PHYS 3280

Physics of the space environment

5. Magnetosphere

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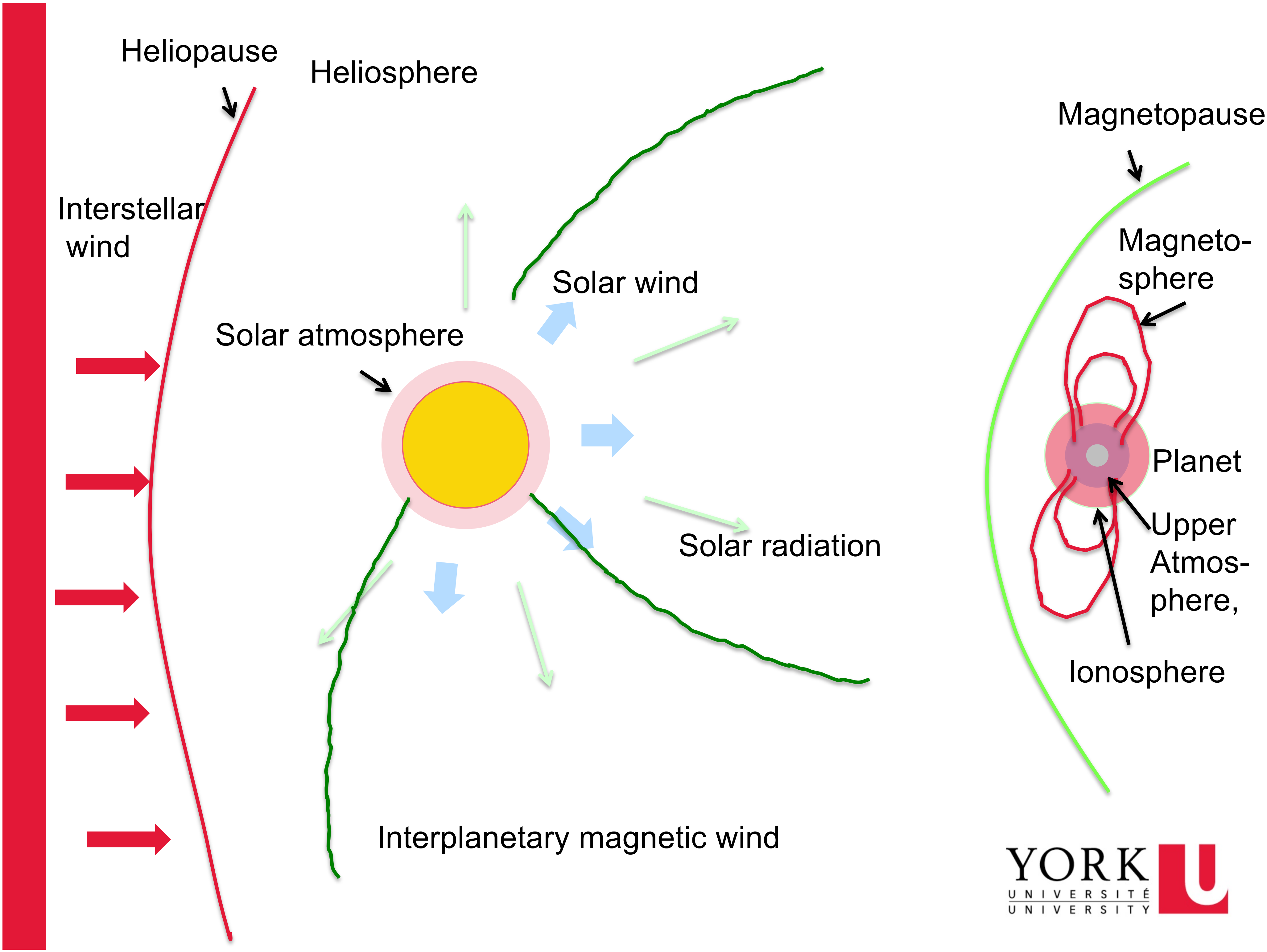
Professor Norbert Bartel



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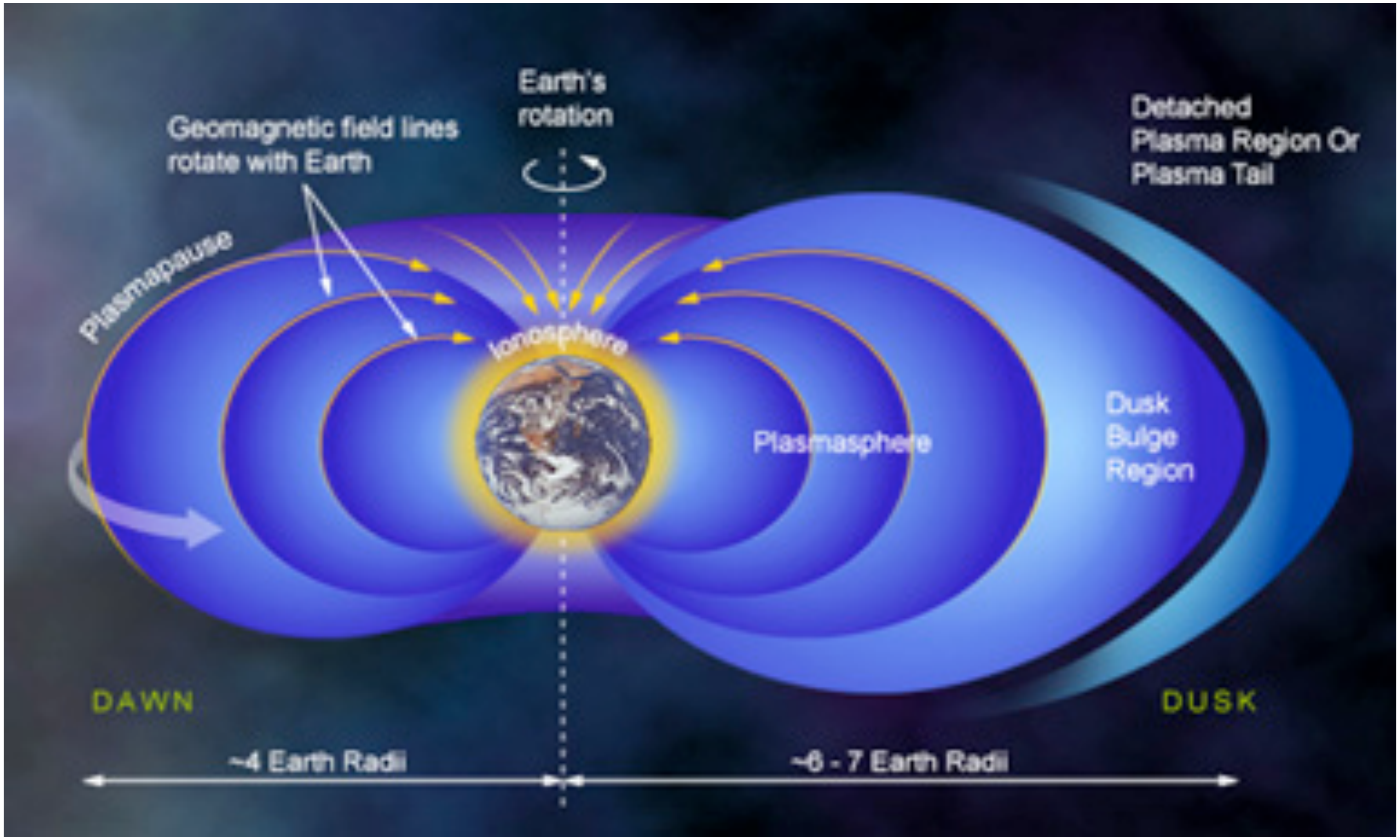

windows2universe

Recall: History

Groundbased observations related to Earth's magnetic field

1600 Gilbert - Earth magnetic field investigated with compass needle
1722 Graham – Short period magnetic field fluctuations
1808 Humboldt – Irregular magnetic field disturbances ➔ magnetic storms
1839 Gauss – small part of magnetic field is extraterrestrial
1842 Schwabe – Solar sunspot cycle
1849 Barlow – First space weather effect: disturbance of telegraphic communications during geomagnetic storms
1852 Sabine – Intensity of magnetic disturbances correlated with sunspot cycle
1859 Carington – Solar flares can be followed by magnetic storms

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Recall History:

Groundbased observations related to the aurora

1733 de Mairan –description of auroras and speculation about the cause: solar particles penetrate Earth’s atmosphere and generate polar lights.

1741 Hjorter & Celsius – Intense magnetic field perturbations occurred during enhanced auroral activity

1866 Ångström– Recording of prominent greenish yellow auroral line at 557.7 nm

~1895 Birkeland – First experimental simulation of an aurora

~1895 Størmer – Calculation of trajectories of electrical particles in Earth magnetic field

Recall History:

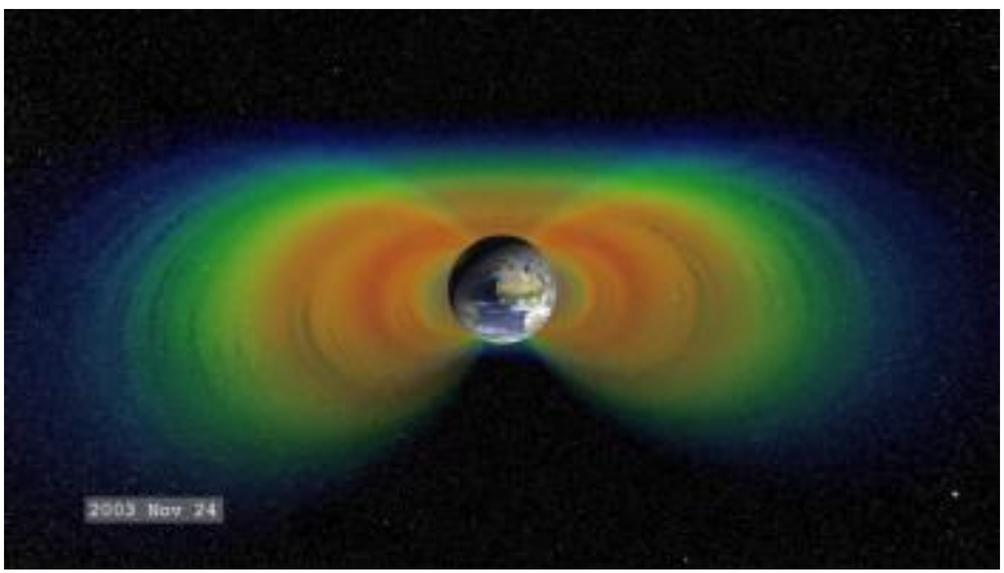
Spacebased observations of the space environment

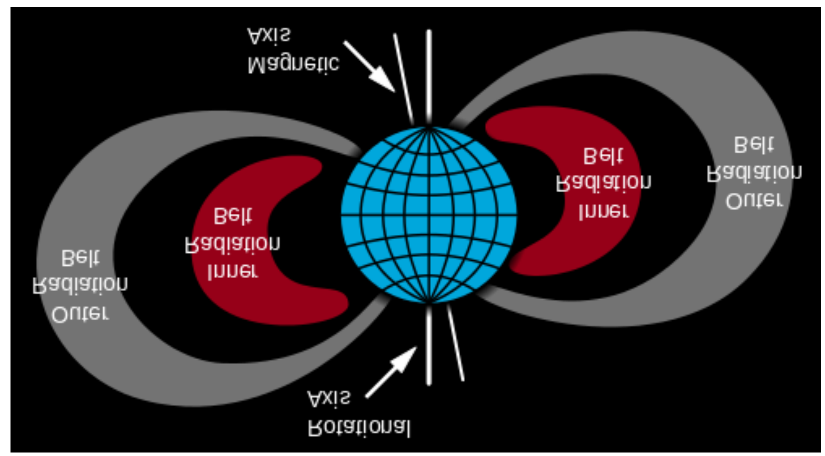
1949 USA -- refurbished German V2 rocket, launch into upper atmosphere, solar UV and X-ray observations

1957 Soviet Sputnik, first artificial satellite

1958 USA, Explorer 1 Earth orbit

1958 USA, detection of Van Allen radiation belt





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Magnetosphere as a vital part of space physics

- Ionosphere is modified by the magnetic field
- Capture of energetic particles by the magnetosphere
- Aurora
- Solar-terrestrial relations based on interplay between solar wind and magnetosphere

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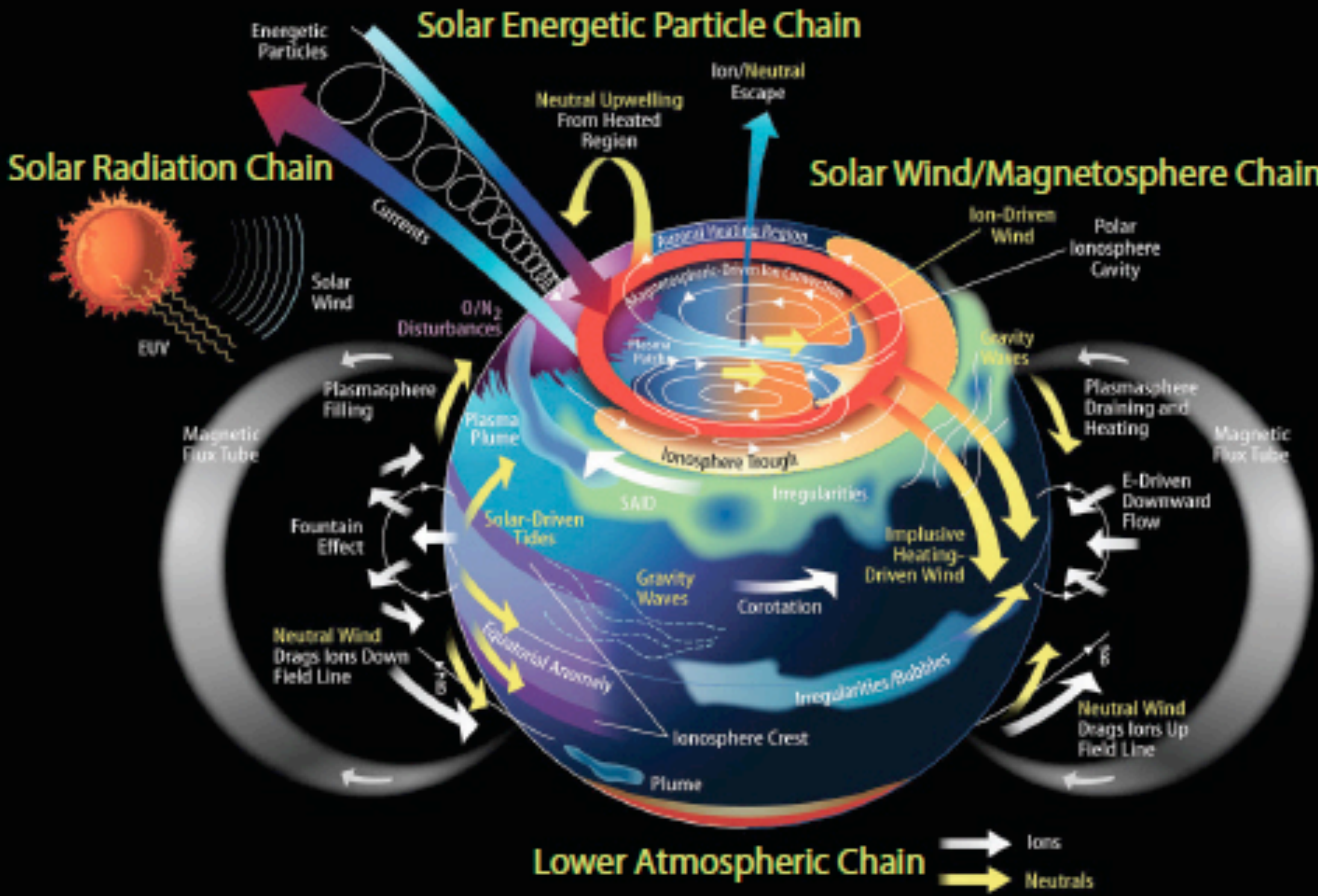
The magnetosphere as part of Earth's space environment



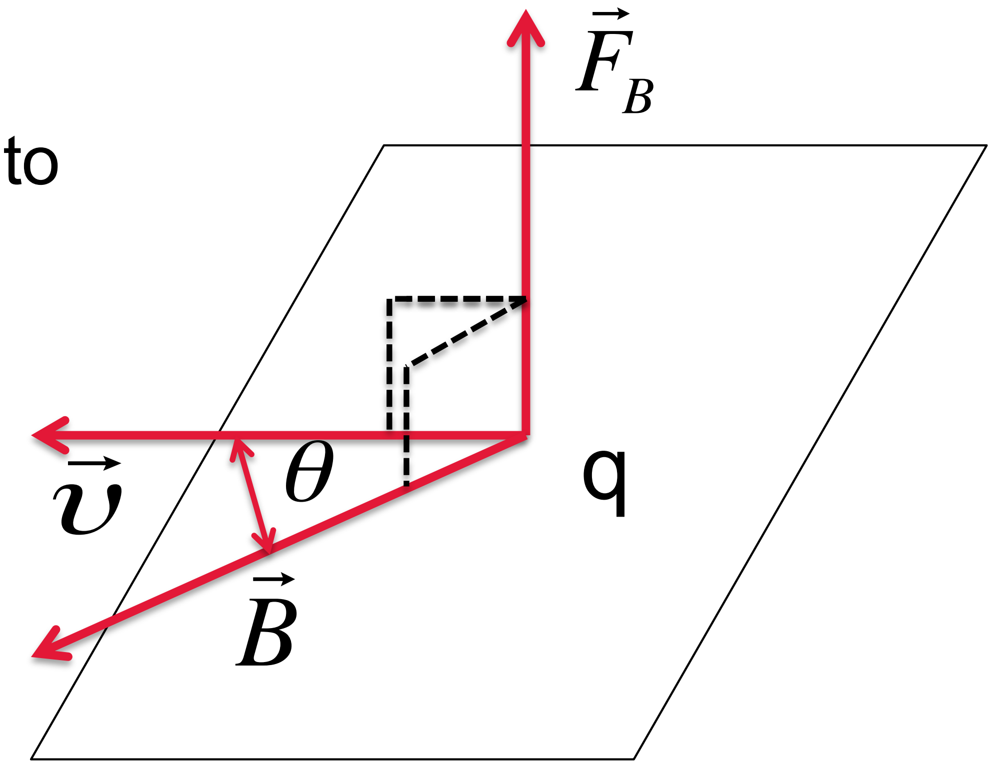
www.nap.edu

Textbook for science of the magnetosphere

- http://how.gi.alaska.edu/ao/msp/#list

Fundamentals of magnetostatic theory

A charged particle moving in a magnetic field is subject to a magnetic force:



Direction:

according to right-hand rule

Magnitude:

$$\left|\vec{F}_B\right| = F_B = q\upsilon B\sin\theta$$

$$\vec{F}_B = q\vec{\upsilon}\times\vec{B}$$ Magnetic force or Lorentz force

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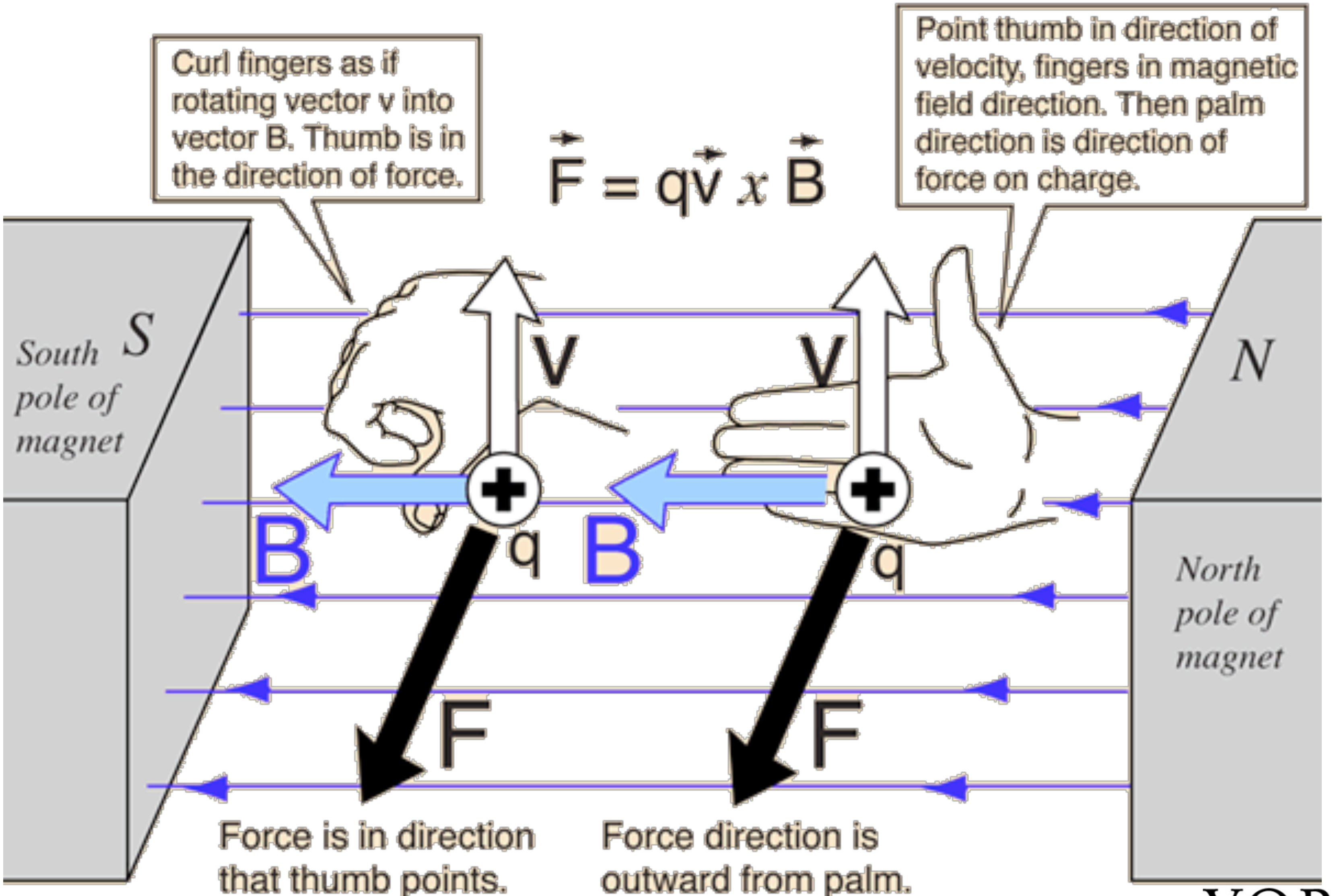
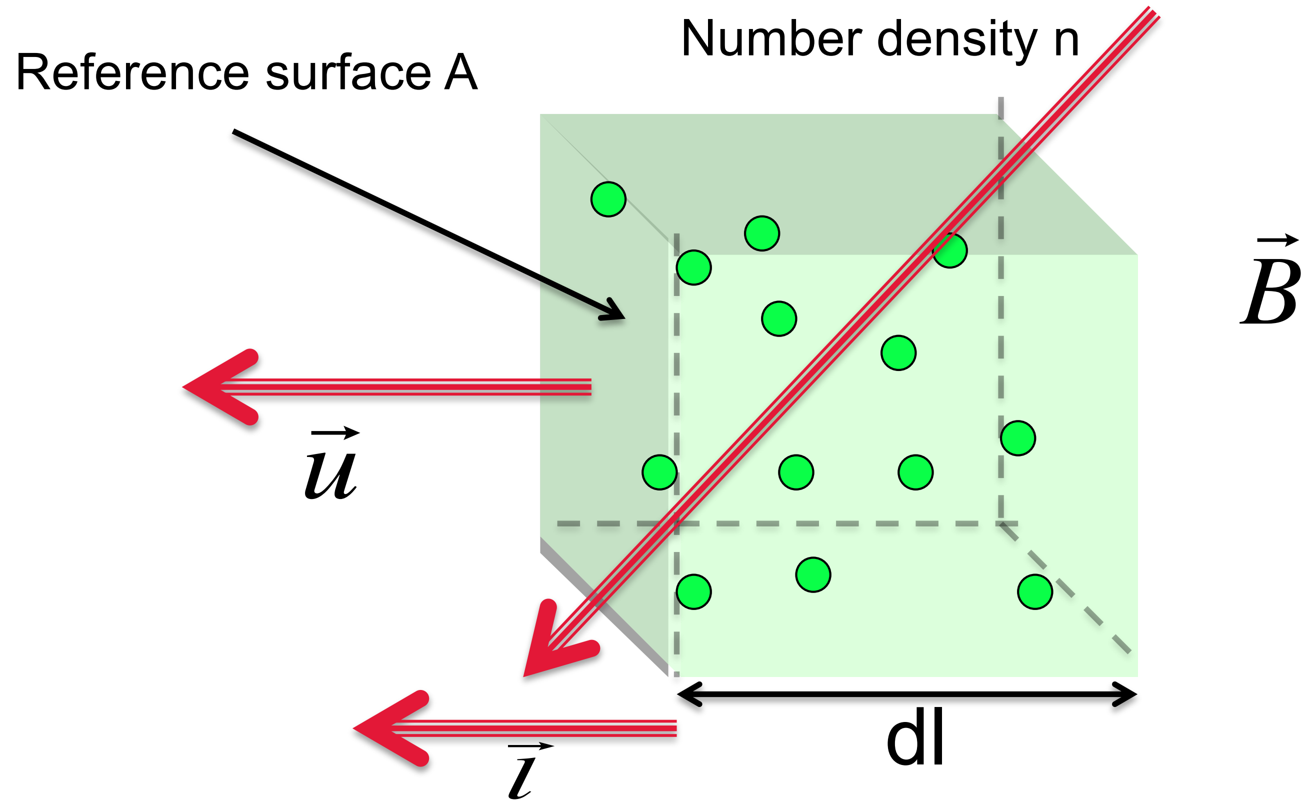
Right-hand rule



http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfor.html

Ensemble of charge carriers

A set of carriers of charge, q, moving in a magnetic field will experience a force as shown below



$$d\vec{F}_B = qnAdl\vec{u} \times \vec{B}$$

Force acting on this set of particles

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The electric current, that is the net charge motion through a reference surface, A, per unit time, associated with this motion is

