5-	79 kV	70 GW







(animation)

• This leads to **expansion** of the convection pattern and **intensifying** electric field. The changes are particularly strong for conditions of southward IMF.

(animation)

• Simultaneously, the particle precipitation pattern intensifies and expands

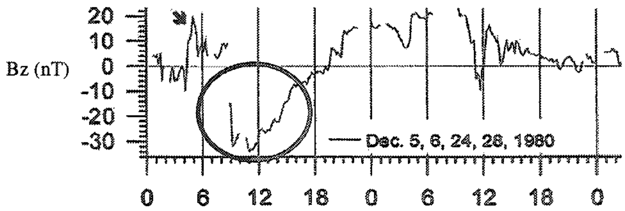
Geomagnetic storm stages:

1) Sudden Storm Commencement (SSC):

- Compression of the magnetosphere, increasing magnetopause current, which causes sudden increases of the horizontal surface magnetic field. The compression phase lasts 2-8 hours.

- Typical rise time is a few minutes, the propagation time of the MHD wave from the magnetopause to the observation point

- If accompanied by an extended period (several hours) of *southward IMF*, this leads to the storm phase

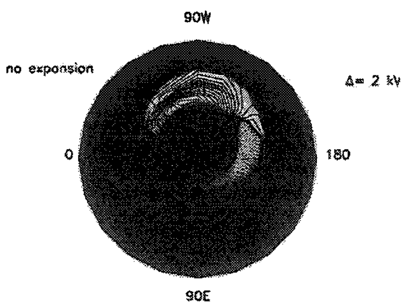


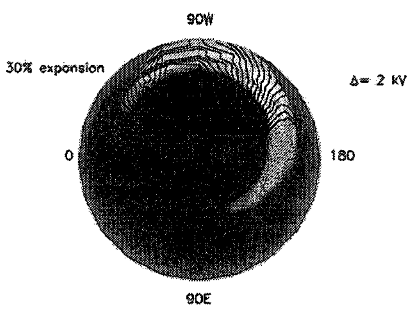
- If not followed by storm phase, this event is referred to as a *sudden impulse*

2) Initial phase:

- Electric field and precipitation intensify

- Plasma convection and particle precipitation patterns expand





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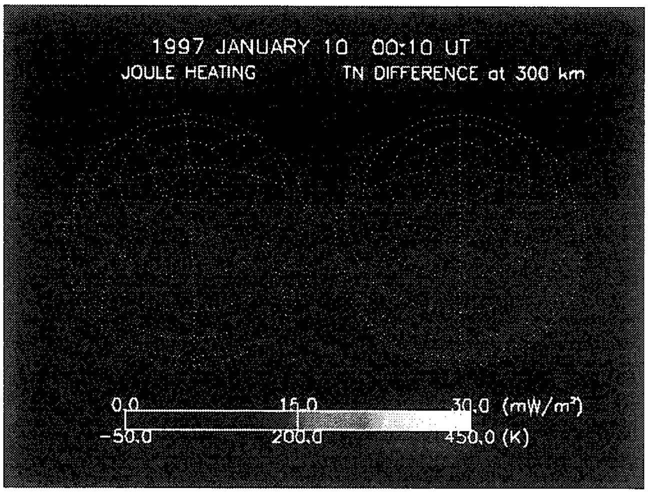
3) **Main phase:**

- Substantial increase in Joule and particle heating, enhancement of Electrojet currents
- Fast ions accelerate neutral winds in auroral zone
- Expanding aurora locally causes increases in plasma densities
- Maximum energy and momentum input into the upper atmosphere
- Temperature changes cause pressure gradients, generating strong neutral winds
- Gravity waves are generated, propagating towards lower latitudes
- Neutral winds transport plasma along the magnetic field lines at mid-latitudes, generating Travelling Ionospheric Disturbances (**TID**)
- Diverging neutral winds cause strong vertical winds, leading to changes in neutral composition, in particular the O/N_2 ratio
- Neutral composition changes affect plasma densities

