# A generic description of planetary aurora

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# Context

We consider a rotating planetary body that orbits a star.

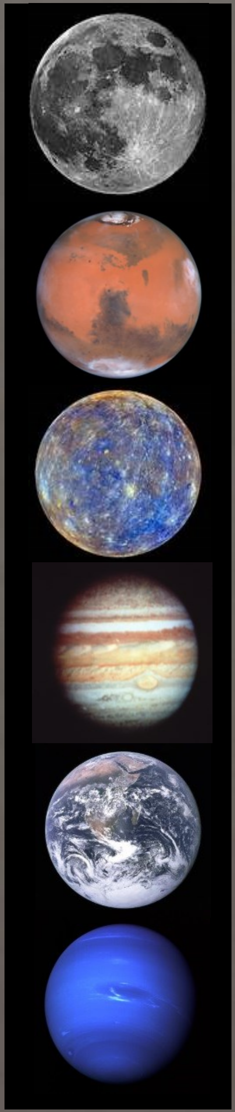
The star is assumed to have a stellar wind.

The motion of the body relative to the stellar wind is supersonic, i.e. the wind speed is supersonic or the planet orbits the star very closely at a high orbital speed.

This situation reflects planets in the Solar System, but it may be applicable to many exoplanets as well.

# Classification of magnetospheres

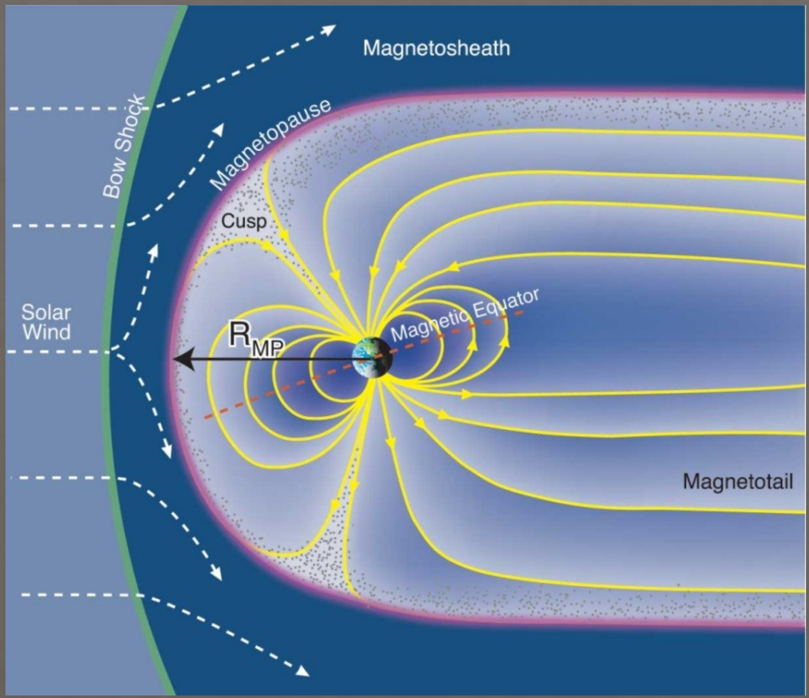
- No or weak magnetic field
  - No ionosphere
    - *stellar wind – exosphere interaction*
  - Ionosphere
    - *induced magnetosphere*
- Strong magnetic field
  - No ionosphere
    - *magnetosphere without inner current closure and without cold plasma*
  - Ionosphere
    - *classical magnetosphere*
    - parallel $\vec{B} \uparrow\uparrow \vec{\Omega}$ / anti-parallel $\vec{B} \uparrow\downarrow \vec{\Omega}$ / tilted $\vec{B} \leftrightarrow \vec{\Omega}$



# Classical magnetospheres

In "classical magnetospheres"

- The planetary object has an intrinsic magnetic field
- It is rotating.
- It has a conducting ionosphere.
- Plasma escapes from the ionosphere.
- There may be additional inner sources of plasma.




Such magnetospheres have

- a plasmasphere,
- a magnetopause & boundary layer,
- a magnetotail with a current sheet.

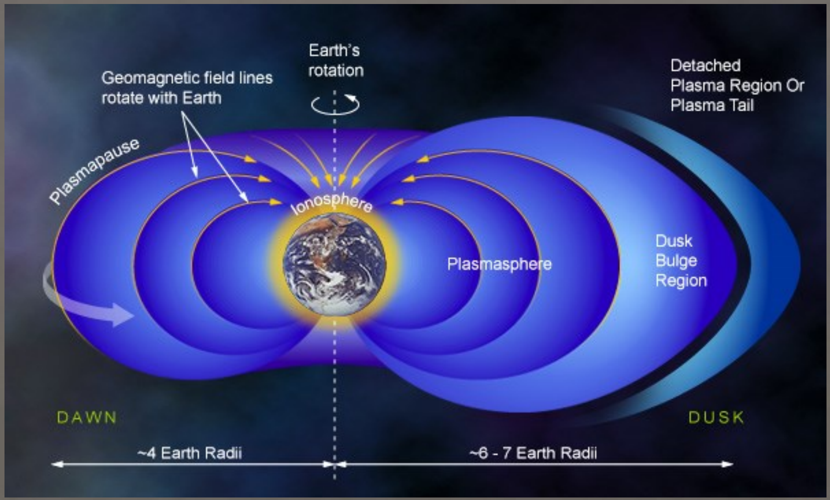
# Plasma circulation

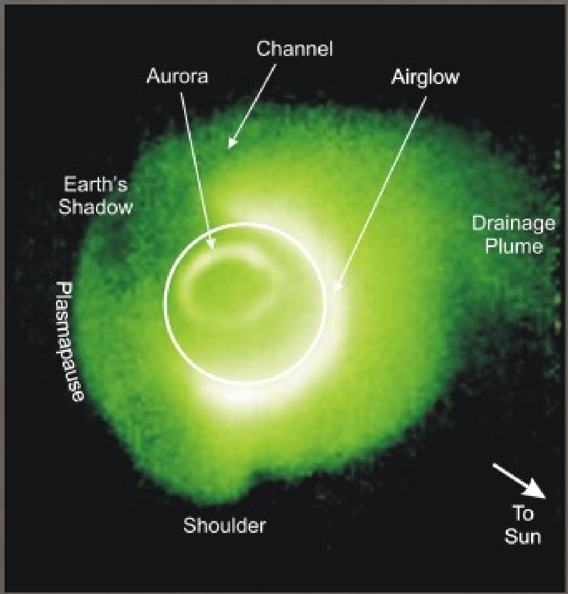
Plasma of solar wind origin :

- Limited entry of solar wind is possible through various mechanisms (reconnection, diffusion, plasma transfer).

Plasma of terrestrial origin :

- Escape from the ionosphere is due to energy input from solar radiation or precipitating particles. These produce a plasmasphere reservoir on closed field lines, which loses mass via a plasmaspheric wind and plumes.



