The planetary environment - III (Earth's magnetosphere)

Lecture 8

W.K. Tobiska

Space Environment Technologies

Announcements

Contributions

- **Helpful article in explaining the butterfly diagram and the flip of the sun's magnetic field**
  http://science.nasa.gov/headlines/y2001/ast15feb_1.htm
- **EM spectrum explained for everyone (interesting site)**
  http://science.hq.nasa.gov/kids/imagers/ems/uv.html
- **Why the main labels of the levels are D, E and F?** The Tribble text gives a possible explanation (pg. 116). It states that when studies of the ionosphere detected ambient plasma it was theorized that induced electric fields where also present. These electric fields were labeled **E**. Later on the plasma region was found to extend above and below the "E" region, leading to the labels D and F, respectively.

Announcements

Contributions

- **Cluster II Mission YouTube video - study the small-scale structures of the Earth's plasma environment** http://www.youtube.com/watch?v=9XifHvoRGsg
- **ESA's Cluster Mission webpage**: http://sci.esa.int/science-e/www/area/index.cfm?fareaid=8
- **Space launch schedule**: http://www.spaceflightnow.com/tracking/index.html

Other resources

Summary page for solar wind with 10 minute updates
http://www.spaceweather.com/

Summary page for solar wind with 4 minute updates
http://space.rice.edu/ISTP/justdials.html

Summary page for solar flares with 1 minute updates
http://spacewx.com/Space_Weather_Now.html

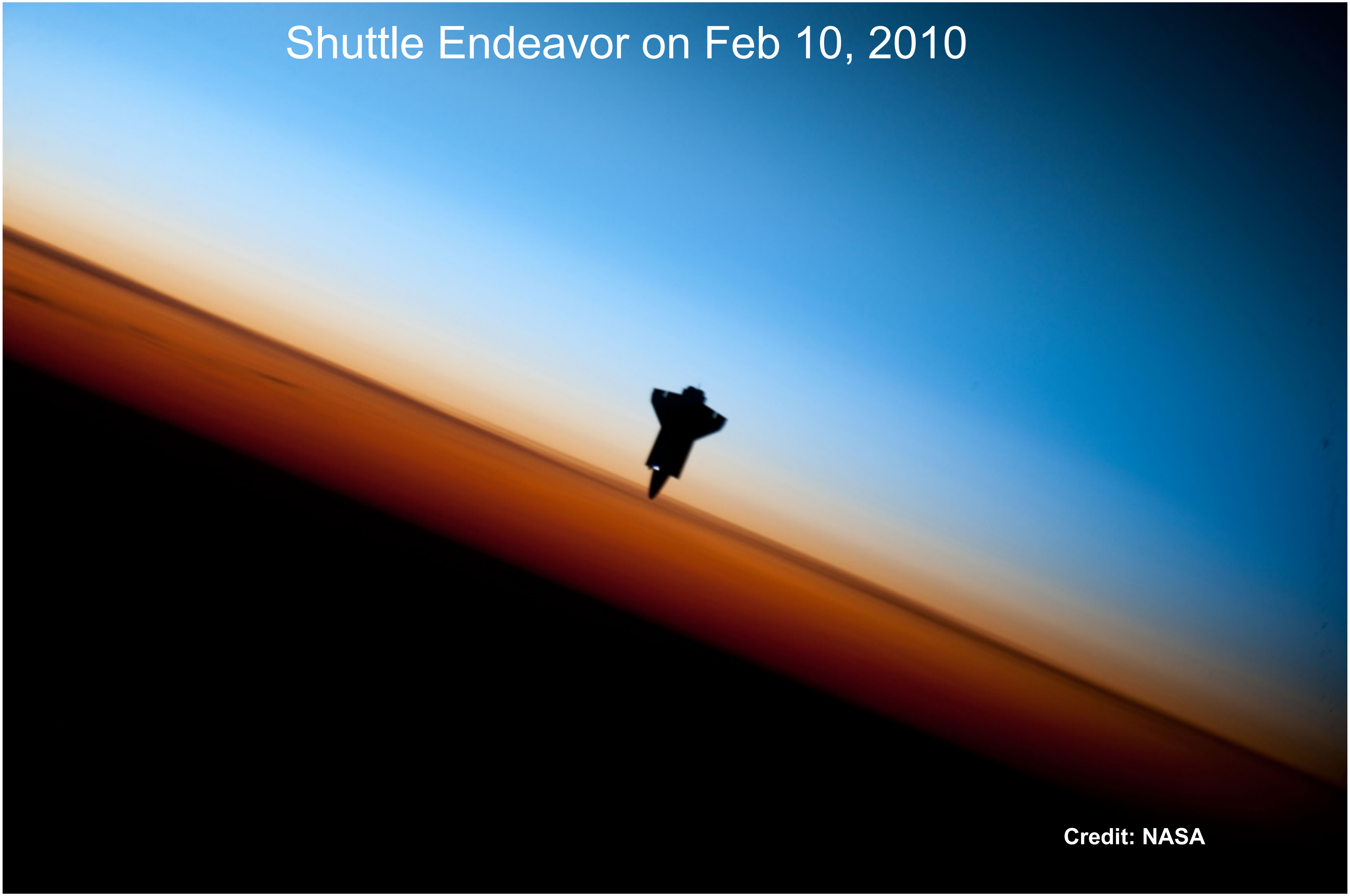
Information on the Advance Composition Explorer space weather satellite
http://www.srl.caltech.edu/ACE/ace_mission.html

A primer on space weather
http://www.swpc.noaa.gov/primer/primer.html

Shuttle Atlantis viewed from ISS

Credit: NASA

Credit: NASA


Shuttle Endeavor on Feb 10, 2010
Credit: NASA

Shuttle Endeavor and ISS on May 23, 2011

Credit: NASA

Shuttle Endeavor along CA coast on Sep 21, 2012

Credit: NASA


Shuttle Endeavor in Los Angeles on Oct 13, 2012
Endeavour
United States
NASA
Credit: Tobiska

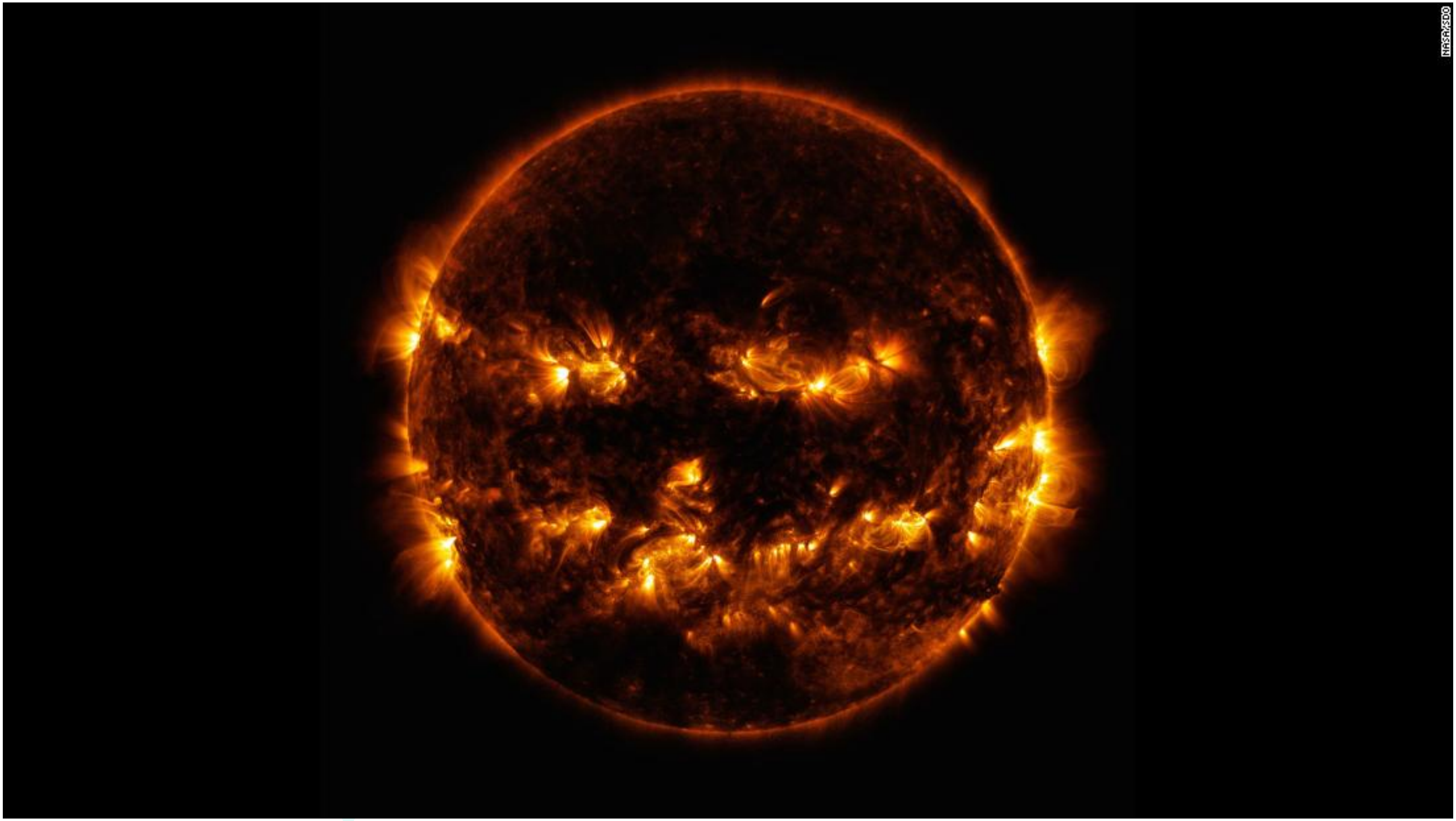
Shuttle Endeavor at California Science Center on June 10, 2016


Tropospheric noctilucent clouds hover 36,000 feet above Nunivak Island, Alaska.

Credit: ???

A10-C aircraft, sunset, and the aurora in Estonia

Halloween Sun



Lecture Overview

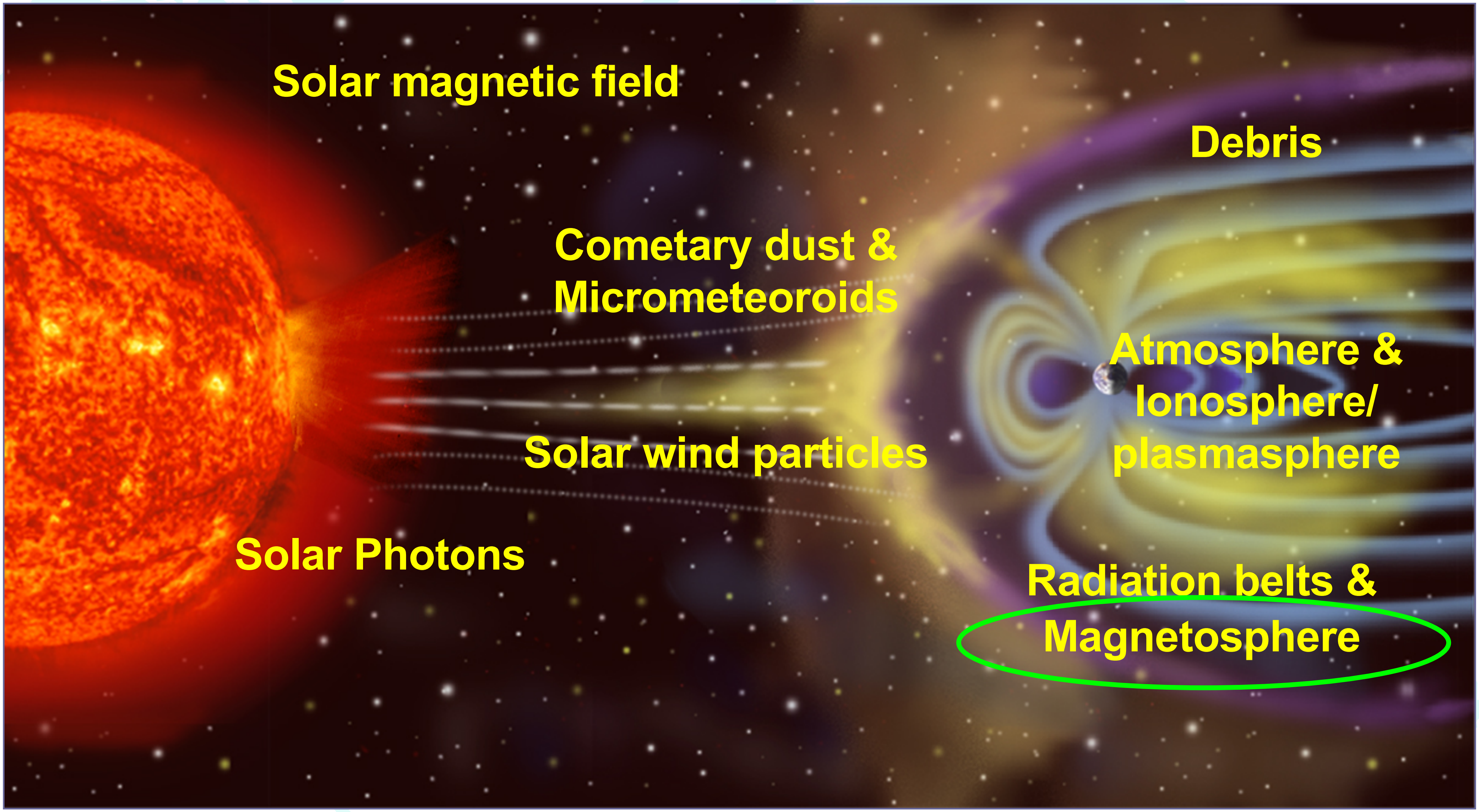
Planetary space environment (Earth's magnetosphere)

- Plasma physics basics
  - Maxwell's Equations, Ohm's Law, Equation of continuity, hydrodynamic equation
  - Particle motion and drifts, magnetic mirroring
- Geomagnetism
  - IGRF, dipole field, geomagnetic coordinates
- Magnetospheric structure
  - Bow shock, magnetosheath, magnetotail, plasma sheet, neutral sheet, polar cusps
- Magnetospheric variability
  - Currents, convection, storms and substorms, magnetic variations, magnetic storms, magnetic indices

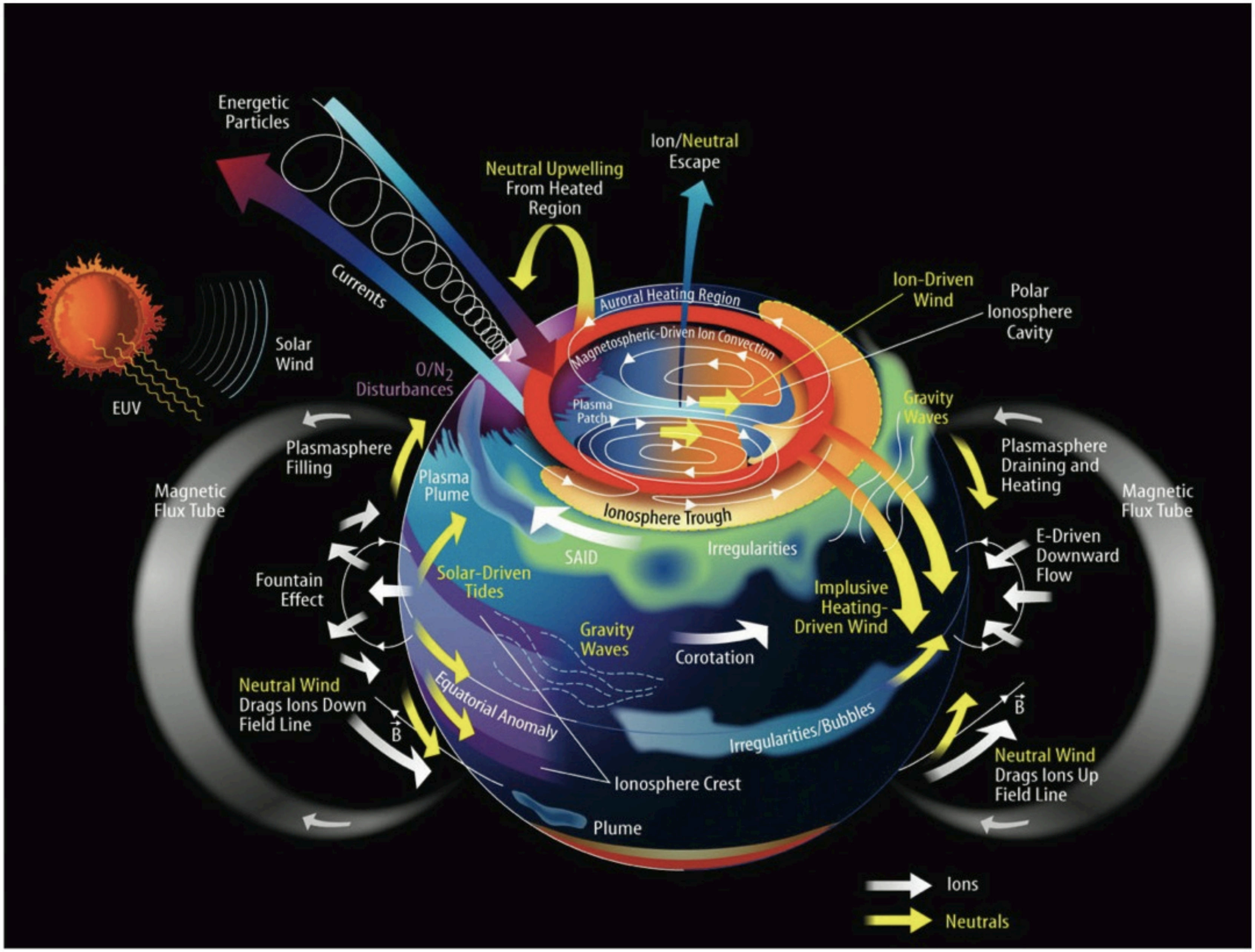
Homework

The planetary space environment

The space environment



Credit: Steele Hill/NASA



Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Currents
Solar Wind
EUV
O/N2 Disturbances
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Plasma Patch
Gravity Waves
Plasmasphere Filling
Magnetic Flux Tube
Plasma Plume
Ionosphere Trough
Plasmasphere Draining and Heating
Magnetic Flux Tube
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
B
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Ions
Neutrals

Plasma physics basics

Maxwell's Equations

Maxwell's Equations are a collection of 4 laws of macroscopic properties

1) Gauss' Law: the integral over a closed surface of an incremental surface area, ds, and an electric field vector, **E**, normal to the surface is proportional via ε_0, the permittivity of free space, to the electric charge, q, enclosed by the surface

$$\varepsilon_0 \int \vec{E} \bullet d\vec{s} = q \quad \textbf{(8-1)}$$

2) Gauss' Law for magnetism: the same concept as above but applied to closed magnetic lines of force, **B**

$$\int \vec{B} \bullet d\vec{s} = 0 \quad \textbf{(8-2)}$$

W. Kent Tobiska <ktobiska@spacewx.com>
Credit: Tascione

Maxwell's Equations

3) Ampere's Law: an electric current produces a magnetic field which encircles the current and, the stronger the current, the stronger the field

$$\int \vec{B} \bullet d\vec{\ell} = \mu_0 \int \vec{J} \bullet d\vec{A} \qquad \textbf{(8-3a)}$$

where dℓ is a differential line element along the closed loop, **J** is the current density, dA is the area through which the current passes, and μ_0 is the magnetic permeability of free space. Using the equation for electric flux

$$\Phi_E = \int \vec{E} \bullet d\vec{A} \qquad \textbf{(8-3b)}$$

Maxwell generalized this to

$$\int \vec{B} \bullet d\vec{\ell} = \mu_0 (\varepsilon_0 \frac{d\Phi_E}{dt} + \int \vec{J} \bullet d\vec{A}) \qquad \textbf{(8-3c)}$$

Maxwell’s Equations

4) **Faraday’s Law**: the law of magnetic induction where the time rate of change of magnetic flux will induce its own electric field. This is the basic principle behind electric generators and transformers.

$$\oint \vec{\mathbf{E}} \bullet d\vec{\ell} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}\int \vec{B} \bullet d\vec{A} \qquad \textbf{(8-4)}$$

Ohm's Law

The impedance to current flow is parameterized by Ohm's Law as a **linear relationship between electric current and the sources of potential difference** that enable the flow of the current.

Sources of potential differences

- Electric fields
- Magnetic fields
- Pressure gradients
- Gravitational forces

The proportionality constant is considered a conductance (mobility of electrons, i.e., inverse of resistance)

$$\vec{J} = \vec{\sigma} \bullet \vec{E} \qquad \textbf{(8-5)}$$

where **J** is current density and σ is the conductivity tensor.

Ohm's Law

The conductivity tensor **σ** is based on a coordinate system drawn so that the z-axis is parallel to **B** and the direction of the electric field is broken into components parallel and perpendicular to **B**.