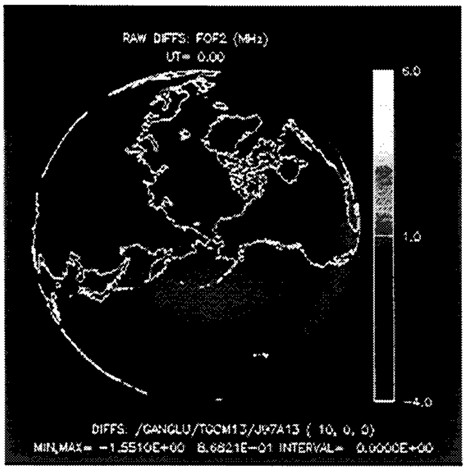
Joule heating and Temperature changes during magnetic storm



(animation)

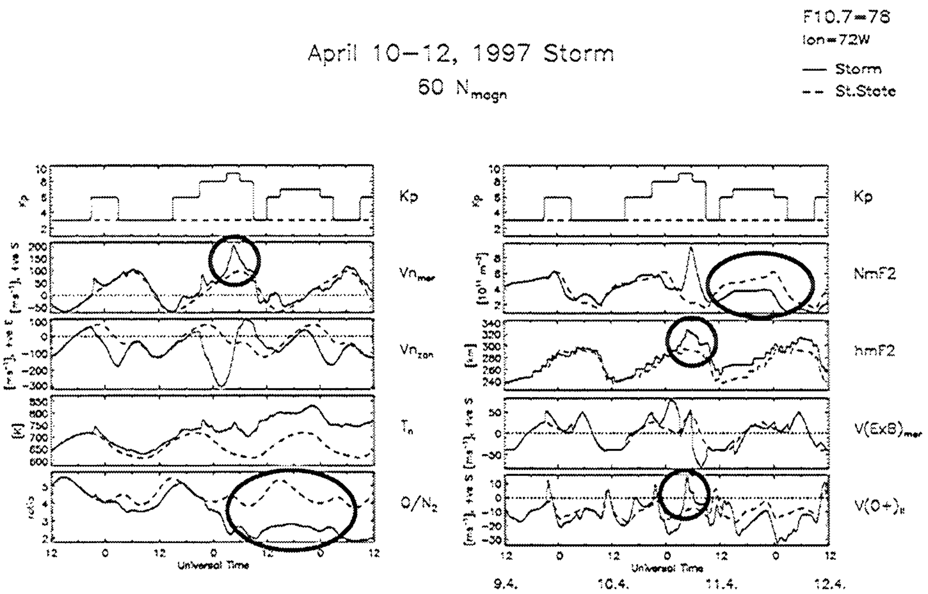
Note the rise in neutral temperature and generation of globally propagating waves!

Electron density changes during magnetic storm



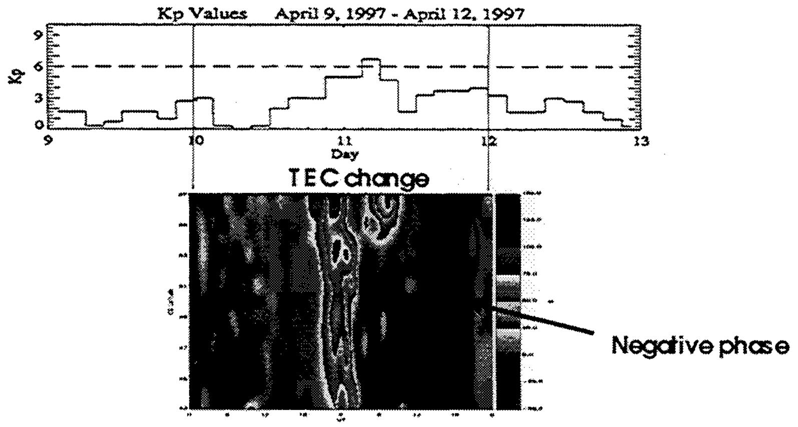
(animation)

Note that electron densities both increase and decrease during the storm. Again, perturbations propagate equatorward (TID's).