$\vec{I} = qnA\vec{u}$ Electric current

Then

$$d\vec{F}_B = dl\vec{I} \times \vec{B} = Id\vec{l} \times \vec{B}$$

The force per unit volume, dV, that the charge carriers will experience is

$$\vec{F}_B^* = \frac{d\vec{F}_B}{dV} = \frac{dl\vec{I} \times \vec{B}}{dlA} = \vec{j} \times \vec{B}$$

with the current density or the charge carrier transport per unit area and time

$$\vec{j} = \frac{\vec{I}}{A}$$

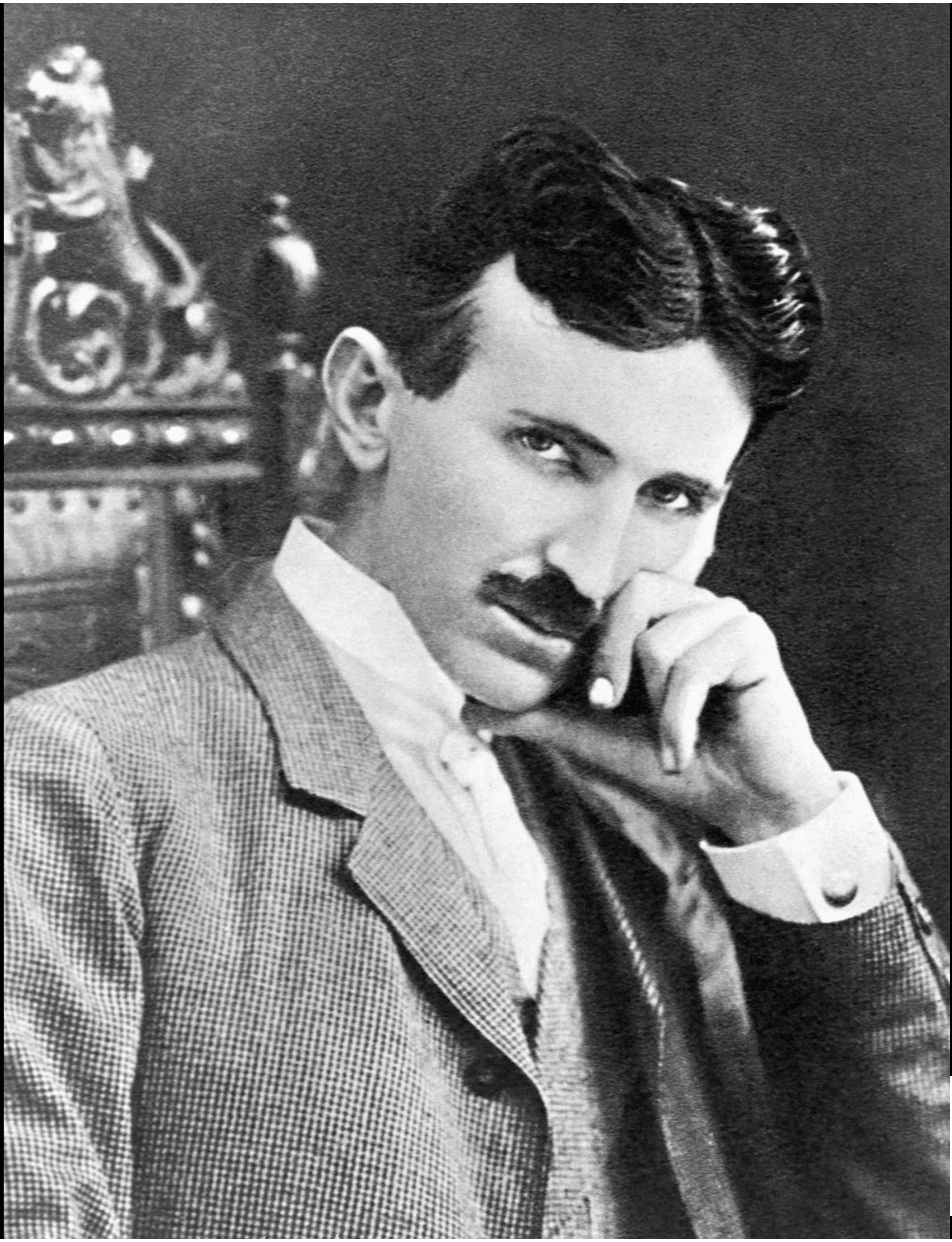
Units of B

- SI units

  T: Tesla

$$T = \frac{Wb}{m^2} = \frac{Vs}{m^2} = \frac{Js}{Cm^2} = \frac{Ns}{Cm}$$

- Non-SI units (Gaussian units)
- 1 G = 10^{-4} T
- 1γ = 10^{-9} T



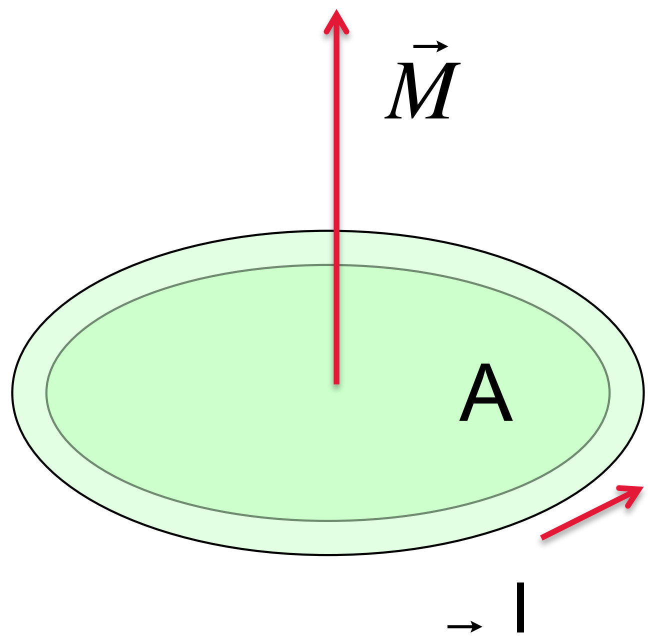
Nikola Tesla
1856-1943

Wikipedia

Magnetic dipole moment

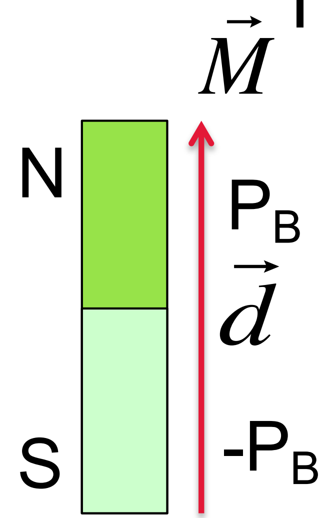
- For a current loop

$$\vec{M} = \vec{A}I$$



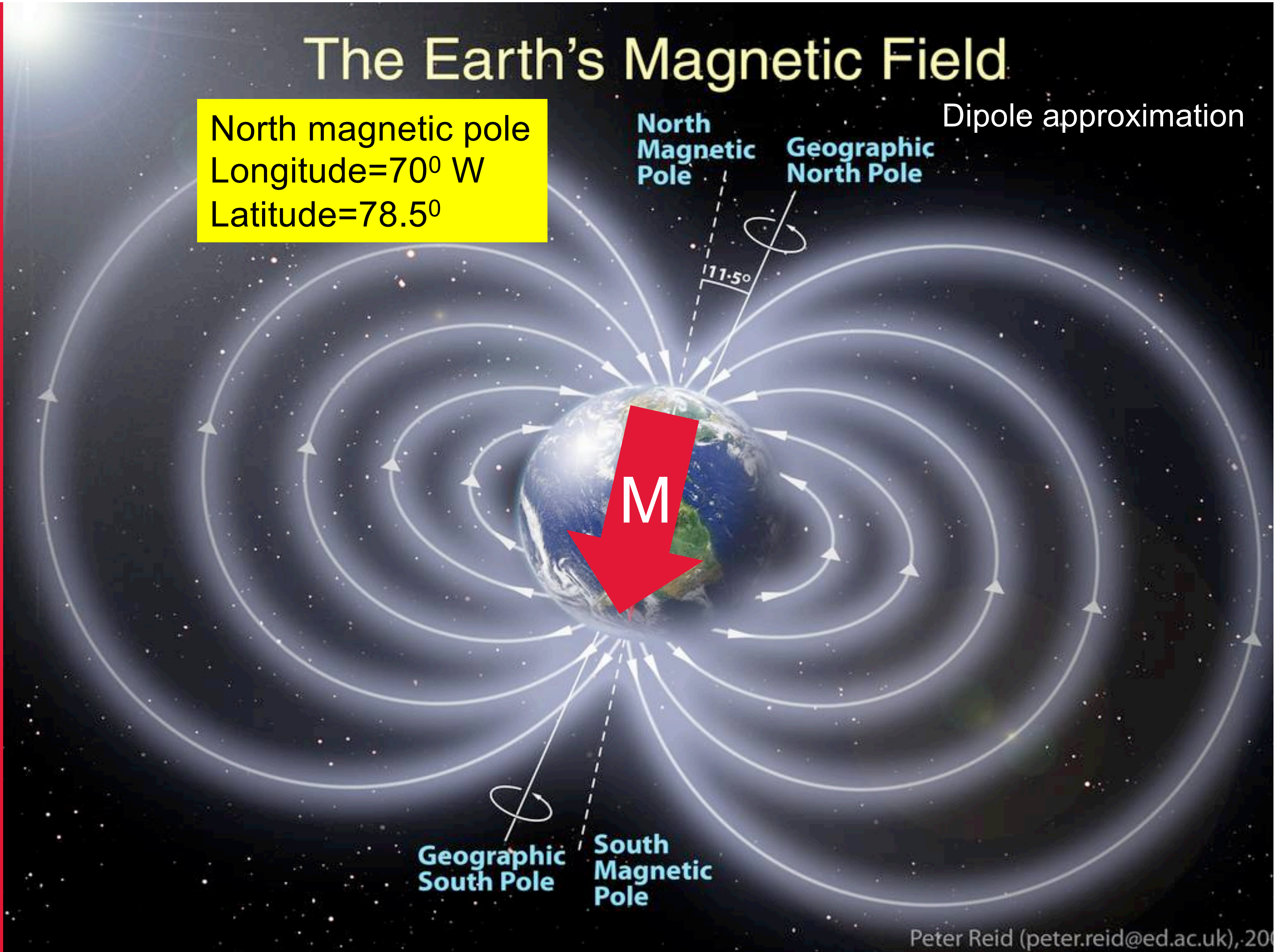
- For bar magnet

$$\vec{M} = \left|\vec{P}_B\right|\vec{d}$$



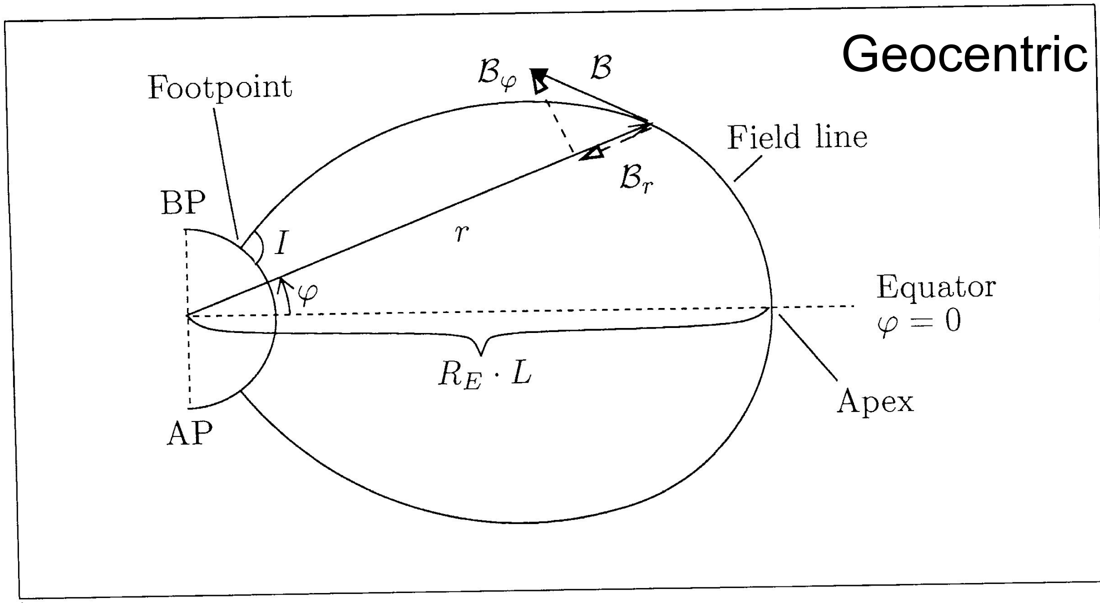
- For Earth

$M_E = 7.7 \times 10^{22}$ A m^2



The Earth's Magnetic Field
North magnetic pole
Longitude=70⁰ W
Latitude=78.5⁰
Dipole approximation
North Magnetic Pole
Geographic North Pole
11.5°
M
Geographic South Pole
South Magnetic Pole
Peter Reid (peter.reid@ed.ac.uk), 20

Geocentric dipole approxiamtion



Geomagnetic poles:	BP (79°N, 290°E)
	AP (79°S, 110°E)
Horizontal component:	$\mathcal{B}_\varphi = \mathcal{B}_{00}\ (R_E/r)^3\ \cos\varphi$
Vertical component:	$\mathcal{B}_r = -2\ \mathcal{B}_{00}\ (R_E/r)^3 \sin\varphi$
Intensity:	$\mathcal{B} = \mathcal{B}_{00}\ (R_E/r)^3 \sqrt{1 + 3\sin^2\varphi}$
with	$\varphi =$ geomagnetic latitude
	$r(\geq R_E) =$ geocentric distance
	$\mathcal{B}_{00} = \mu_0\ \mathcal{M}_E/(4\pi\ R_E^3) \simeq 30\mu\mathrm{T}$
Field line equation:	$r(\varphi) = L\ R_E\ \cos^2\varphi$
Shell parameter:	$L = r(\varphi = 0)/R_E$
Footpoints:	$\varphi(R_E) = \arccos\sqrt{1/L}$
Inclination:	$I = \arctan(2\tan\varphi)$
Declination:	$D = -\arcsin(\cos\varphi_g^{BP}\ \sin(\lambda_g - \lambda_g^{BP})/\cos\varphi)$
Curvature:	$\rho_c = \mathcal{B}/\lvert\nabla_\perp\mathcal{B}\rvert$

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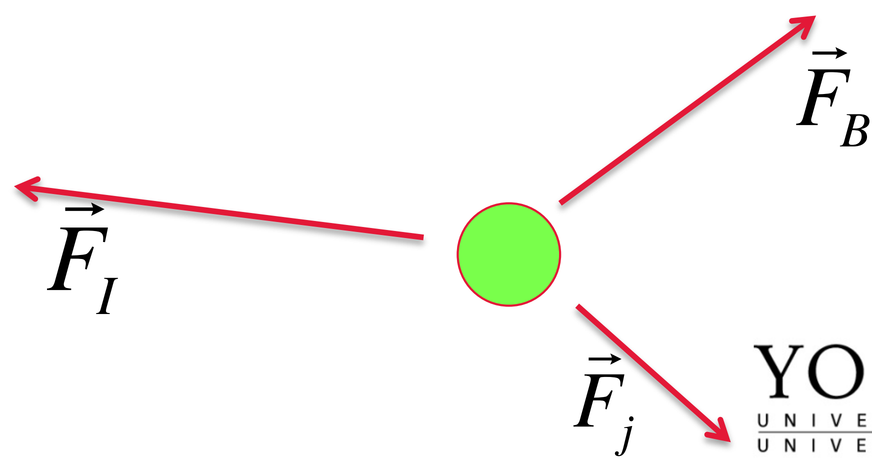
Charged particle motion

Three forces need to be considered

Inertial force $\vec{F}_I$

Magnetic force (velocity dependent) $\vec{F}_B$

External force (velocity independent) $\vec{F}_j$



$$\vec{F}_I = \vec{F}_j + \vec{F}_B$$

$$m\frac{d\vec{\upsilon}}{dt} = \vec{F}_j + q\vec{\upsilon} \times \vec{B}$$

- The principally different motions of a charged particle can be seen by separating the equation into components parallel and perpendicular to the magnetic field.

Parallel: $$m\frac{d\vec{\upsilon}_{\parallel}}{dt} = \vec{F}_{j\parallel}$$

Perpendicular: $$m\frac{d\vec{\upsilon}_{\perp}}{dt} = \vec{F}_{j\perp} + q\vec{\upsilon}_{\perp} \times \vec{B}$$

- This leads to the consideration of four special cases.

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Four special cases of charged particle motion

1. $\vec{F}_{j\perp} = 0$, $\vec{B}$ uniform ➔ gyration

2. $\vec{F}_{j\perp} = 0$, $\nabla B \parallel \vec{B}$ ➔ bouncing

3. $\vec{F}_{j\perp} = 0$, $\nabla B \perp \vec{B}$ ➔ drift

4. $\vec{F}_{j\perp} \neq 0$, $\vec{B}$ uniform ➔ drift

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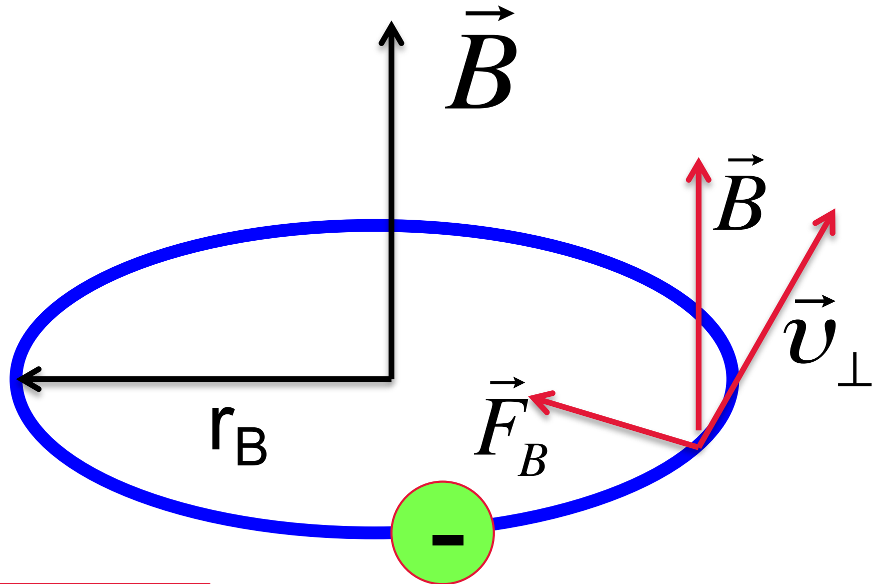
Gyro motion

- The inertial force = centrifugal force

$$\frac{m\upsilon_\perp^2}{r_B} = |q|\upsilon_\perp B$$



$$r_B = \frac{m\upsilon_\perp}{|q|B}$$ Gyroradius or Larmor radius

$$\tau_B = \frac{2\pi r_B}{\upsilon_\perp} = 2\pi\frac{m}{|q|B}$$ Orbital period

$$\omega_B = \frac{2\pi}{\tau_B} = \frac{|q|B}{m}$$ Gyro frequency

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- The magnetic dipole moment can be obtained by considering a reference surface parallel to the magnetic field vector. The charged particle will move through this surface once per orbit. So the charge transport or current is for an electron

$$I = \frac{|q|}{\tau_B}$$

- From this it follows:

$$\boxed{\vec{M}_g = I\vec{A} = \frac{|q|\pi r_B^2}{\tau_B}\frac{\vec{B}}{B} = \frac{m\upsilon_\perp^2}{2B^2}\vec{B} = \frac{E_\perp}{B^2}\vec{B}}$$

- The magnetic (far) field is a dipole field.

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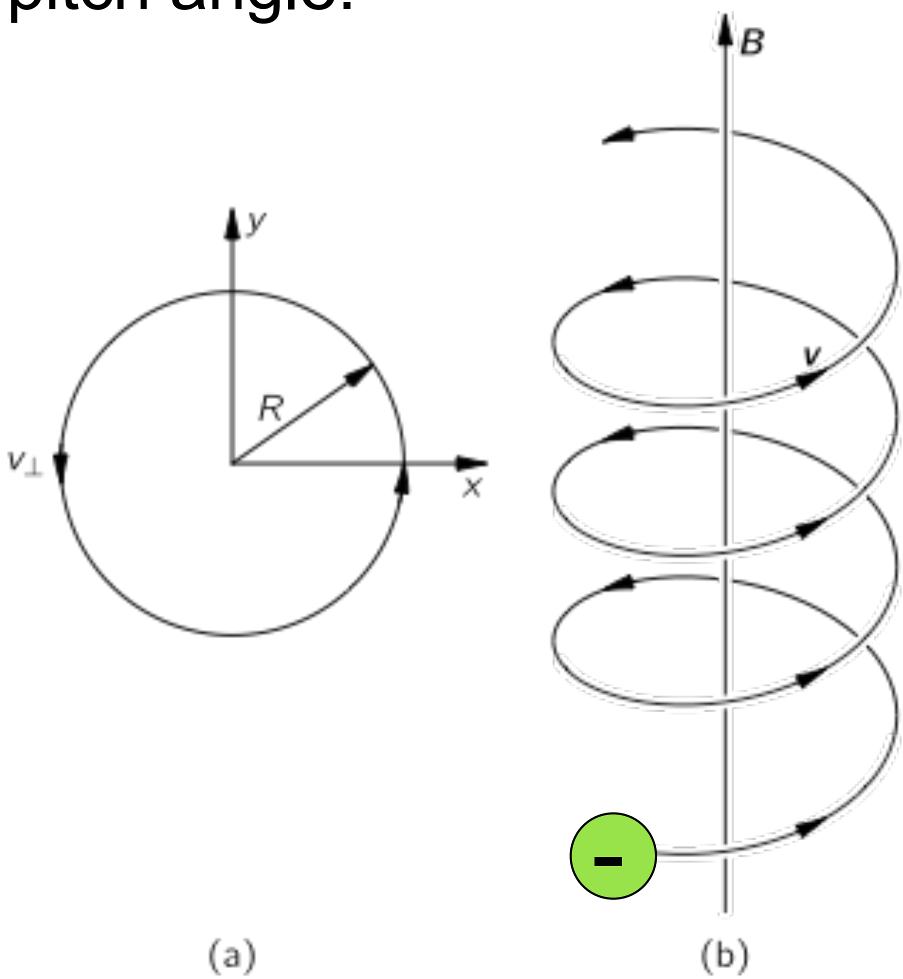
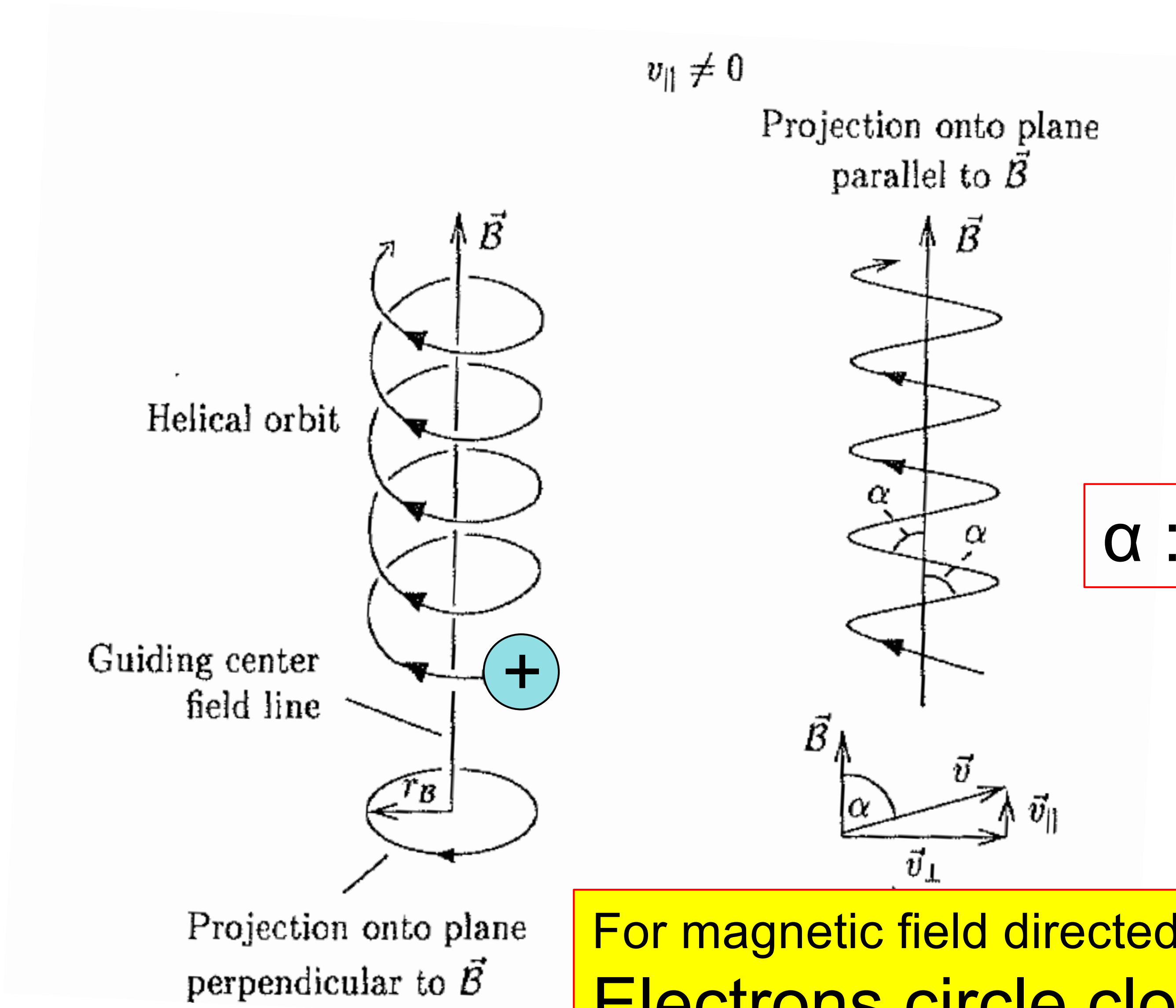
- If there is an initial velocity component parallel to the magnetic field, then the circular motion becomes a helical motion around the magnetic field. The inclination angle is called the pitch angle.