Pederson conductivity σ_P is parallel to **E** and perpendicular to **B**

Hall conductivity σ_H is perpendicular to both **B** and **E**

Parallel conductivity $\sigma_{||}$ is parallel to **B**

$$\vec{\sigma} = \begin{pmatrix} \sigma_P & \sigma_H & 0 \\ -\sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_{||} \end{pmatrix} \qquad \textbf{(8-6)}$$

Continuity Equation

The time rate of change of charged particles in a given unit volume is proportional to the net flow **in** and **out** of the volume plus the **production** (ionization) and **loss** (recombination) of charged particles

$$\frac{\partial \rho}{\partial t} = -\nabla \bullet \rho \vec{v} + Q - L \qquad \textbf{(8-7a)}$$

where mass density ρ = nm, **v** is the flow velocity, Q is the electron production rate, and L is the electron loss rate and, for charge neutrality (i = ions and e = electrons)

$$\rho = n_i m_i + n_e m_e \approx n_e m_i \qquad \textbf{(8-7b)}$$

Hydrodynamic Equation

The Boltzmann transport equation is simplified in order to characterize the fluid properties of a plasma

The magnetohydrodynamic equation of motion is written as

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho \vec{v} \bullet \nabla \vec{v} = -\nabla \mathrm{p} + \rho \vec{\mathrm{g}} + \vec{\mathrm{J}} \times \vec{\mathrm{B}} \qquad \text{(8-8)}$$

where ρ is the plasma density, **v** is the bulk flow velocity, p is the gas pressure, **g** is acceleration of gravity, **J** is the current density, and **B** is the magnetic field vector.

This equation, plus the preceding ones, must be solved simultaneously to obtain valid results, thus requiring computational methods even for the simplest cases.

Single particle motion

The bulk flow properties of a plasma described in equations (8-1) through (8-8) are the ***macroscopic*** properties.

The individual particle motions can also be described in a ***microscopic*** sense

In the presence of a magnetic field and a gravitational force, a charged particle will feel the effect of the **Lorentz force** (eq 8-9) where q is the charge intensity, **v** is the particle's velocity, and **B** is the magnetic field strength

$$\vec{F} = q\vec{v} \times \vec{B} \qquad \textbf{(8-9)}$$

Single particle motion

In the added presence of an electric field, a charged particle will feel the Lorentz force from both magnetic and electric components where **E** is the electric field strength and q is the charge intensity of the particle

$$\vec{F} = m\frac{d\vec{v}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) \qquad \textbf{(8-10)}$$

In the case where there is no electric field, the acceleration of the particle is perpendicular to the velocity from the vector cross product and is

$$\frac{d\vec{v}}{dt} = q(\vec{v} \times \vec{B})/m \qquad \textbf{(8-11)}$$

Single particle motion

The acceleration produces a curvature of motion (circular motion or spiraling) of the charged particle with a change in direction but not speed.

When the particle's motion is perpendicular to the magnetic field then (8-11) reduces to

$$\frac{mv^2}{r} = qvB \qquad \text{(8-12)}$$

with a radius of gyration (or cyclotron radius)

$$r_c = \frac{mv}{qB} \qquad \text{(8-13)}$$

Single particle motion

The cyclotron frequency is

$$\nu = \frac{\mathrm{v}}{2\pi \mathrm{r}} = \frac{\mathrm{qB}}{2\pi \mathrm{m}} \qquad \text{(8-14)}$$

or, as angular frequency (gyrofrequency)

$$\omega_c = 2\pi\nu = \frac{\mathrm{qB}}{\mathrm{m}} \qquad \text{(8-15)}$$

We note that current, I, is charge per unit time so

$$\mathrm{I_e} = \mathrm{q}(\frac{1}{\mathrm{T}}) = \mathrm{q}\nu = \mathrm{qf_c} = \frac{\mathrm{q}\omega_\mathrm{c}}{2\pi} \qquad \text{(8-16)}$$

Single particle motion

Thus, eliminating terms for a gyrating particle we write current, I, as

$$I_e = \frac{q\omega_c}{2\pi} = \frac{q^2 B}{2\pi m} \quad \textbf{(8-17)}$$

For representative values at Earth where B = 0.2–0.5 gauss (G) or 20,000 – 50,000 nano Tesla (nT)

Quantity	Proton	Electron
q (coul)	1.6×10^{-19}	-1.6×10^{-19}
m (kg)	1.67×10^{-27}	9.1×10^{-31}
E (MeV)	1	0.5
r_c (m)	1.5×10^{4}	7.5×10^{1}
ω_c (s^{-1})	958	1.76×10^{6}

Particle drifts

For the above examples, a uniform magnetic field was assumed.

For the conditions where there is an external force (gravity) or where the magnetic field is non-uniform, then charged particles drift as well as have circular motions.

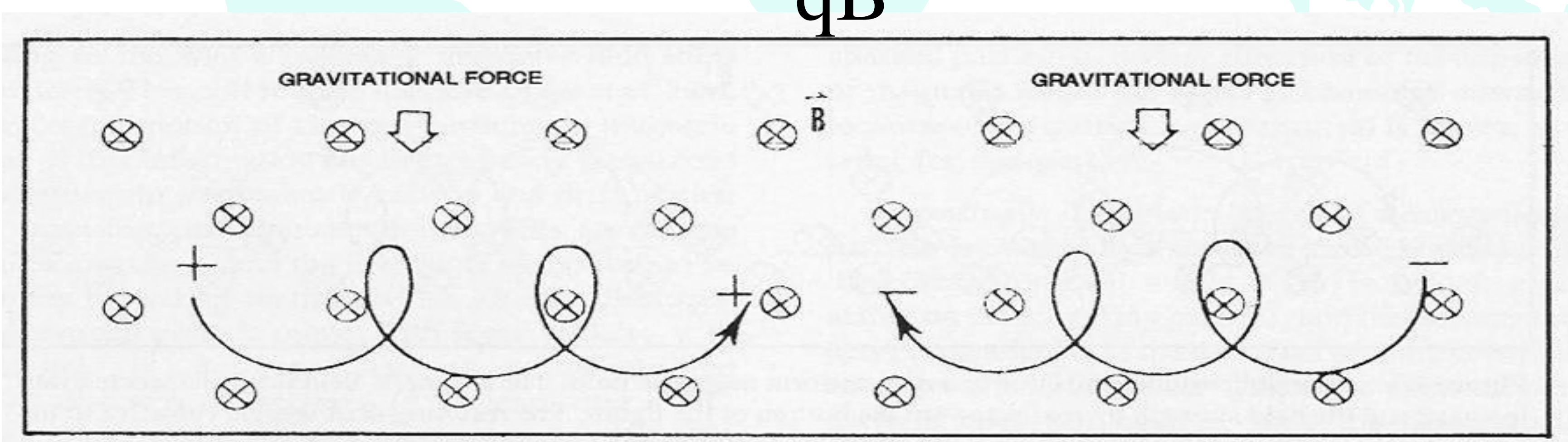
We examine four cases of particle drifts:

1) External force independent of charge (gravity) (current)
2) External force dependent on charge (charge in an electric field) (no current)
3) Non-uniform magnetic field (gradients) (current)
4) Curvature in magnetic field geometry (current)

External force (gravity) drift

External force independent of charge (gravity) where gravity force $\mathbf{F_G}$ is downwards and **B** is into page. For part of time, $\mathbf{F_G}$ and **B** both have downward force on particle path and for other part, $\mathbf{F_G}$ and **B** are in opposition. This results in net positive drift to the right from charge separation and **creates a current**.

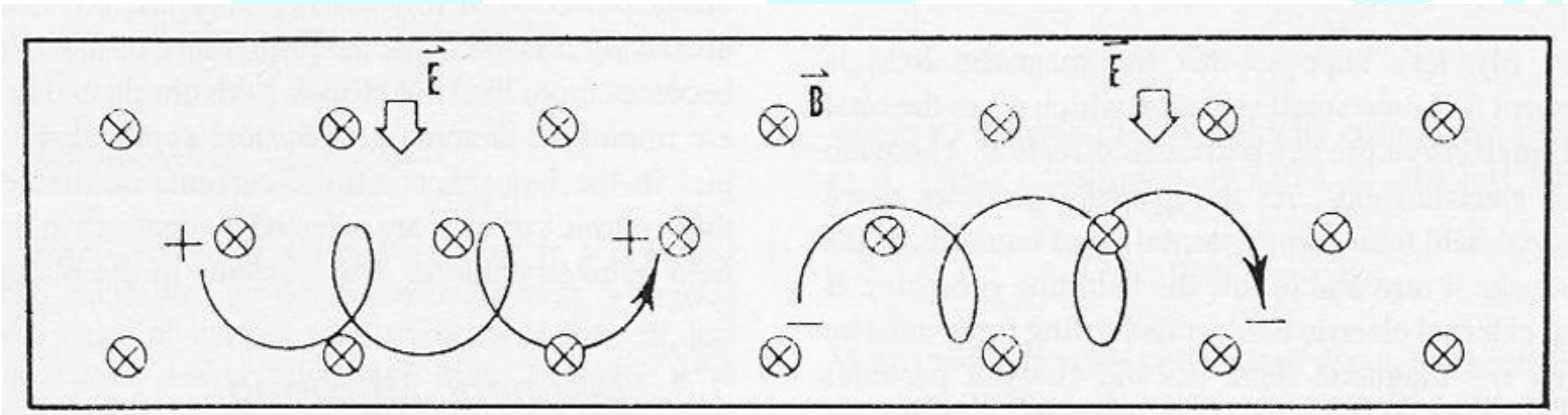
$$\vec{v}_d = \frac{\vec{F} \times \vec{B}}{qB^2} \quad \textbf{(8-18)}$$



Electric field drift

External force dependent on charge (charge in an electric field) with **B** into page and **E** in the plane of page directed toward bottom. Force created with charge and **E** where protons, electrons drift in same direction for no charge separation and **no net current**.

$$\vec{v}_E = \frac{q\vec{E} \times \vec{B}}{qB^2} = \frac{\vec{E} \times \vec{B}}{B^2} \qquad \textbf{(8-19)}$$



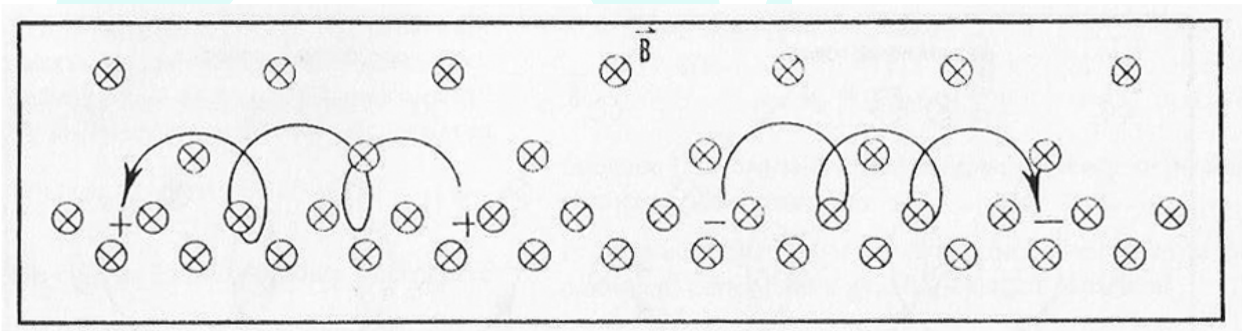
Non-uniform drift

A non-uniform magnetic field has **B** into the page with greater field strength to the bottom of the page. Thus, there is a magnetic field gradient with an external force

$$\vec{F} = -\frac{1}{2} m v_\perp^2 \frac{\nabla \vec{B} N}{B} \quad (8\text{-}20)$$

and particle velocity creating gradient drifting and **a net current**

$$\overrightarrow{v_{grad}} = \frac{1}{2} \frac{m v_\perp^2}{q} \frac{\vec{B} \times \nabla \vec{B}}{B^3} \quad (8\text{-}21)$$



Gradient drift

The magnetic dipole moment, μ, is basically the current in a loop times the area of the loop. The gyrating particle goes around once in a unit of time as $2\pi/\omega_c$ and carries an equivalent current of $q\omega_c/2\pi$; it can be written as

$$\mu = \frac{q\omega_c}{2\pi}\pi r_c^2 = \frac{1}{2}\frac{mv_\perp^2}{B} \quad \textbf{(8-22)}$$

μ is nearly always constant for space science and engineering applications. Gradient drift depends on particle's perpendicular kinetic energy. Electrons and protons that have same kinetic temperature have gradient drifts at same rates, in opposite directions, even though electrons have much greater thermal velocities, thus **creating a net current**.

Curvature drift

Curvature in magnetic field geometry that is otherwise uniform with no electric fields is a special case. Some force must act on the particles to make them follow a curved field line and this turning force is provided by the magnetic field.

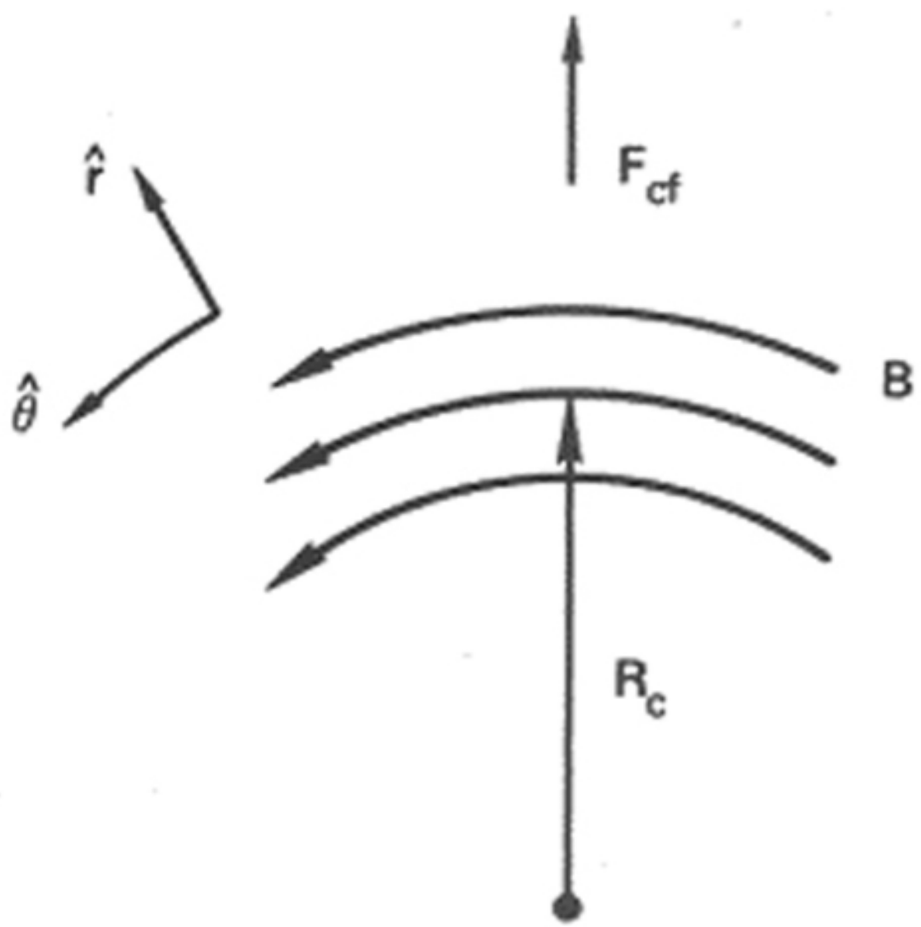
$$F_{cf} = \frac{m v_{\parallel}^2}{R_c} \hat{r} \quad \text{(8-23)}$$

Thus, with R_c as the radius of curvature (not gyroradius), r hat as unit vector, the velocity parallel to B, $v_{\parallel}$, is

$$\vec{v}_c = \frac{m v_{\parallel}^2}{q} \frac{\vec{R}_c \times \vec{B}}{R_c^2 B^2} \quad \text{(8-24)}$$

and the sign of q moves particles in opposite directions such as the Ring Current to **create a net current**

Curvature drift

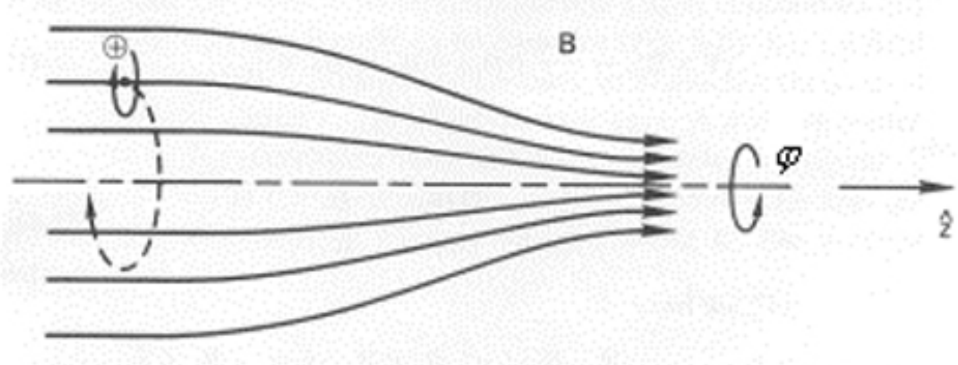


A curved magnetic field.

Credit: Fletcher

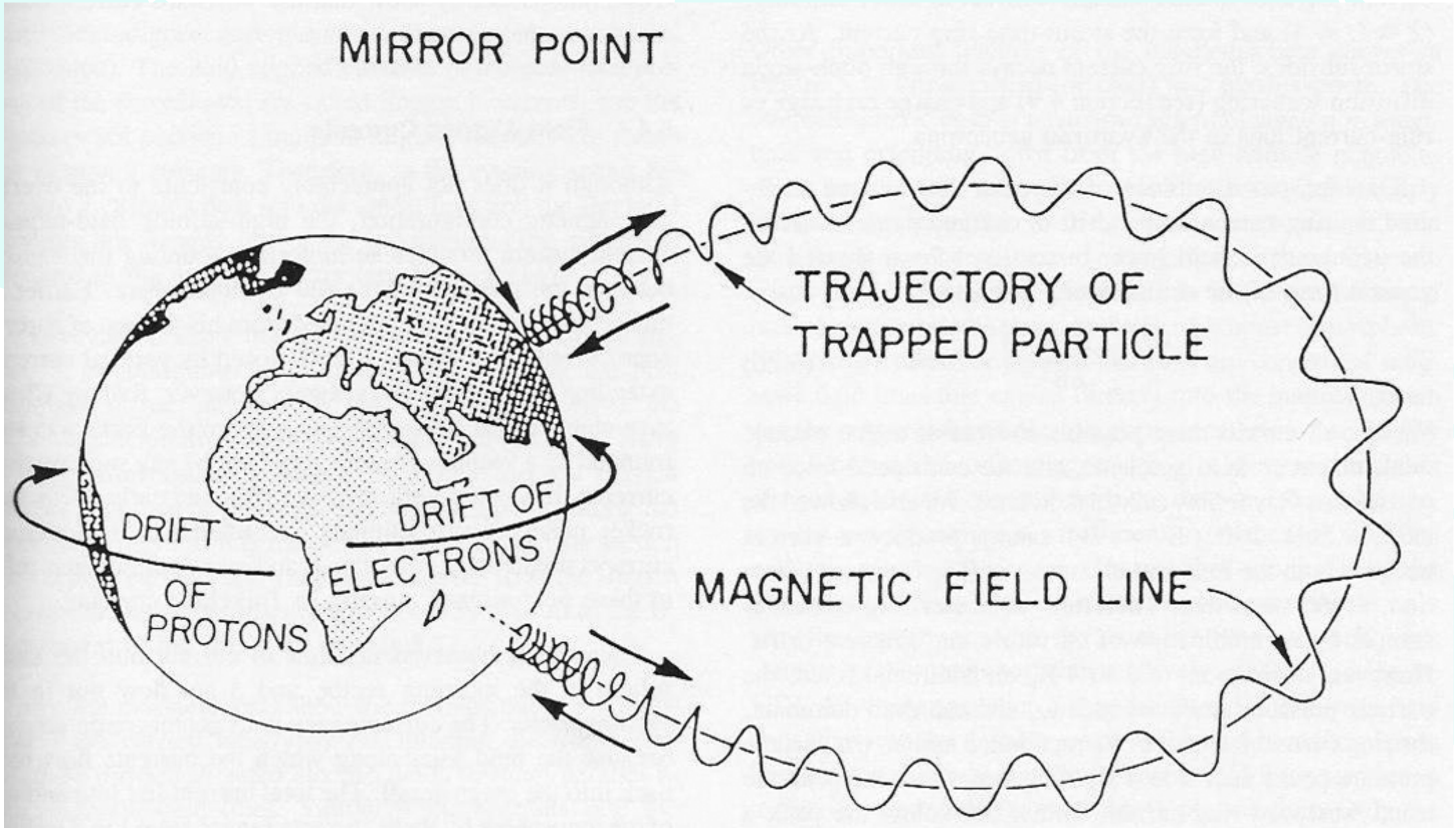
Magnetic mirroring

Planetary fields (or artificial fields in Tokamaks) can trap charged particles. Previously, we saw that the motion of a charged particle in the direction of **B** was unaffected. This is not the case when field lines converge or diverge and, in this case, ***charged particles experience a force in the direction of the weakest magnetic field strength***. A particle can *change direction or reverse* ("bouncing") and this is known as mirroring