4) Recovery phase:

- Geomagnetic activity and energy input decrease
- Neutral and plasma temperatures fall
- Neutral composition changes induced during the main phase relax slower, the enhanced O/N_2 ratio leads to the *negative phase*, reduced plasma densities



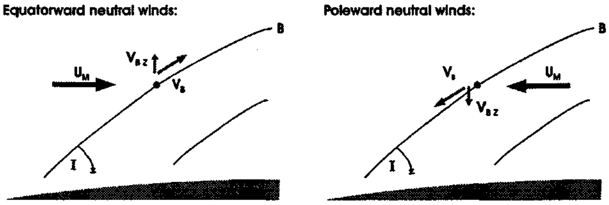
RESPONSE OF THE EQUATORIAL IONOSPHERE THERMOSPHERE SYSTEM TO MAGNETIC DISTURBANCES

Mechanisms for transferring disturbances into the equatorial ionosphere:

1) Disturbance Dynamo
2) Penetration of magnetospheric electric fields
3) Collisional transport of plasma up and down geomagnetic field lines (for dip>0!)
4) Horizontal transport of plasma (across equator)

Collisional transport of plasma by meridional winds

- Push plasma up or down the ***B*** field lines, changing *h*mF2 and NmF2
- Dependent on dip angle, *I*: $U_m \cos I \sin I$
- This effect not at magnetic equator



- Effect may occur throughout day
- Will affect plasma recombination rate, and thereby NmF2

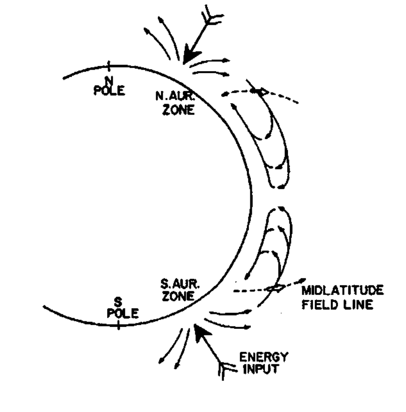
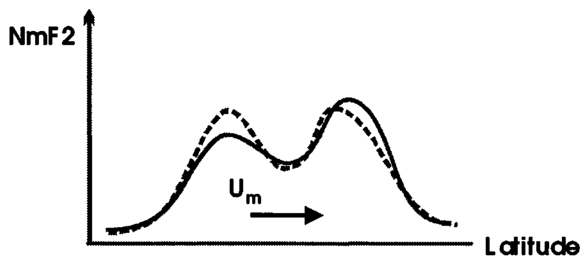


Fig. 1. Sketch of the storm circulation in the *F* region. The equatorward winds are probably strongest at heights above 150 km, while the return circulation is probably located at around 100 km (Appleton Laboratory: Crown Copyright).

Meridional wind change over the equator

- Transport plasma horizontally along the ***B*** field lines
- Affect the horizontal shape of the Appleton anomaly:



- Potentially important near **dusk** only
- Reduces probability for occurrence of ESF?

Disturbance Dynamo

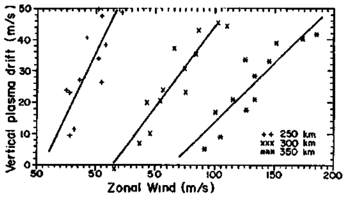
Enhanced eastward winds

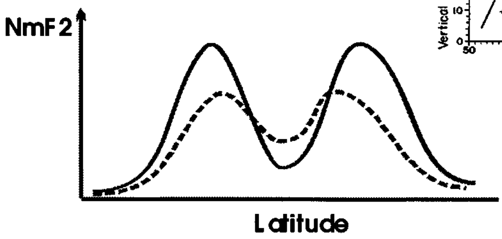
- Stronger **eastward** wind increases the eastward electric field through the F-region dynamo