# Magnetospheric electric field

Corotation + dawn-dusk electric field is

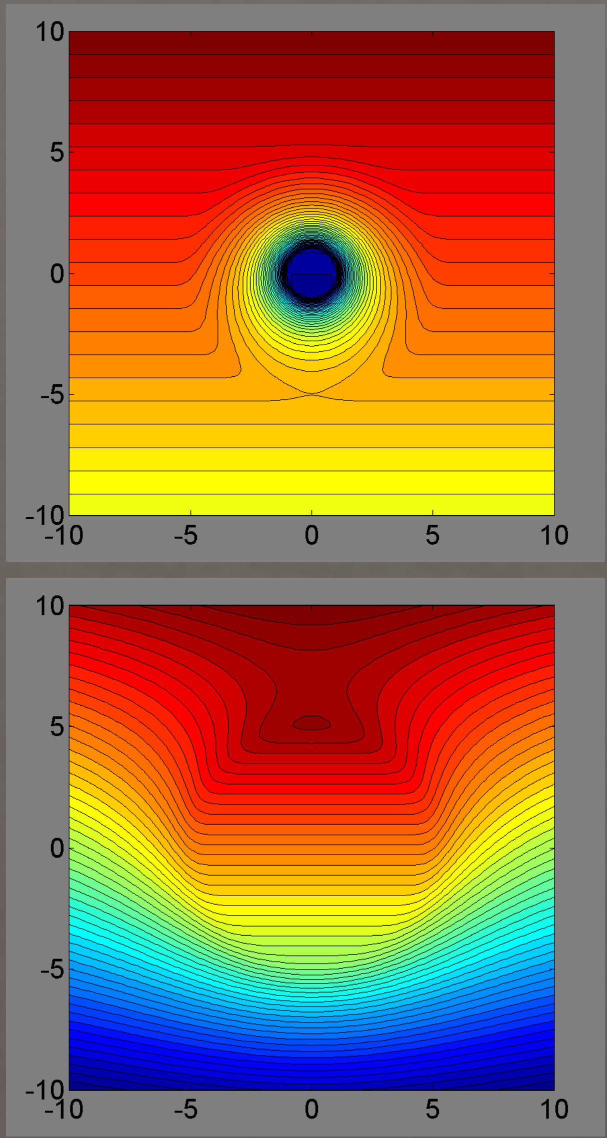
$$\vec{E} = -(\vec{\Omega} \times \vec{R}) \times \vec{B} + \overrightarrow{E_{dd}}$$

where $\vec{\Omega}$ is the angular rotation vector.

Basic assumptions

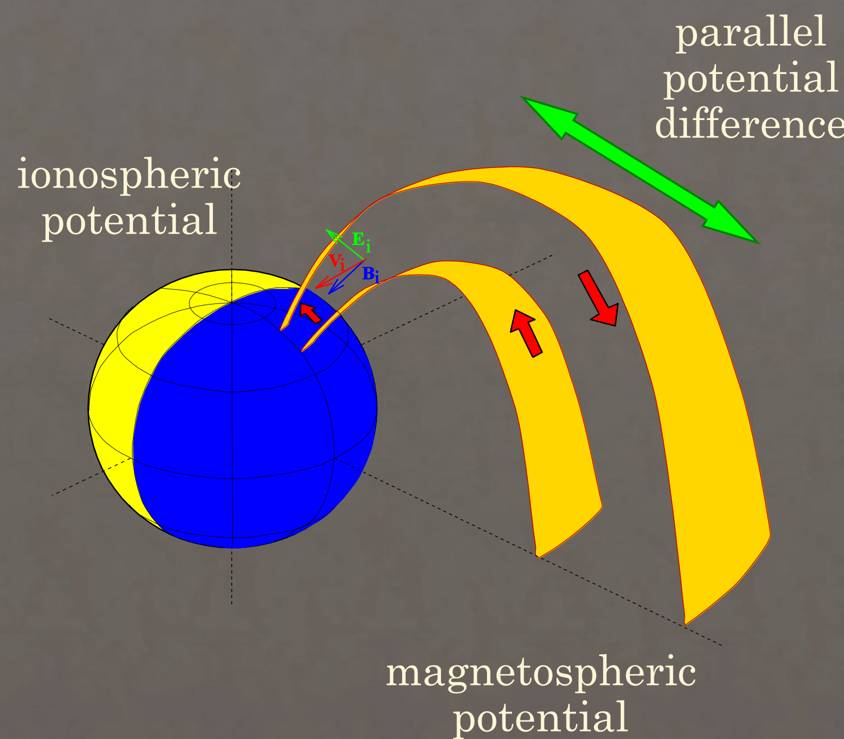
- No dynamic effects (no induced $\vec{E}$)
- No charge separation (small scales)

This is the basis of the Volland-Stern model. You can look at it in an inertial frame, or in the corotating frame (useful if you want to relate it to the ionosphere). The pictures show the corresponding equatorial equipotentials for a dipole field.



# Magnetosphere – ionosphere coupling

Electric potential differences across field lines in the magnetosphere map onto the ionosphere, thereby producing parallel electric fields.




Up- and downward currents connect the magnetospheric generator to the ionospheric load as dictated by the current-voltage relationship $j_{||} = f(\Delta\Phi)$.

# Current continuity

$x_{iono}$ or $\Lambda$ : ionospheric coordinate
$\Phi_{iono}$, $\Phi_{msph}$, : ionospheric and magnetospheric potential
$\Delta\Phi = \Phi_{iono} - \Phi_{msph}$: parallel potential difference
$\Sigma_P$: height-integrated Pedersen conductivity
$j_{||}$ : parallel current
$I_P$ : horizontal Pedersen current

Current continuity (assuming a vertical field geometry)

$$\frac{dI_P}{dx_{iono}} = -j_{||}\ , \quad I_P = -\Sigma_P \frac{d\Phi_{iono}}{dx_{iono}}$$

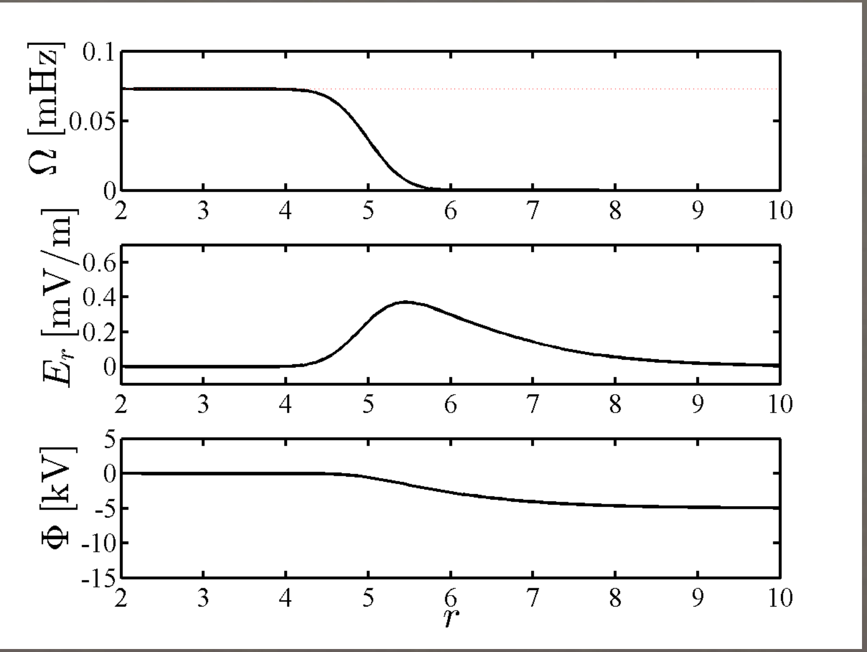
i.e. the nonlinear second order ODE

$$\frac{d}{dx_{iono}}\left(\Sigma_P \frac{d\Phi_{iono}}{dx_{iono}}\right) = j_{||}$$

where $\Sigma_P$ and $j_{||}$ may depend nonlinearly on $\Delta\Phi$.

# Structure at the midnight meridian

From the Volland-Stern type magnetospheric potential in the corotating frame, we obtain the profiles for $\vec{\Omega}$, for $E_r$, and for the magnetospheric potential $\Phi$, along the equator in the midnight meridian plane. There is an electric field peak between the corotating plasmasphere and the inner edge of the plasma sheet.