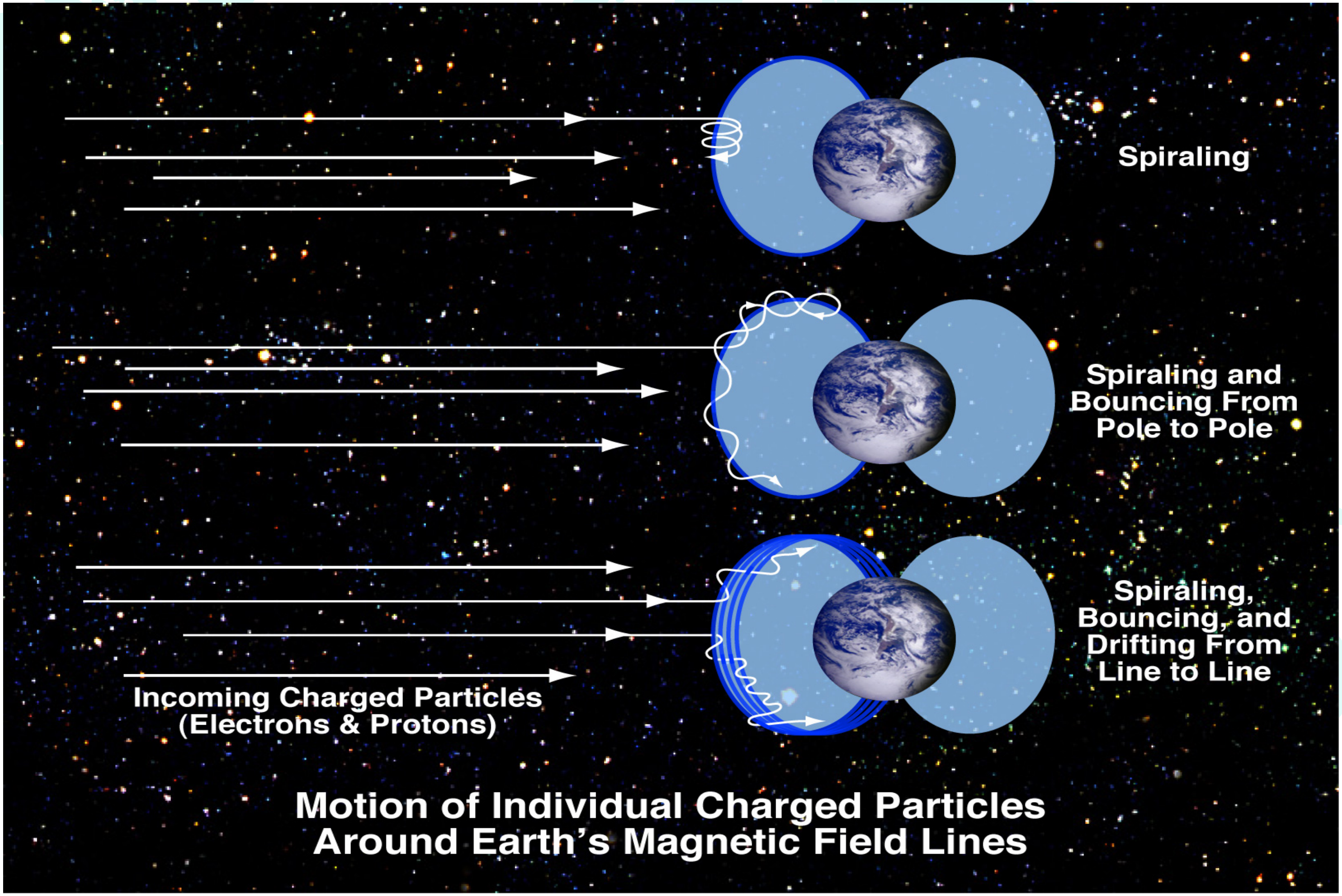
Drift of a particle in a magnetic mirror field.

Magnetic mirroring



W. Kent Tobiska <ktobiska@spacewx.com>
Credit: Tascione

Charged Particle Motions



BREAK

Debye length

Plasma, on a large enough scale that is near equilibrium, must also be approximately charge neutral.

The length of scale in a plasma over which this **charge neutrality** is established is known as the **Debye length**.

An electric potential, V, having a charge Q and a permittivity ε_0 at a distance r from an object of interest (e.g., a spacecraft surface) is written as

$$V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r} \qquad \textbf{(8-25)}$$

In a plasma the surface will attract the opposite charge which will end up screening the potential from the rest of the plasma. This causes the potential to fall off in intensity with a power greater than 1/r.

Debye length

Poisson's equation provides the relationship between the electric potential, V, of a surface and ion density, n_i, electron density n_e, ε_0 free space dielectric constant (permittivity of free space), and an elementary charge, e (or q).

$$\nabla^2 V = \frac{e(n_e - n_i)}{\varepsilon_0} \quad \textbf{(8-26)}$$

For a Maxwellian-distributed plasma, electrons and ions have the same temperature kT and electron density is

$$n_e = n_{e0} \exp\left(\frac{-eV}{kT}\right) \quad \textbf{(8-27)}$$

while ion density is

$$n_i = n_{i0} \exp\left(\frac{eV}{kT}\right) \quad \textbf{(8-28)}$$

Debye length

At infinity, the potential, V, is 0 and, by definition, ion and electron densities are equal. Thus $n_{e0} = n_{i0} = n_0$.

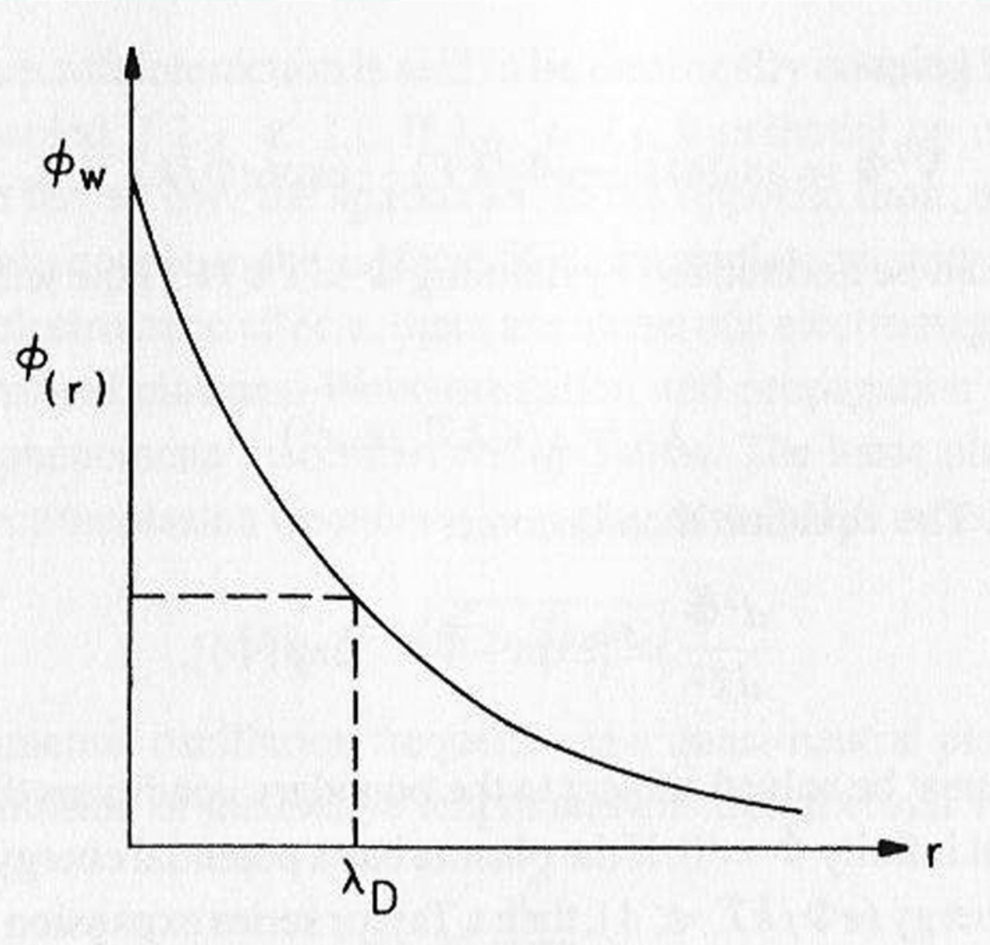
Rewriting the Poisson Equation

$$\nabla^2 V = e n_0 \frac{\exp(-eV/kT) - \exp(eV/kT)}{\varepsilon_0} \quad \text{(8-29)}$$

we can also define the Debye length λ_D as the distance over which a spacecraft surface is shielded and where the plasma is charge neutral (in practice, one uses a few Debye lengths for actual shielding)

$$\lambda_D = \sqrt{\varepsilon_0 kT/(n_0 e^2)} \quad \text{(8-30)}$$

Debye length



Empirically, the Debye length in meters can be approximated by the relationship where T_e or T_i is the electron or ion temperature in Kelvin (T_i can be approximated with neutral species temperature) and n_0 is the plasma concentration (particles m^{-3}).

$$\lambda_{e,i} = 69\sqrt{T_{e,i}/n_0} \quad \textbf{(8-31)}$$

(ϕ is potential, V, in this figure)

Debye length

The total Debye length for ions plus electrons is given by

$$\frac{1}{\lambda_D^2} = \frac{1}{\lambda_e^2} + \frac{1}{\lambda_i^2} \qquad \textbf{(8-32)}$$

and the potential at some distance r, V(r), is

$$V(r) = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}\exp\left(-\frac{r}{\lambda_D}\right) \qquad \textbf{(8-33)}$$

Geomagnetism

Earth's magnetic field

The total magnetic field of the Earth

Composed of contributions from four types of fields: 1) Earth's main magnetic field, $\mathbf{B}_d$; 2) the Ring Current, $\mathbf{B}_{rc}$; 3) the Cross-tail Current, $\mathbf{B}_{tail}$; and 4) the Magnetopause surface current, $\mathbf{B}_{magnetopause}$

$$B_T = B_d + B_{rc} + B_{tail} + B_{magnetopause} \quad \textbf{(8-34)}$$

The tilted dipole geomagnetic coordinates (latitude Φ and longitude Λ) are related to geographical coordinates (ϕ, λ) by

$$\sin\Phi = \sin\phi\sin\phi_0 + \cos\phi\cos\phi_0\cos(\lambda - \lambda_0) \quad \textbf{(8-35)}$$

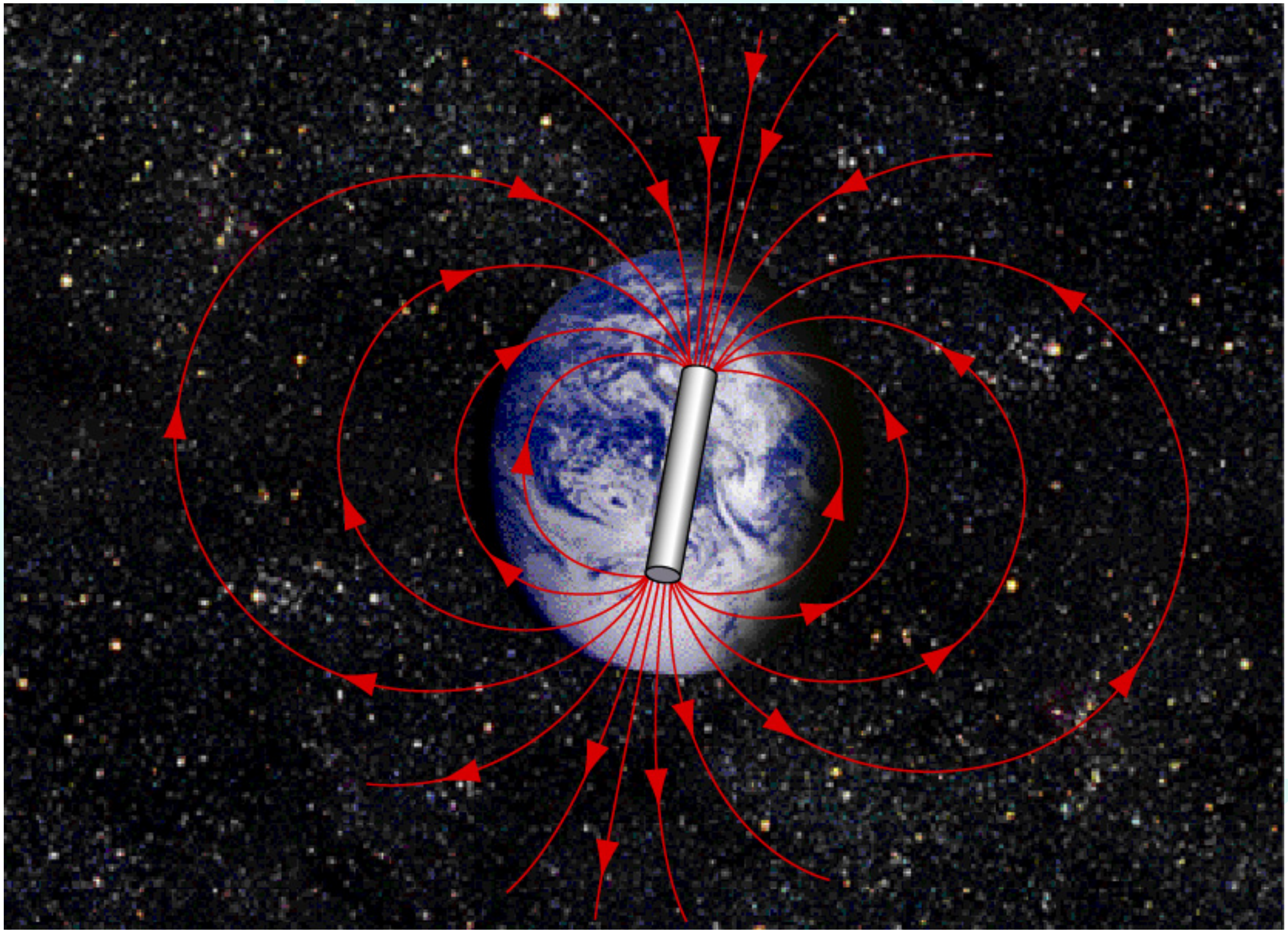
$$\sin\Lambda = \frac{\cos\phi\sin(\lambda - \lambda_0)}{\cos\Phi} \quad \textbf{(8-36)}$$

Dipole field

Earth's magnetic field is a dipole field

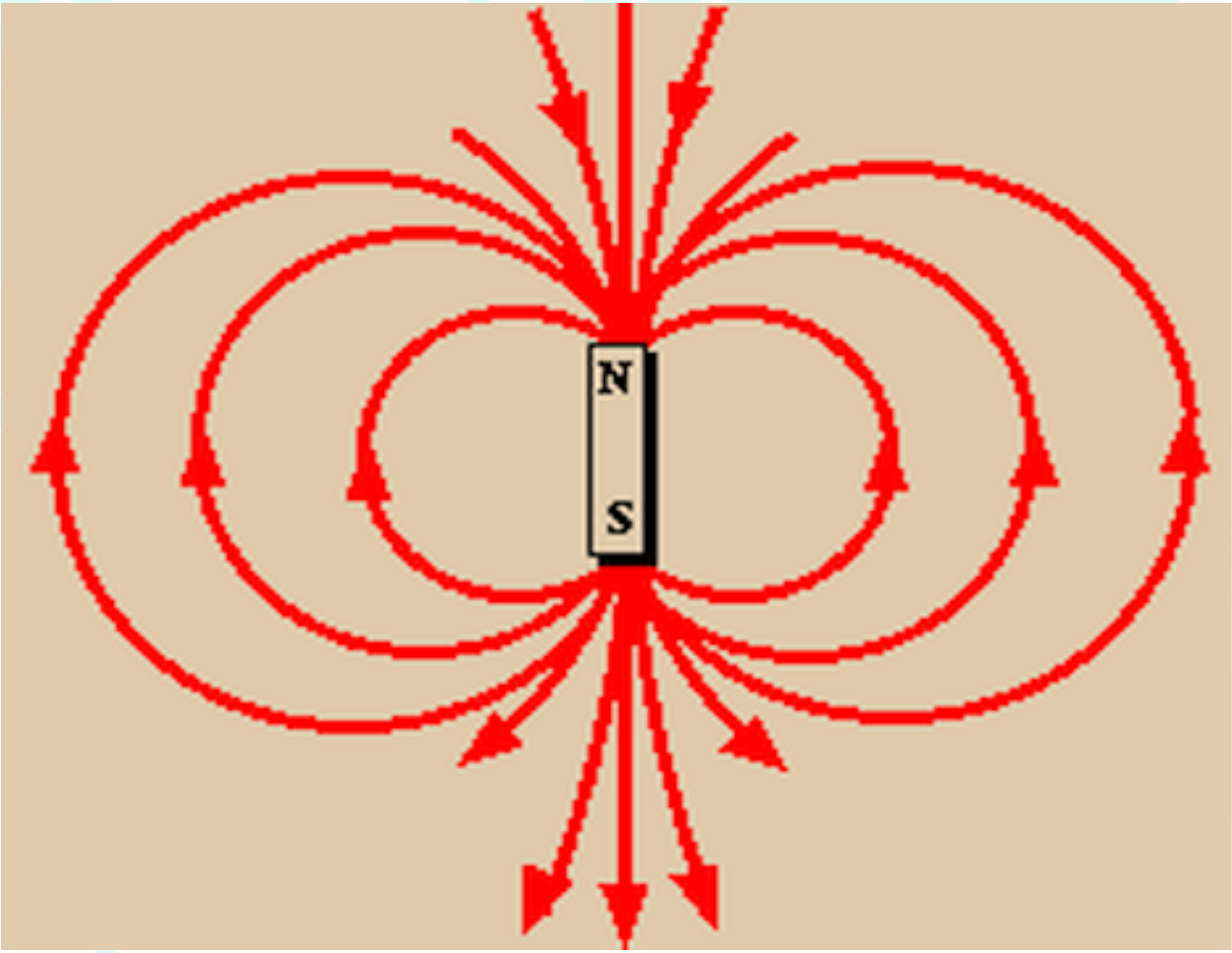
ϕ_0 = 78.5° N and λ_0 = 291.0° E for the coordinates of the geographical north dipole pole (1950); 80.65° N & 287.32° E (2020)

The dipole angle of displacement from the rotational axis of Earth's north pole is 11.7° (1950); now 9.41° (2020)



Credit: ESA

Dipole field



IGRF

International Geomagnetic Reference Field (IGRF)

The IGRF is a global model of the geomagnetic field from the Earth's core out into space.

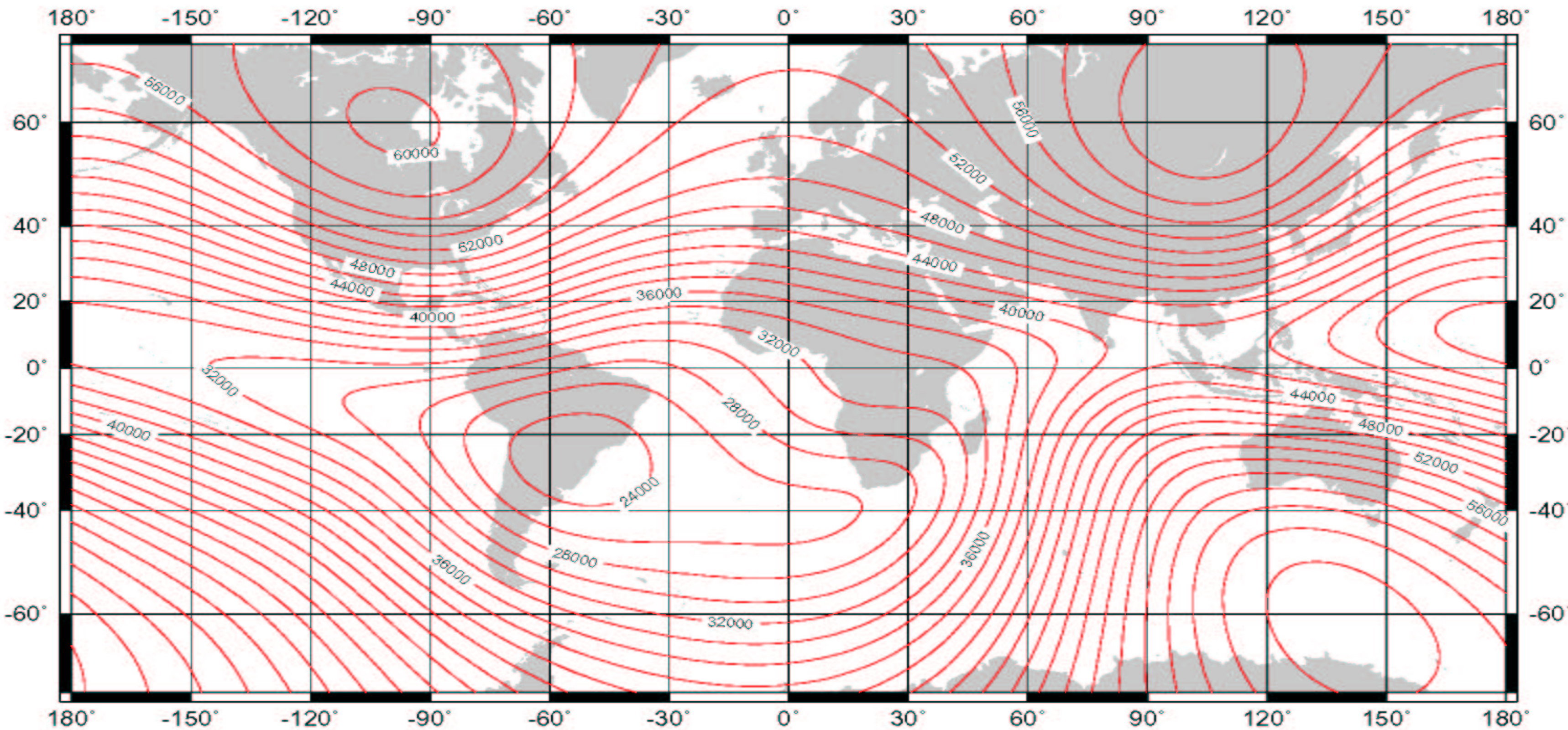
The IGRF is generally revised every five years by the International Association of Geomagnetism and Aeronomy (IAGA).