http://www.feynmanlectures.caltech.edu/II_29.html



α : pitch angle

For magnetic field directed away from viewer:

Electrons circle clockwise

Ions circle counterclockwise

Oscillatory (bounce) motion

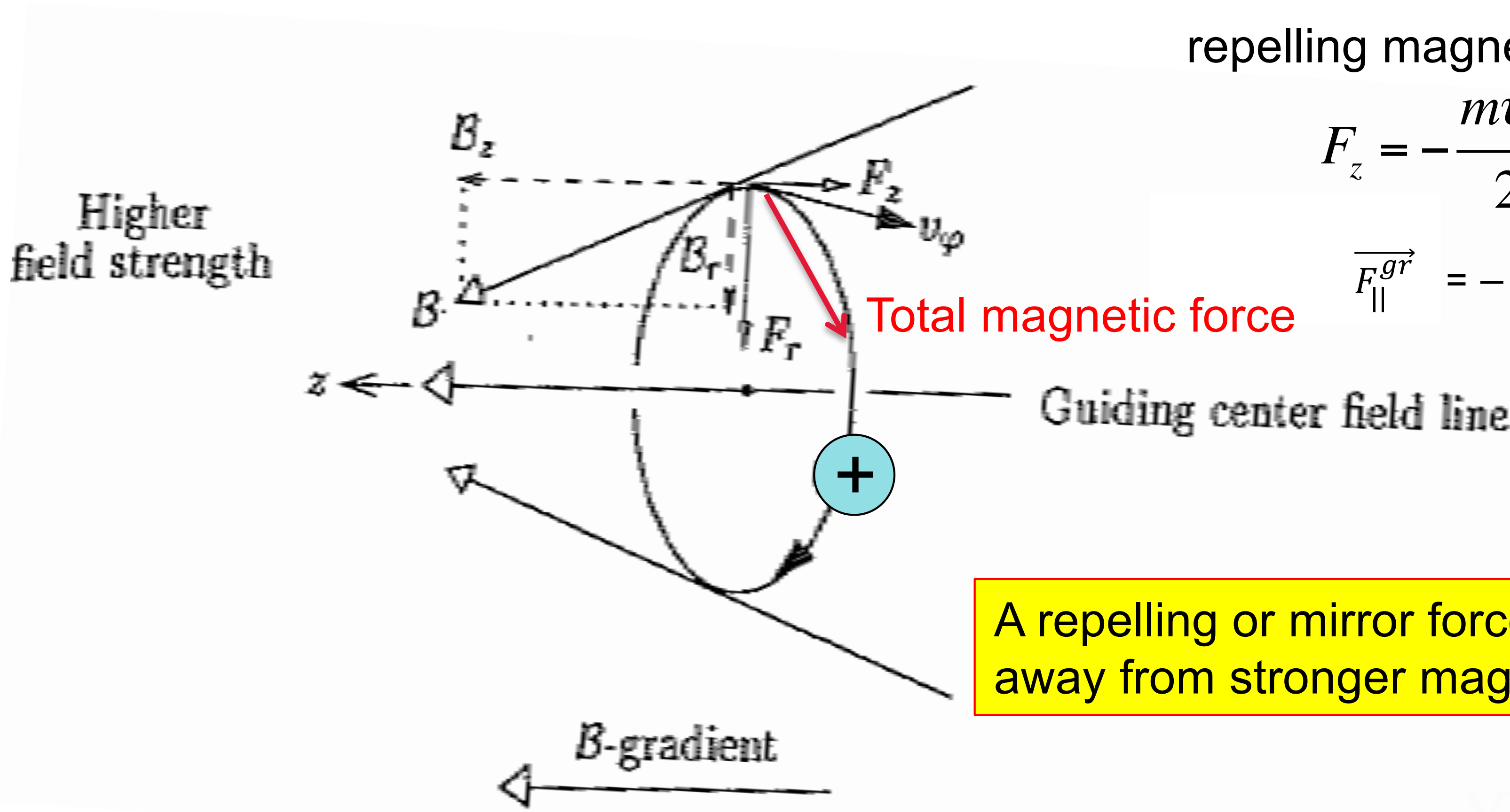
- Particle motion in a non-uniform magnetic field with gradient along field lines

From Maxwell equations:

repelling magnetic force

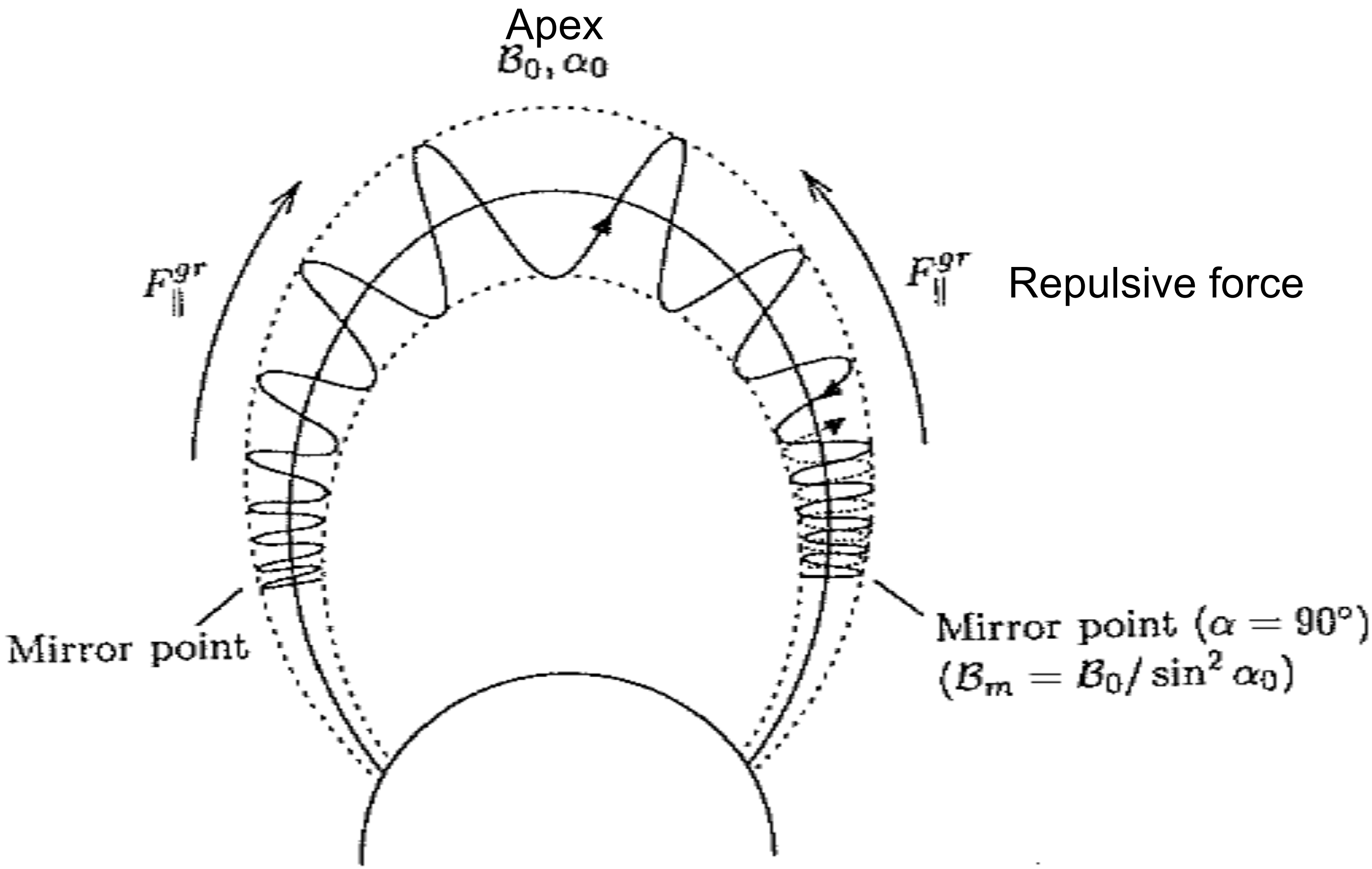
$$F_z = -\frac{m v_\varphi^2}{2}\frac{1}{B}\frac{dB}{dz}$$

$$\overrightarrow{F_{||}^{gr}} = -\frac{E_\perp}{B}\nabla_{||}\vec{B}$$ In vectorial form



A repelling or mirror force is generated away from stronger magnetic field

Oscillating motion in the dipole field of Earth



- While a particle circles its guiding magnetic field line toward increasing magnetic field, the particle feels a repulsive force (mirror force).
- The motion of the guiding center slows down and the pitch angle increases.
- At the mirror point the guiding center stops. The pitch angle is now $\alpha = 90^0$. All the kinetic energy of the particle is now in the gyrating motion. The kinetic energy of the particle due to motion along the guiding center is zero.
- The repulsive force accelerates the particle gyrating around the guiding center away from the mirror point. The pitch angle α decreases, the velocity along the guiding center increases.
- At the apex point (in the magnetic equatorial plane), the pitch angle assumes a minimum value, $\alpha = \alpha_0$.

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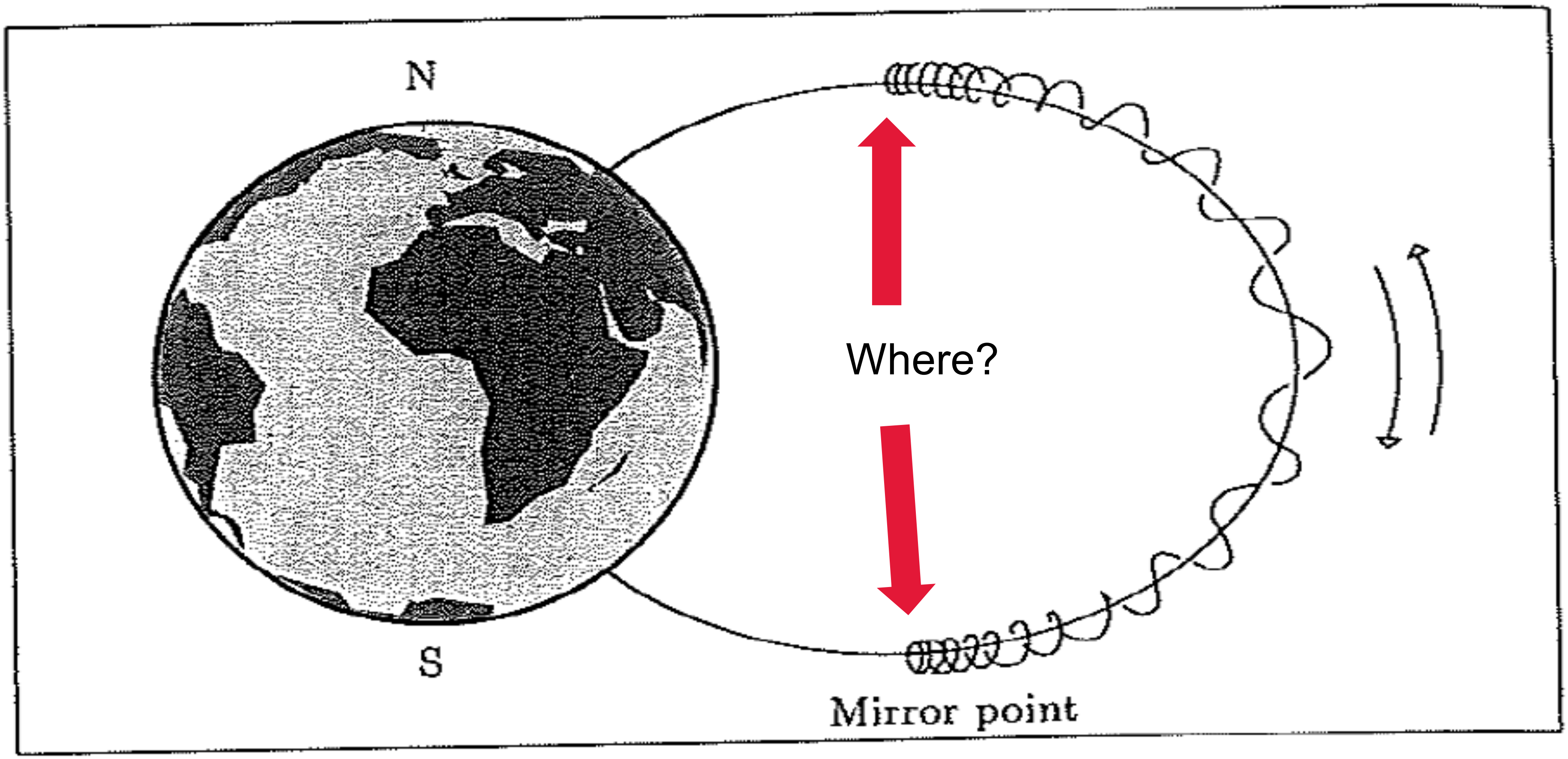
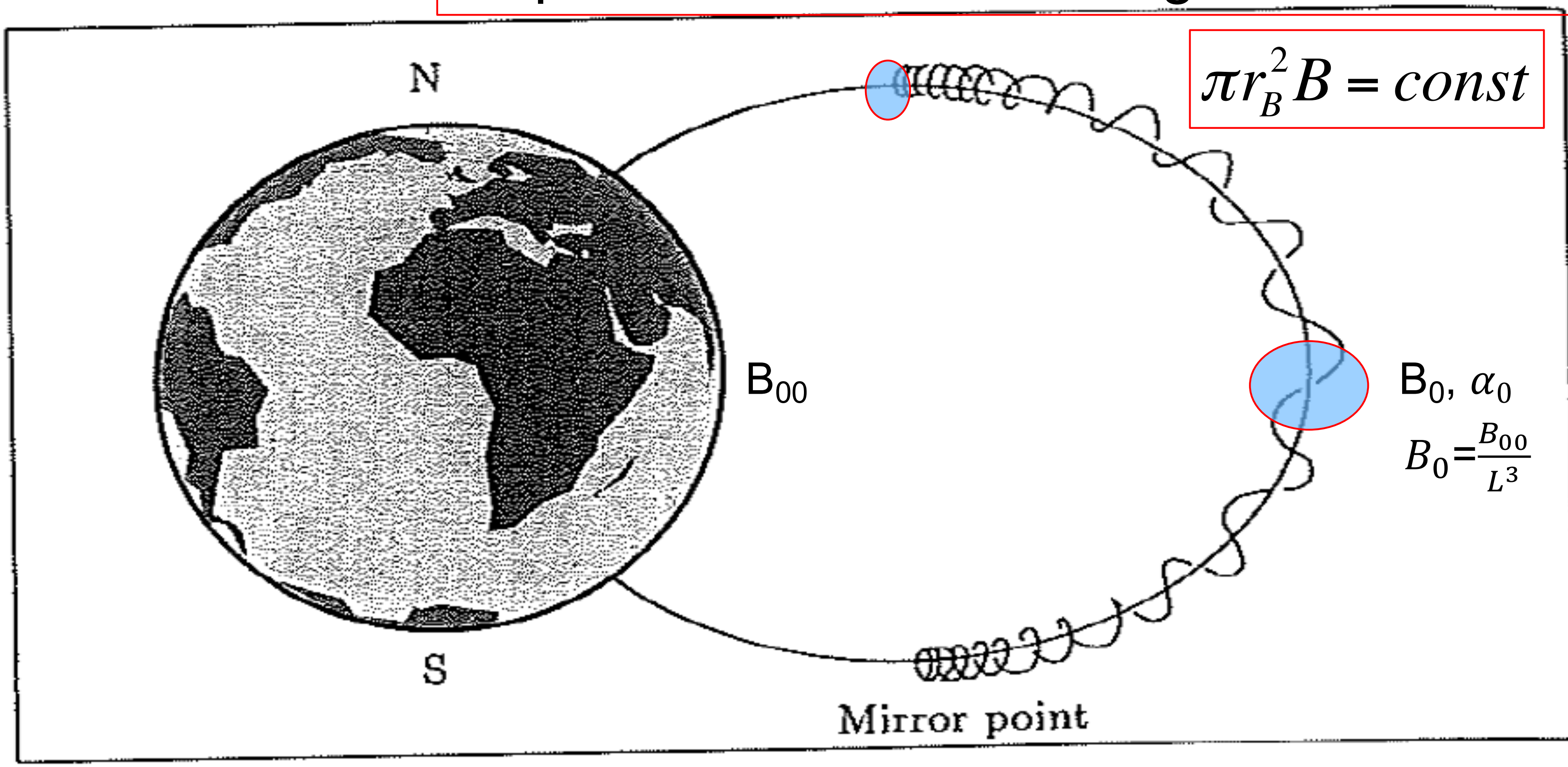
- From there on the particle is again decelerated and its pitch angle increases till the particle reaches its conjugate mirror point in the other magnetic hemisphere.
- There it is again reflected.
- The particle bounces back and force and is captured in the dipole field of the Earth.
- However, the mirror point position is sensitive to the pitch angle at the apex.
- If the pitch angle is too small, the mirror point may be deep in the lower atmosphere where the electron could be absorbed, or it may be mathematically below the earth surface.
- Where is the mirror point?


N
S
Where?
Mirror point

The position of the mirror point

The magnetic flux through the gyration orbit loop remains constant along the field line

$$\pi r_B^2 B = const$$



$$\pi r_B^2 B = const$$

$$r_B = \frac{m\upsilon_\perp}{|q|B}$$

$$\upsilon_\perp = \upsilon \sin\alpha$$

$$\upsilon = const$$

kinetic energy does not change

$$\frac{B}{\sin^2\alpha} = const$$

$$r = LR_E \cos^2\varphi$$

- Now we know the magnetic strength at the mirror point.
- For a given dipole field line it is a function of the pitch angle at the apex.

$$B_m = \frac{B}{\sin^2\alpha} = \frac{B_0}{\sin^2\alpha_0} = \frac{B_{00}}{L^3\sin^2\alpha_0}$$

- Where is the mirror point for a pitch angle at apex of 90^0?
- Where is the mirror point for a pitch angle at apex of 0^0?
- Where is the mirror point for a pitch angle at apex of 30^0?

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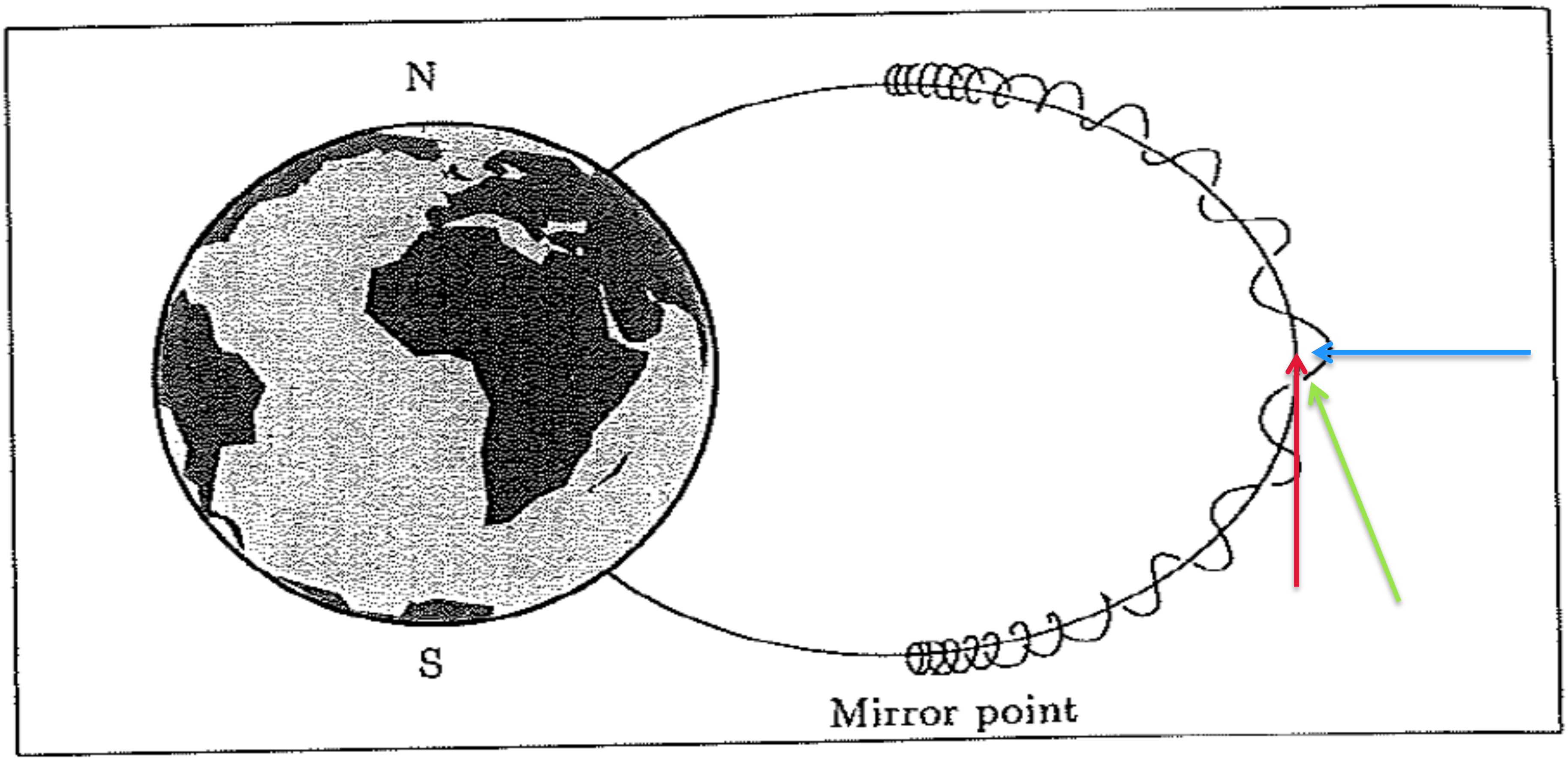
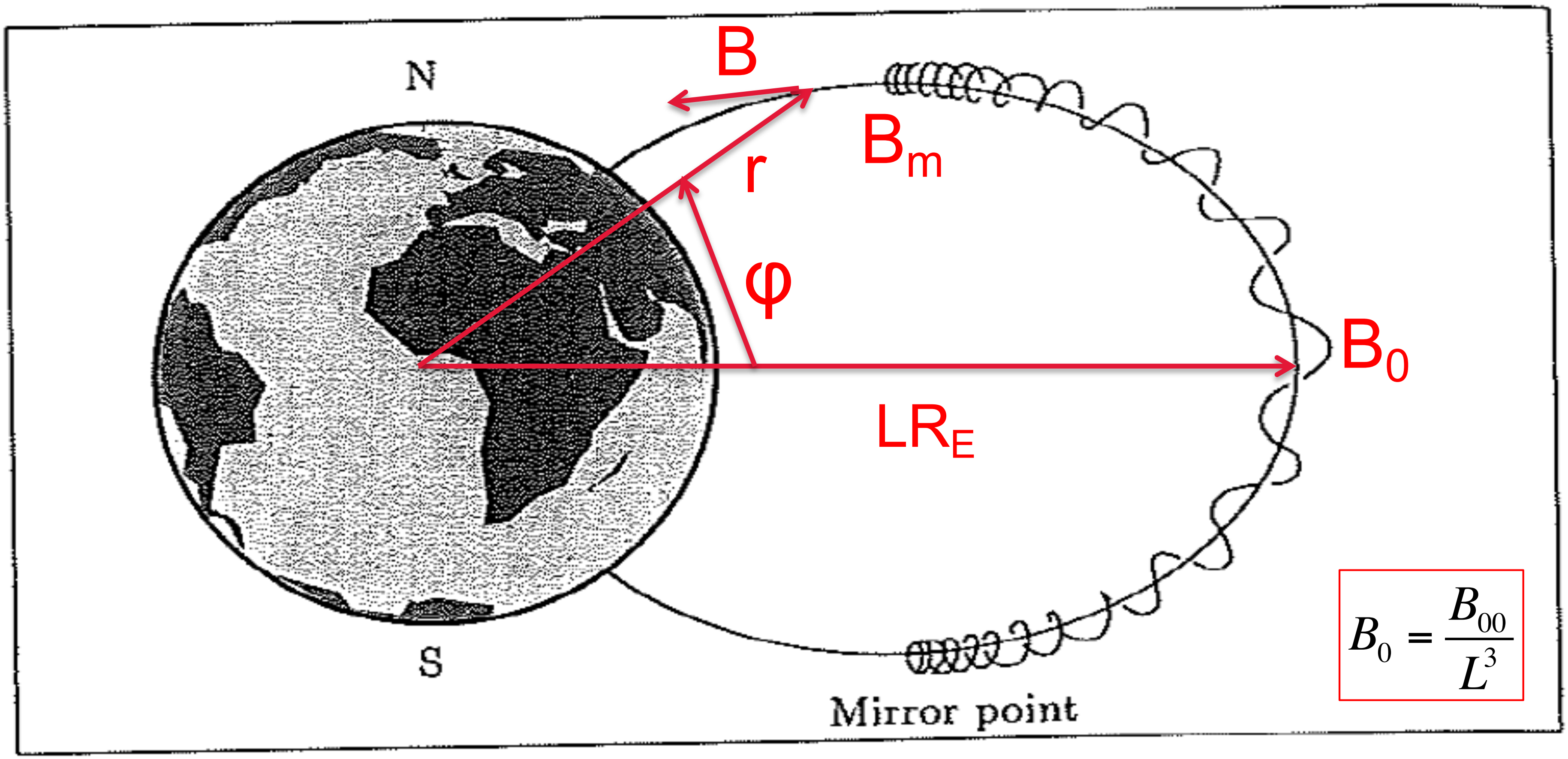
The position of the mirror point