Note: Failure for large $r$ as the field is no longer dipolar.

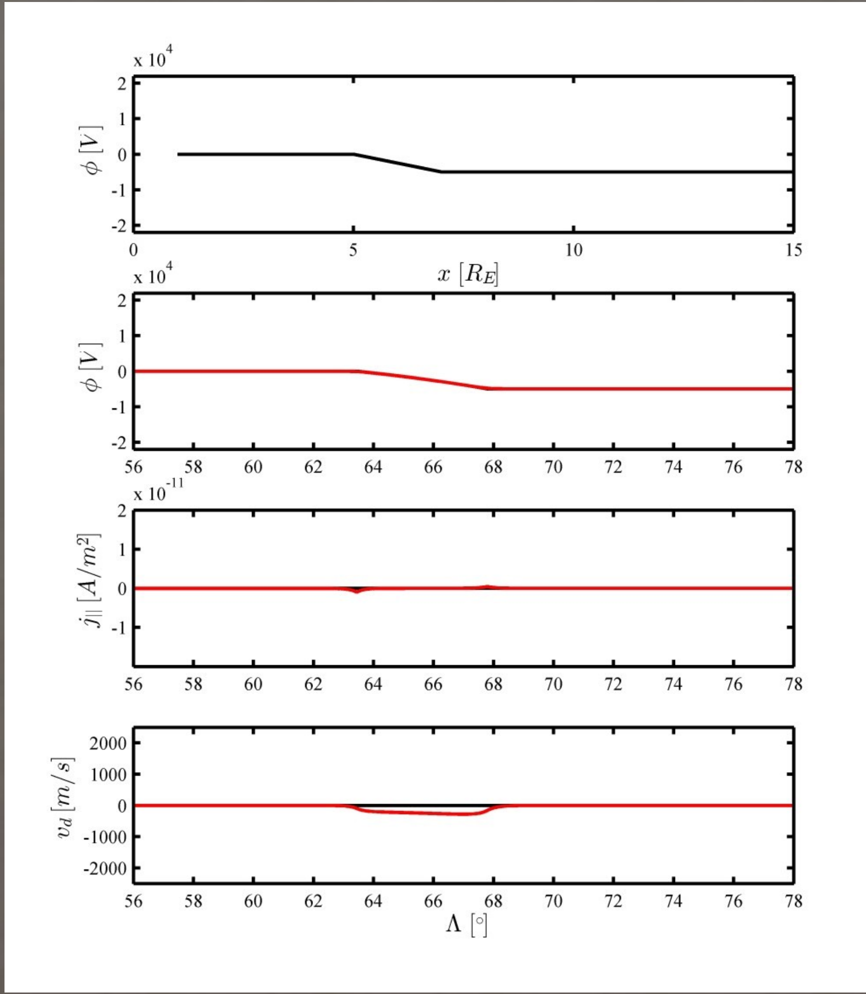
# Auroral structure for a ↑↓ planet

Modelling $\Phi_{msph}$ as a step-like profile, for a constant $\Sigma_P$, and

$j_{||} = K_+ \Delta\Phi$ if $\Delta\Phi > 0$ and
$j_{||} = K_- \Delta\Phi$ if $\Delta\Phi < 0$,

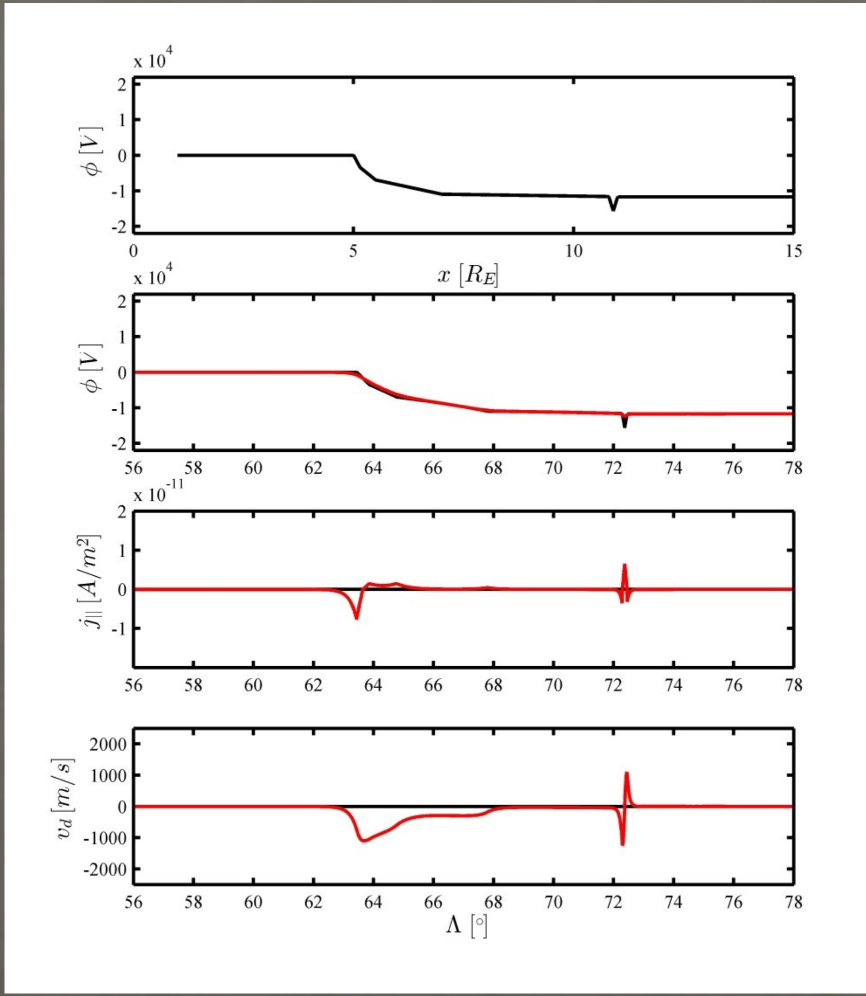
the solution shows :

- *persistent westward convection* over the ionospheric projection of the corotation edge (*SAEF*)
- (small) downward current at low latitude, with $\Delta\Phi$ removing electrons from the ionosphere
- (small) upward current at high latitude, with $\Delta\Phi$ accelerating electrons into the ionosphere
- auroral effects are permanent, but depend on $\Omega$, $B$, $K$ and $\Sigma_P$



In an active magnetosphere, short-scale potential variations appear in the near tail. The plasma sheet moves inward and the corotation edge steepens:

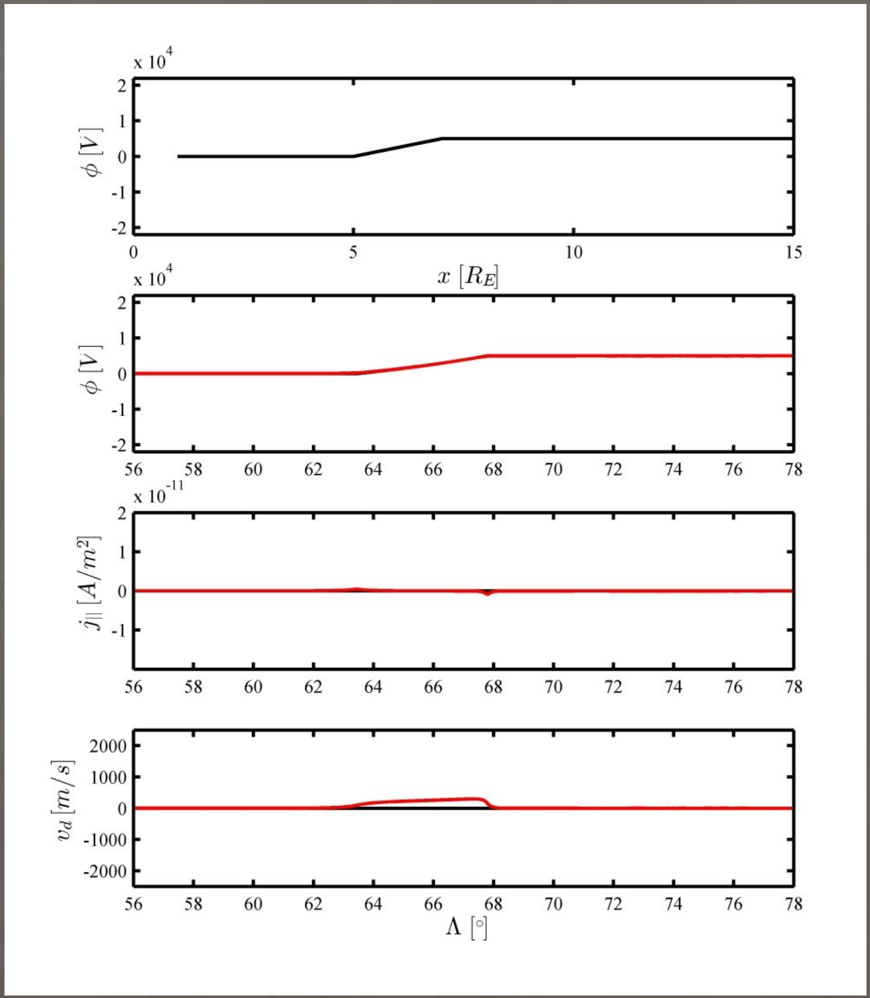
- downward current and *transient strong westward convection (SAPS/SAID),*
- upward current in *transient discrete auroral arcs (larger* ΔΦ, *strong spatially concentrated emission)*
- downward current in *transient black aurora (spatially concentrated absence of emission, electrons removed from ionosphere).*



# Auroral structure for a ↑↑ planet

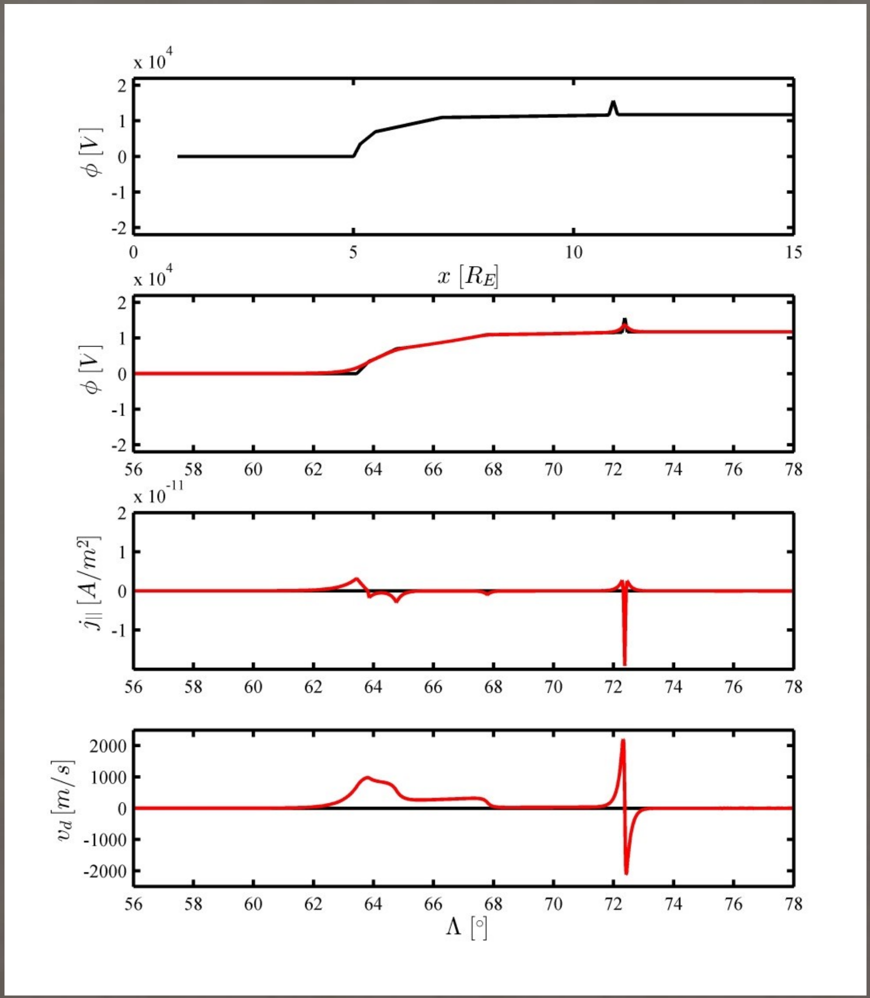
The situation is now reversed.
The configuration consists of

- *persistent eastward convection* over the ionospheric projection of the corotation edge (*SAEF*)
- (small) upward current at low latitude, with $\Delta\Phi$ accelerating electrons into the ionosphere
- (small) downward current at high latitude, with $\Delta\Phi$ removing electrons from the ionosphere
- auroral effects are permanent, but depend on $\Omega$, $B$, $K$ and $\Sigma_P$



In an active magnetosphere :

- upward current, *transient strong eastward convection, and broad auroral arcs* at low latitude,
- upward current in *transient discrete auroral arcs (larger* ΔΦ*, strong spatially concentrated emission)* at high latitude
- downward current in *transient black aurora (spatially concentrated absence of emission, electrons removed from ionosphere).*