Officially in 12th generation (1900.0-2020.0)

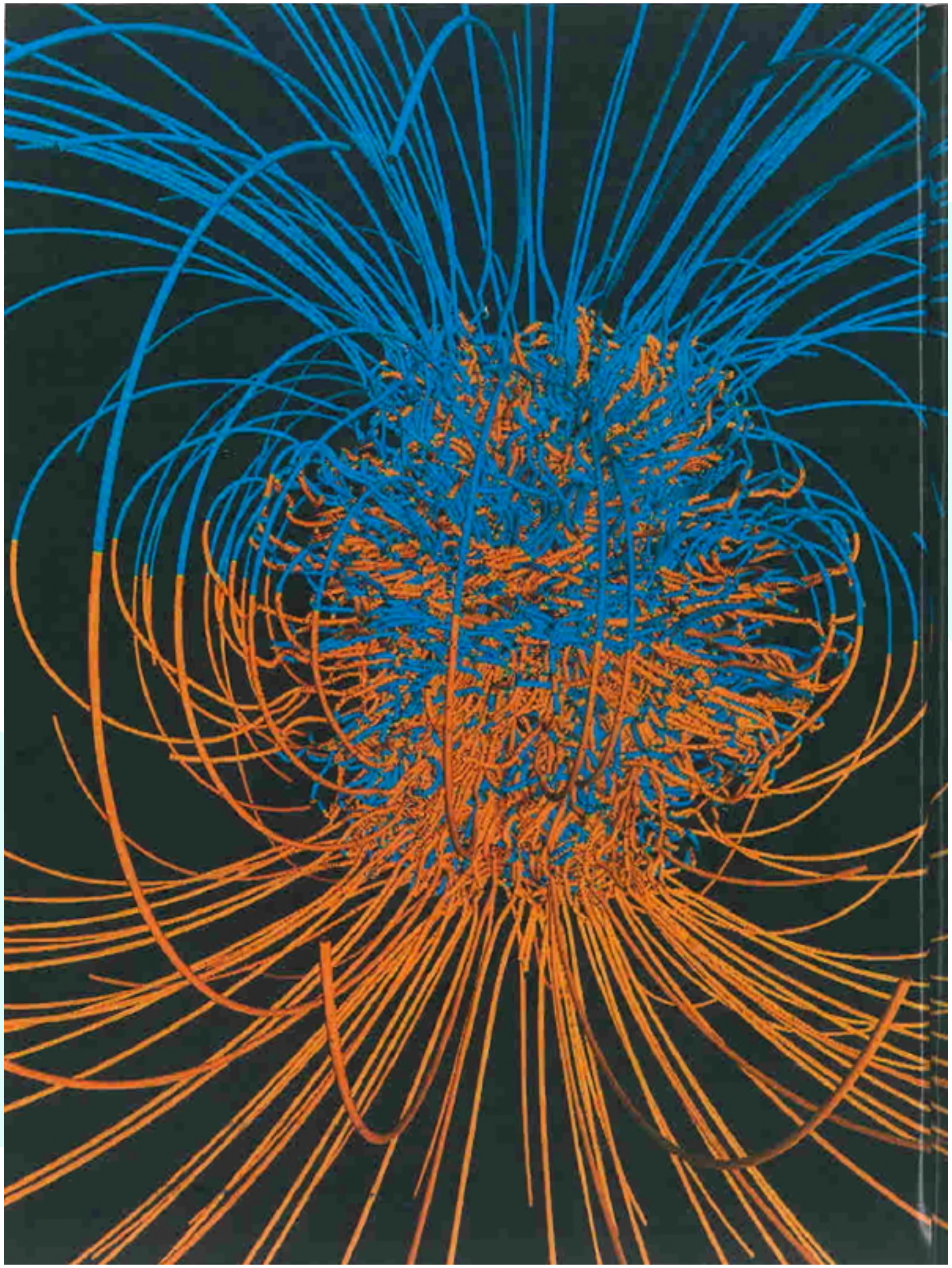
Official location is http://www.iugg.org/IAGA/iaga_pages/pubs_prods/igrf.htm

Included in ISO 16695 – Earth Main Field standard

WMM - Earth surface in nT



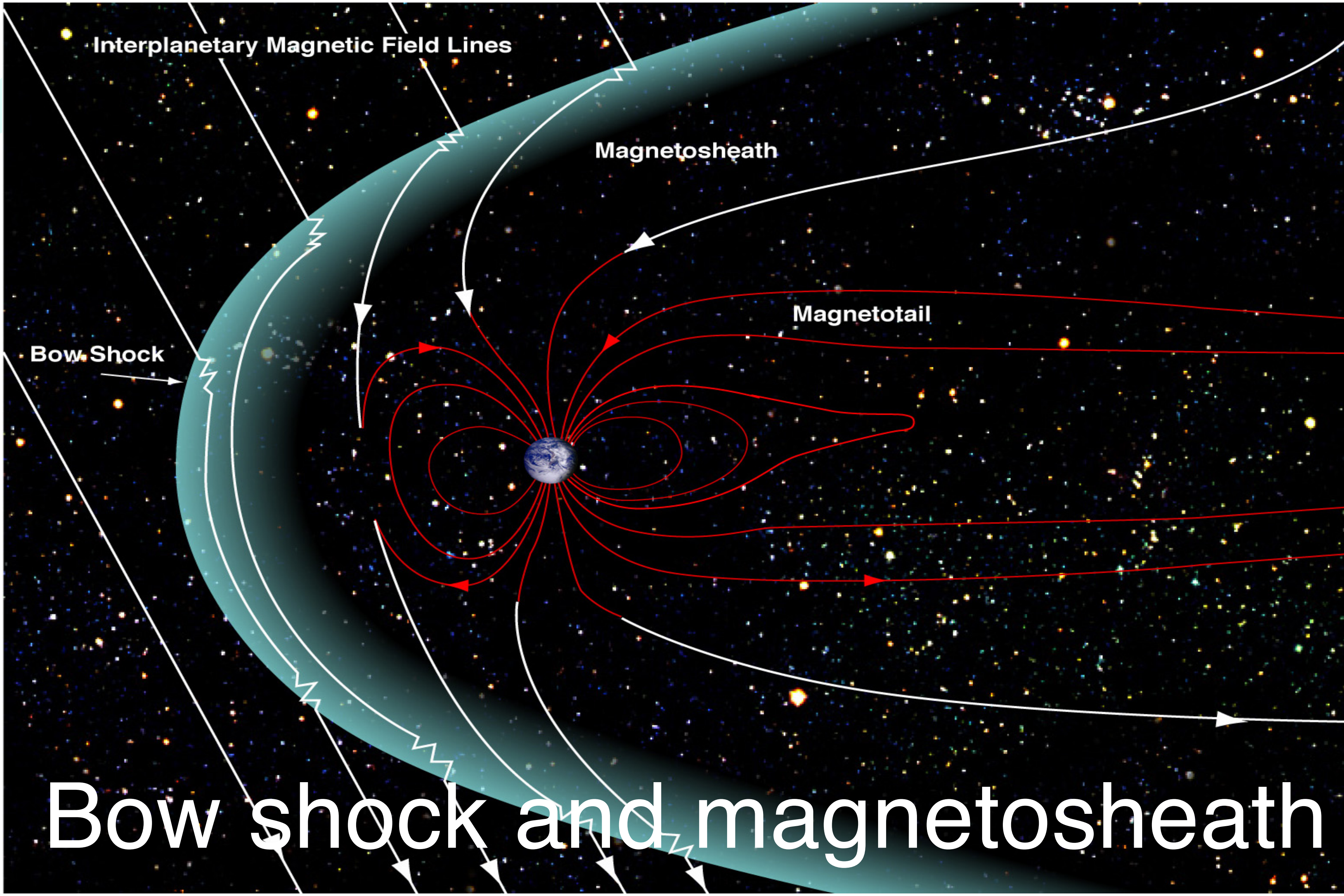
Total intensity (*F*) at 2000.0 from the World Magnetic Model (WMM2000). Contour interval is 2000 nT and projection is Mercator. This is an example of an isodynamic chart.