The magnetic field as a function of L and φ



$$B_0 = \frac{B_{00}}{L^3}$$

$$r = LR_E \cos^2 \varphi$$

$$B_m = B_{00}\left(\frac{R_E}{r_m}\right)^3 \sqrt{1 + 3\sin^2 \varphi_m}$$

$$B_{00} \cong 30\mu T$$

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- The magnetic field strength of a dipole field is given by

$$B_m = B_{00}\left(\frac{R_E}{r_m}\right)^3 \sqrt{1+3\sin^2\varphi_m}$$

$$B_m = B_{00}\left(\frac{R_E}{LR_E\cos^2\varphi_m}\right)^3 \sqrt{1+3\sin^2\varphi_m}$$

$$B_m = B_{00}\left(\frac{1}{L\cos^2\varphi_m}\right)^3 \sqrt{1+3\sin^2\varphi_m}$$

- We therefore have to find the magnetic latitude, φ, for which the magnetic field strength of the guiding center field line with apex distance LR_E is equal to

$$B_m = \frac{B_{00}}{L^3\sin^2\alpha_0}$$

- This needs to be done through iteration.

Example 5-1

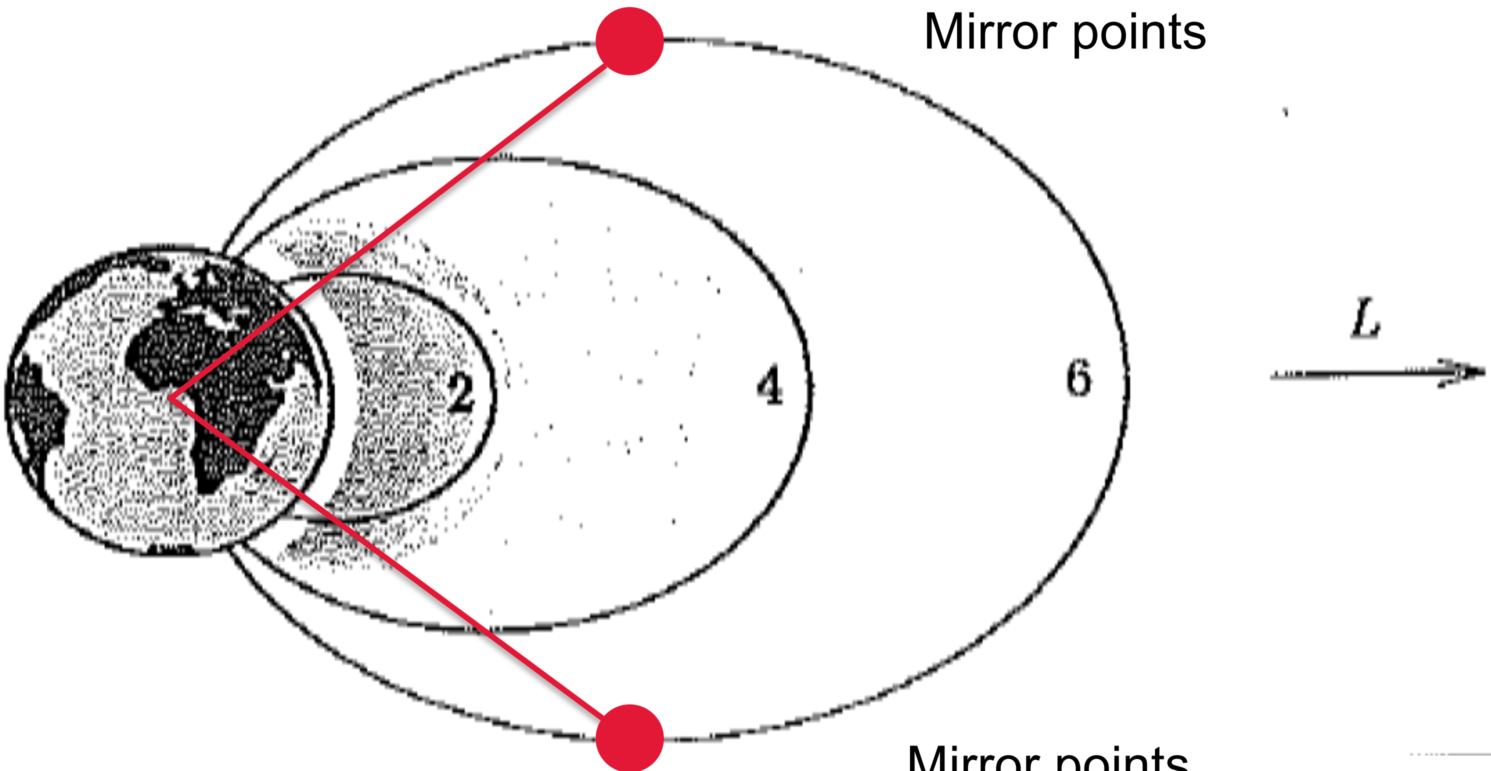
$$B_m = \frac{B_{00}}{L^3 \sin^2 \alpha_0} = \frac{B_{00}}{L^3 \cos^6 \varphi_m} \sqrt{1 + 3\sin^2 \varphi_m}$$

$$\frac{1}{\sin^2 \alpha_0} = \frac{1}{\cos^6 \varphi_m} \sqrt{1 + 3\sin^2 \varphi_m}$$

- For a pitch angle of 30^0 we get $\varphi=44^0$
- If L=6, then with

$$r_m = LR_E \cos^2 \varphi_m$$

- r_m=6x6378x0.570=3.08R_E=19,626 km


Mirror points
2
4
6
L
Mirror points

- The mirror point is independent of the kinetic energy of the particle or whether the particle is an ion or an electron.
- Particles with pitch angles smaller than a limiting pitch angle will not bounce.
- These pitch angles are in the “loss cone.”

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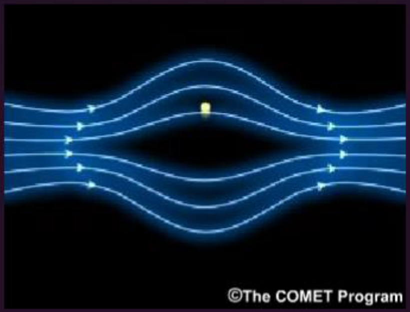
Magnetic bottle

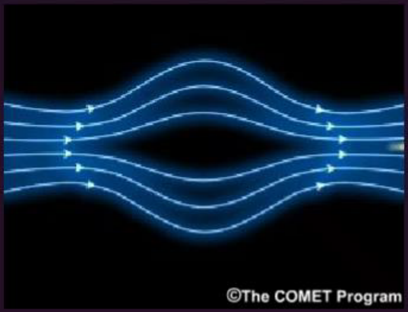
stuck in the center

A particle with pitch angle $\theta = 90°$ $(sin^2\theta = 1)$ cannot move into a region of stronger magnetic field, so a particle with $\theta_{min} = 90°$ (at the center of the magnetic mirror, where $B = B_{min}$) cannot move away from the center of the mirror.



straight and narrow

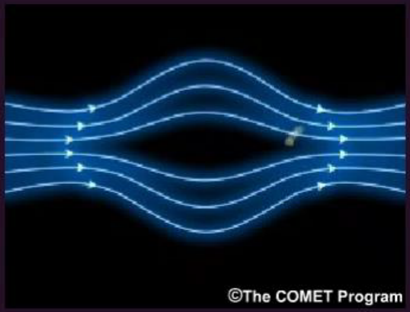
On the other hand, a particle with pitch angle $\theta_{min} = 0°$ is free to move anywhere and readily travels out of the magnetic mirror.



trapped in the mirror

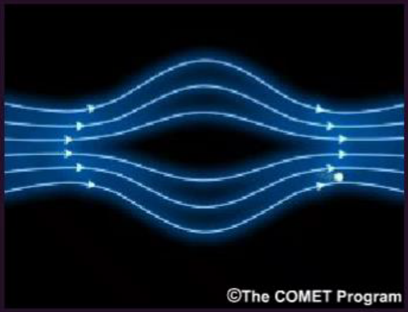
In a magnetic mirror geometry, particles with pitch angles in the following range are trapped within the magnetic mirror:

$$\theta_{min} > \sin^{-1} \left[(B_{min}/B_{max})^{1/2} \right]$$



into the loss cone

However, particles with $\theta_{min} < \sin^{-1} \left[(B_{min}/B_{max})^{1/2} \right]$ are said to be in the loss cone and can escape the magnetic mirror.



Oscillation (bounce) period

- The exact derivation of the oscillation period, is complicated
- An approximate expression is given by

$$\tau_O \cong \frac{4LR_E}{\upsilon}$$

$$\tau_O \cong \frac{4LR_E}{\upsilon} s_1(\alpha_0)$$
$$s_1(\alpha_0) \cong 1.3 - 0.56 \sin \alpha_0$$
$$\alpha_0 = 30^0 \Rightarrow \sin \alpha_0 = 0.5 \Rightarrow s_1(\alpha_0) \cong 1$$

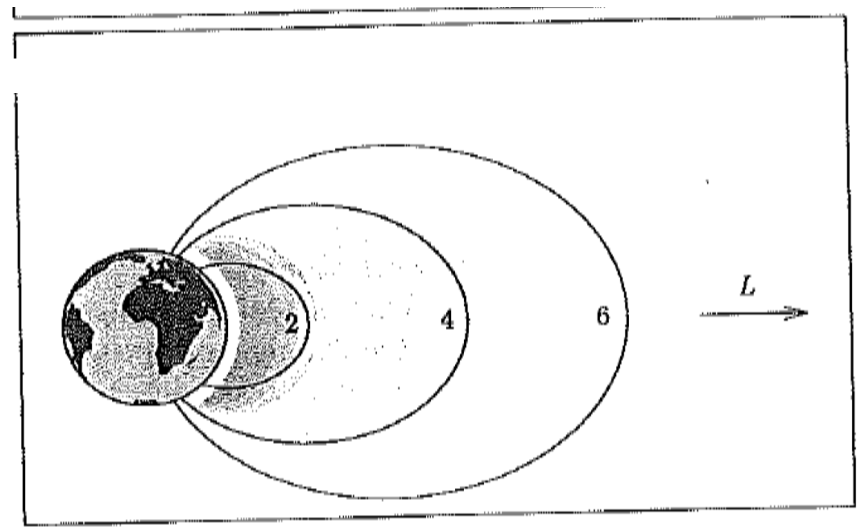
- Or with $\frac{1}{2} m_e \upsilon^2 = E$ for electron

$$\tau_O \cong \sqrt{\frac{8m_e}{E}} LR_E$$ **Oscillation (bounce) period**

Drift motion

- Consider that the gradient of the magnetic field is perpendicular to the magnetic field. The figure below provides an example where such a scenario is given.

- Consider the magnetic equator Which direction is the magnetic gradient vector pointing to?



$$B_0 = \frac{B_{00}}{L^3}$$

- How is the motion of the
- charged particles affected by
- this gradient?

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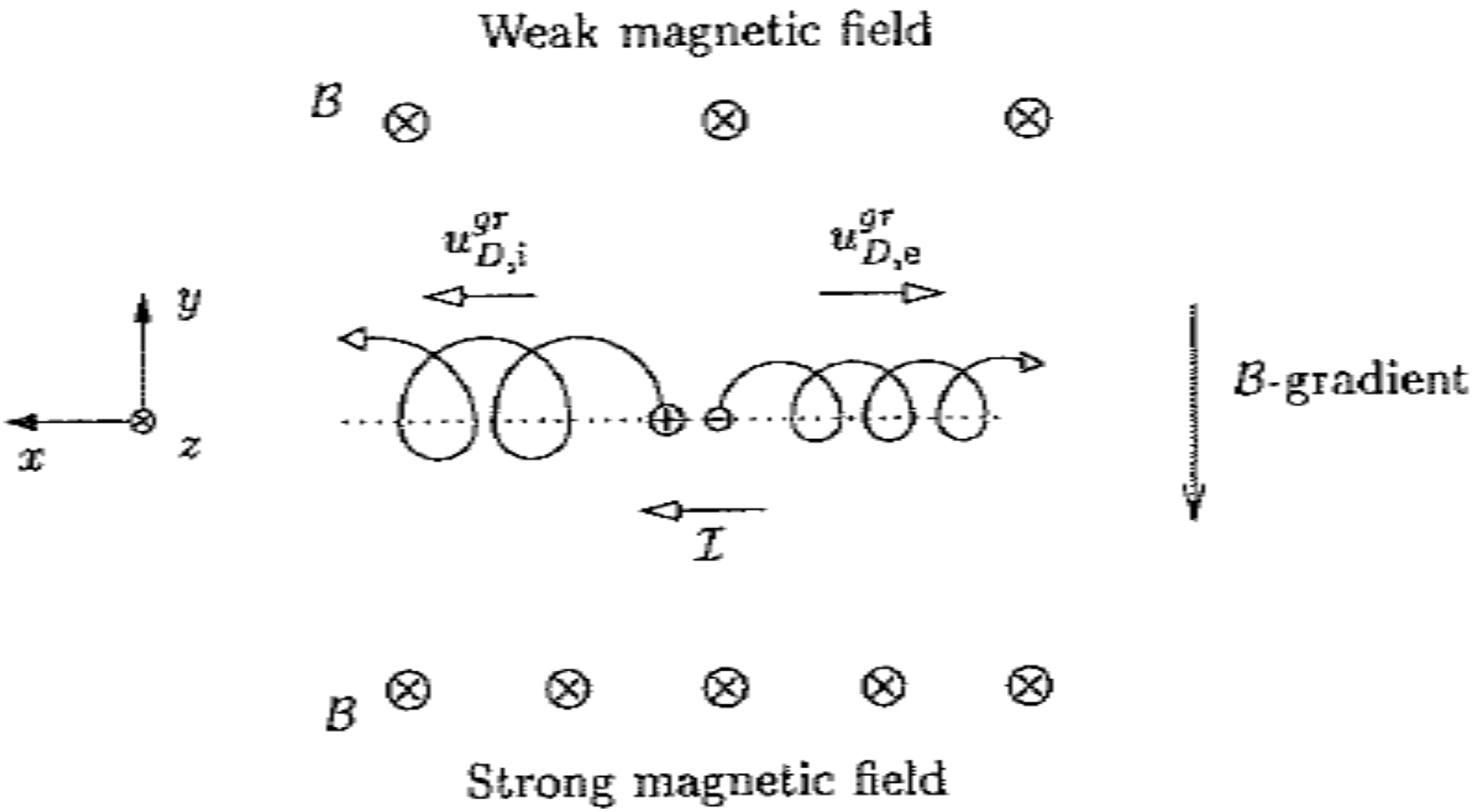
Particle motion perpendicular to a gradient in the magnetic field (example)



Proelss

- In the example of a jump of the magnetic field strength (dotted line) the particles will have a relatively large gyro radius where B is weak and a smaller radius where B is strong. This leads to a displacement of the particle for each gyro period in a direction perpendicular to the field lines and perpendicular to the gradient.

$$\Delta x = \frac{1}{B}\frac{dB}{dy}\pi r_B^2$$

- The drift velocity is then given by

$$\boxed{u_D^{gr} = \frac{\Delta x}{\tau_B} = \frac{E_\perp}{|q|B^2}\frac{dB}{dy}}$$

with $E_\perp = \frac{1}{2} m\upsilon_\perp^2$

- Or in general by

$$\vec{u}_D^{gr} = \frac{E_\perp}{|q|B^3}\vec{B}\times\nabla_\perp B$$

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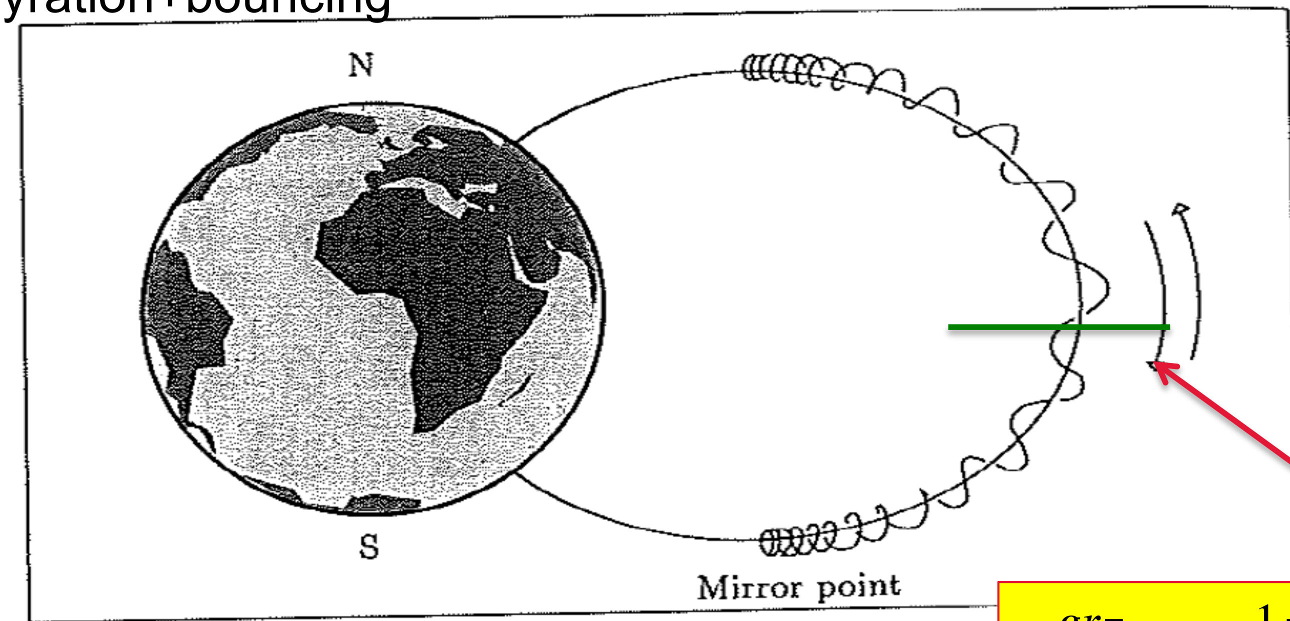
Gyration+bouncing