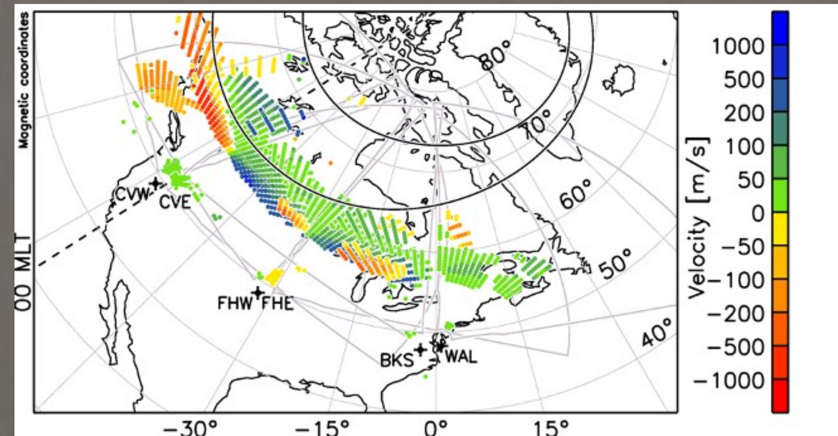


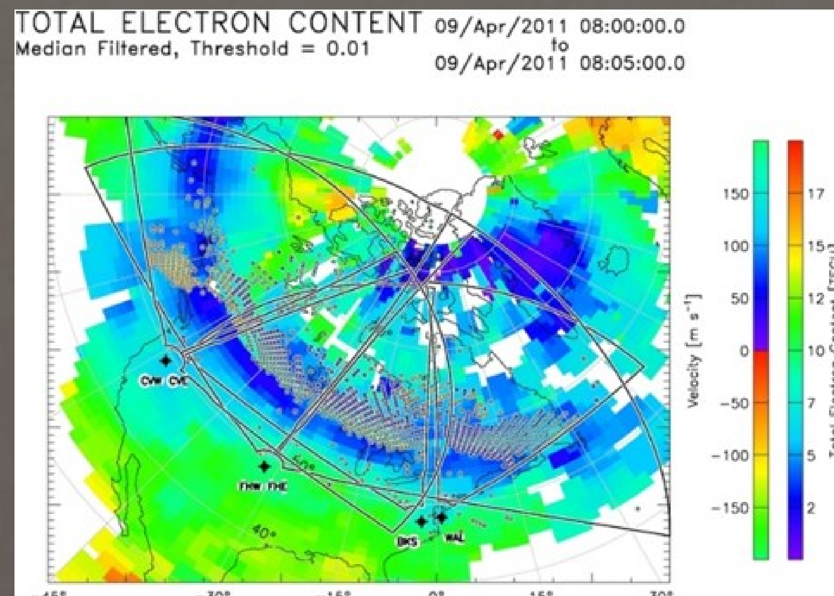
# Earth : an ↑↓ planet

# Earth : corotation border

The corotation border corresponds to subauroral electric fields (SAEFs). For increasing geomagnetic activity, the corotation boundary becomes steeper and SAPS/SAID appear:

- Because of the high $K_-$, there is only a small negative $\Delta\Phi$: $\vec{E}_{msph}$ is projected into the ionosphere, leading to strong westward flow ($\vec{E} \times \vec{B}$ drift).
- As electrons are accelerated out of the ionosphere, there is a charge carrier depletion.



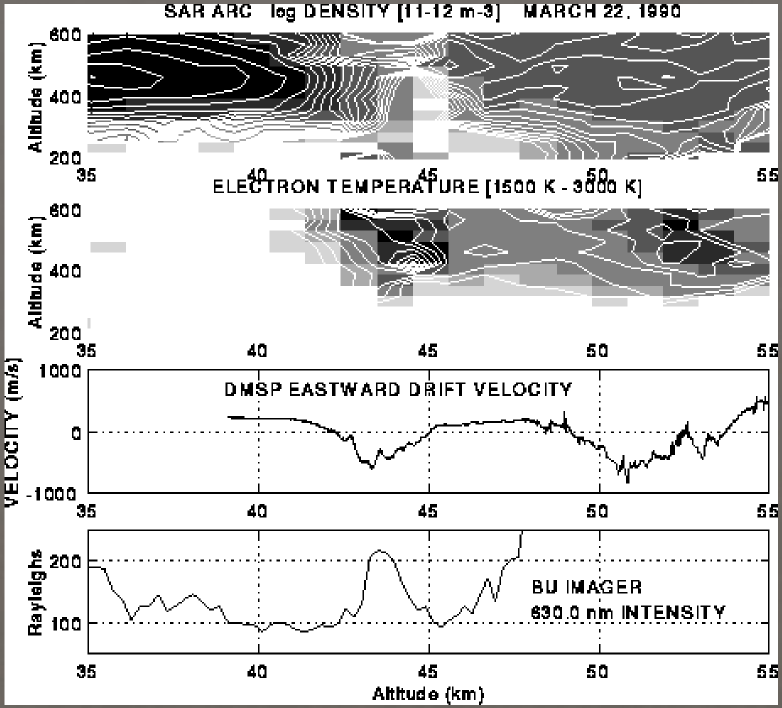
Observations indeed show :

- ionosphereic electron depletion

- very strong ionospheric flows (> 1 km/s)

- ion-neutral collisions may produce stable auroral red arcs (630 nm)

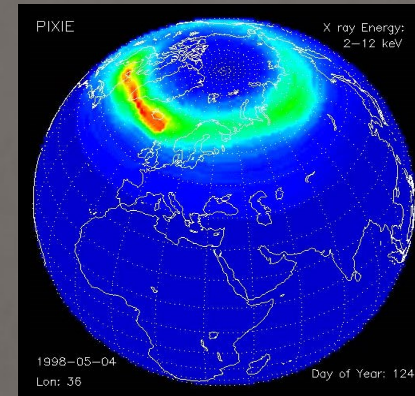
- local heating of the ionosphere and upward flow

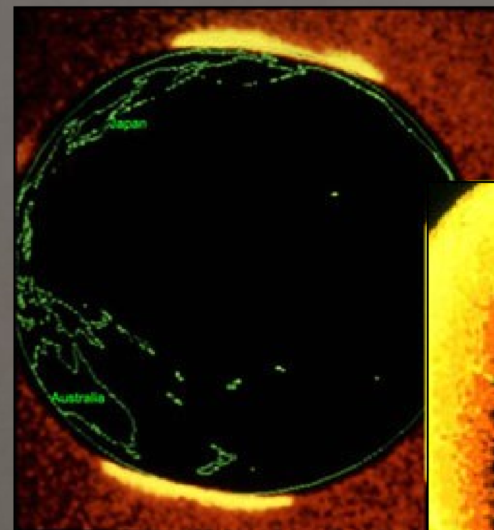


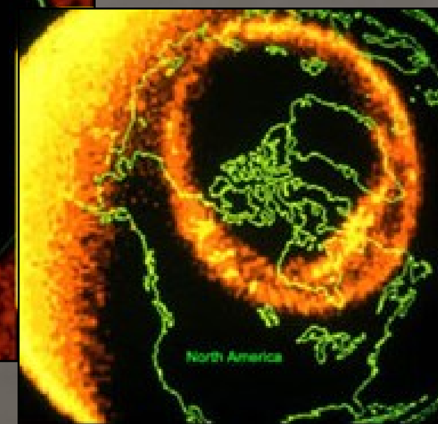

# Earth : aurora

Higher latitude :

More or less permanent oval with transient appearance of discrete auroral arcs and black aurora.