Credit: Glatzmeier

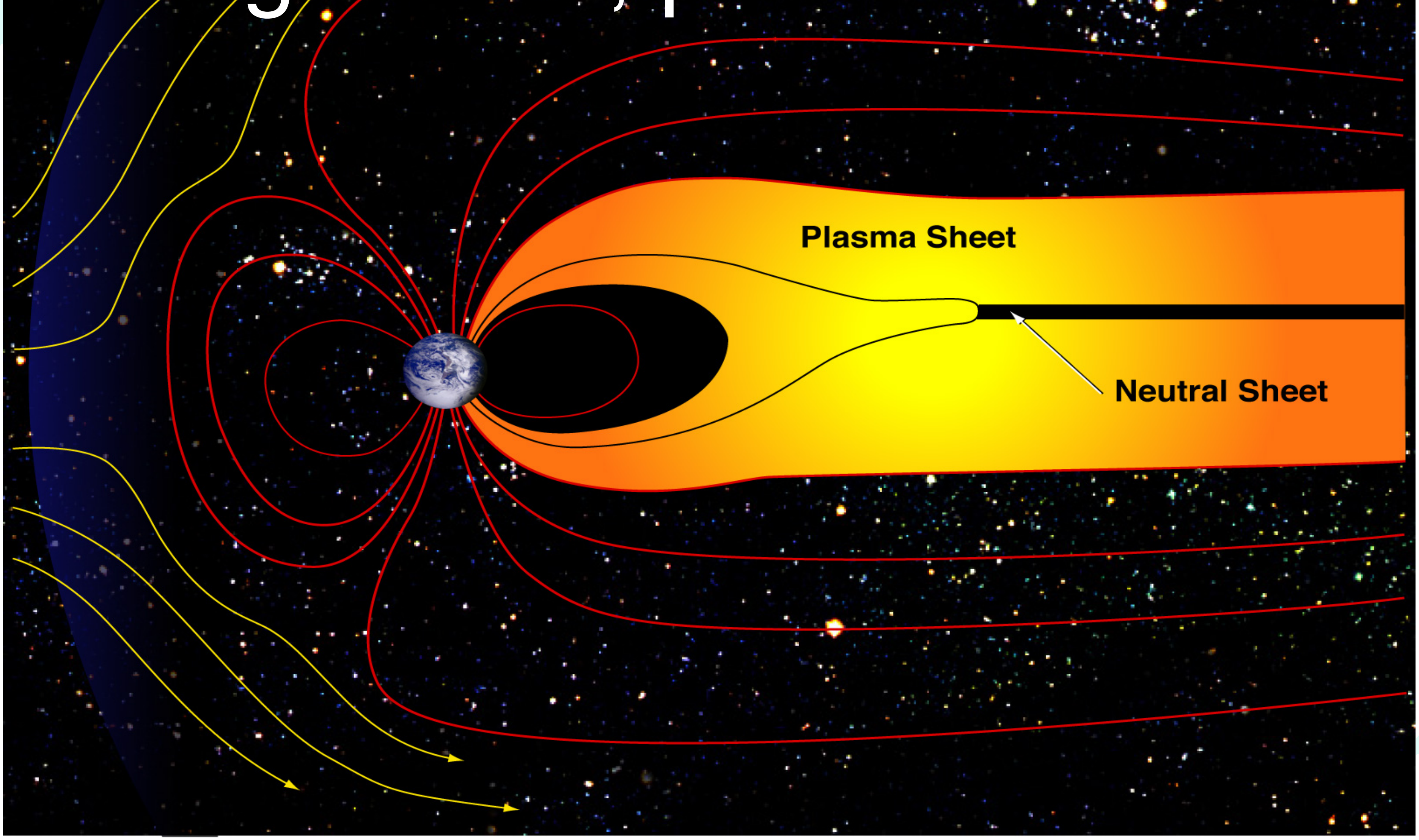
Magnetospheric structure

Bow shock and magnetosheath

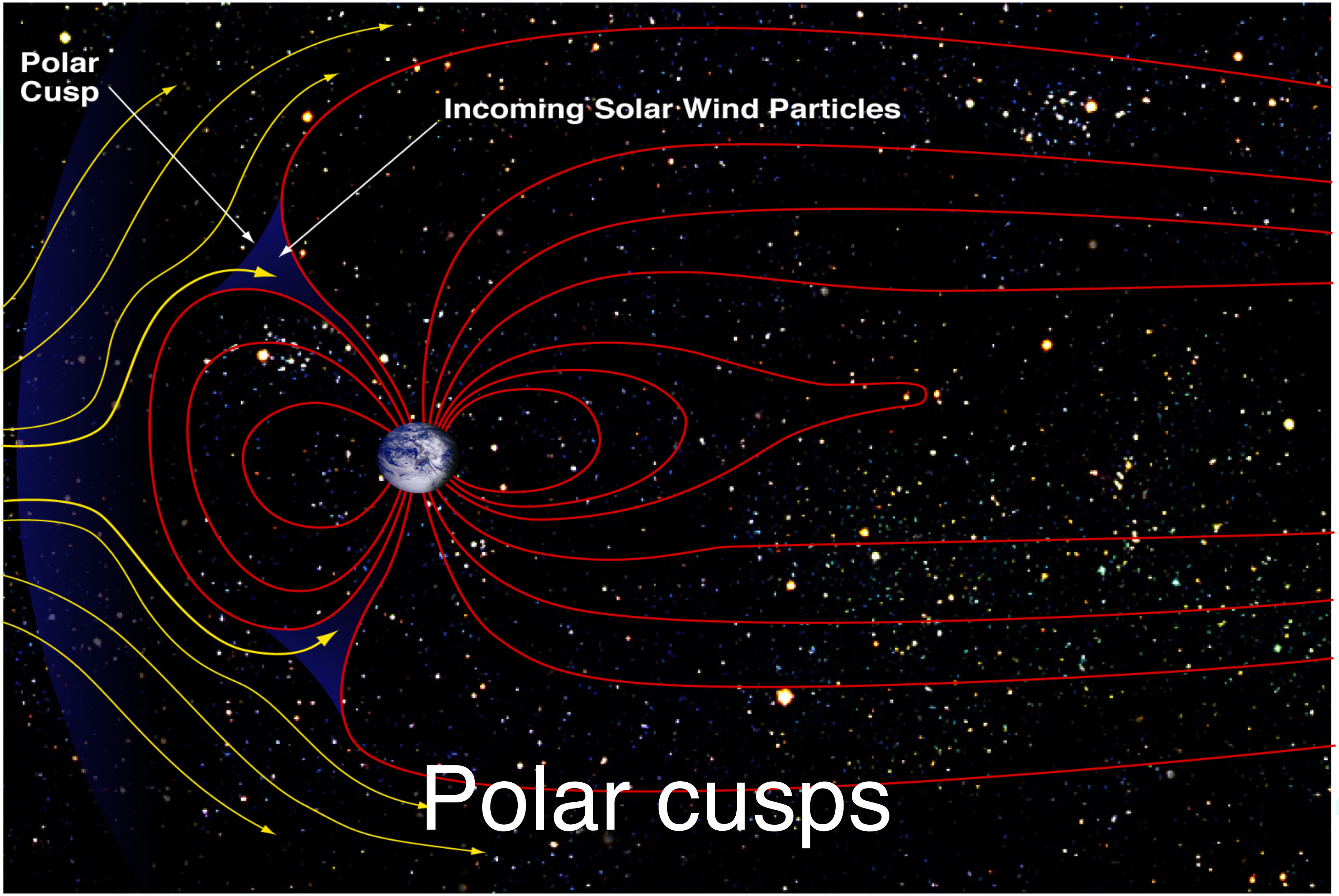


Credit: ESA, GSFC

Magnetotail, plasma sheet

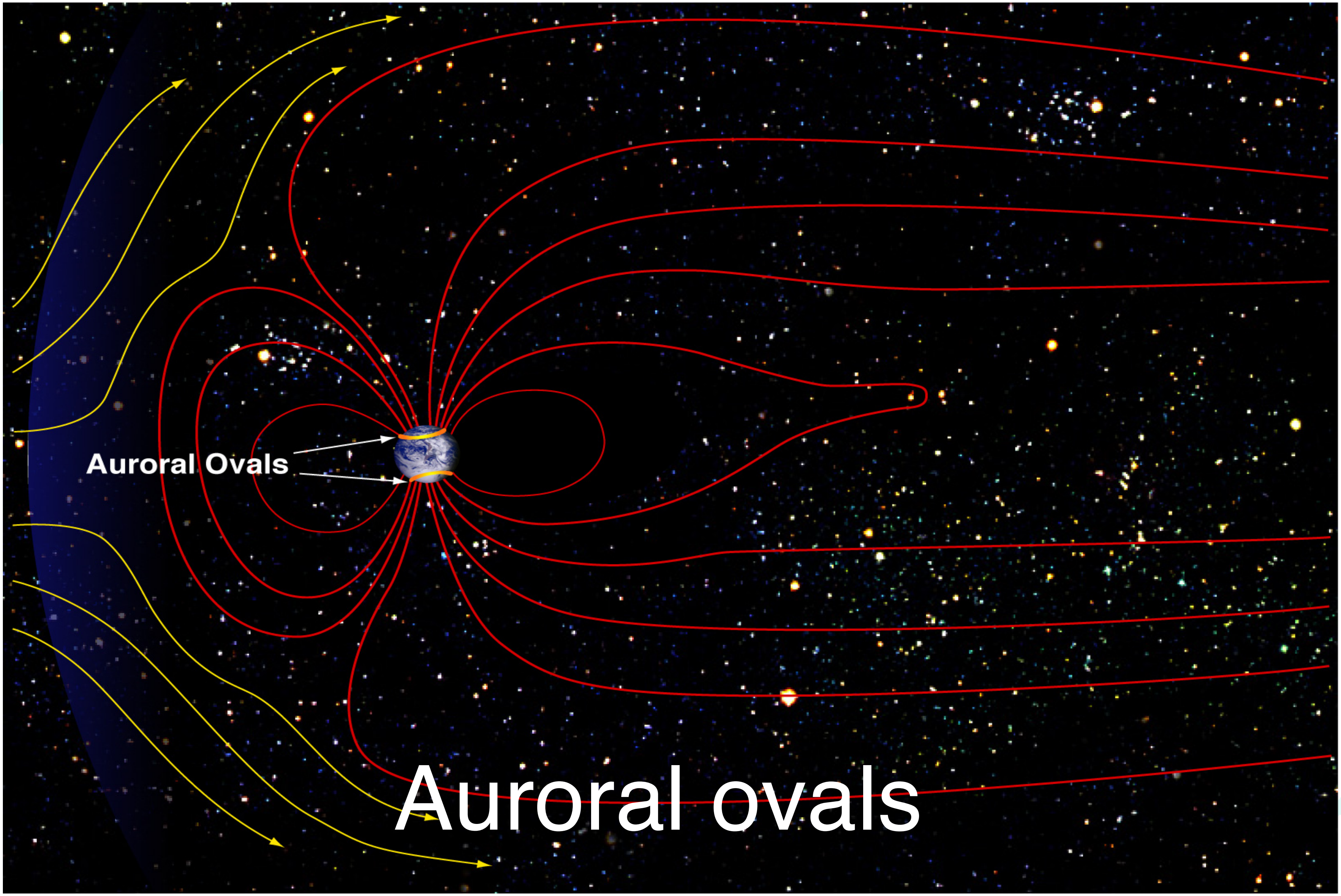


Credit: ESA, GSFC



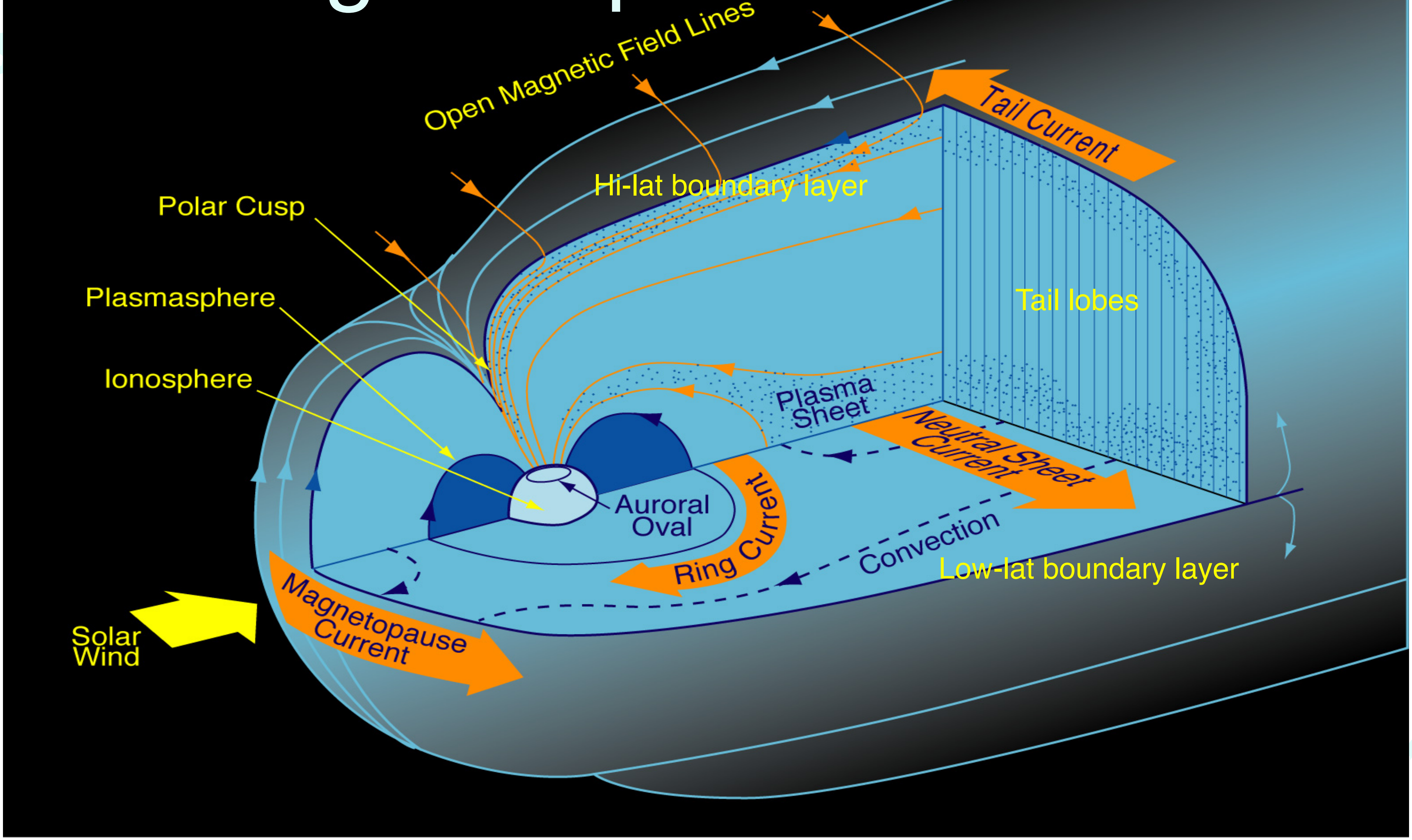
Polar cusps

Credit: ESA, GSFC



Credit: ESA, GSFC

Magnetospheric Structure



Credit: ESA, GSFC

Plasma characteristics

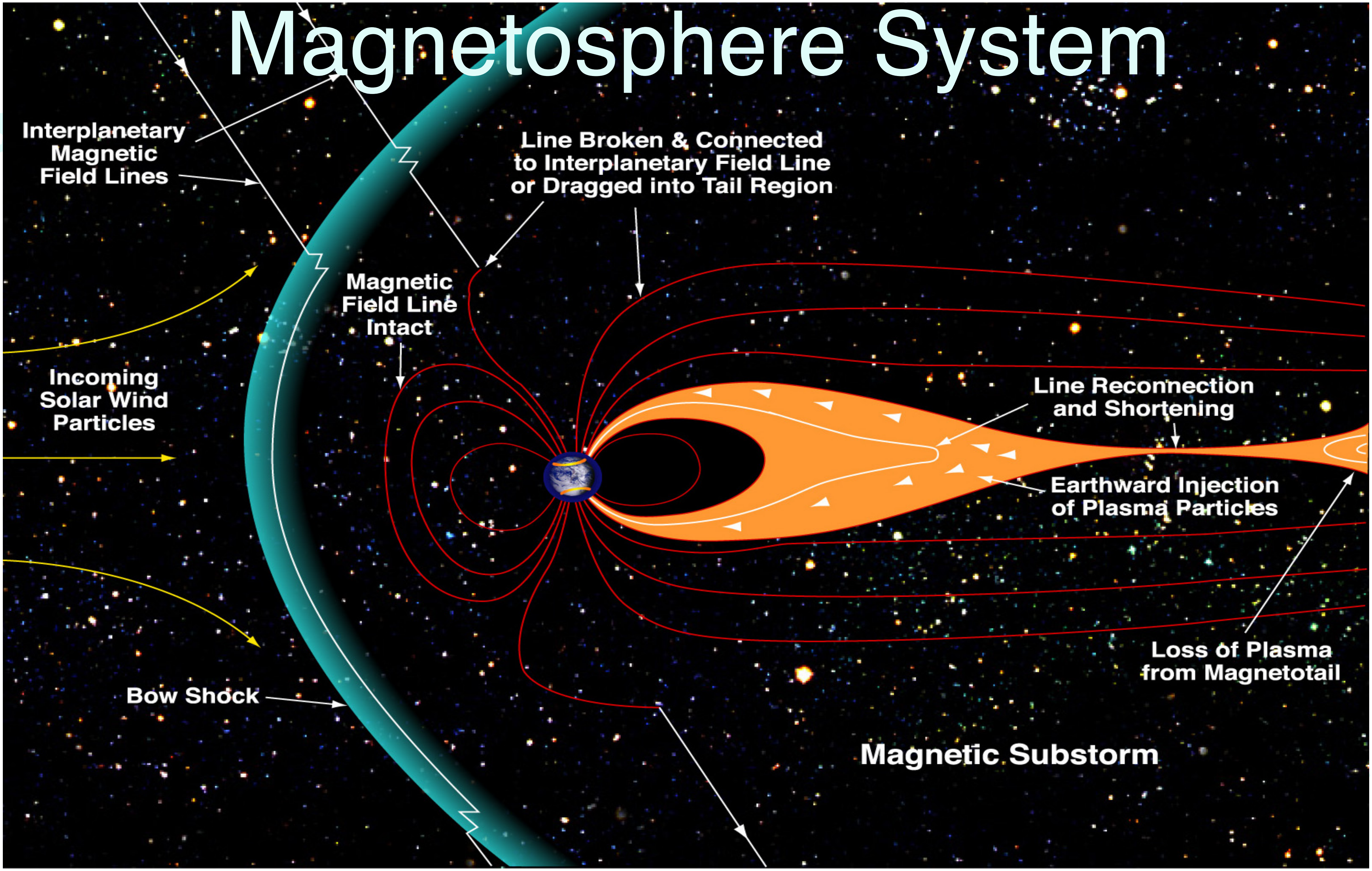
Table 1: Plasmas in the Earth's Magnetosphere

	Density N	Velocity Ve	Velocity Vp	Electron Temperature Te	Proton Temperature Tp	Magnetic Field	Comments
Solar Wind	1 - 10 cm^{-3}	200 - 600 km/sec	200 - 600 km/sec	$6x10^4$ to $3x10^5$ °K	$2x10^4$ to $2x10^5$ °K	2-15 nT	• High Speed Streams Associated With Coronal Hole • Low Speed Streams Near Sector Boundaries
Magnetosheath	2 - 50 cm^{-3}	200 - 500 km/sec	200 - 500 km/sec	10^5 to 10^6 °K	$5x10^5$ to $5x10^6$ °K	2-15 nT	• Turbulent Solar Wind Plasma and Magnetic Fields
High Latitude Boundary Layer	0.5 - 50 cm^{-3}	No Reported Measurements	100 - 300 km/sec	10^5 to 10^6 °K	$5x10^5$ to $8x10^6$ °K	10-30 nT	• Entry Layer into the Magnetosphere of Magnetosheath Plasma
Plasma Sheet Boundary Layer	0.1 - 1.0 cm^{-3}	500 - 5000 km/sec	100 - 1500 km/sec	$2x10^6$ to 10^7 °K	10^7 to $5x10^7$ °K	20-50 nT at 20 Re	• Region Which Maps to Auroral Zone Producing Discrete Auroral Arcs
Plasma Sheet	0.1 - 1.0 cm^{-3}	10 - 50 km/sec	10 - 1000 km/sec	$2x10^6$ to $2x10^7$ °K	Always Hotter by a factor of 3 to 5 such that $T_p/T_e>1$	9 nT in Deep Tail	• Thickness of 4 to 6 Re • Forms into the Ring Current at 5-6 Re From Earth
Lobe	10^{-3} to 10^{-2} cm^{-3}	No Reported Measurements	No Reported Measurements	$<10^6$ °K	$<10^7$ °K	Increases with Southward IMF	• Lowest Densities Found in the Magnetospheric Cavity

Credit: ESA, GSFC

Magnetospheric variability

Magnetosphere System



Currents

Magnetopause currents

Interaction between magnetosheath plasma and geomagnetic field

Cross-tail or plasma current

Current connecting oppositely directed magnetic fields emanating from north and south polar cusps

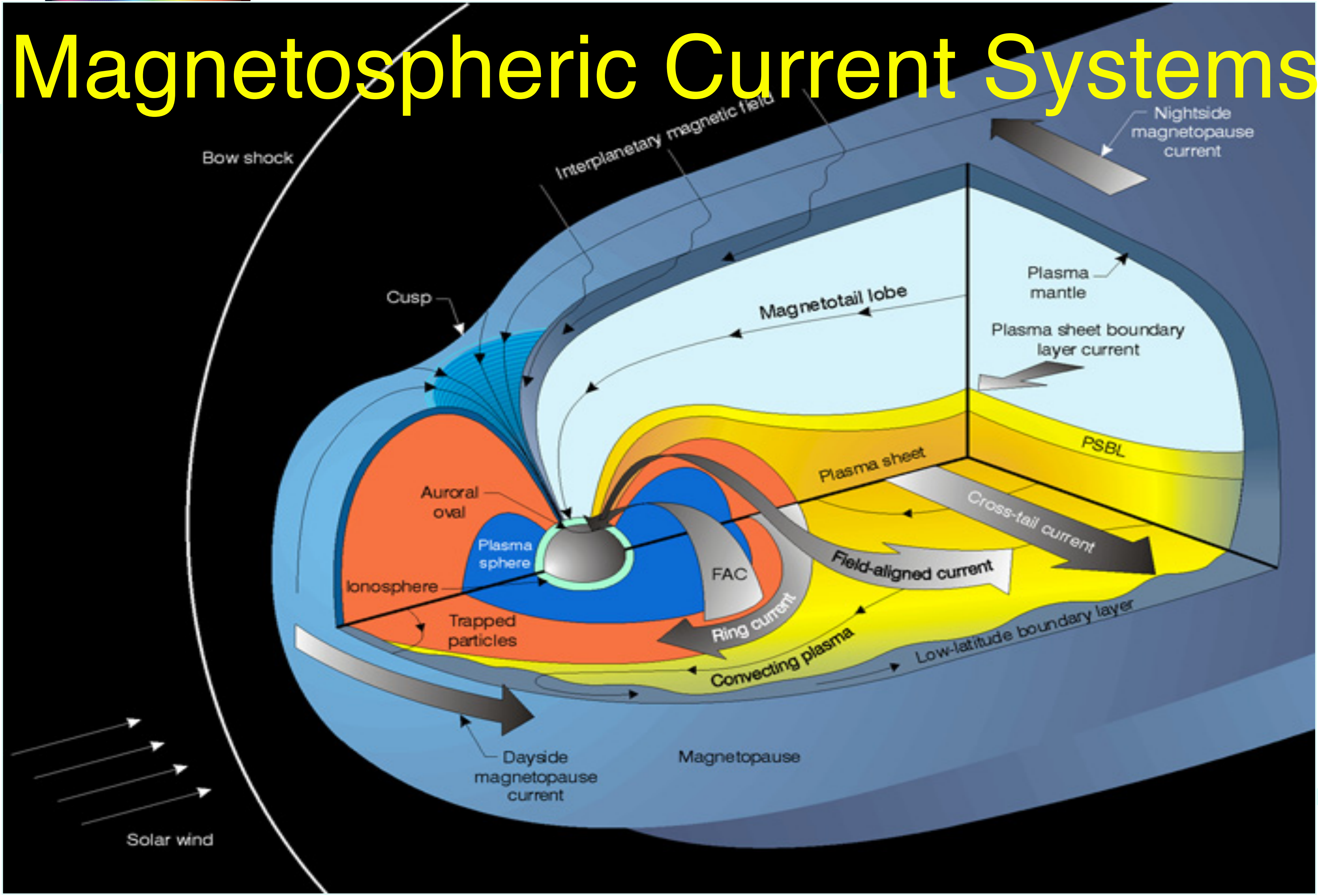
Ring current

Current encircling the magnetic equator

Field-aligned current

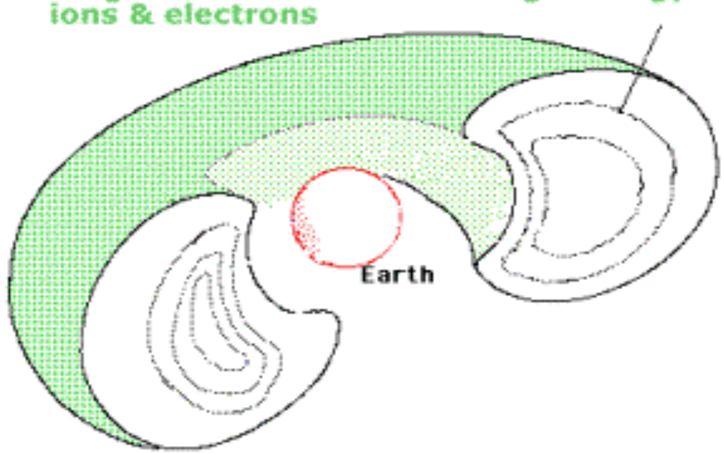
High-latitude current system between magnetosphere and ionosphere