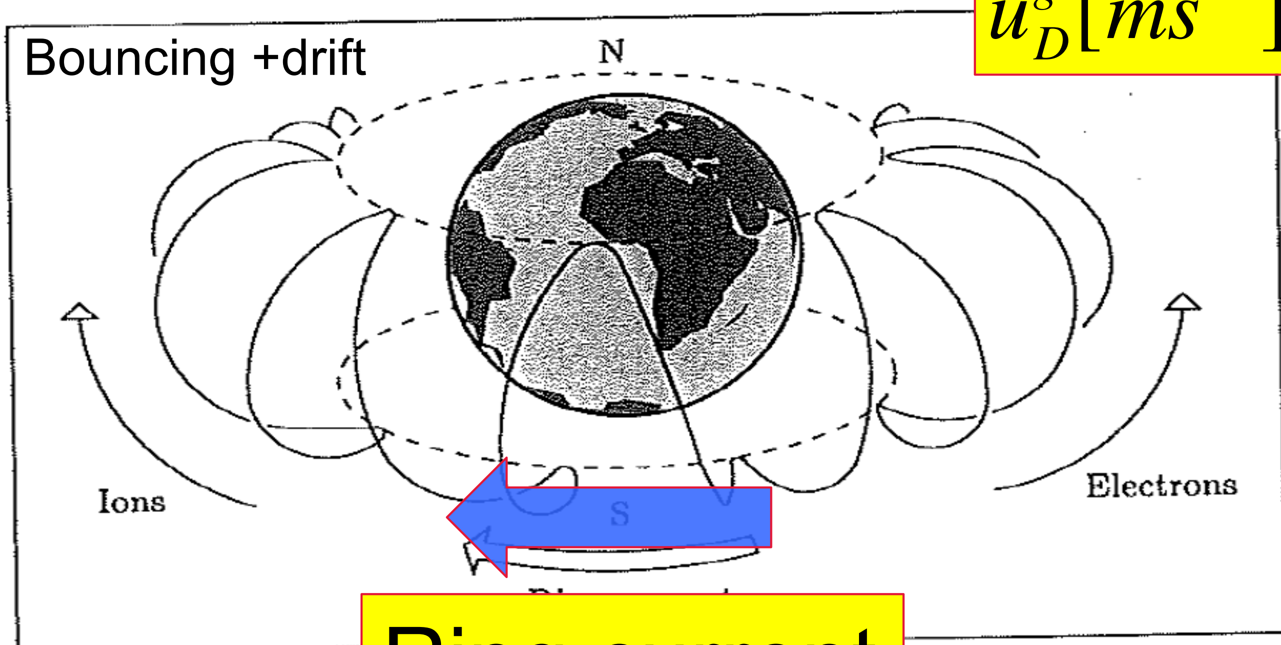
Drift velocity

for

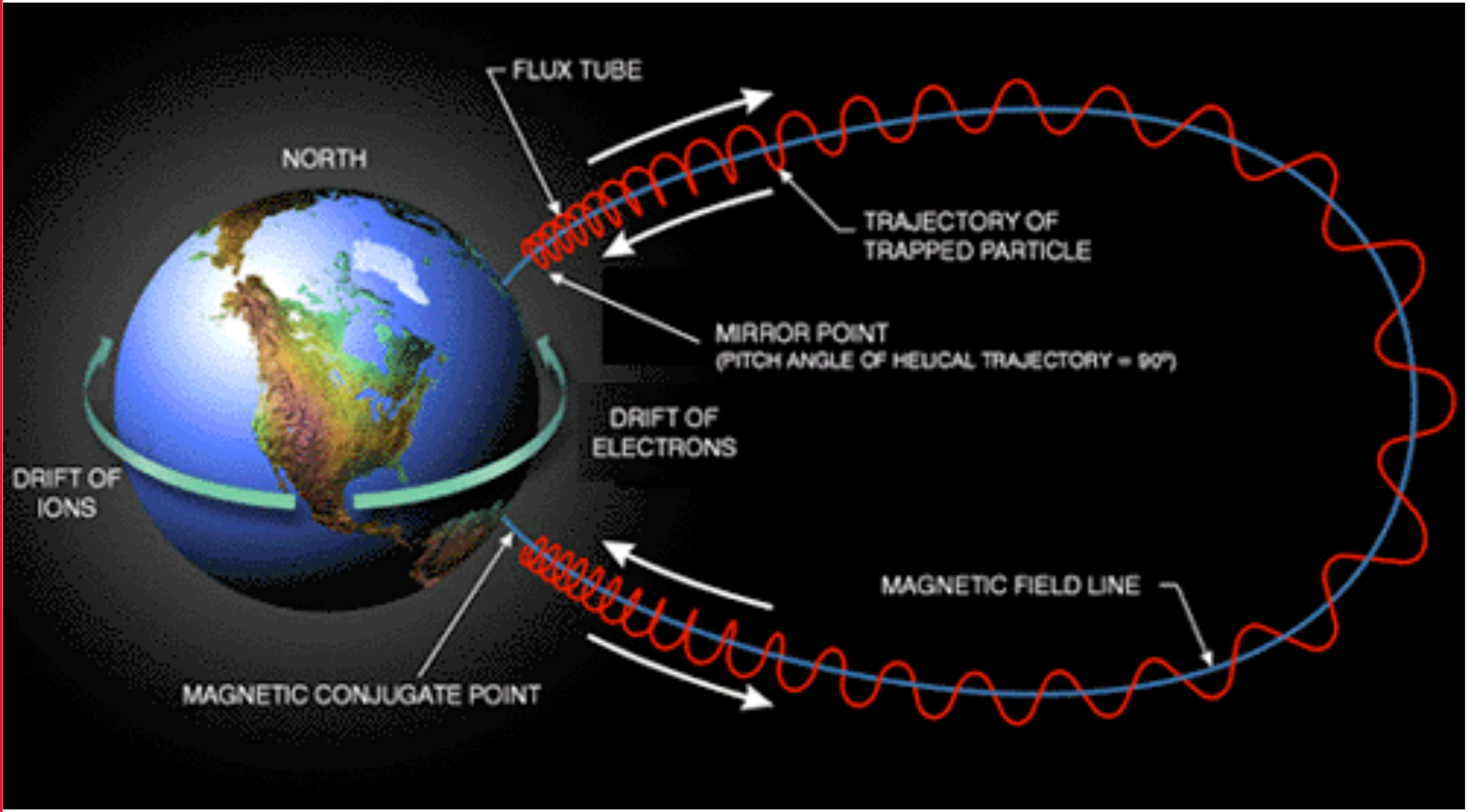
$$\alpha_0 = 90^0, \varphi = 0$$

$$u_D^{gr}[ms^{-1}] \cong 15.7 L^2 E[keV]$$

Bouncing +drift



Ring current

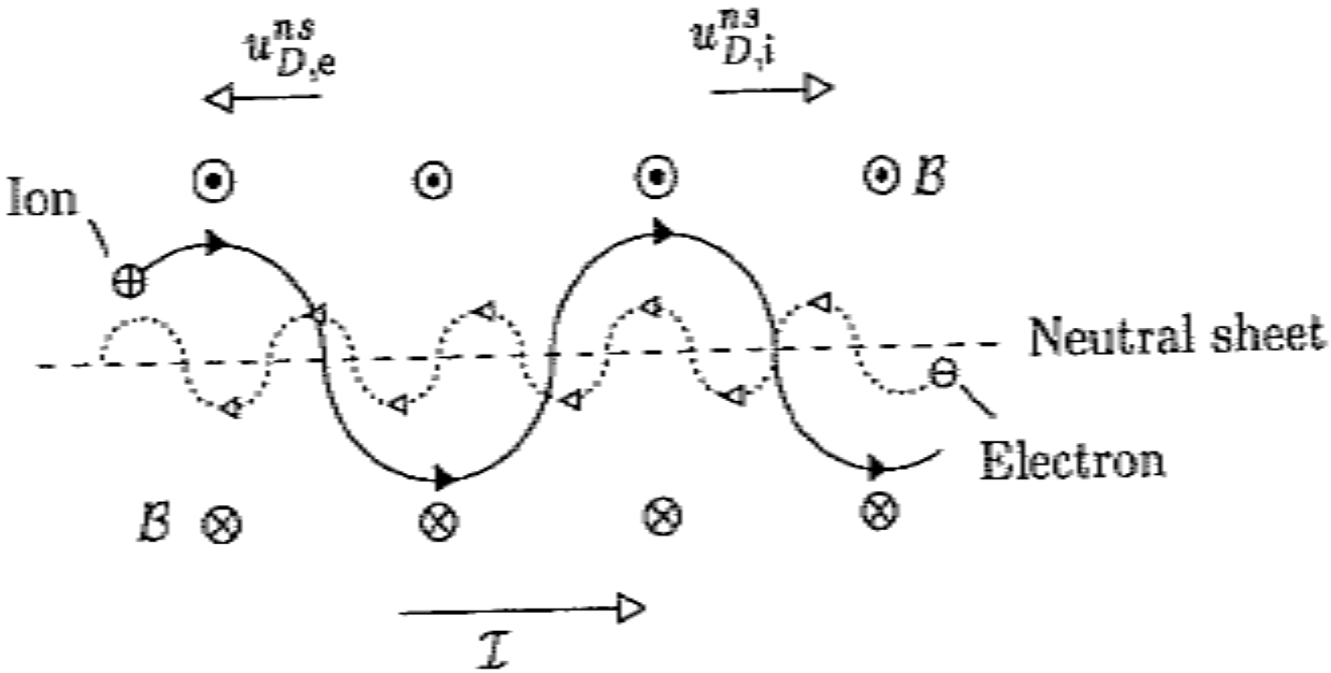


http://pluto.space.swri.edu/IMAGE/glossary
/pitch.html

Neutral sheet drift

- Magnetic field reversed at discontinuity

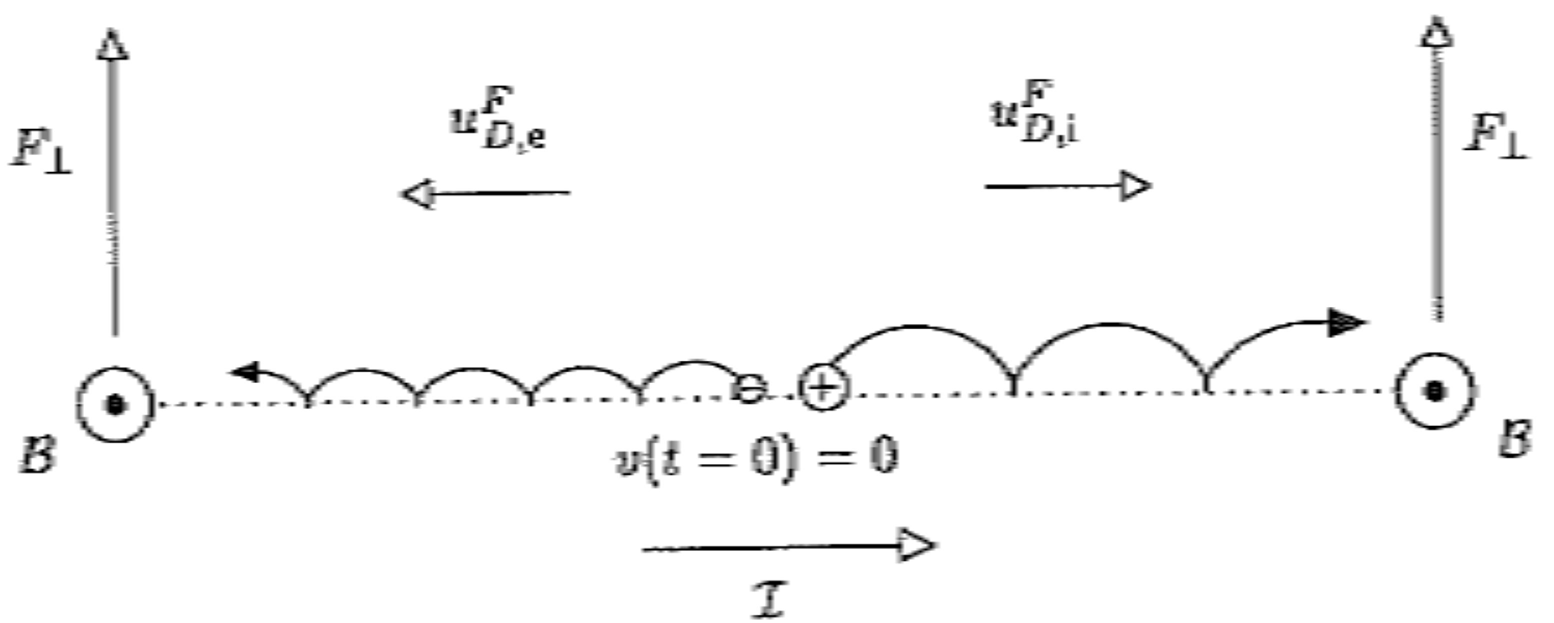
→ neutral sheet current with electrons and ions moving in opposite directions



Important in tail of magnetosphere

External force drift in uniform magnetic field
with force independent of charge

1. Particle is accelerated by F
2. With velocity>0, particle moves into gyration orbit
3. Particle is decelerated when moving against F
4. Particle is halted at displaced position
5. Cycle starts again



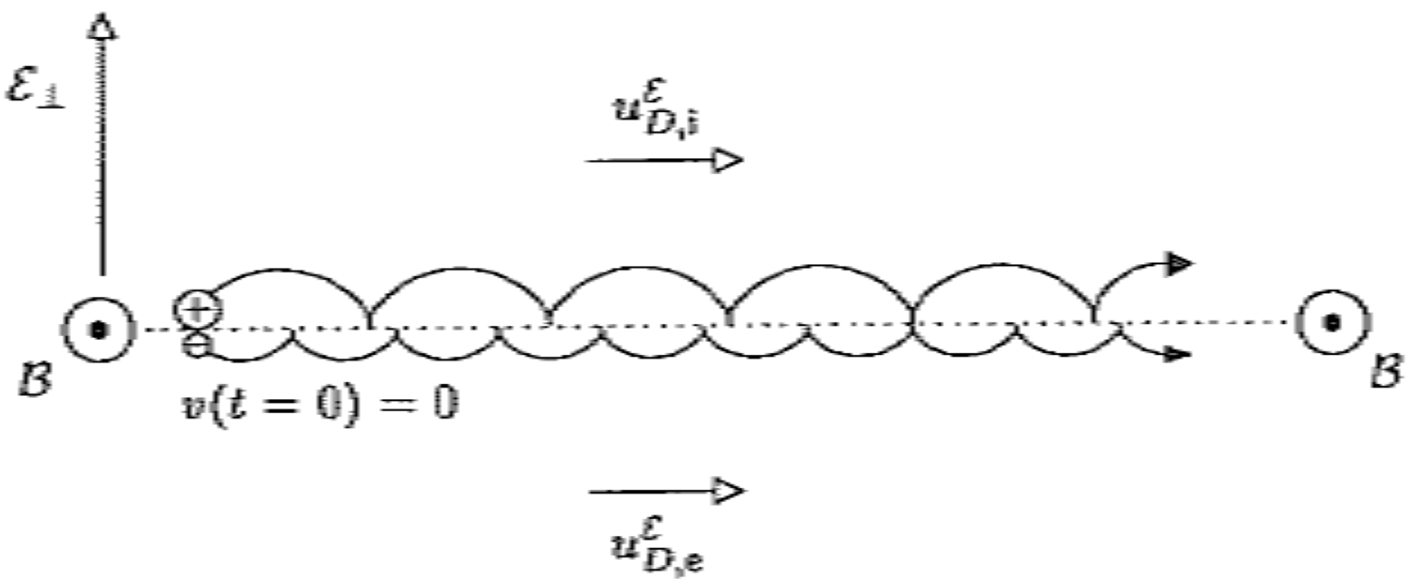
$$\vec{u}_D^F = \frac{\vec{F}_\perp \times \vec{B}}{qB^2}$$

External force drift in uniform magnetic field with force dependent on charge, q

$$\boxed{\vec{\in} \times \vec{B} \ \text{Drift}}$$

Same as before, but now $\vec{F}_{j\perp} = q\,\vec{\in}_{\perp}$

$$\vec{u}_D^{\in} = \frac{\vec{\in}_{\perp} \times \vec{B}}{B^2}$$



Comparison of the gyration (B), oscillation (O) and combined drift (D) periods

	Protons			Electrons		
Energy	0.6 eV	20 keV	20 MeV	0.6 eV	20 keV	20 MeV
L	3	4	1.3	3	4	1.3
Period						
T_B	0.1 s	0.1 s	5 ms	X 5.4×10^{-4}	X 5.4×10^{-4}	X 5.4×10^{-4}
T_O	2 h	1 min	0.5 s	X 2.3×10^{-2}	X 2.3×10^{-2}	X 2.3×10^{-2}
T_D	45 yr	9 h	2 min	X 1	X 1	X 1

1 eV ←→ 7700 K

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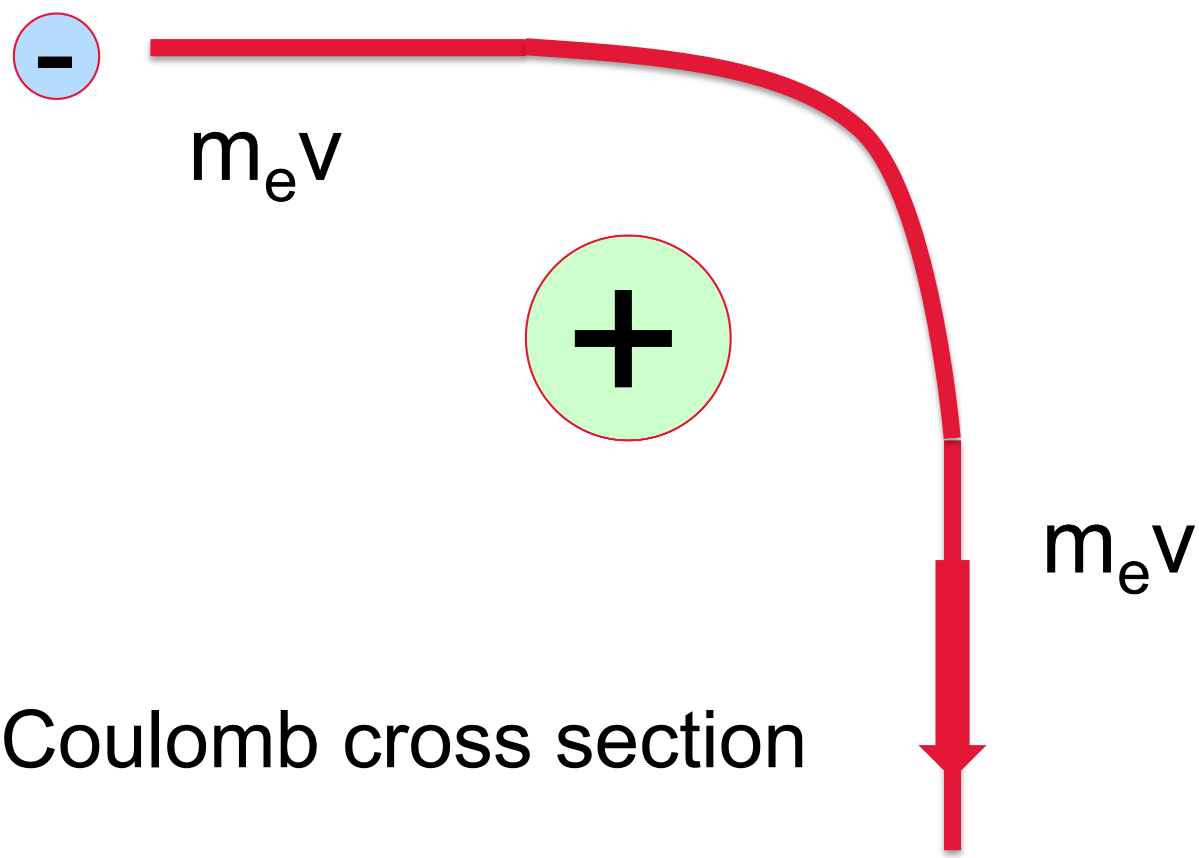
Coulomb collisions (elastic)

- Deflection of an electron by an ion without change of speed



$\sigma_{e,i}^{Cb} \propto \frac{1}{E_e^2}$ Coulomb cross section

➔ Coulomb collision frequency

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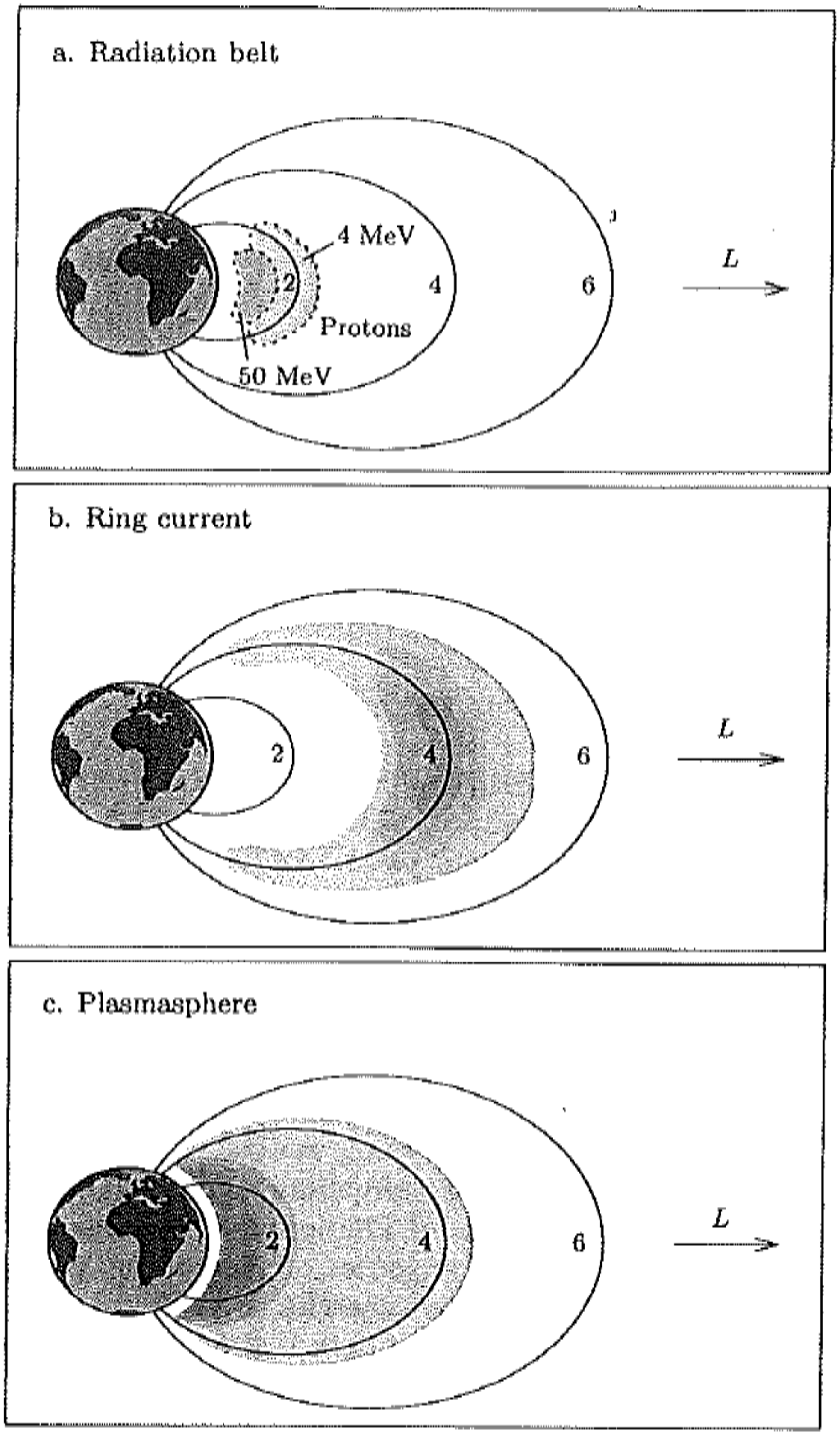
Particle population in the inner magnetosphere

- Lots of charged particles are confined within the dipole field of the Earth
- We distinguish between three particle populations:
  - Radiation belt
  - Ring current
  - Plasmasphere

Spatial distribution



Radiation belt

Inner radiation belt / Van Allen belt

Ring current

Outer radiation belt / Van Allen belt

Plasmasphere

Proelss

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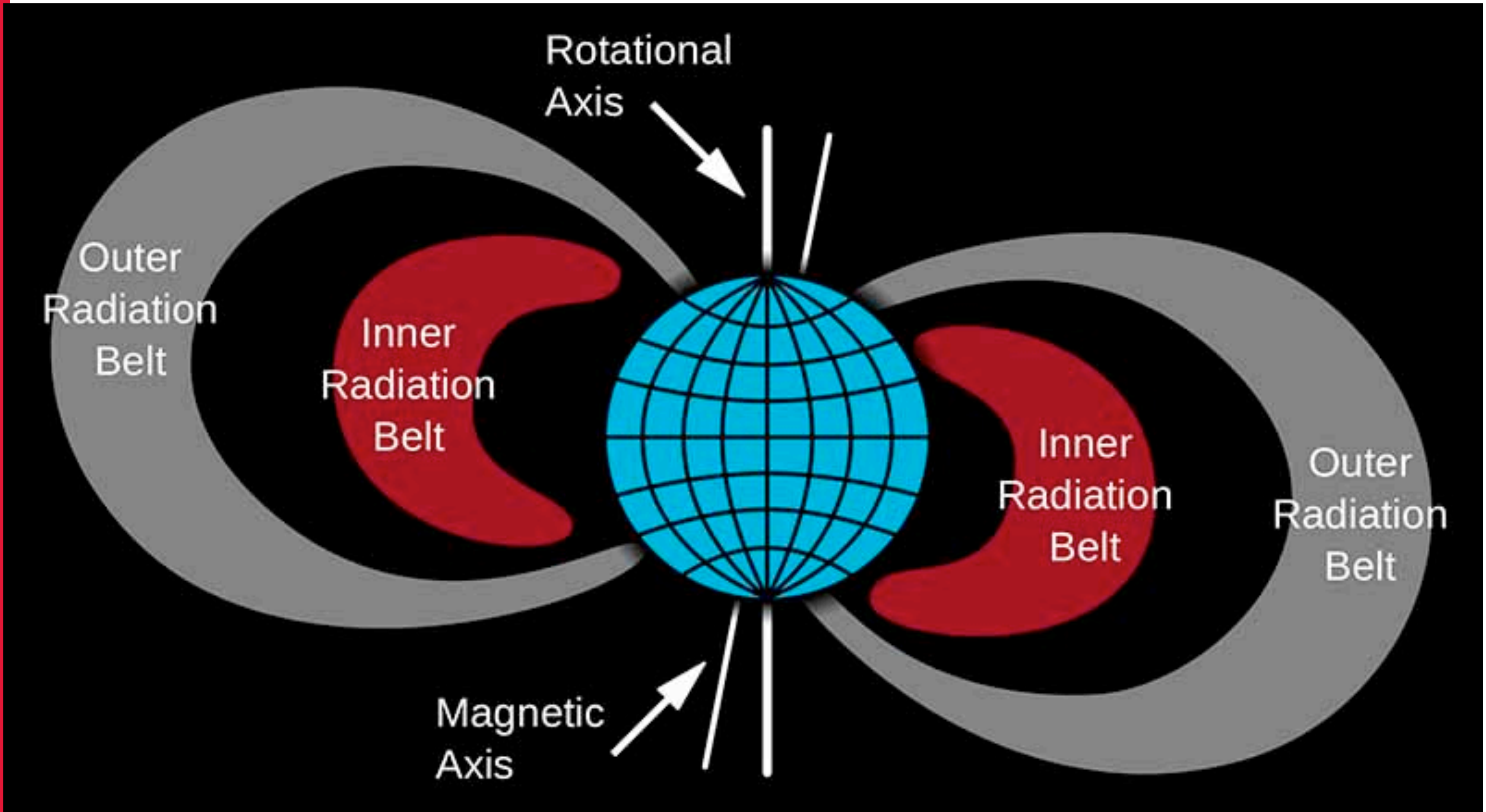
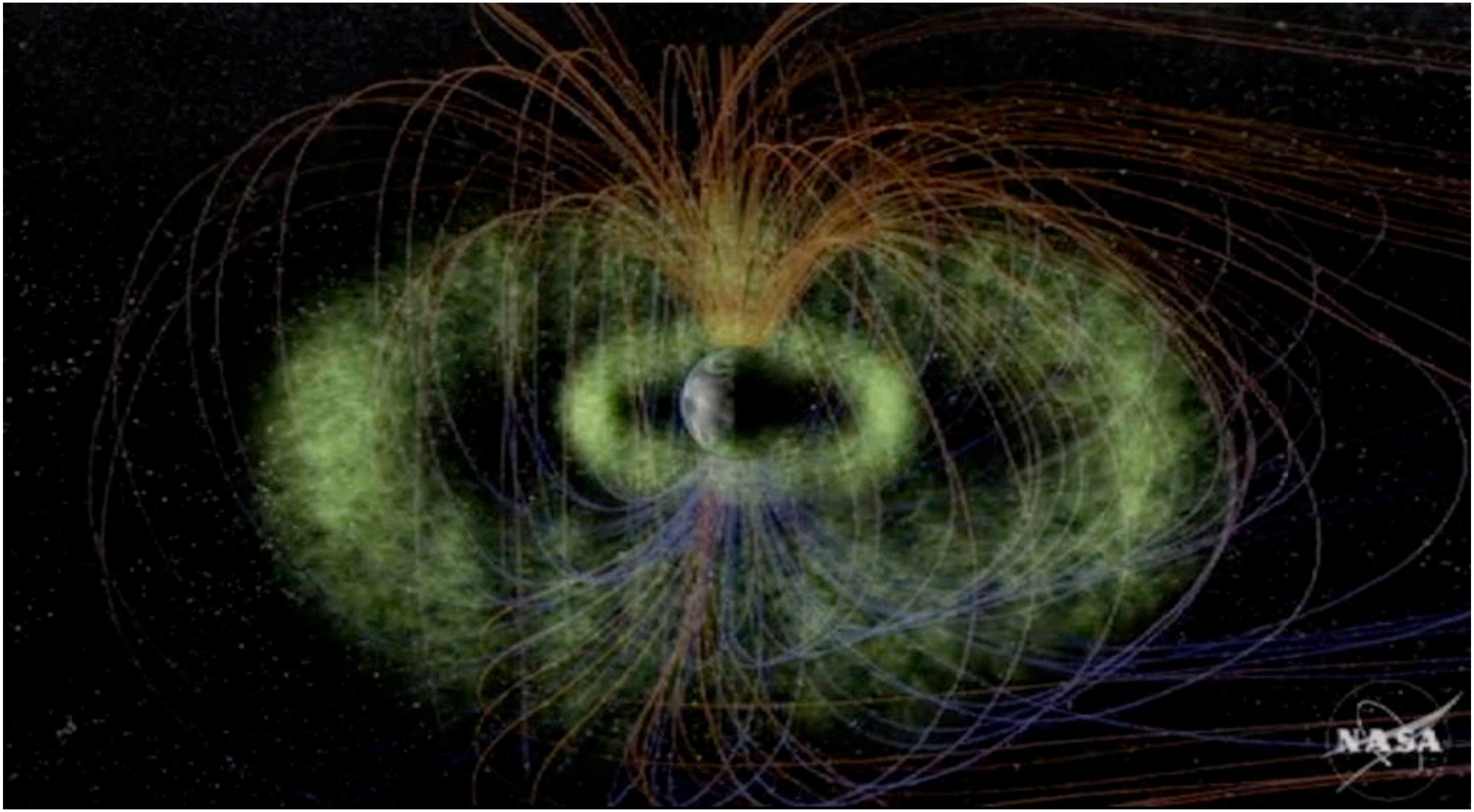
Main characteristics