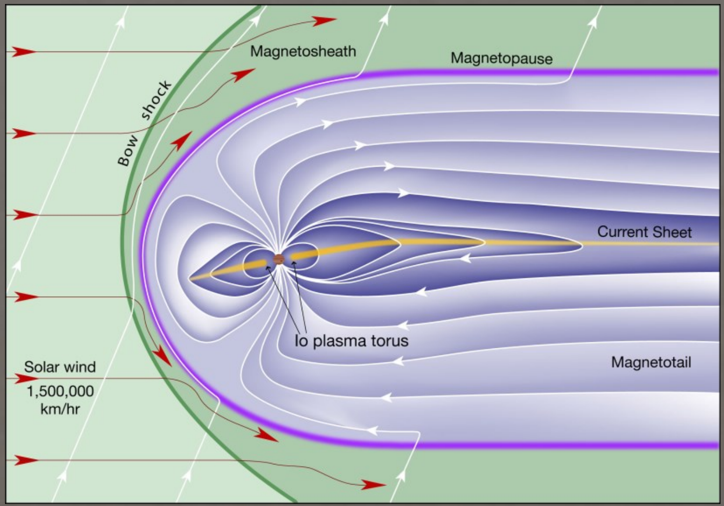




# Jupiter and Saturn : ↑↑ planets

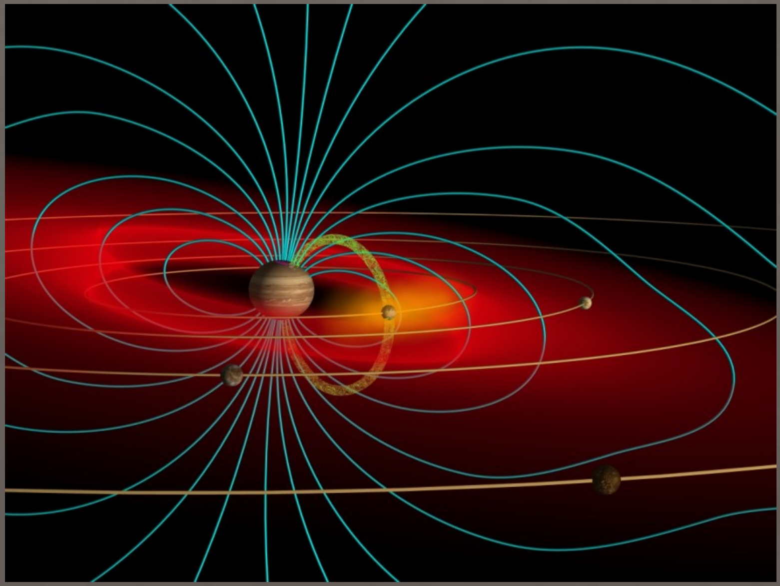
# Inner plasma sources

Jupiter and Saturn are ↑↑ planets, but with one additional ingredient: additional sources of plasma inside a magnetosphere in the form of a moon that releases neutrals.



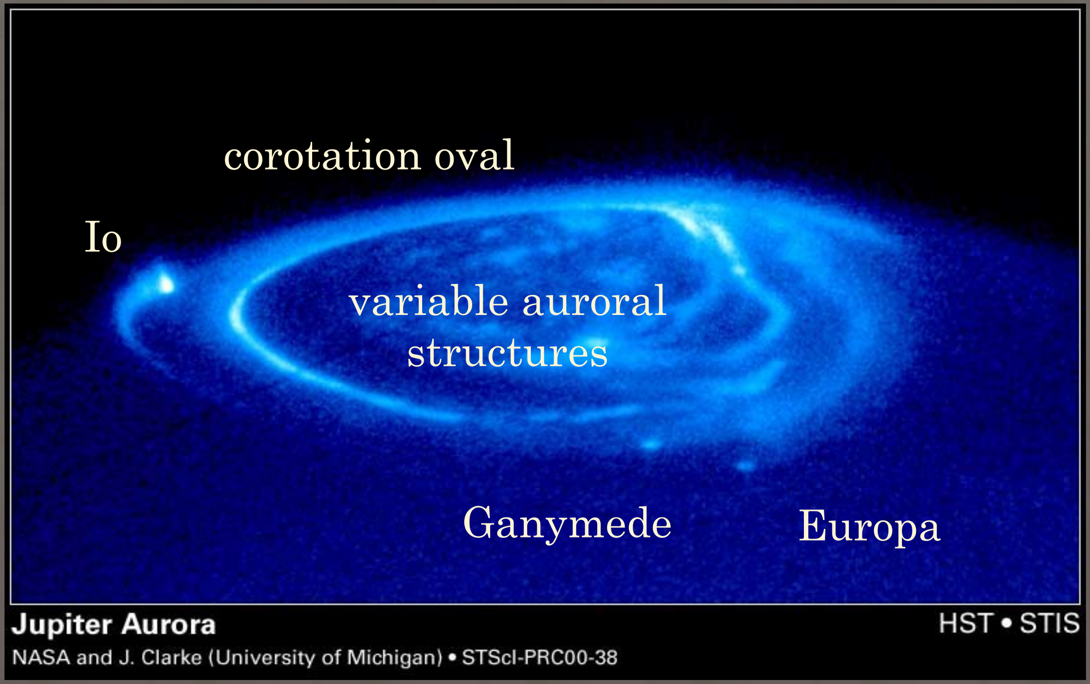

Neutrals are typically photo-ionized. The ions

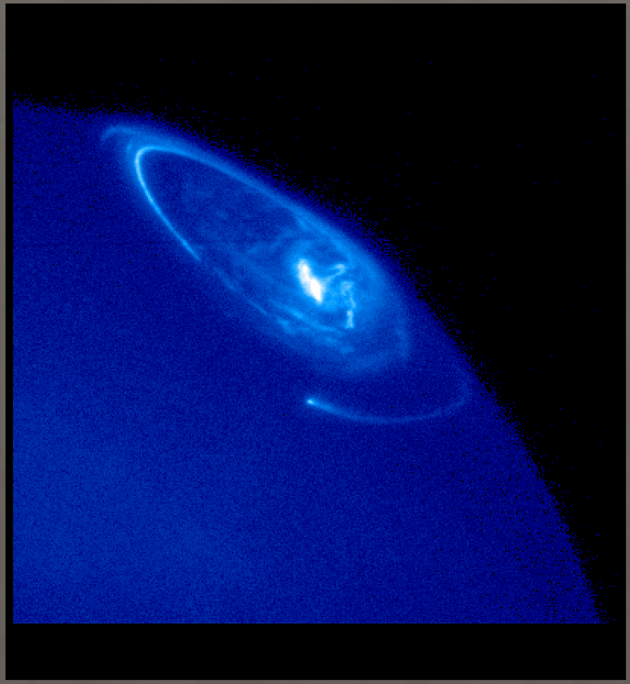
- lead to mass-loading : *deformation of the field*
- follow the field : *(conjugate) auroral footpoints*



# Jovian aurora

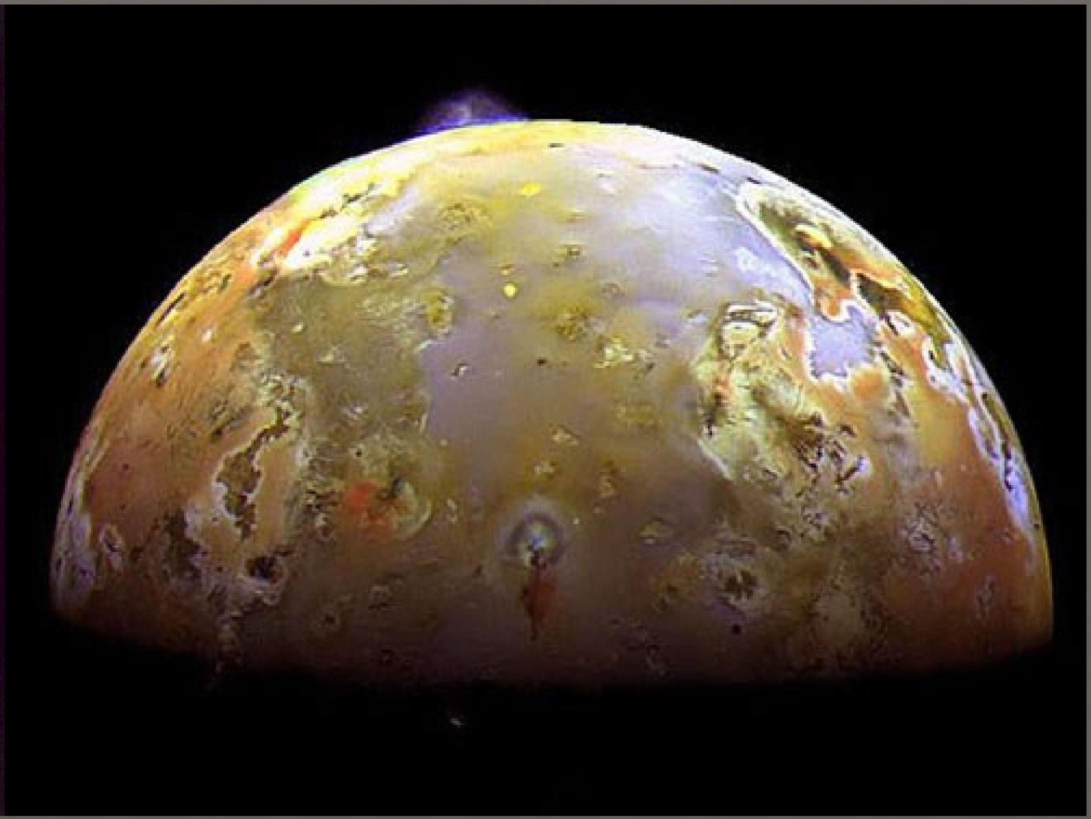
- Corotation boundary : permanent aurora
- Higher latitude : varying, depending on magnetospheric activity
- Footpoints of the moons