Magnetospheric Current Systems



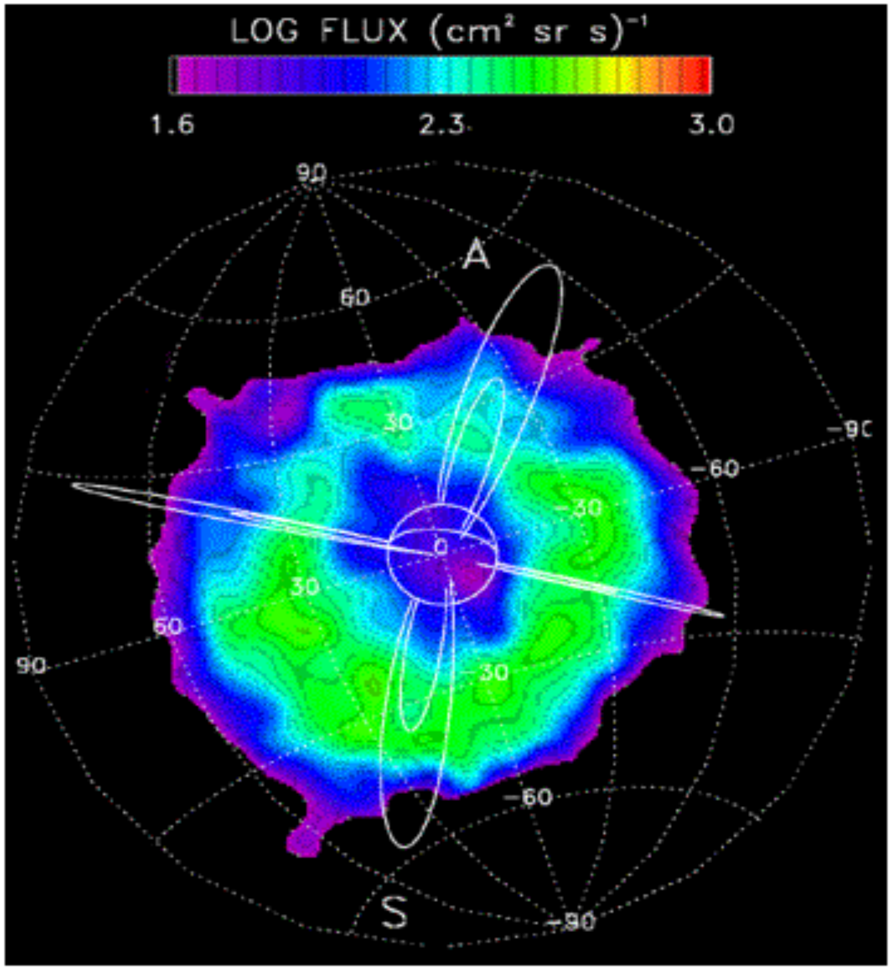
Credit: D.N. Baker

Ring currents



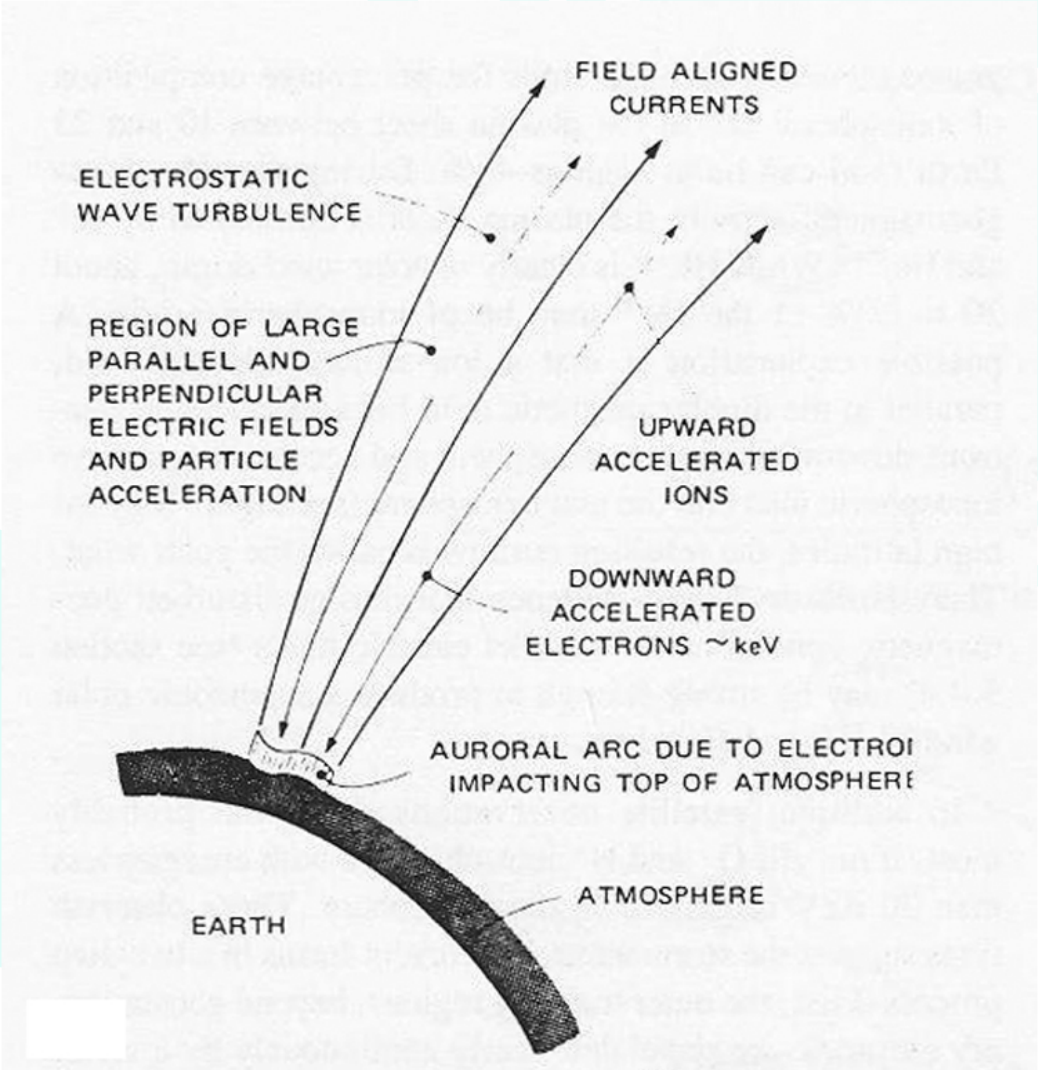
Contours of ring current density

Earth's ring current viewed from above North Pole

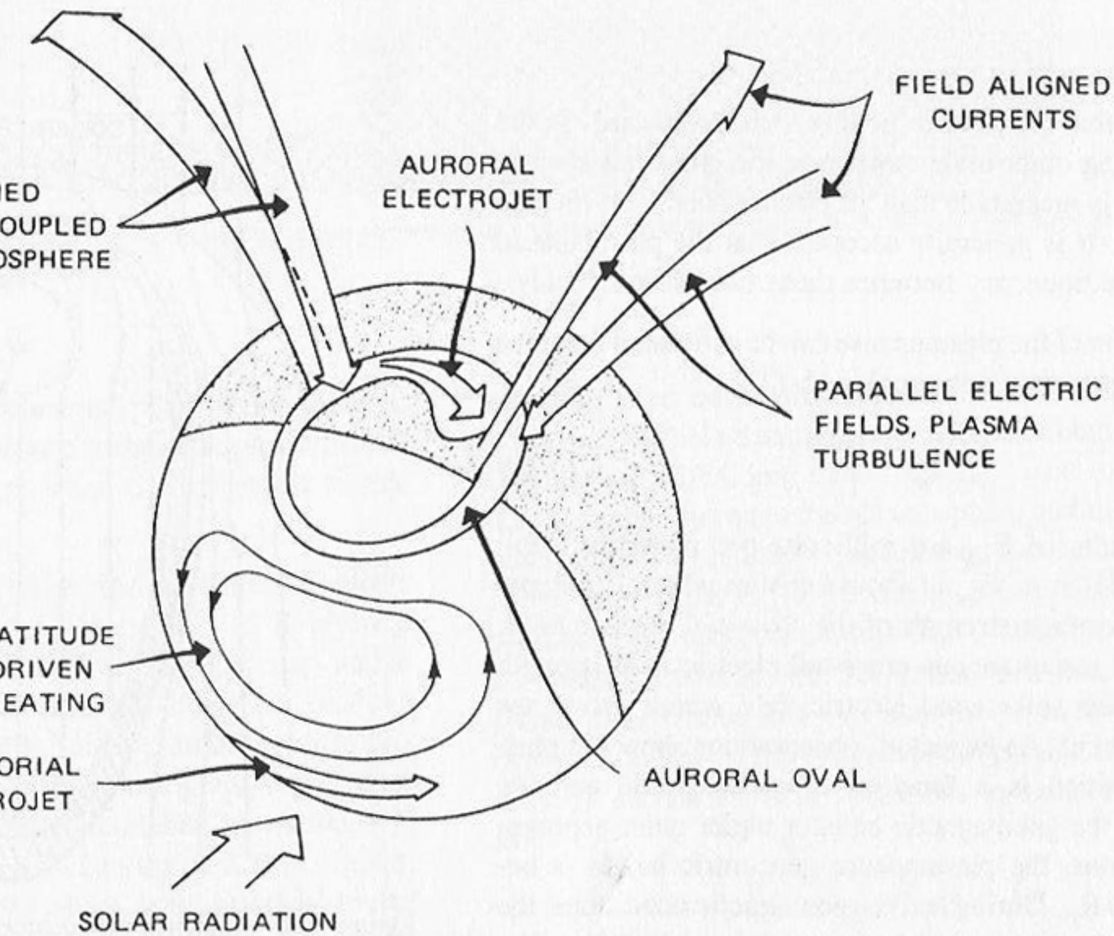


From HENA/IMAGE/NASA

Field-aligned Currents



Ionosphere-connected currents

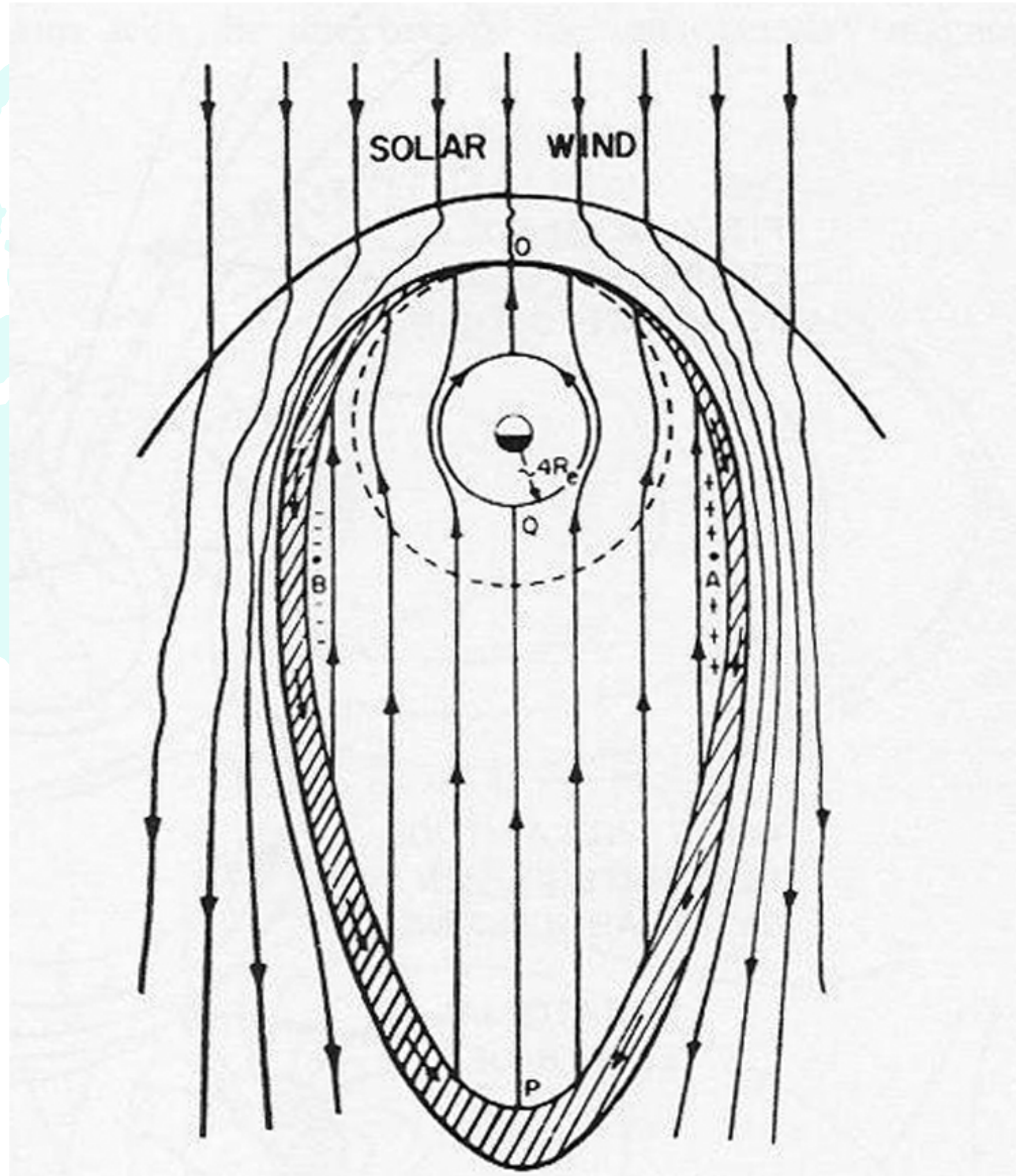


Credit: Tascione

Convection

North pole perspective

- Streamlines of the solar wind are outside the magnetopause boundary
- Interior streamlines show convective motion of the plasma
- Convective streamlines are also equipotentials of an associated electric field

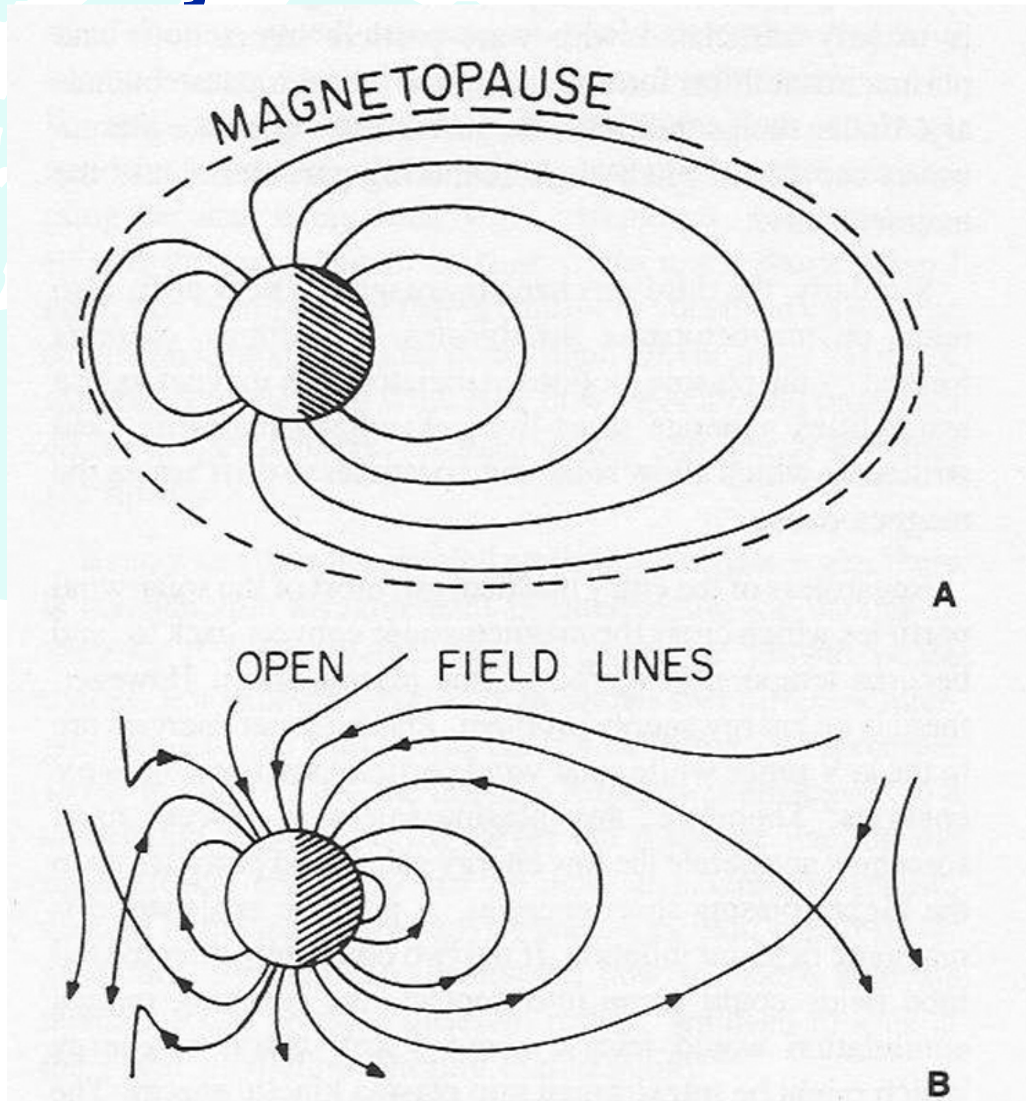


Credit: Tascione

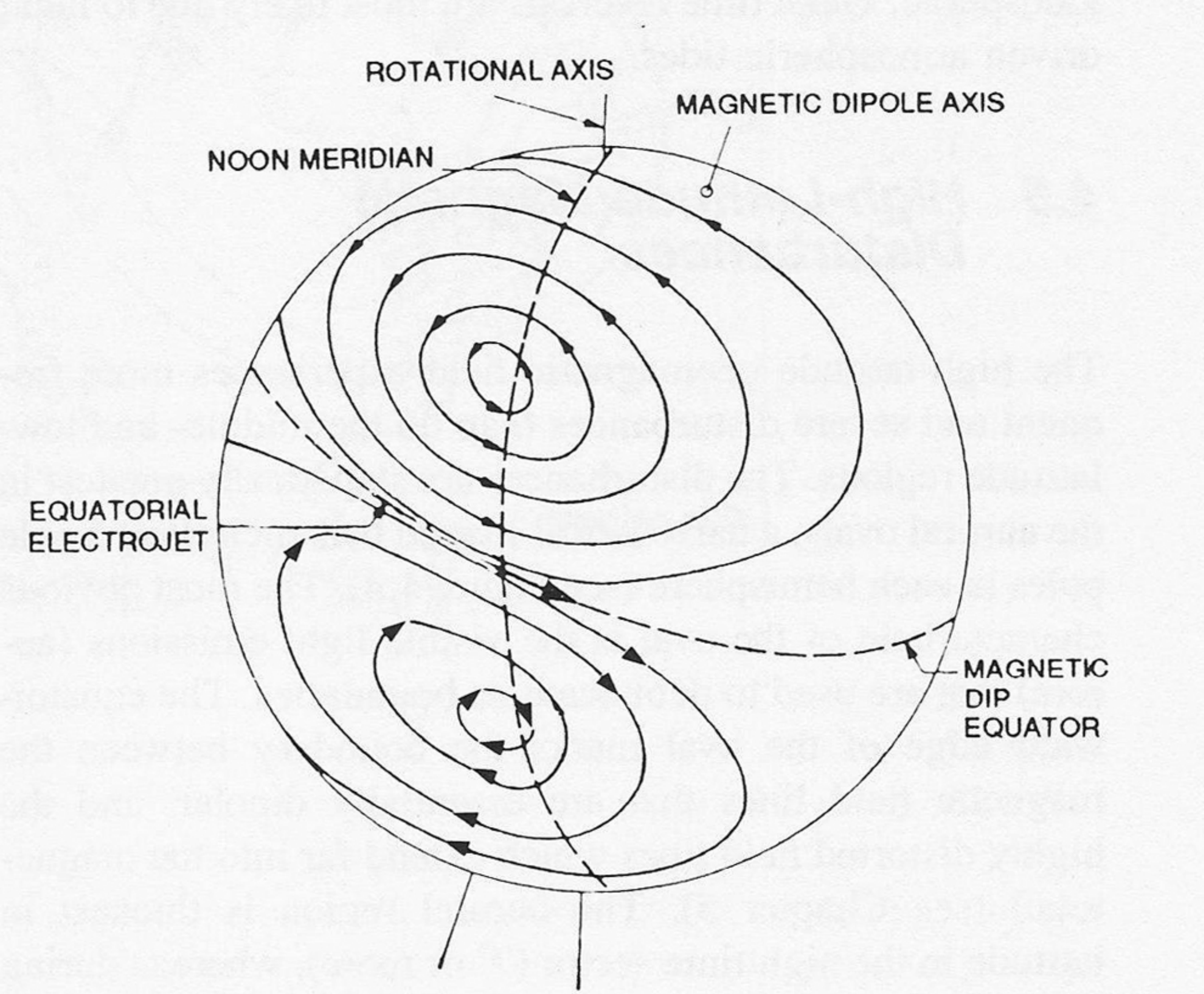
Solar wind injection

Mechanisms proposed for injecting solar wind particles into the magnetosphere (model B more consistent)

1) Magnetic merging at the magnetopause
2) Diffusion of particles across the magnetopause
3) Magnetic field drift of particles across the magnetopause



Sq (solar quiet) current system



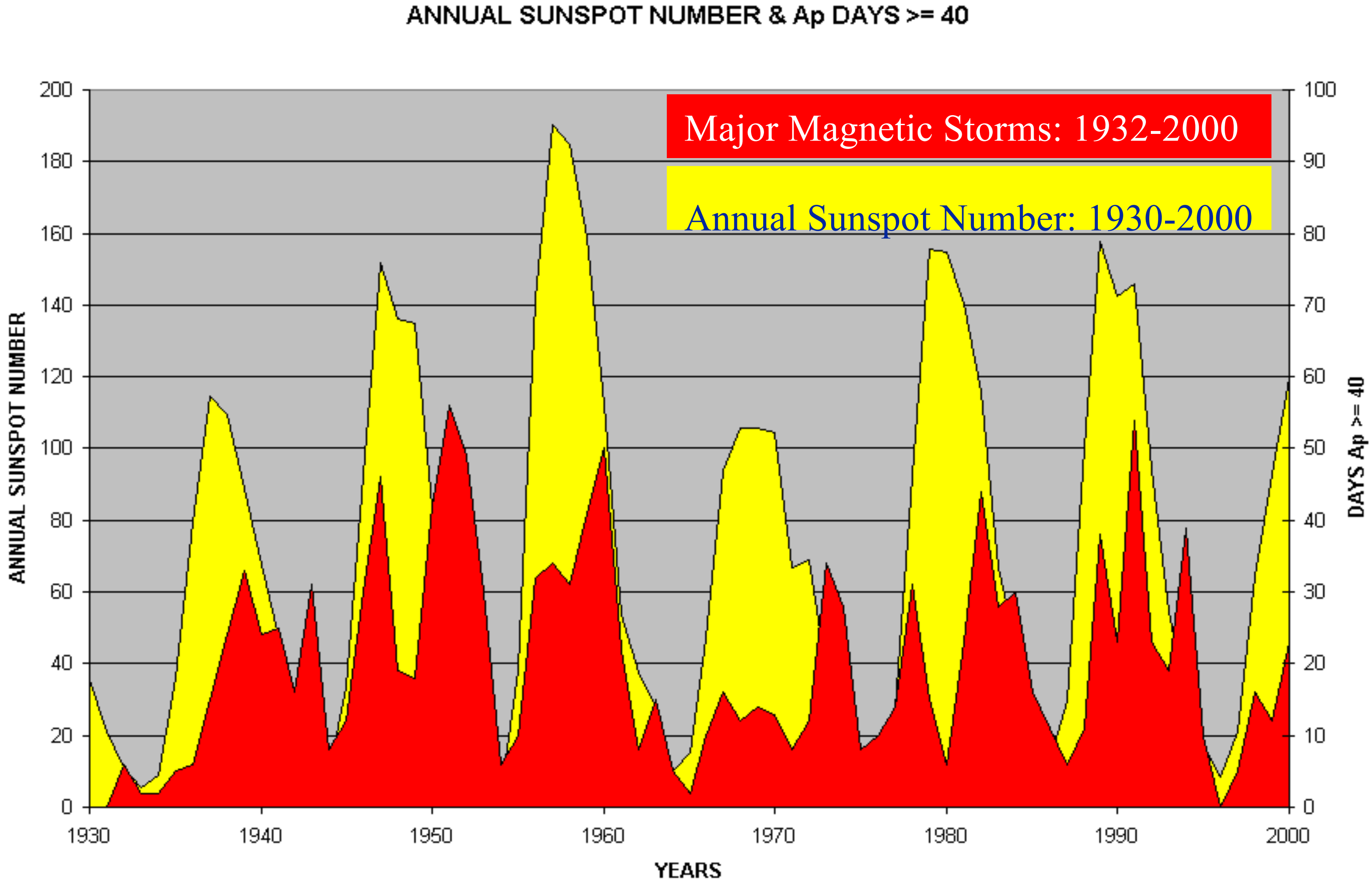
Storms and substorms

Geomagnetic Storms

- **Geomagnetic storms** are large disturbances in the near-Earth environment, which are caused by solar wind and interplanetary field structures that originate from solar disturbances such as coronal mass ejections. These storms are associated with:
- 1) Major disturbances in the geomagnetic field.
- 2) Strong increase of energetic (tens to hundreds of keV) ions in the (ring current) region.
- 3) Occasional intense fluxes of relativistic (MeV) electrons in the outer van Allen radiation belt.

Credit: ESA & Tascione

Sunspots and Magnetic Storms



Credit: D.N. Baker

Magnetic substorms

- **Magnetospheric substorms** are caused by the dynamic response of the magnetosphere to varying solar conditions. The energy input from the solar wind is governed by the orientation of the interplanetary field and, as long as the magnetospheric region remains stable, energy is stored as magnetic energy. At some critical point the magnetotail becomes unstable and the magnetic energy will be released via the "substorm expansion phase", which involves:
- 1) Injection of energetic (tens to hundreds of keV) particles (electrons and ions) to the vicinity of the geostationary orbit.
- 2) Strong electric currents in the auroral region.
- 3) Rapid fluctuations and configurational changes of the magnetospheric magnetic field.