	Radiation belt Inner rariation belt / Van Allen belt	Ring current Outer radiation belt/ Van Allen belt	Plasmasphere
Energy Ions electrons	 1-100 MeV 0.05 – 10 MeV	 1-200 keV <10 keV	 < 1eV < 1 eV
L	1.2 -2.5	3 - 6	1.2 - 5
Particle motion	Gyration Bouncing drift	Gyration Bouncing drift	Gyration corotation
Significanc e	Radiation damage	Magnetic field disturbance	Plasma reservoir for ionosphere



http://www.crystalinks.com/vanallenbelt.html

Van Allen radiation belts with magnetic field lines

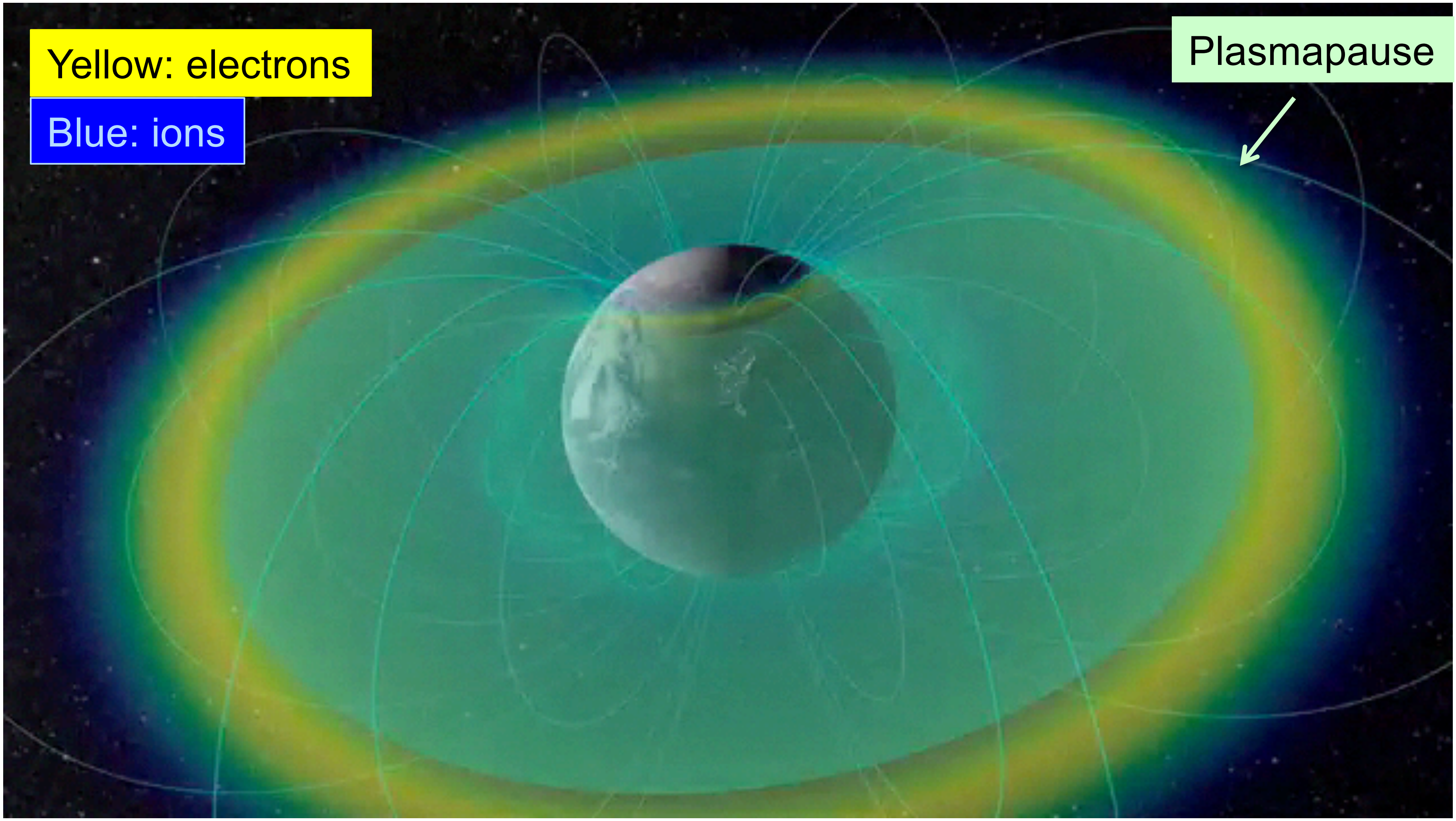


Screenshot from graphic animation

https://www.nasa.gov/mission_pages/sunearth/news/gallery/vab-graphic.html

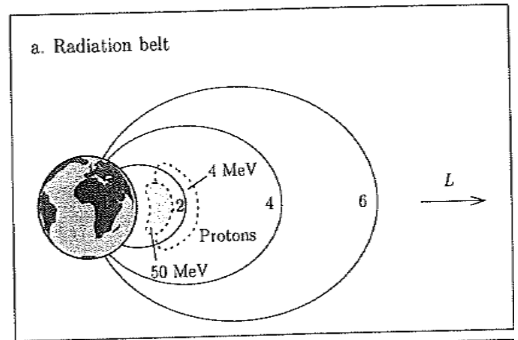
- https://www.nasa.gov/feature/goddard/2016/nasas-van-allen-probes-catch-rare-glimpse-of-supercharged-radiation-belt

Radiation belts and plasmapause



https://svs.gsfc.nasa.gov//cgi-bin/details.cgi?aid=4241

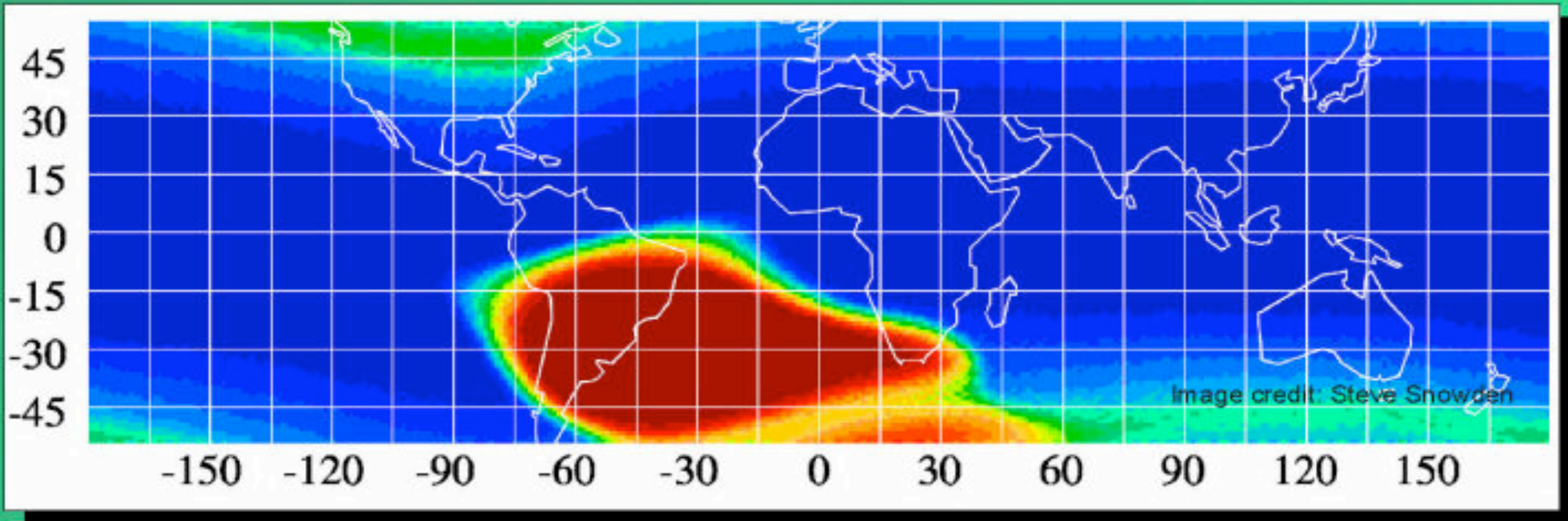
Radiation belt (inner)



- Part of the inner magnetosphere with a high energy particle (p and e) population.
  - January 1958, Explorer 1-3 (first US satellites) had Geiger counter on board.
  - Energy of p, >1-100 MeV! They penetrate spacecraft and can damage instruments and be hazardous to astronauts.
  - Maximum p flux: 10^{10} $m^{-2}s^{-1}$ (4 MeV) and 10^{8} $m^{-2}s^{-1}$ (50 MeV).
  - Height: for p: peak L=1.8 (5000 km) – range between 1000 and 6000 km, but can go down to 200 km during solar activity of in South Atlantic Anomaly.
  - Properties are stable
- Source: CRAND (Cosmic Ray Albedo Neutron Decay)

- Rosat

South Atlantic Anomaly



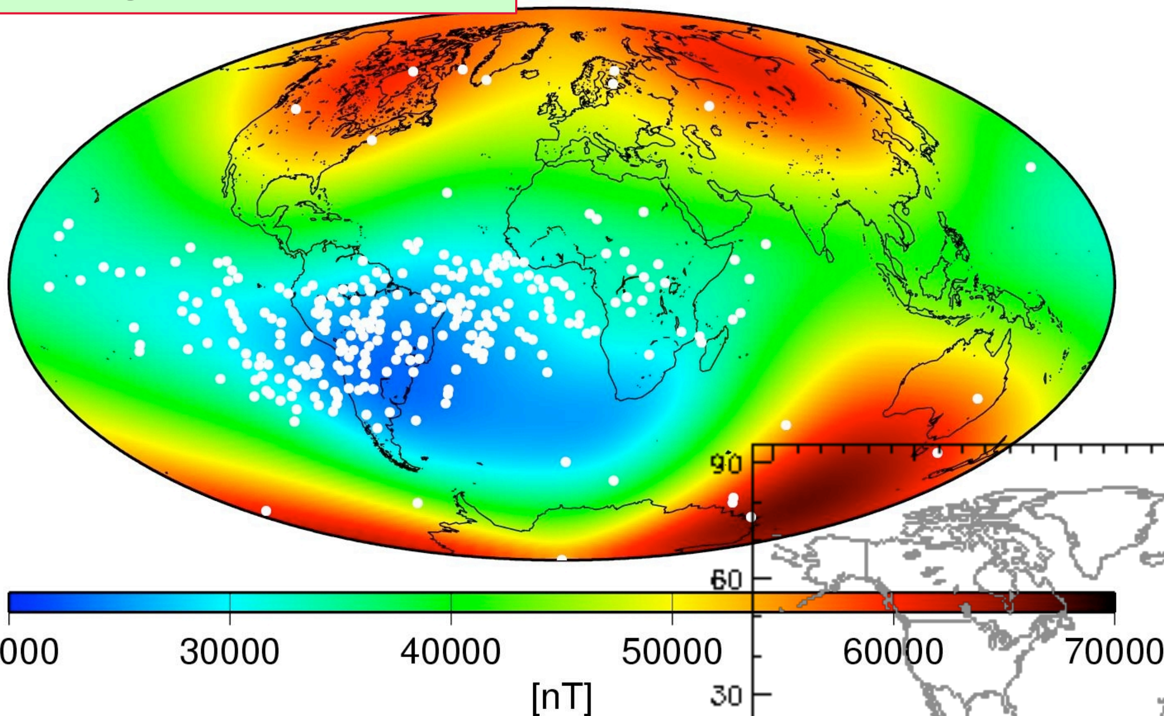
The South Atlantic Anomaly (SAA) is a dip in the Earth's magnetic field which allows cosmic rays and charged particles to reach lower into the atmosphere and interfere with communication with satellites, aircraft, and the Space Shuttle. The geologic origin is not yet known.

The enhanced particle flux in the SAA also strongly affects X-ray detectors, which are in essence particle detectors. The ROSAT PSPC had to be turned off during passage through the SAA to prevent severe damage. While the ROSAT HRI could be left on during the passage, it could collect no useful data. The light blue and green bands at the top and bottom of the image are due to an enhanced particle flux above Earth's auroral zones (particle belts).

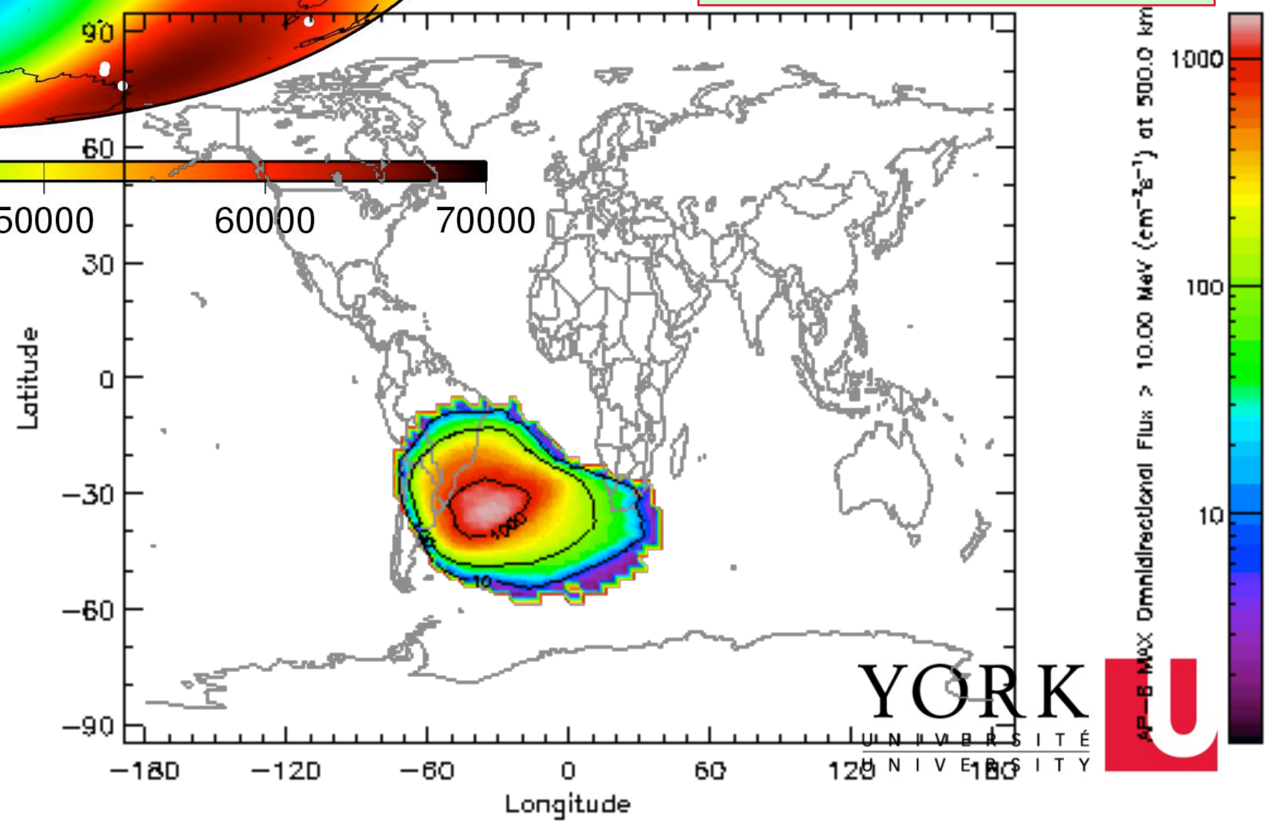
Rosat: X-ray telescope

South Atlantic Anomaly (SAA)

Magnetic field



Particle flux



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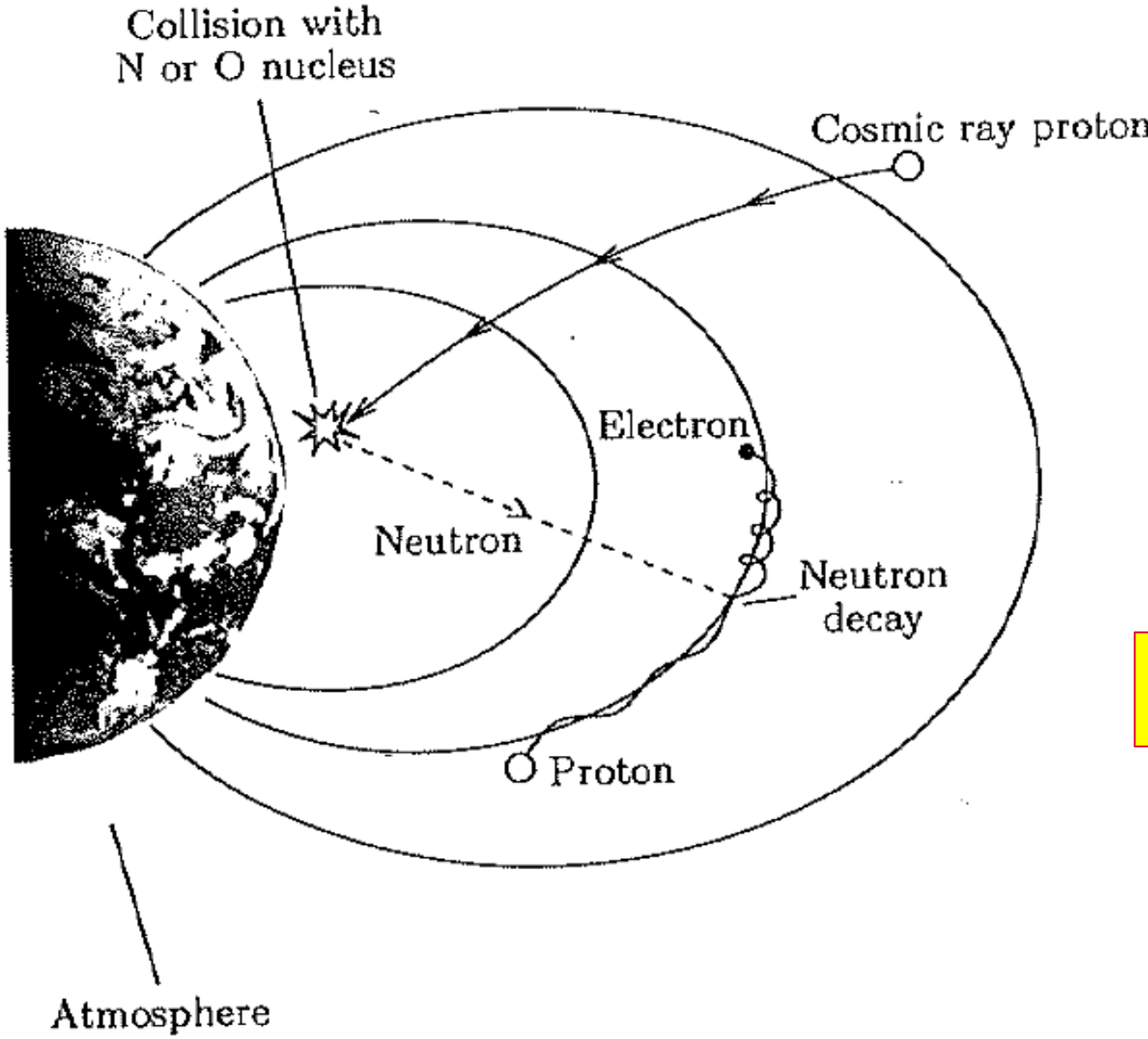
Source of the radiation belt particles



$$n = p + e + \overline{v}$$

- High energy particles are high energy protons and ions.
- They come from the Sun and also have galactic and even extragalactic origin.
- Galactic and extragalactic high energy particles are cosmic ray particles. They are from supernovae and possibly from the environment of black holes in the center of distant galaxies.
- The high energy particles collide with nuclei of molecules and atoms in the atmosphere.
- A cosmic ray proton with, e.g., 5 GeV can produce 7 free neutrons.
- The neutrons undergo beta-decay in the radiation belt after about 10 min. producing p and e and anti neutrinos.
- The charged particles gyrate and drift. Protons, e.g., can drift around Earth in 2 min.
- They collide and eventually end up in the loss cone.