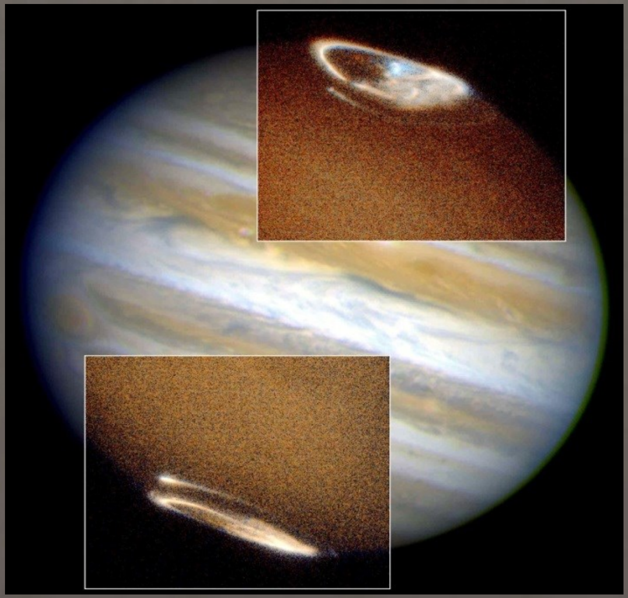
# Io

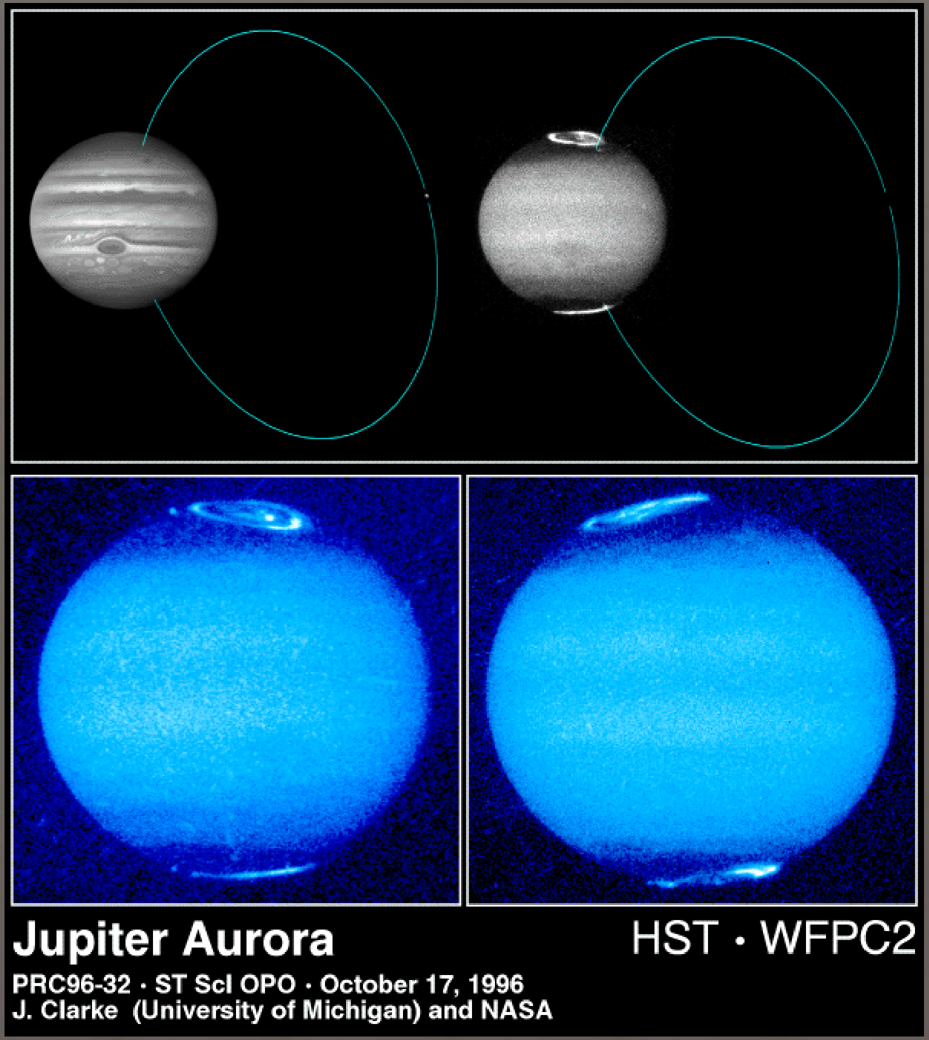
For Jupiter, especially the volcanic moon Io is a source of gas.



# Conjugate aurora

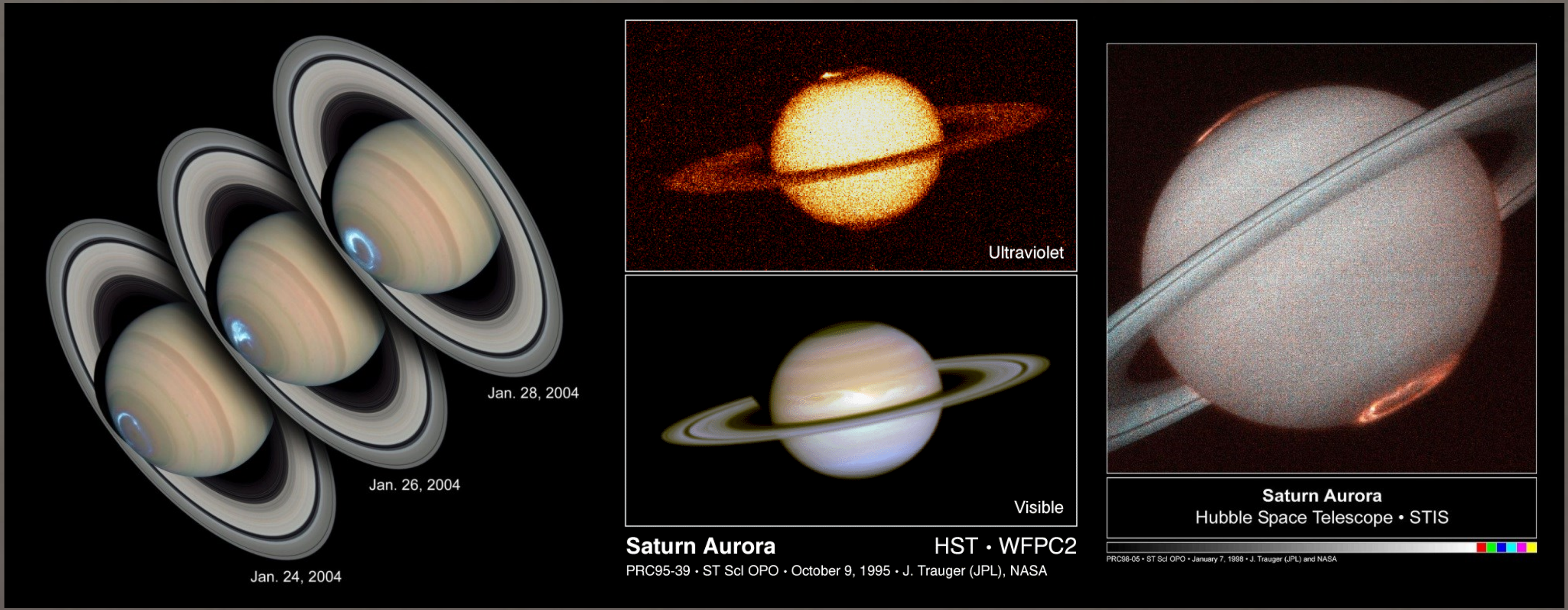
Not only the footpoints, also much or the other aurora are magnetically conjugate.