How we identify currents and magnetic disturbances – magnetic indices

- **Kp**
  planetary index for geomagnetic activity
- **Ap**
  Ap invented to create daily average values from eight 3-hourly ranges
- **Sq**
  Solar **q**uiet day variation from electric currents in the ionosphere produced by solar heating
- **Dst**
  The **D**isturbance **s**torm **t**ime (Dst) index is an indicator for the electrical interaction of the nightside magnetosphere and ionosphere due primarily to the ring current but also other currents
- **PC**
  Polar **C**ap proxy for the electric field imposed on the polar ionosphere by the solar wind

Geomagnetic proxies

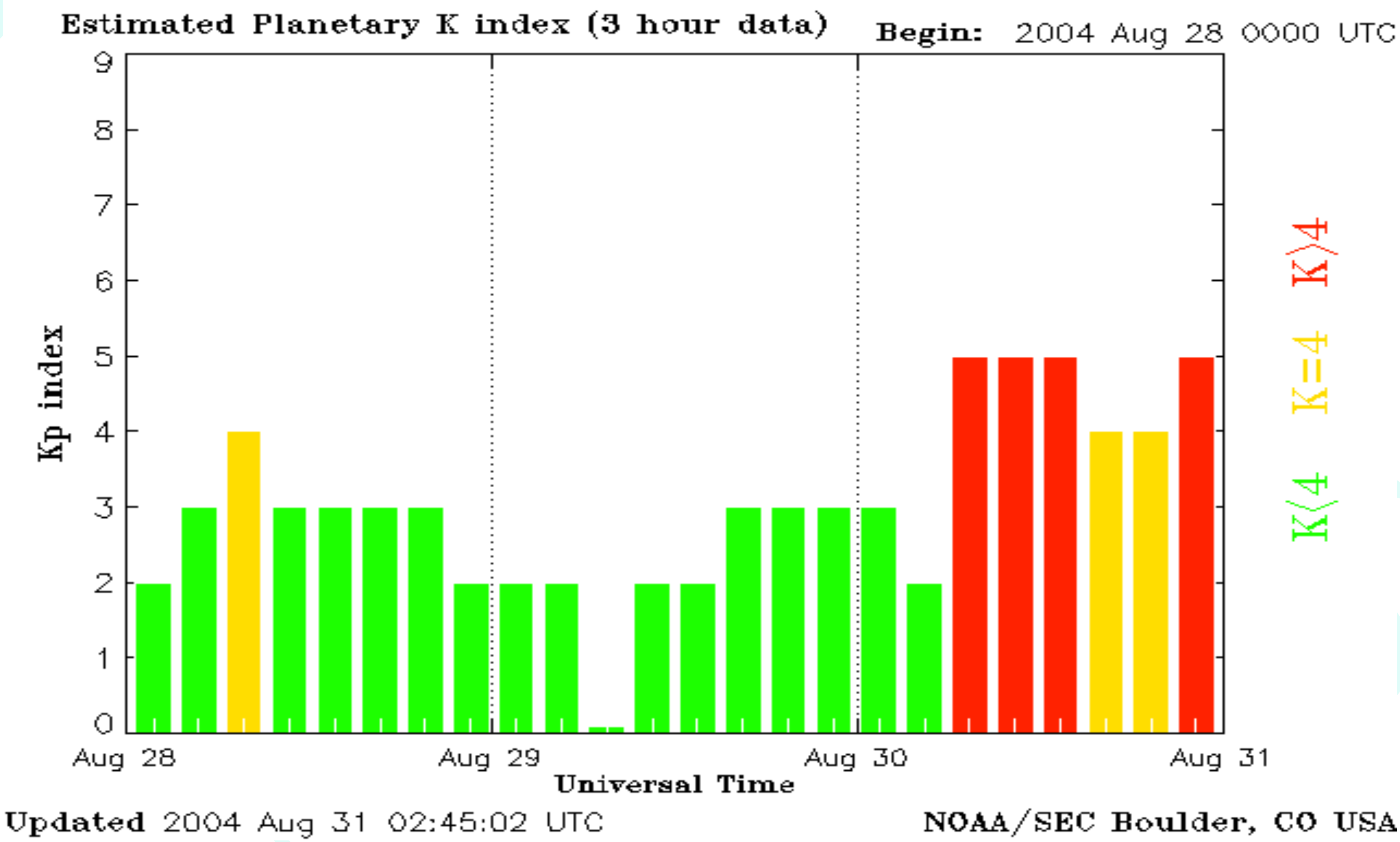
Ap / Kp

- Kp is the planetary index for geomagnetic activity
- Calculated as a weighted average of K-indices from a network of geomagnetic observatories
- Observatories do not report their data in real-time, necessary for an operations center to make the best estimate of this index based on available data
- Ap invented to create daily average values from eight 3-hourly ranges

K	A	NOAA G
0	0	
1	3	
2	7	
3	15	
4	27	
5	48	G1
6	80	G2
7	140	G3
8	240	G4
9	400	G5

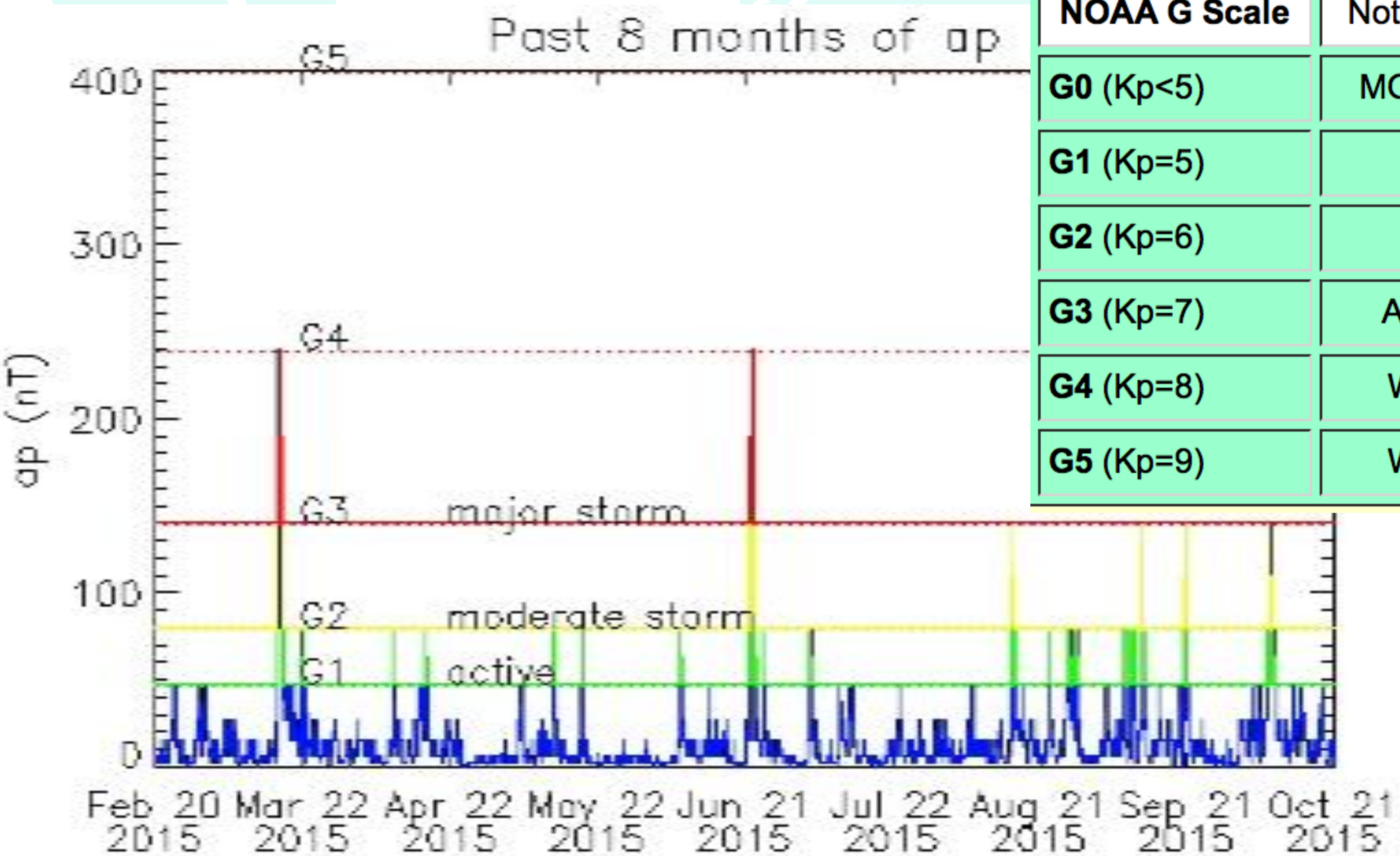
Credit: NOAA

Kp



Credit: NOAA

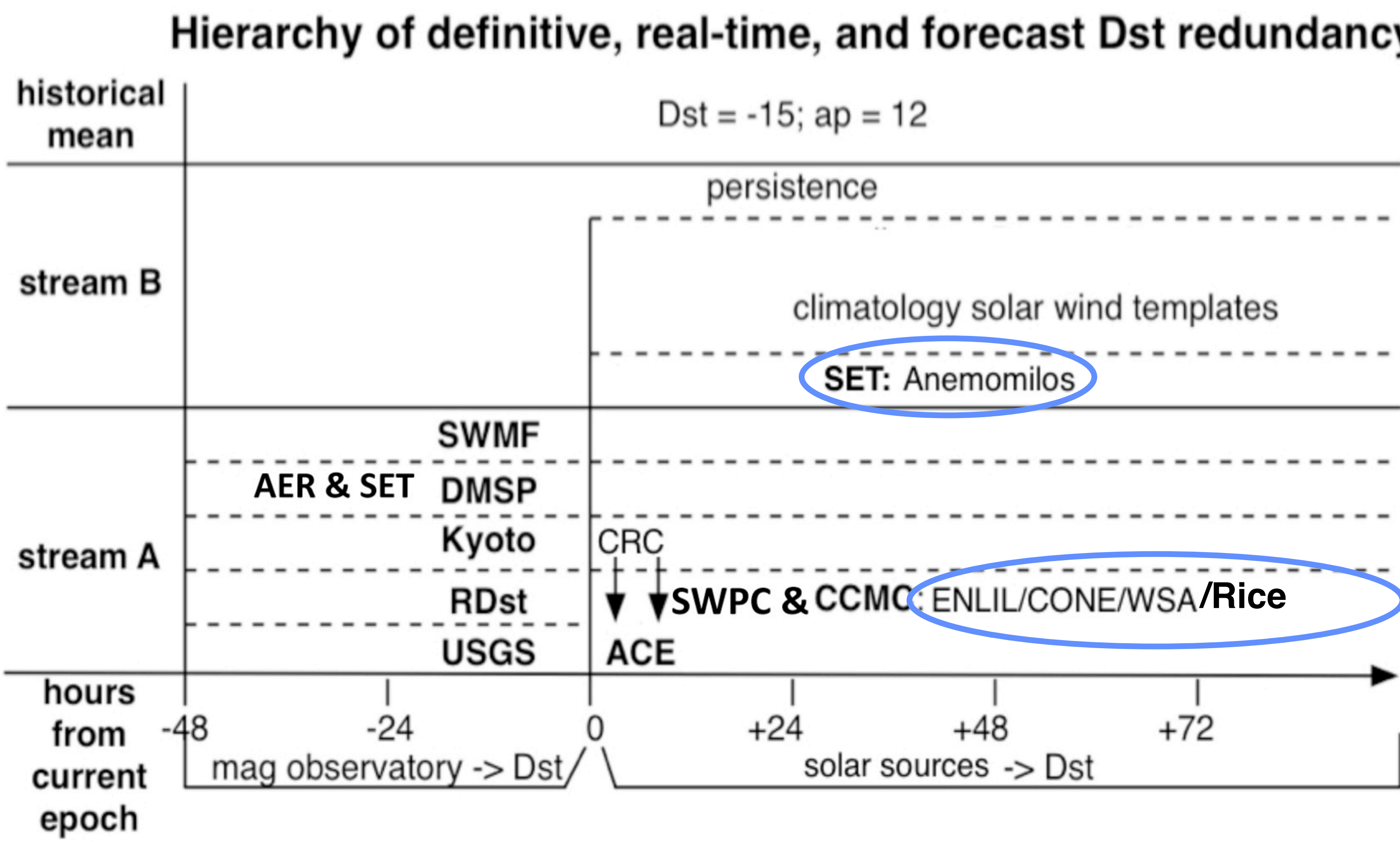
Geomagnetic indices



NOAA G Scale	Notice message	
G0 (Kp<5)	MONITORING	
G1 (Kp=5)	ALERT	
G2 (Kp=6)	WATCH	
G3 (Kp=7)	ADVISORY	
G4 (Kp=8)	WARNING	
G5 (Kp=9)	WARNING	

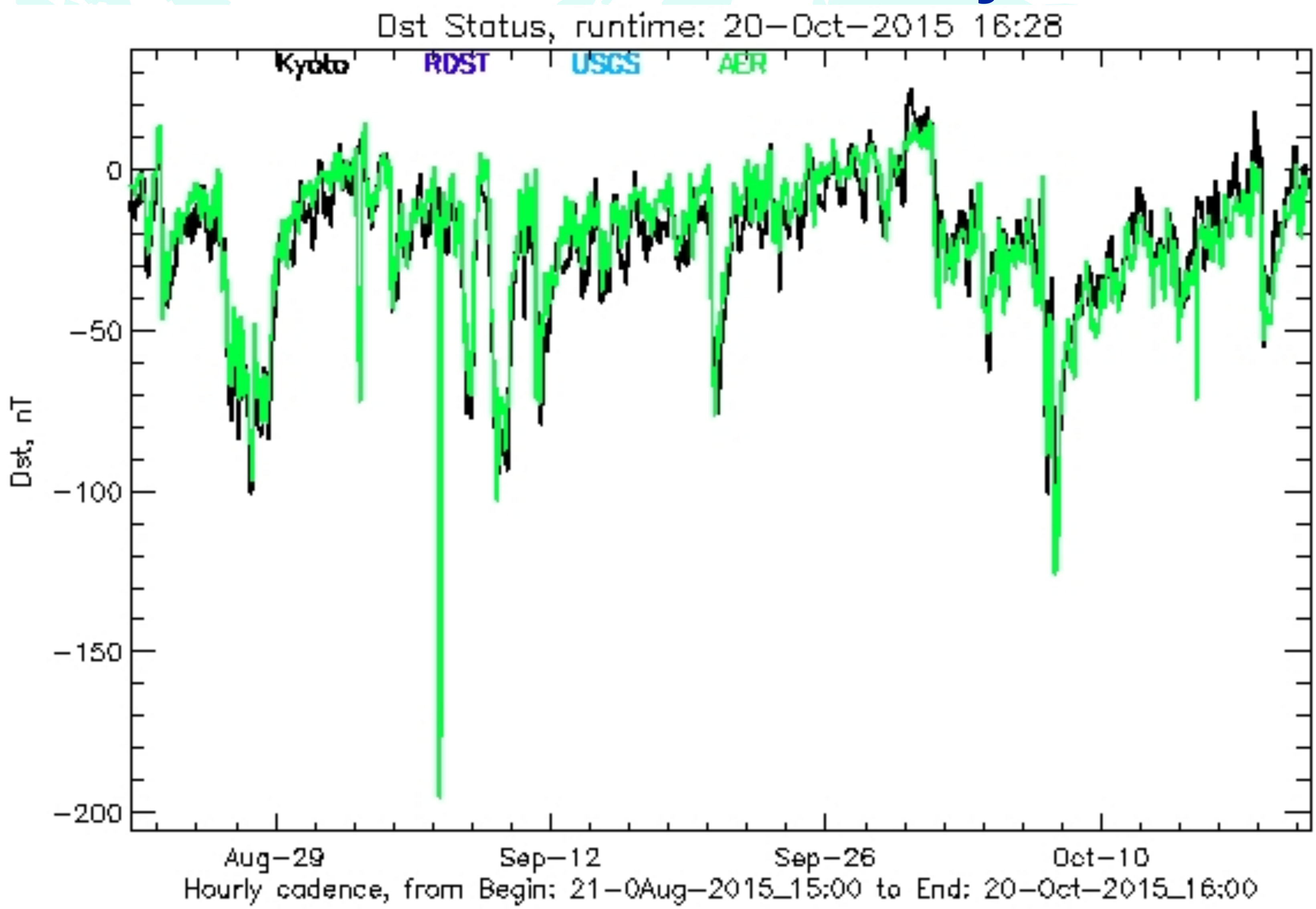
Credit: SET

Operational Dst requirement: -48 to +72 hours with 3-hour granularity, 3-hour latency



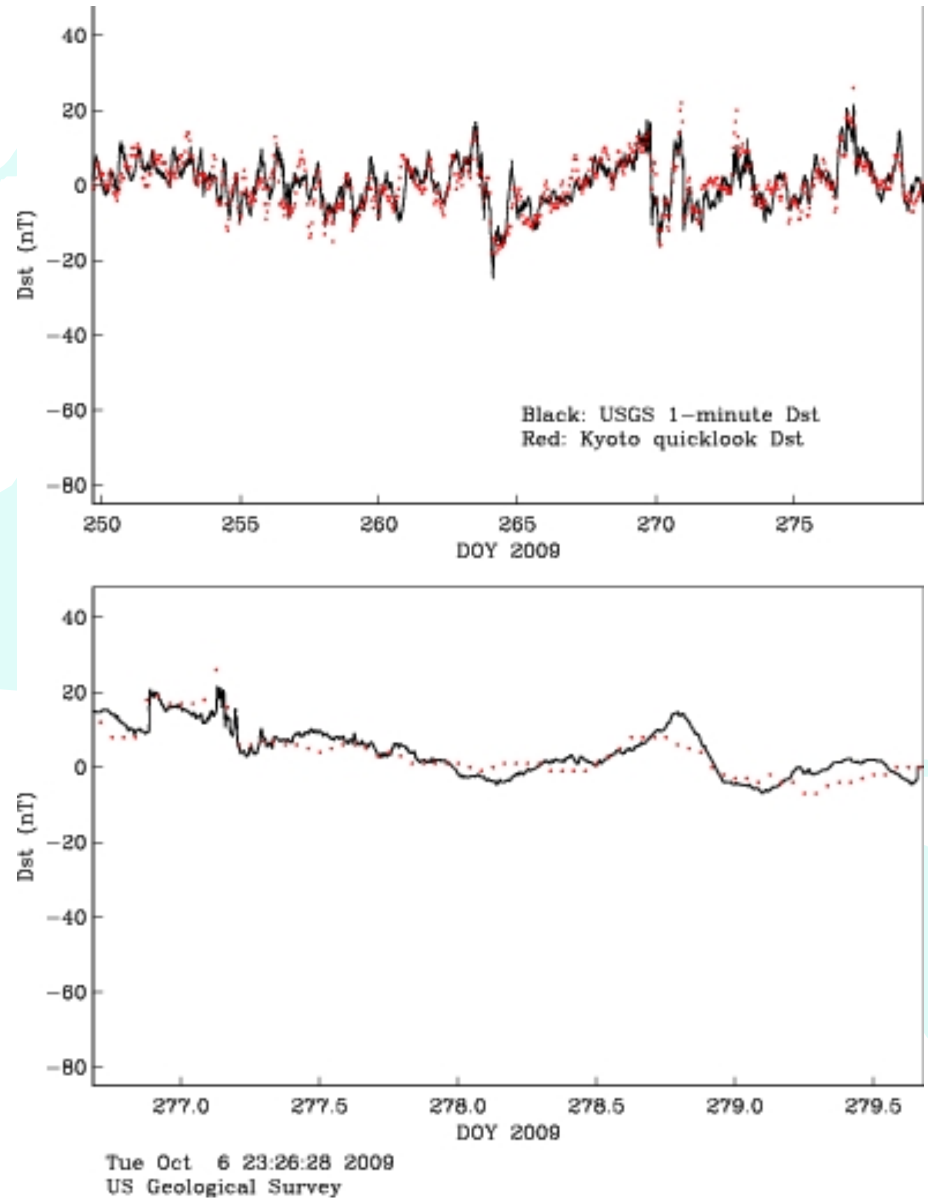
W. Kent Tobiska <ktobiska@spacewx.com>

Real-time Dst used by SET

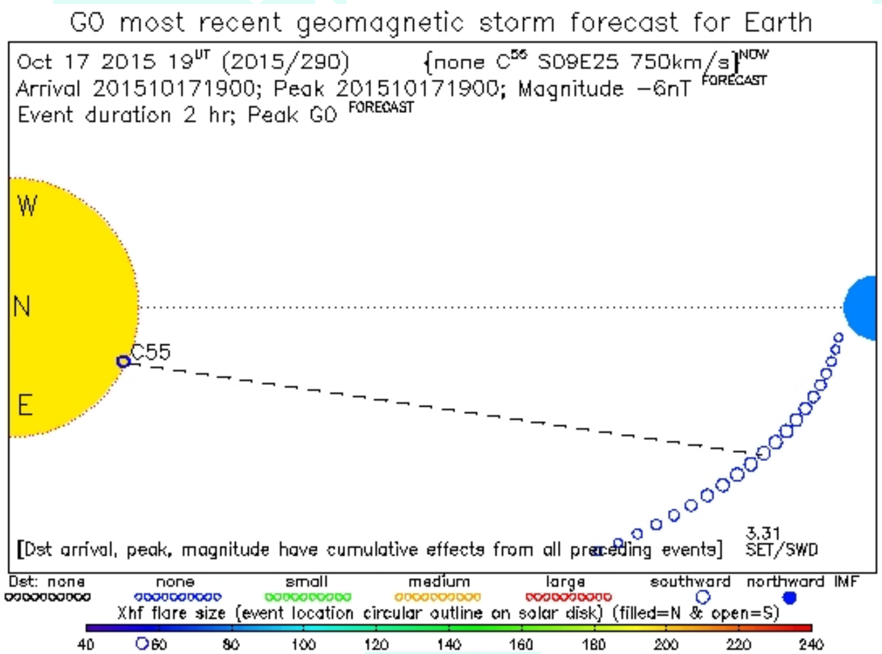


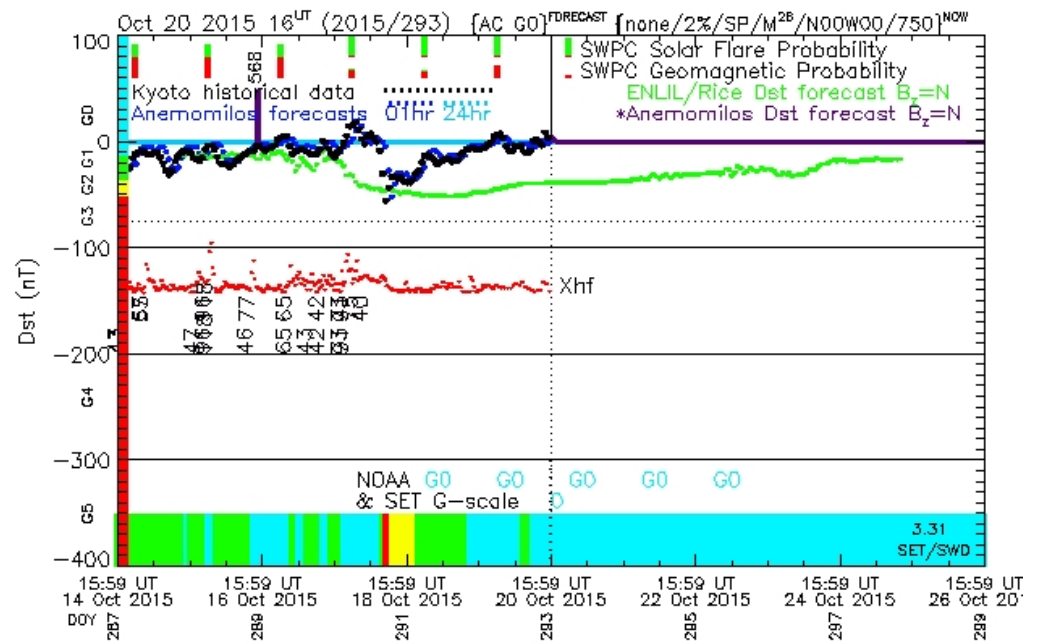
USGS high accuracy Dst (MAPS website

http://sol.spacenvironment.net/~maps/)