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Particle energy levels

- 0.03 eV
  - The energy of a molecule of oxygen or nitrogen on Earth. It moves as fast as a speeding bullet, but is still rather low on the scale of energies.
- 0.5 eV
  - An atom or molecule at the temperature of the Sun's surface.
- 0.67 eV
  - The energy needed by a proton or neutron to escape the Earth's gravity.
- 1000 - 15,000 eV
  - Typical energy of an electron in the polar aurora.
- 40,000 eV
  - Energy required by an electron to penetrate a thin-wall Geiger counter
- 50,000 eV
  - Typical energy of an ion in the ring current.
- 10-100 MeV
  - Typical proton energies in the inner radiation belt.
- 10-15,000 MeV
  - Range of energies in solar outbursts
- 1-100,000,000,000 GeV
- Range of energies among cosmic ray ions. As their energy goes up, their intensity goes down: ions at the high energy end are quite rare. The Pierre Auger Cosmic Ray Observatory in Argentina has observed particles whose energy was estimated to be around 57 EeV and up (1,000,000,000 GeV = **1 Eev** (Exa-electron-volt))

Adopted from Newland

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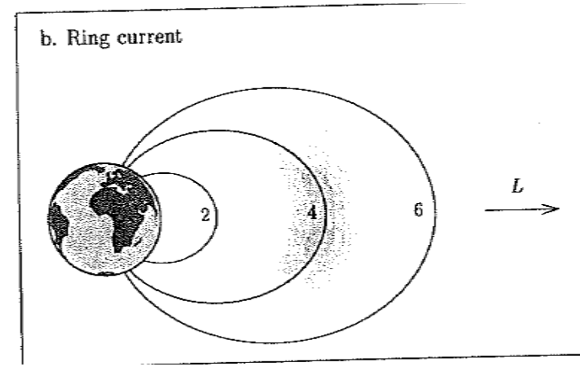
Source of cosmic rays: Sun, Supernovae, centers of galaxies

Ring current (outer radiation belt)



- While (inner) radiation belt is very stable, the ring current or outer radiation belt is very variable due to magnetic storms
- Most particles come from the long magnetic tail, the night side of the magnetosphere
- Particles are at lower energy (1-200 keV for ions, factor 10 lower for electrons)
- While main constituency is H^+, ionosphere plays a role in supplying other charged particles, particularly O ions.
- Loss process for H is

$$\underline{H}^+ + H \rightarrow \underline{H} + H^+$$

High energy

- Neutral high energy particles escape to interplanetary space
- The lifetime of ring current particles (protons) is ~2h.

$$\boxed{\tau_{S,H}^{CE} = \frac{1}{v_{S,H}^{CH}} = \frac{1}{\sigma_{S,H}^{CH} n_H \upsilon_S}}$$

Lifetime

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Example 5-2

- 20 keV proton orbiting on L=3 and colliding with H
- ➔v=2.5×10^{6} ms^{-1}

$$\upsilon = \sqrt{\frac{2E_{kin}}{m_p}} = \sqrt{\frac{2\bullet 1.6\bullet 10^{-19}\bullet 2\bullet 10^{4}}{1.66\bullet 10^{-27}}} = 2.5\bullet 10^{6}\, ms^{-1}$$

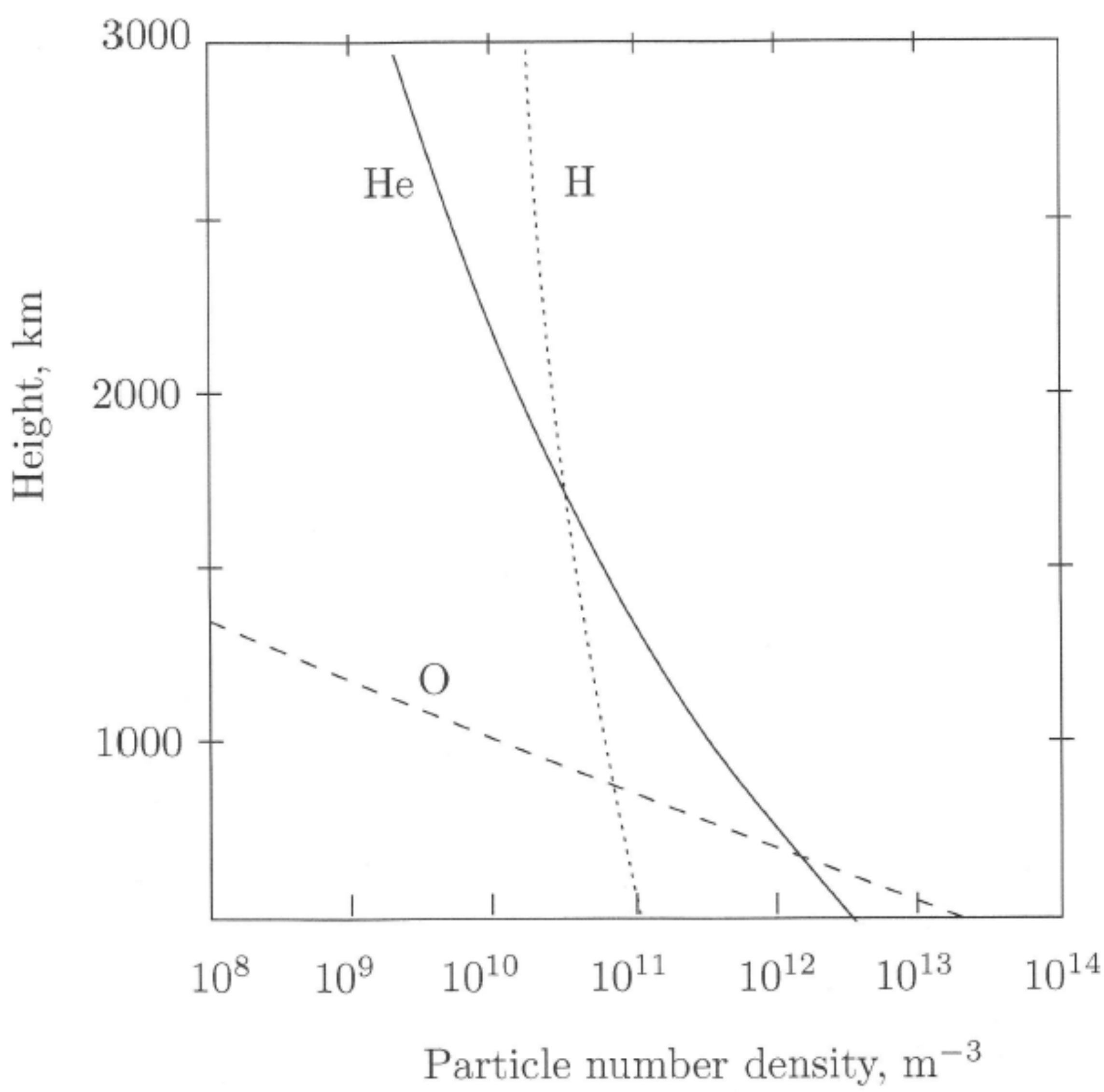
- with $n_H = 7\times10^{8}$ m^{-3}

$$\tau_{S,H}^{CE} = \frac{1}{\sigma_{S,H}^{CH} n_H \upsilon_S} = \frac{1}{10^{-19}\bullet 7\bullet 10^{8}\bullet 2.5\bullet 10^{6}} = 5760s = 1.6h$$

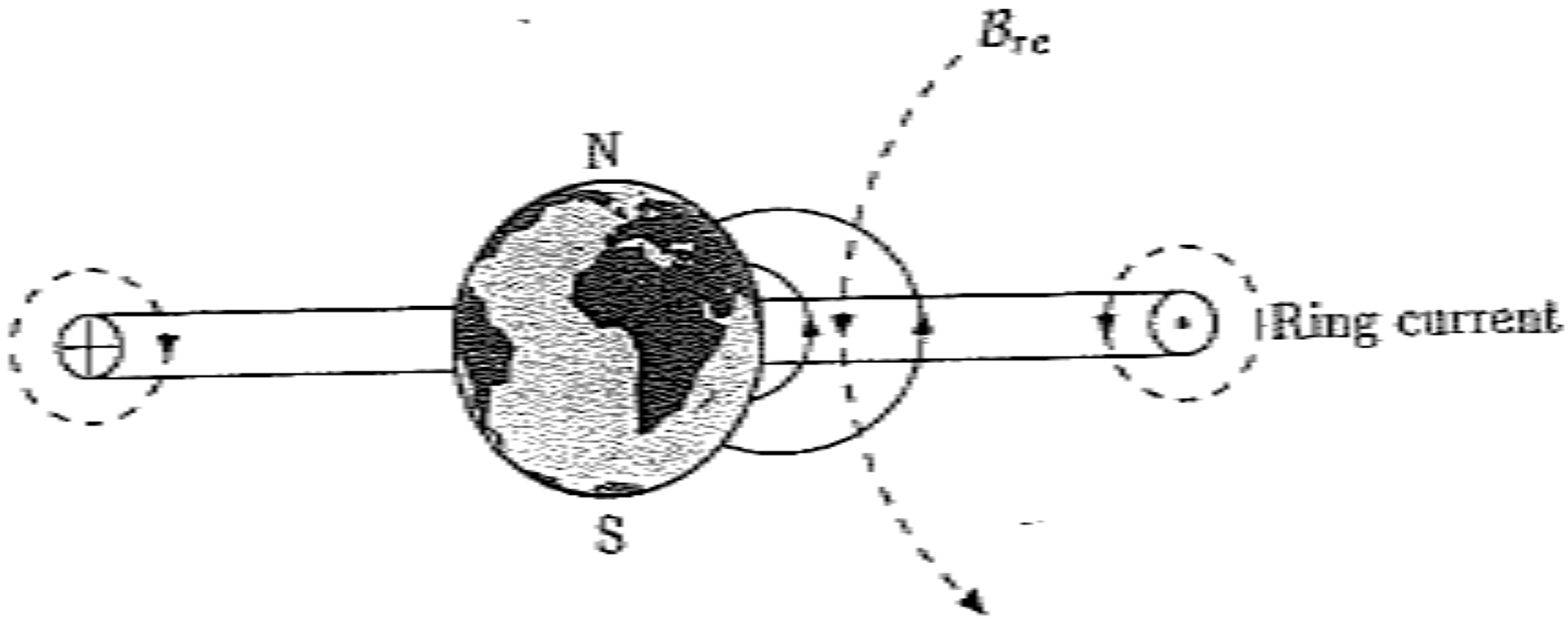
- ➔ Average lifetime is 1.6 h.

Note: 1 eV = 1.60×10^{-19} J

Recall: Particle number density



- The ring current generates a ring current magnetic field that works against the dipole field and therefore distorts it.



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Plasmasphere

- The plasmasphere is a continuation of the ionosphere into the magnetosphere
- It starts at 500 to 2000 km height.
- The inner boundary is given by the very different scale heights of for H^+ and O^+.
- The outer boundary, the plasmapause, is between L=3.5 to 5.5, depending on the degree of disturbance of the magnetosphere
- Particle energies are ~0.6 eV. Proton collision times much shorter than bounce period and certainly drift period. Many coulomb collisions occur. Therefore, only gyration is clearly established
- The plasmasphere co-rotates with Earth

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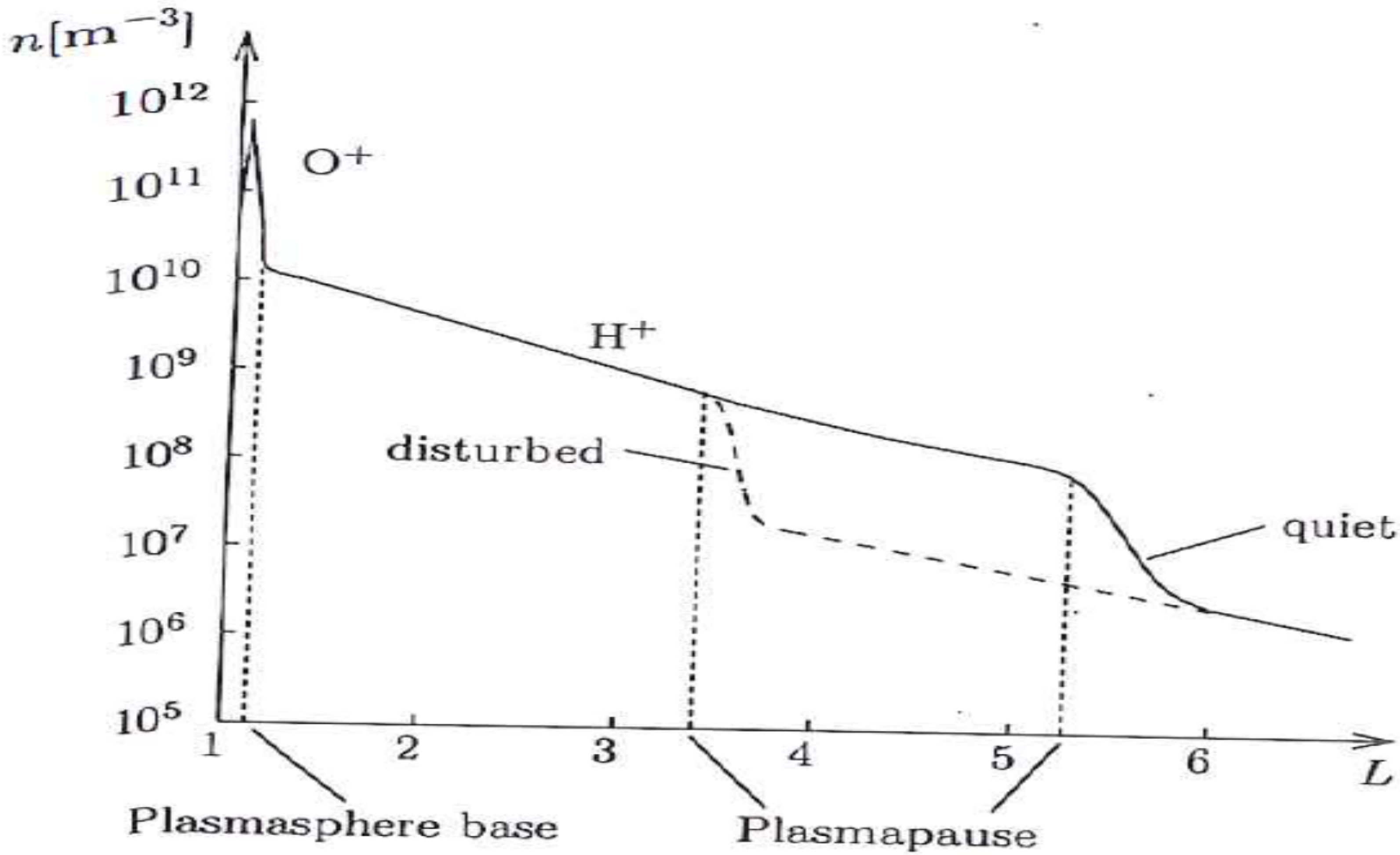
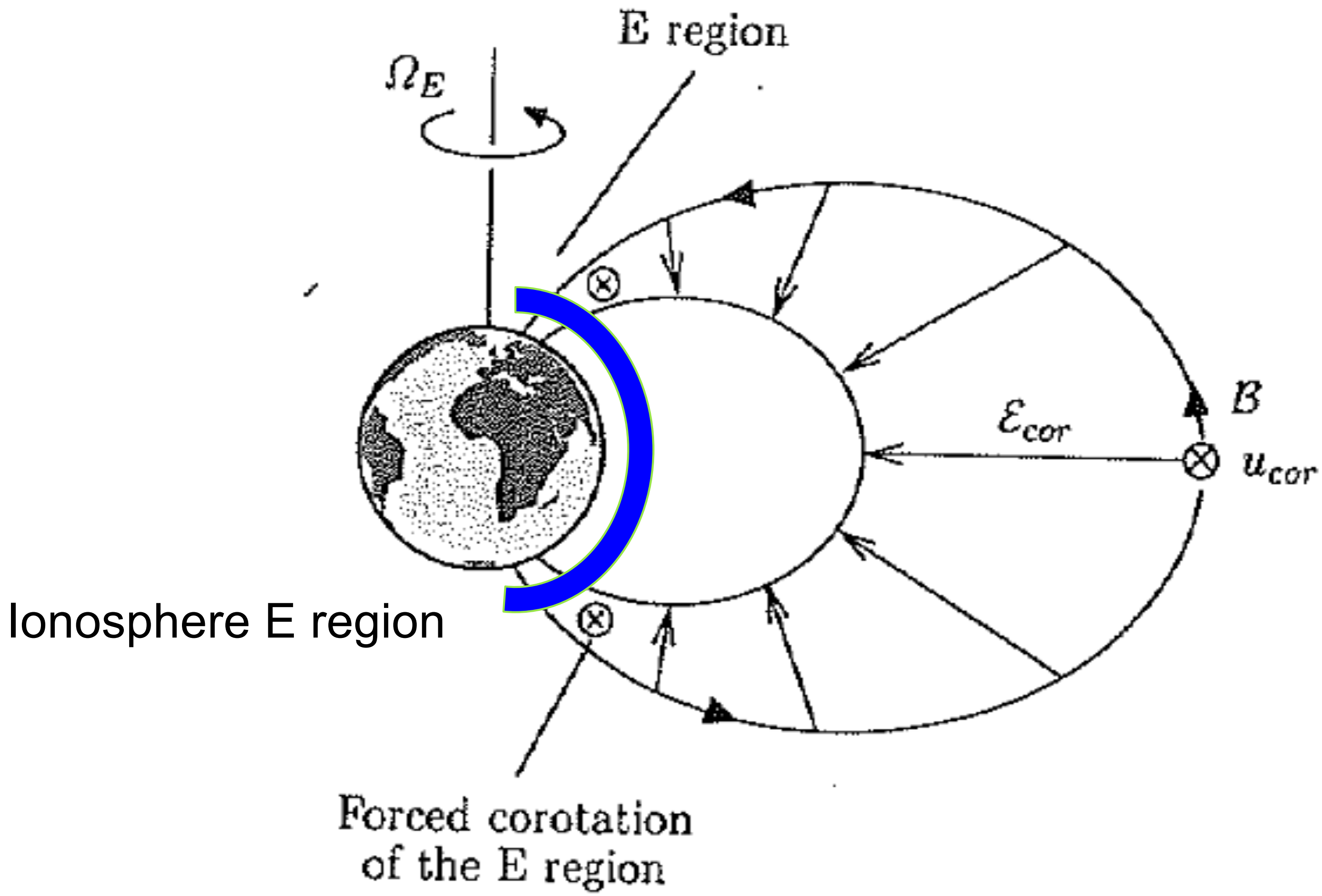
Plasmasphere density profile



The corotation of the plasmasphere



- Ionosphere corotates because of friction with the neutral atmosphere
- Electric dynamo field is induced $\vec{\in} = -\vec{u}_{cor} \times \vec{B}$
- This field is linked to the magnetic field lines and forces the plasmasphere to corotate with the ionosphere.

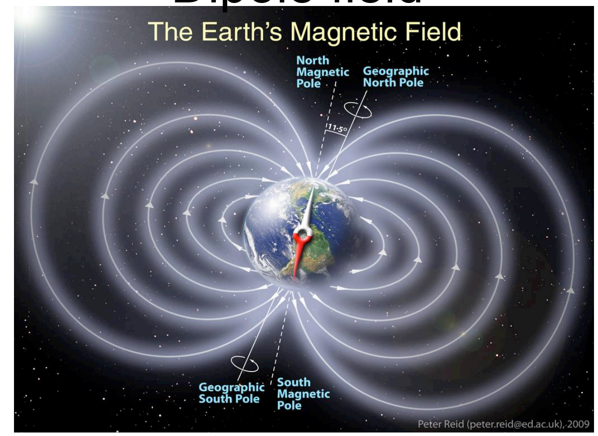
Some more description…

- The inner magnetosphere
  - This is different from most of the magnetosphere in that the magnetic field is mostly dipolar and perturbations of the field are small compared to the average dipole field. However, there can still be large amounts of energy stored in this region in particular during so-called storm times. During such times the ring current (current due to gradient curvature drifts of charged particles) intensifies strongly and is responsible for strong magnetic perturbations at low geomagnetic latitudes on the Earth.
- Magnetosphere-Ionosphere interaction
  - The ionosphere is the region where the atmosphere is partially ionized and plasma and neutrals strongly interact. This interaction exerts a drag on the plasma. The plasma density can be very high but also strongly variable such that the ionospheric conductance can vary by orders of magnitude. Magnetospheric plasma motion is transmitted into the ionosphere and forces ionospheric convection. This also implies the existence of strong currents along magnetic field lines which close through the ionosphere. In particular at high latitudes these currents lead to magnetic perturbations during times of strong magnetospheric activity (fast convection and changes of the magnetospheric configuration).

Adopted from Newland

The outer magnetosphere

Dipole field



- If Earth were in empty space, then the dipole field would extend to infinity.
- However, Earth is embedded in solar wind which changes configuration.
- Also, interplanetary magnetic field has influence on Earth magnetic field configuration.

Magnetosphere is confined

- The boundary is the Magnetopause

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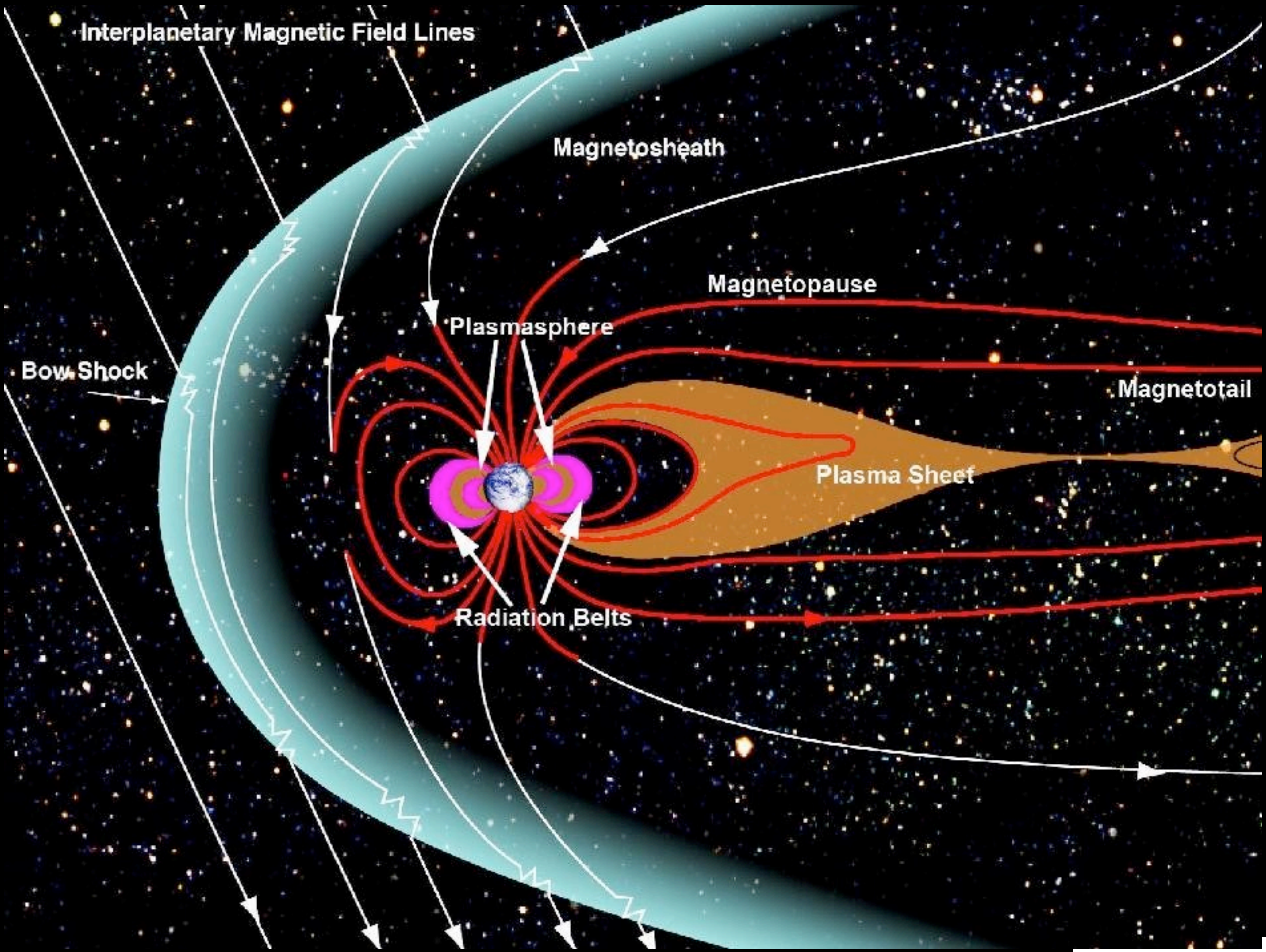
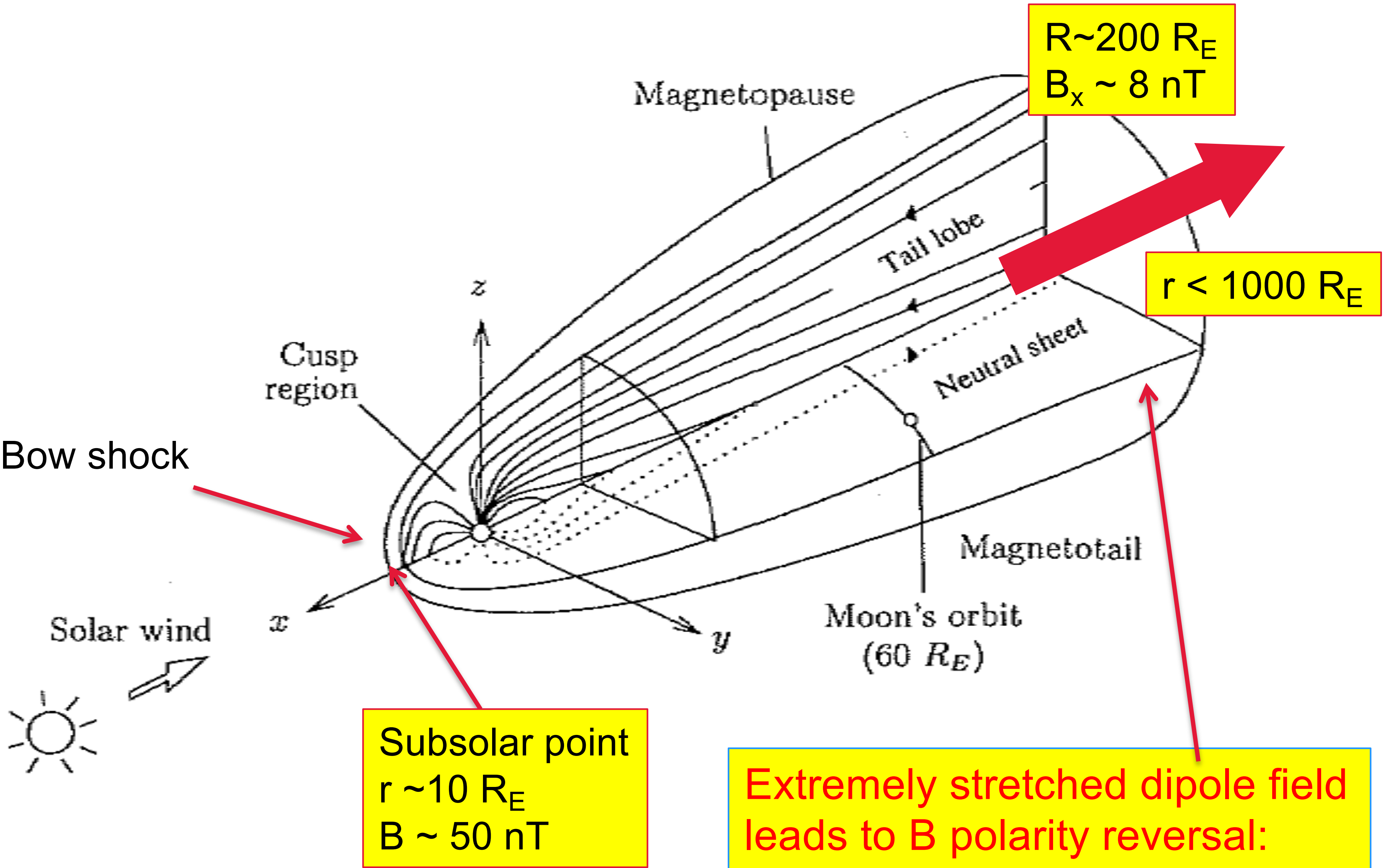


http://i1.wp.com/www.universetoday.com/wp-content/uploads/2015/10/Earths-magnetosphere.jpg