  ⇒ Stronger vertical ***E×B*** plasma drifts

  ⇒ Enhanced pre-reversal enhancement

  ⇒ **Enhanced** Appleton anomaly

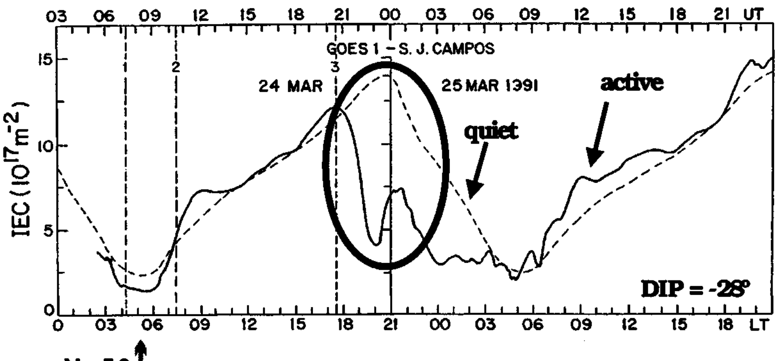


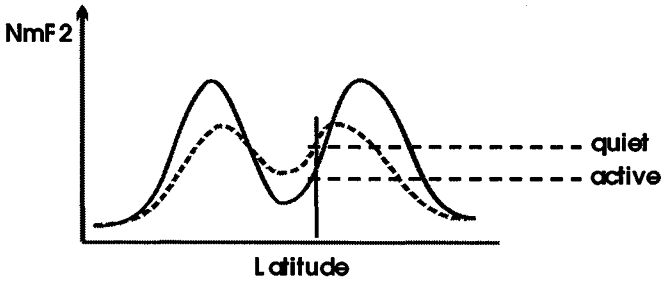


  ⇒ Possibility of increased occurrence of Equatorial Spread-F (ESF)

- Effect likely to occur primarily for enhancements of eastward wind at **dusk**

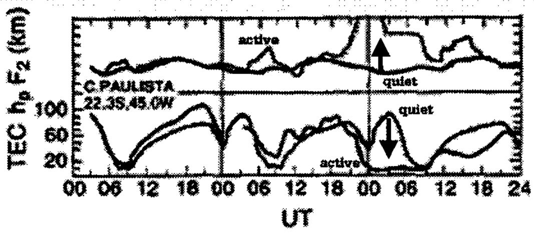
Effect of enhanced eastward winds on Appleton anomaly





Effects of expanded Appleton anomaly for locations inside Appleton anomaly:

- Locally **depleted NmF2 (TEC)**
- Locally **enhanced *h*mF2**

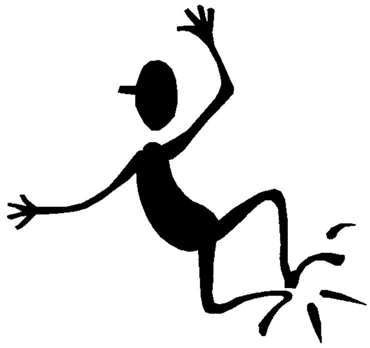


- **Opposite effect for locations normally outside the Appleton anomaly**

Effects of enhanced westward winds

- Westward wind generated by
  - equatorward meridional winds, through Coriolis forces
  - propagating gravity wave
- Reduce or reverse eastward dusk electric field
- Reduce vertical dusk plasma drifts or reverse them to downward
- Reduce or inhibit Appleton anomaly
- Reduce occurrences of ESF

AND FINALLY....



Concluding comments

- Equatorial ionosphere coupled to high latitudes primarily through neutral dynamics
- Meridional winds move plasma vertically in regions outside the magnetic equator
- Zonal winds affect the strength and distribution of the Appleton anomaly through changes in the dusk zonal electric field, which controls vertical plasma drifts
- Outside the magnetic equator the overall response of *h*mF2 and NmF2 to storm events depends on the balance between meridional wind induced and zonal wind induced vertical plasma drifts
- The storm-induced changes in Appleton anomaly affect other phenomena, such as the occurrence of ESF
- The exact response depends critically on the timing and strength of the geomagnetic storm

Further Reading

Key text books:

• Rishbeth, H., and O. Garriott: *Introduction to Ionospheric Physics*, Academic Press, New York, 1969

• Banks, P. M., and G. Kockarts, *Aeronomy*, Academic Press, New York, 1973

• Kelley, M. C., *The Earth's Ionosphere*, Academic Press, London, 1989

• Rees, M. H., *Physics and Chemistry of the Upper Atmosphere*, Cambridge University Press, Cambridge, U.K., 1989

• Gombosi, T. I., *Physics of the Space Environment*, Cambridge University Press, Cambridge, U.K., 1998

• Schunk, R. W., and A. F. Nagy, *Ionospheres*, Cambridge University Press, Cambridge, U.K., 2000

Key articles:

• *Journal of Atmospheric and Terrestrial Physics* Vol. 57, No. 10, pp 1063-1133, 1995: Special Issue with papers from the Equatorial Ionosphere-Thermosphere Coupling and Dynamics (EITCD) symposium, held in Buenos Aires in 1993.