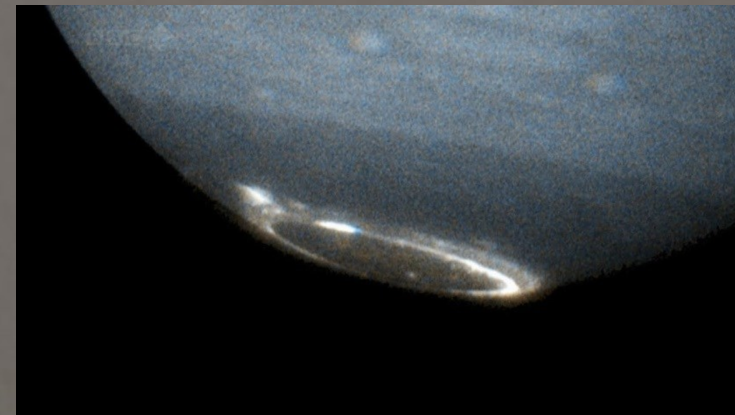
# Saturn : same story

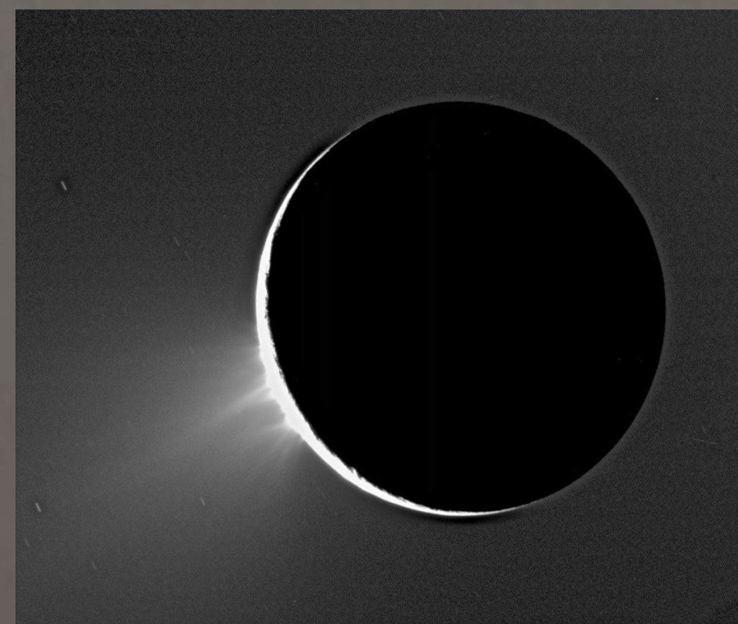
Also Saturn has a permanent corotation boundary oval, more transient higher latitude auroras, and moon footpoint auroral spots.



# Enceladus

For Saturn, the icy moon Enceladus is a source of gas release from fissures in its crust, fueled by tidal deformation.



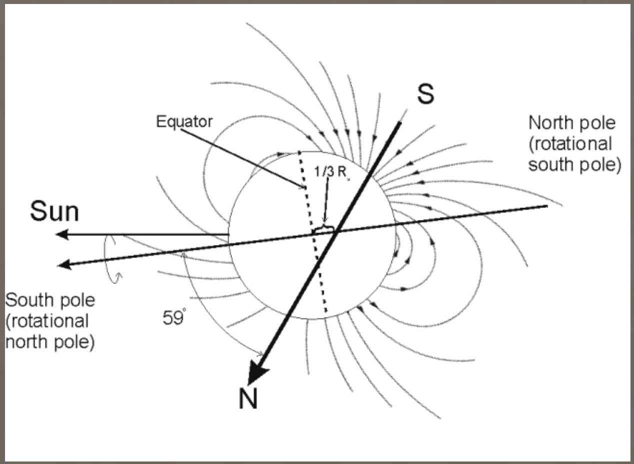


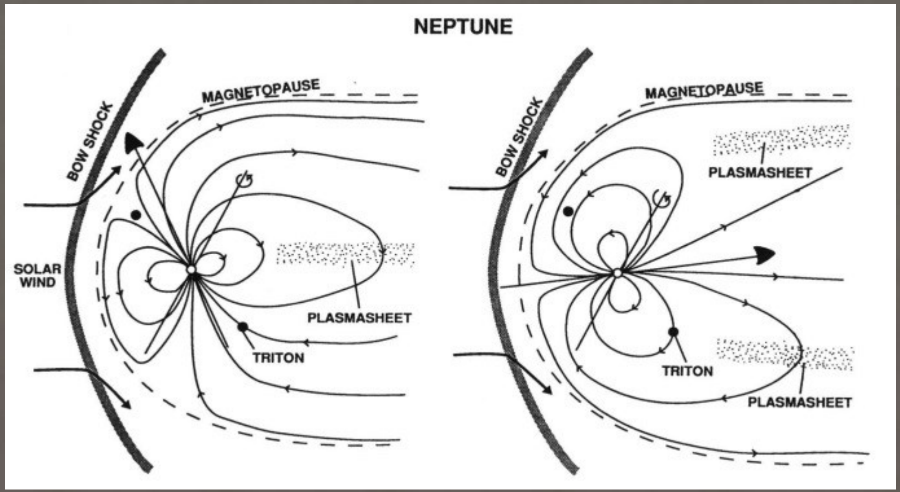
# Uranus and Neptune : ↔ planets

# Auroral structure for a ↔ planet

Depends not only on the angle between $\vec{B}$ and $\vec{\Omega}$, but also on the angle between $\vec{\Omega}$ and the ecliptic; there is a seasonal modulation.

Uranus, with obliquity 97°, may be in a situation where one pole constantly points sunward.




# Conclusions

The major structure of auroral patterns of magnetized planets can be understood in terms of a simple model of the auroral current circuit.

Details of the actual aurora depend on the size of the dipole field, its strength relative to the stellar wind pressure, and of course on the composition of the planet's atmosphere.

| | ***Moon as inner source*** | ***Corotation boundary*** | ***Higher latitude*** |
|---|---|---|---|
| ***parallel*** $\vec{B} \uparrow\uparrow \vec{\Omega}$ | conjugate footpoint spots | permanent eastward drift and aurora with transient intensification | transient aurora |
| ***anti-parallel*** $\vec{B} \uparrow\downarrow \vec{\Omega}$ | conjugate footpoint spots | permanent westward drift with transient intensification (SAPS/SAID) | permanent aurora + transient arcs |
| ***tilted*** $\vec{B} \leftrightarrow \vec{\Omega}$ | conjugate spots only when moon is on closed field lines | variable | variable |

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