Operational Dst today: full redundancy, -6 to +6 days, 1-hour granularity, 1-hour latency





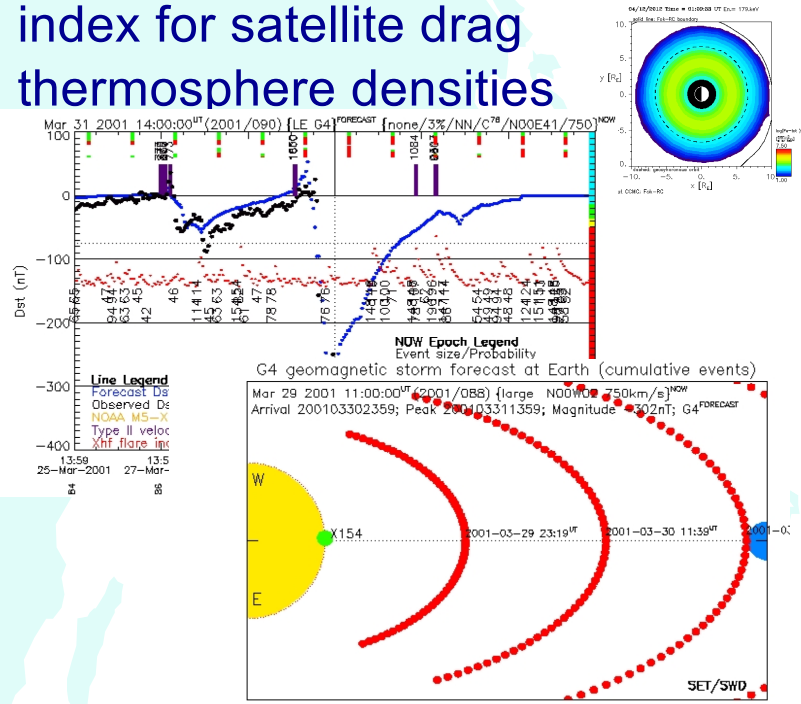
http://sol.spacenvironment.net/~sam_ops/index.html?

Anemomilos Forecast Dst

Anemomilos

- The Greek word for "windmill"
- 6-day forecast of hourly Dst with 1-hour latency
- It is a data-driven deterministic algorithm using solar observables to identify geoeffective events

geomagnetic ring current index for satellite drag thermosphere densities

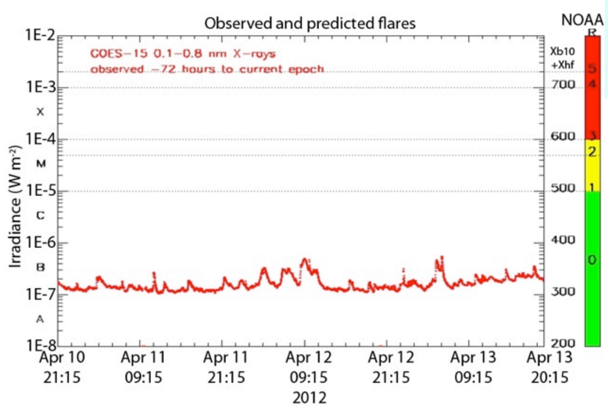


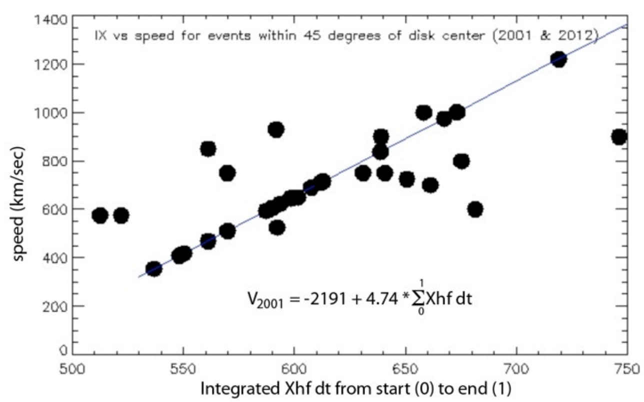
Credit: Tobiska

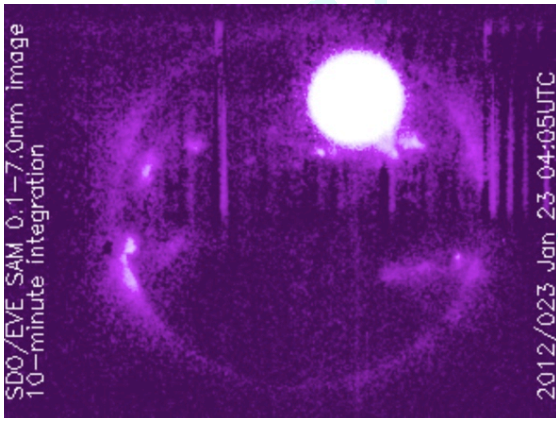
Anemomilos Basis

Three solar observables are used for operational Dst forecasting: flare magnitude, integrated flare irradiance, and event location

- Magnitude is a proxy for ejecta quantity (mass) and, combined with speed derived from the integrated flare irradiance, represents the kinetic energy
- Speed is estimated as line-of-sight velocity for events within 45° radial of solar disk center
- Solar disk, not limb, observable features are used for predictive techniques based on SDO/EVE/SAM centroid of flare event







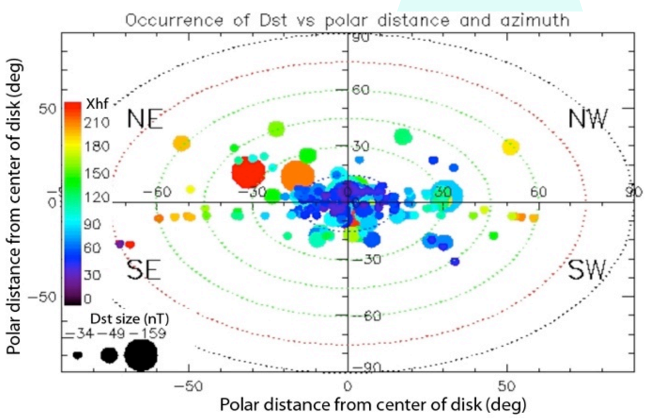
W. Kent Tobiska <ktobiska@spacewx.com>

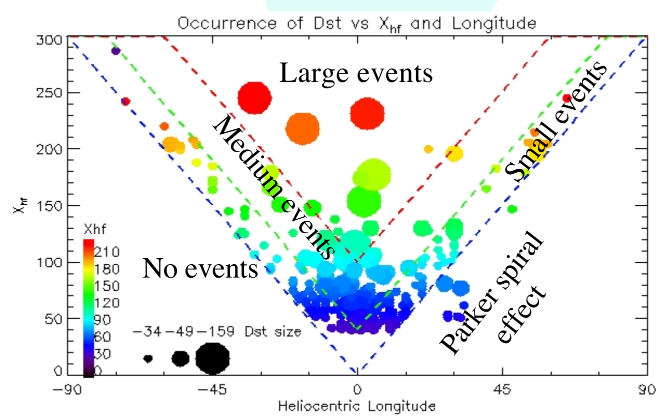
Anemomilos geoeffectiveness of location

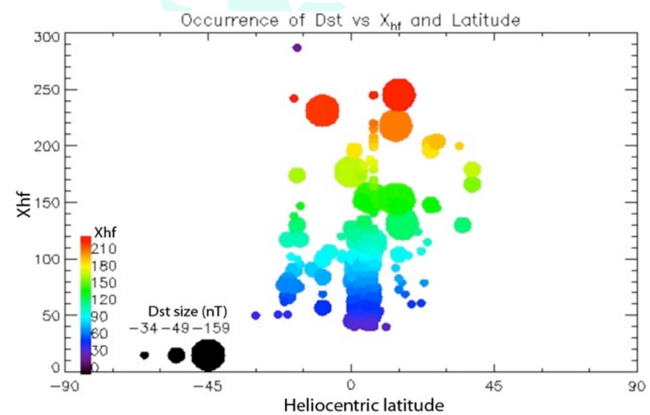
Occurrence of Dst vs Xhf in solar latitude & longitude (25 months)

- 2001 (Jan-Jul), 2005 (Mar-Sep), 2011-2012 (Dec-Nov)

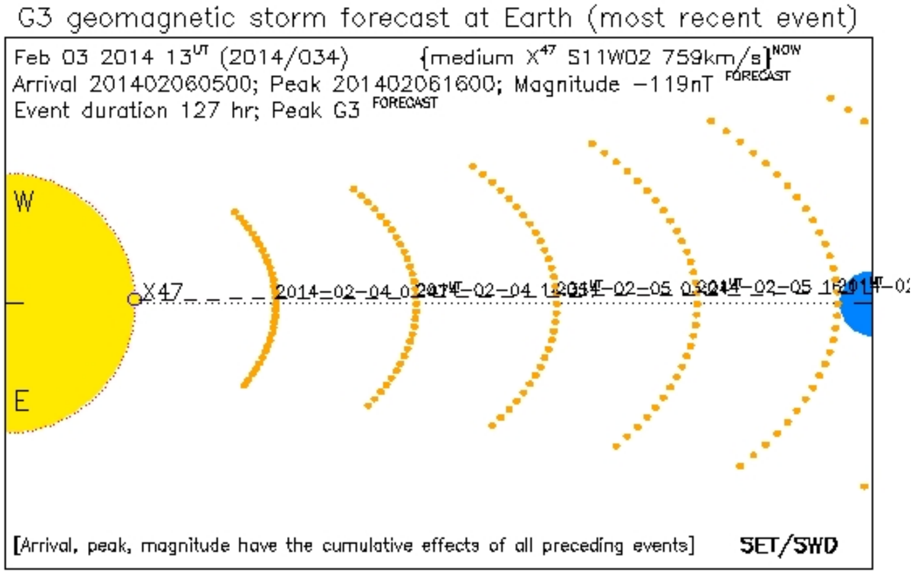
Resulting Dst event size can be sorted by Xhf size and flare longitude/latitude

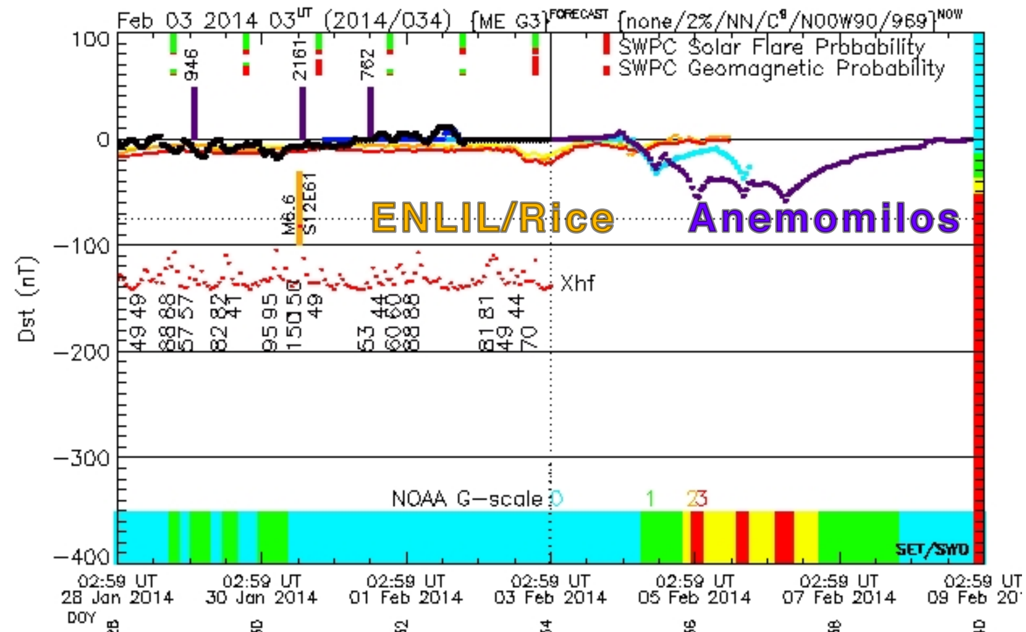






SET's operational Dst forecasting

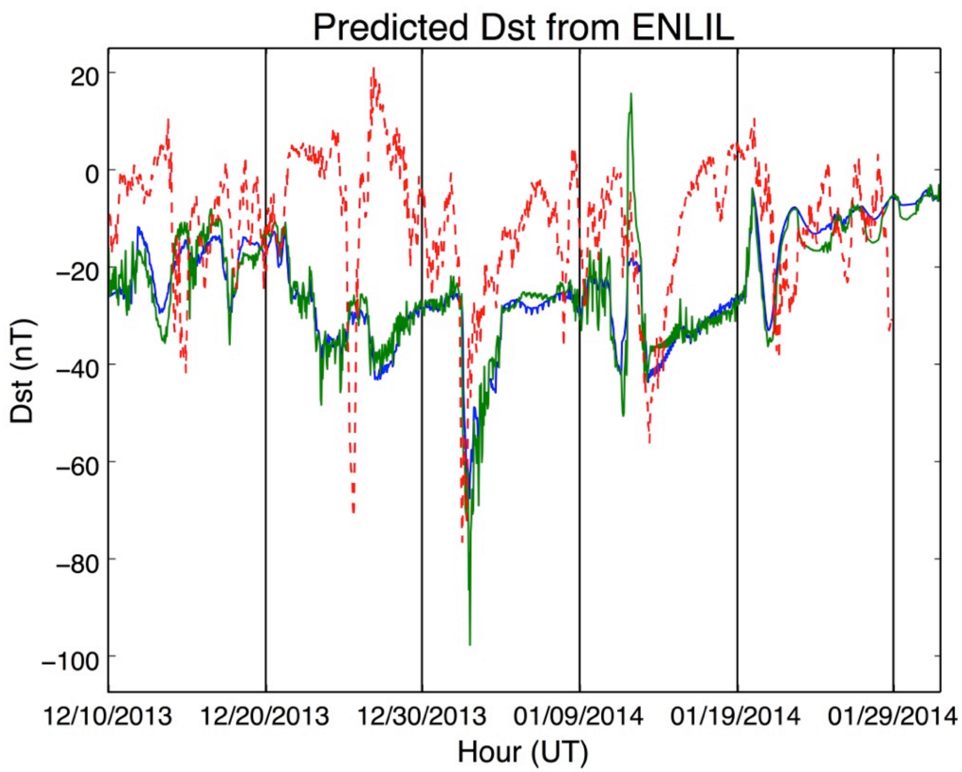


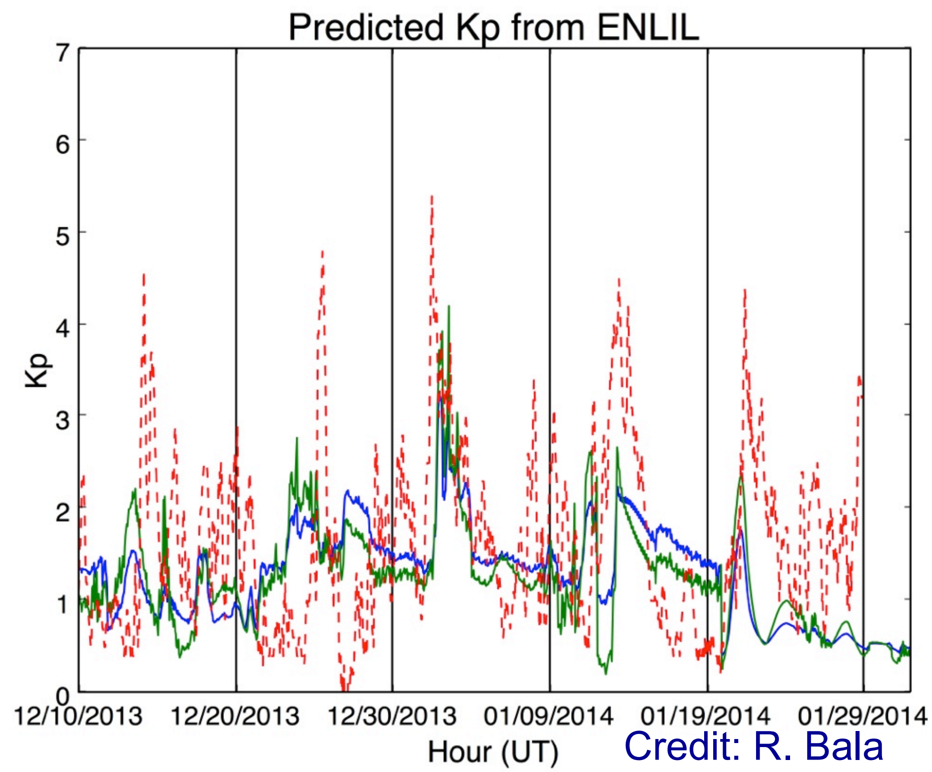


- *Anemomilos* is the Greek word for "windmill"
- The data-driven deterministic algorithm uses **3 solar observables** to identify geoeffective events: **http://sol.spacenvironment.net/~sam_ops/index.html?**
- It has a **15-minute cadence**, **1-hour time granularity**, **144-hour prediction** window (+6 days), and 1-hour latency
- Most flare events above a certain irradiance threshold, occurring within defined solar longitude/latitude regions and having sufficient liftoff velocity of ejected material, will produce a geoeffective Dst perturbation

ENLIL/Rice Prime Dst Forecast and ACE Comparison

- ACE near-realtime predictions are plotted here in red
- http://mms.rice.edu/realtime/forecast.html
- ENLIL/Rice models under predict but largely in line with the trend and are within acceptable range
- Magnetospheric activity on the New Year's day is well captured





Credit: R. Bala

Rice real-time models of Kp, Dst and AE

- Near near-realtime predictions models based on neural network
- Uses empirical coupling functions as sequential time inputs generated using ACE data to feed the neural networks
- Predicts Kp, Dst and AE (short-term) over1-hour and 3-hour periods (subject to prevailing solar wind conditions)
- Subscribers to their network receive free "alerts" for values exceeding pre-defined thresholds

$$\mathrm{Kp;\ Dst}^{*}_{t+1} = f\,(\Phi_{t=0}, \Phi_{t=-1}, \ldots, \Phi_{t-8}) \text{ and}$$

$$\mathrm{Kp;\ Dst}^{*}_{t+1} = f\,(\Phi_{t=0}, \Phi_{t=-1}, \ldots, \Phi_{t-8}; \mathrm{Press}_{t=0}\ \mathrm{Press}_{t=-1}, \ldots, \mathrm{Press}_{t-8})$$

Dst^{*} is pressure corrected

Bala and Reiff [2012]

Resources

- *Space Weather,* Geophysical Monograph 125, Eds. Song, Singer, Siscoe, AGU, 2001.
- *Spacecraft-Environment Interactions,* Hastings and Garrett, Cambridge Univ. Press, 1996.
- *Introduction to the Space Environment,* Tascione, Krieger Pub. Co., 1994.
- ISO 16695 Earth's Main Field
- ISO 22009 Model of the Earth's magnetospheric magnetic field

Credit: Tobiska

Summary

- **Planetary space environment (Earth's magnetosphere)**
  - Plasma physics basics
    - Maxwell's Equations, Ohm's Law, Equation of continuity, hydrodynamic equation
    - Particle motion and drifts, magnetic mirroring
  - Geomagnetism
    - IGRF, dipole field, geomagnetic coordinates
  - Magnetospheric structure
    - Bow shock, magnetosheath, magnetotail, plasma sheet, neutral sheet, polar cusps
  - Magnetospheric variability
    - Currents, convection, storms and substorms, magnetic variations, magnetic storms, magnetic indices