Extremely stretched dipole field leads to B polarity reversal: Neutral sheet

Proelss

- Bow shock and magnetosheath
  - The magnetosheath is an outer layer embedding the magnetosphere. The solar wind plasma travels usually at super-fast speeds relative to the magnetosphere. Therefore a standing shock wave forms around the magnetosphere. The bow shock is the shock in front of the magnetosphere and the magnetosheath is the shocked solar wind plasma. Therefore it is not directly the solar wind plasma which constitutes the boundary of the magnetosphere but the strongly heated and compressed plasma behind the bow shock.
- Magnetopause
  - The magnetopause is the actual boundary between the shocked solar wind and the magnetospheric plasma. However, the magnetosphere is not closed in terms of the magnetic field but there is considerable magnetic flux crossing the magnetopause. Thus it is not easy to define this boundary precisely. Also the boundary does permit a certain amount of solar wind plasma entry. This entry is easier along magnetic field lines. The magnetopause is an highly important region because the physical processes at this boundary control the entry of plasma, momentum, energy and the redistribution of geomagnetic flux

Adopted from Newland

- The cusp and mantle regions
  - These are directly adjacent and inward of the magnetopause. The cusp is the region where dipolar field lines converge. The mantle region represents a boundary to the magnetotail usually filled with solar wind plasma but with a stretched magnetospheric magnetic field. The role of the cusps is not fully understood but it is a region where highly energetic particles can be produced and it is very active in terms of turbulence and wave energy because the boundary field lines converge in the cusp and all waves which travel along the magnetic field are channeled into this region
- The magnetotail
  - This is the long tail-like extension of the magnetosphere on anti-sunward side of the magnetosphere. Since the magnetic field points toward the Earth in the northern lobe and away in the southern lobe there is a current in the westward direction. Because of its structure there is considerable energy stored in the magnetic field in the magnetotail. During magnetically quiet times convection is typically low and energy in the plasma flow is only a tiny fraction of the overall energy density

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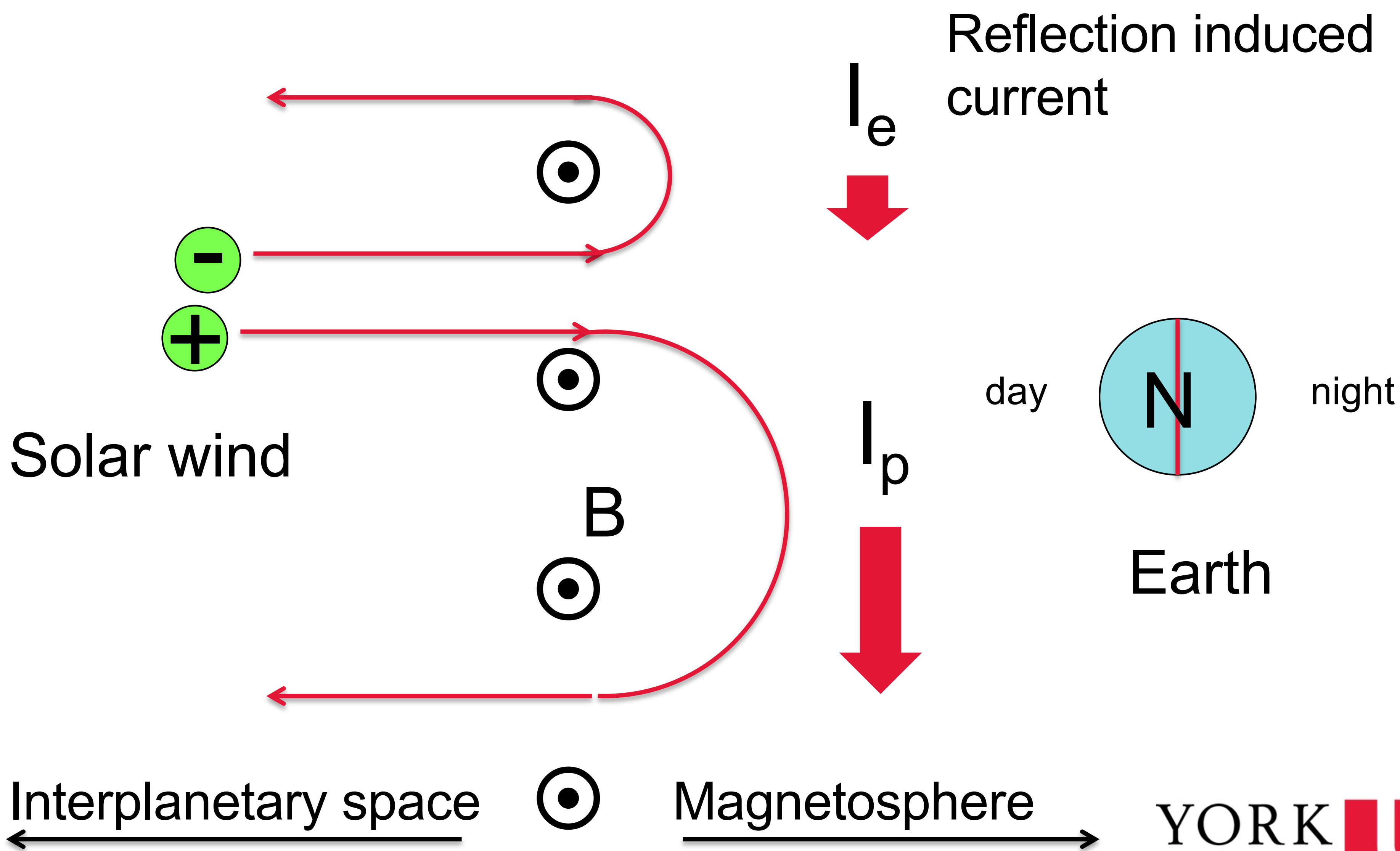
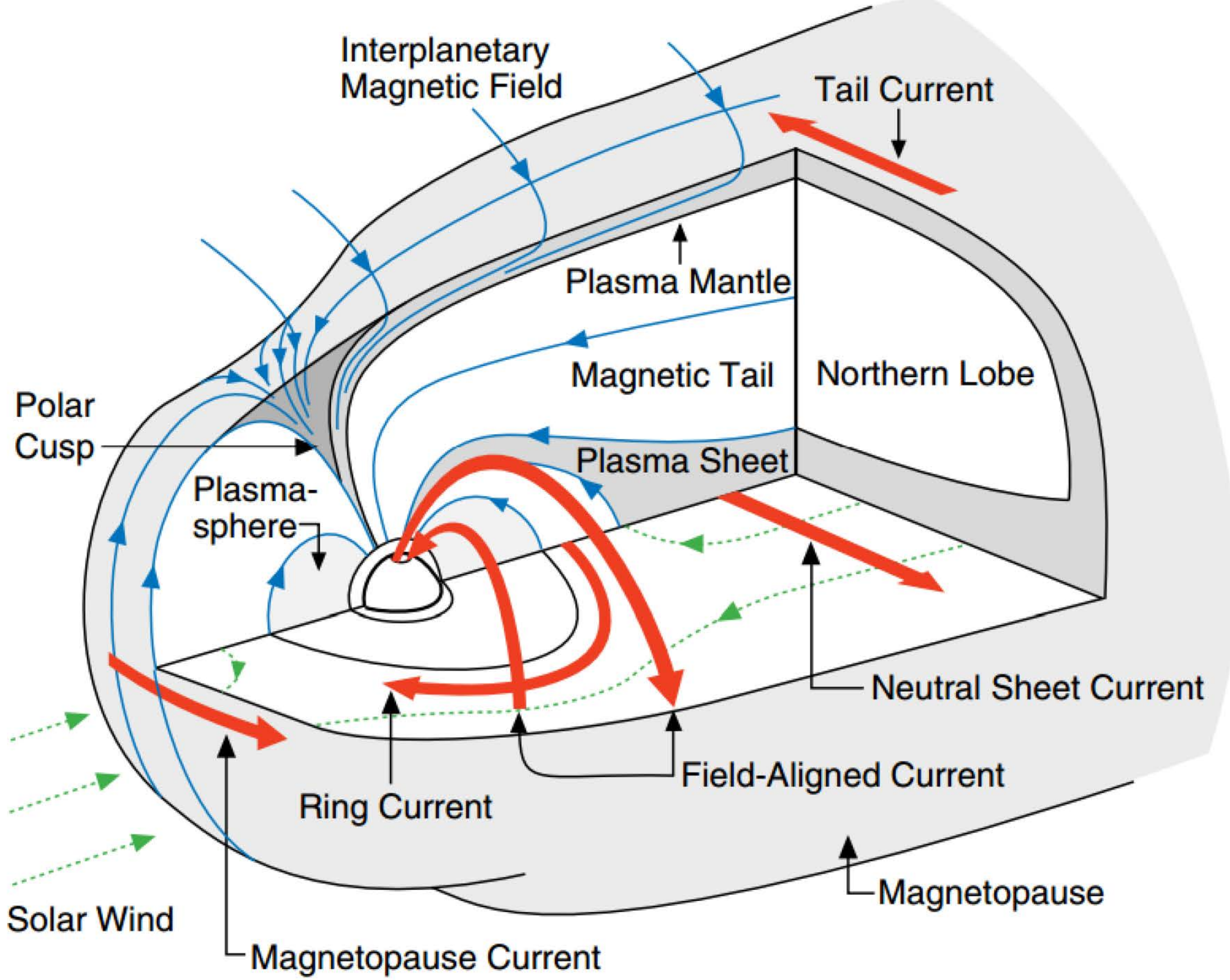
Reflection of solar wind





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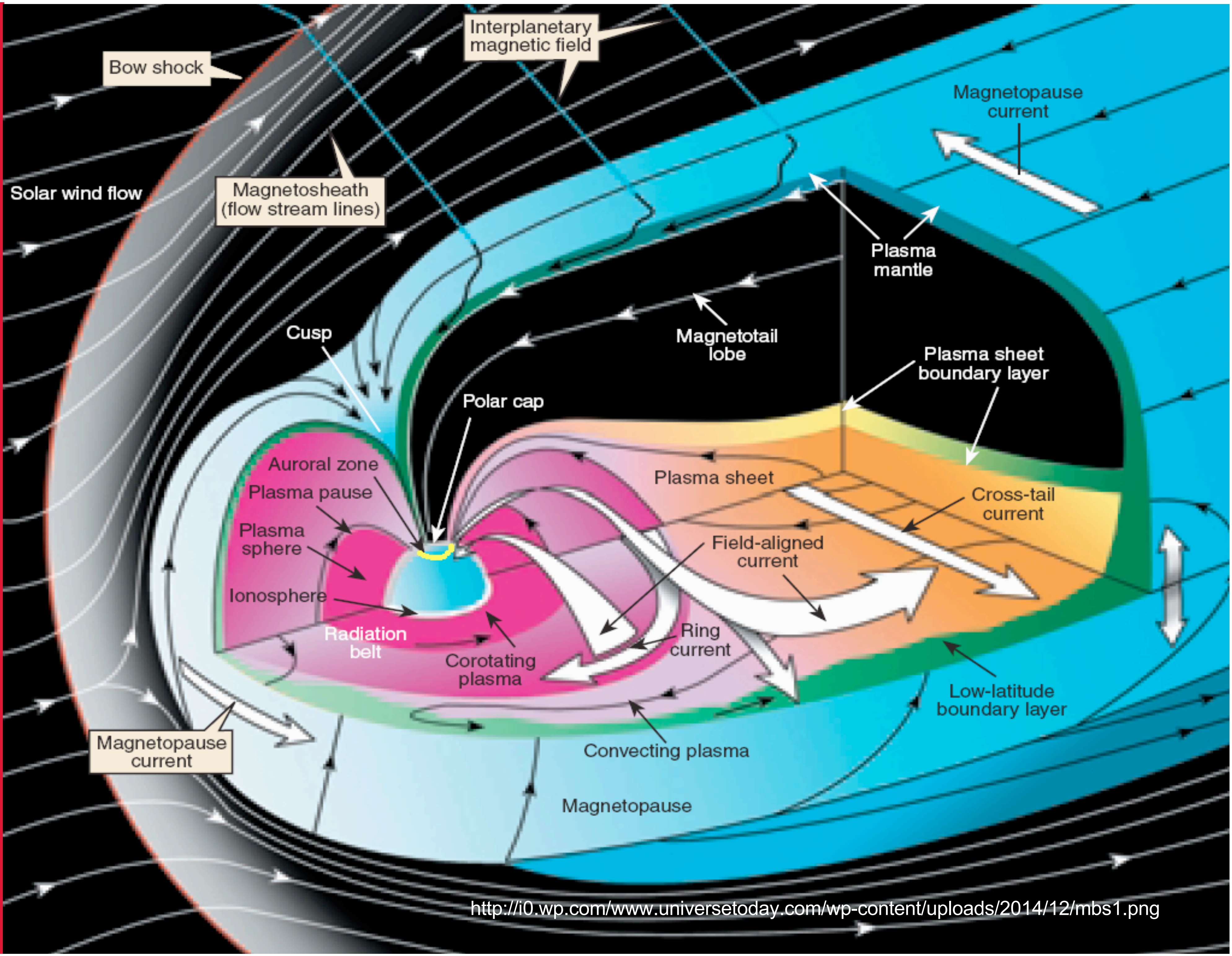
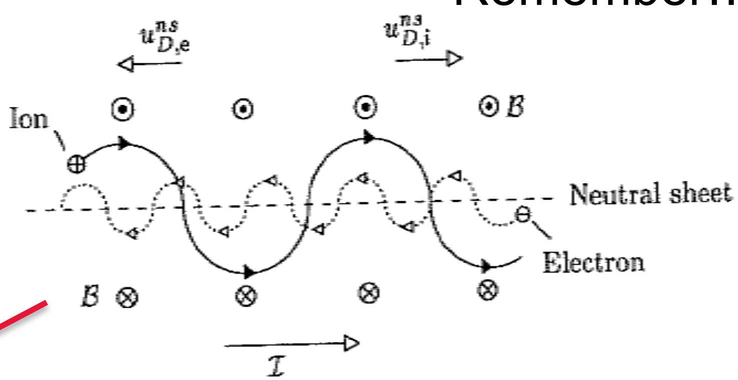


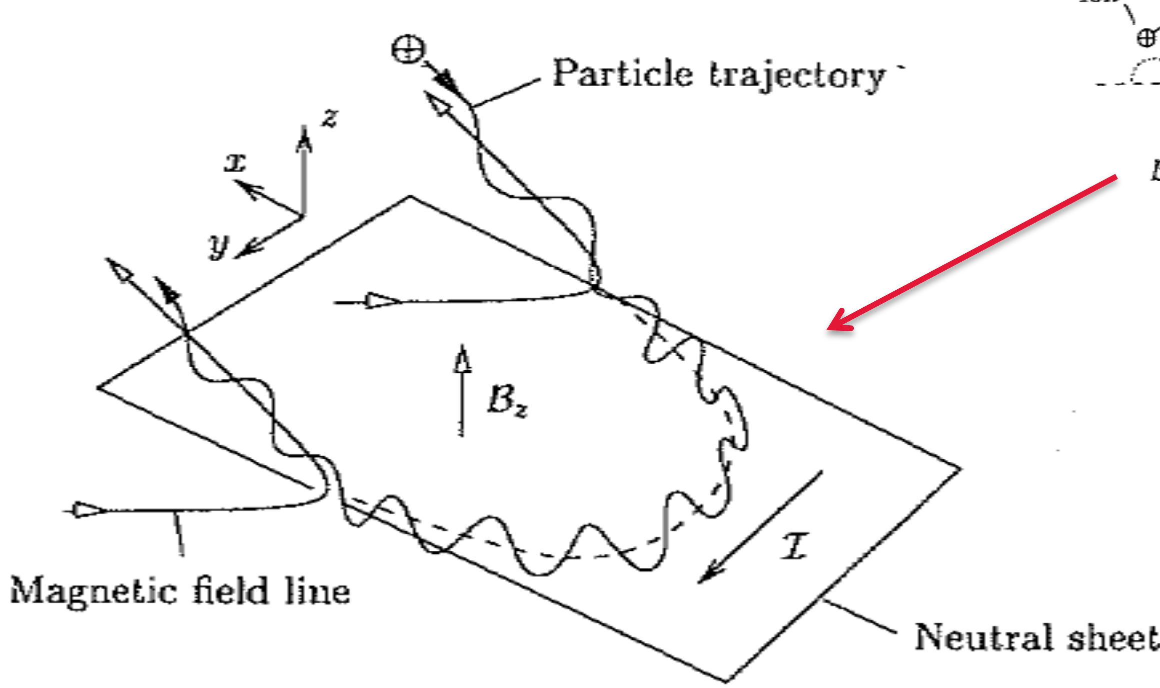
http://i0.wp.com/www.universetoday.com/wp-content/uploads/2014/12/mbs1.png

Geomagnetic tail

- The geomagnetic tail has a neutral sheet in the middle which separates the two polarities of the magnetic field.
- This generates a neutral sheet current

Remember…





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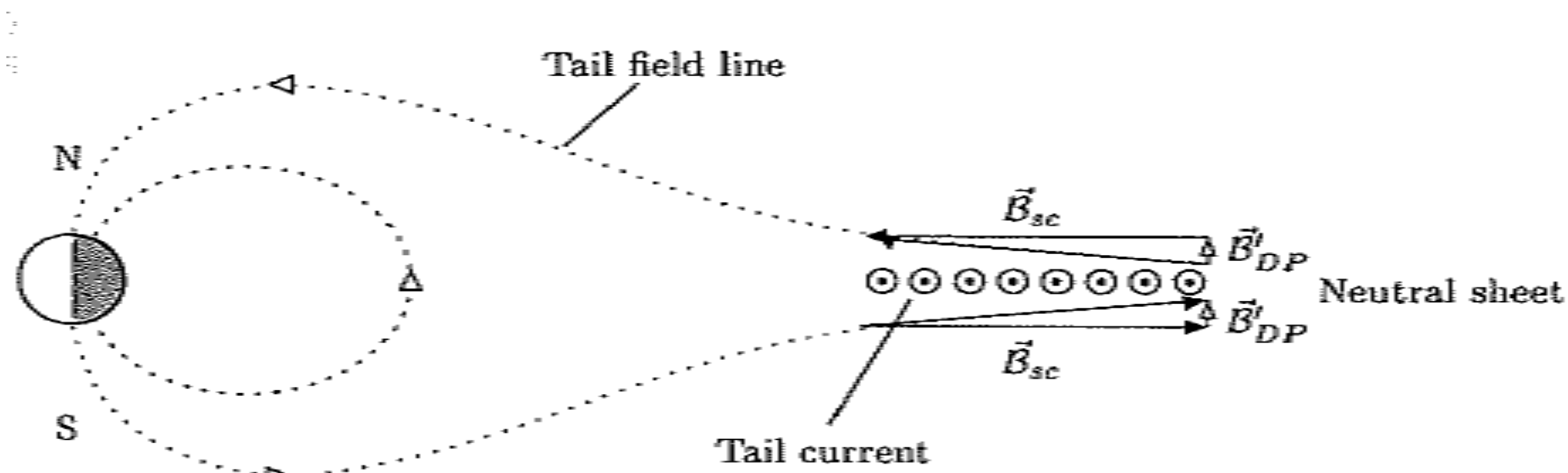
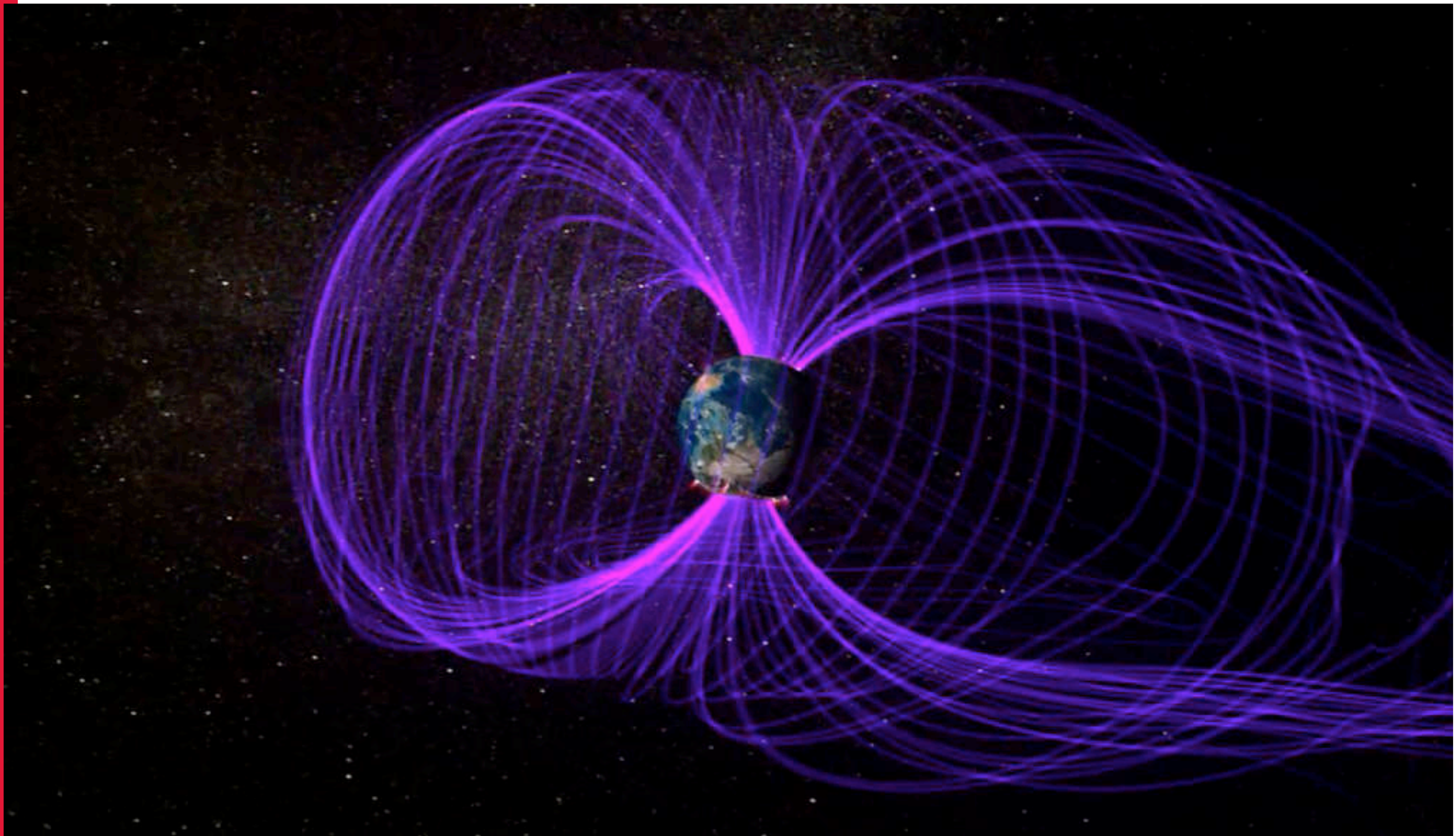


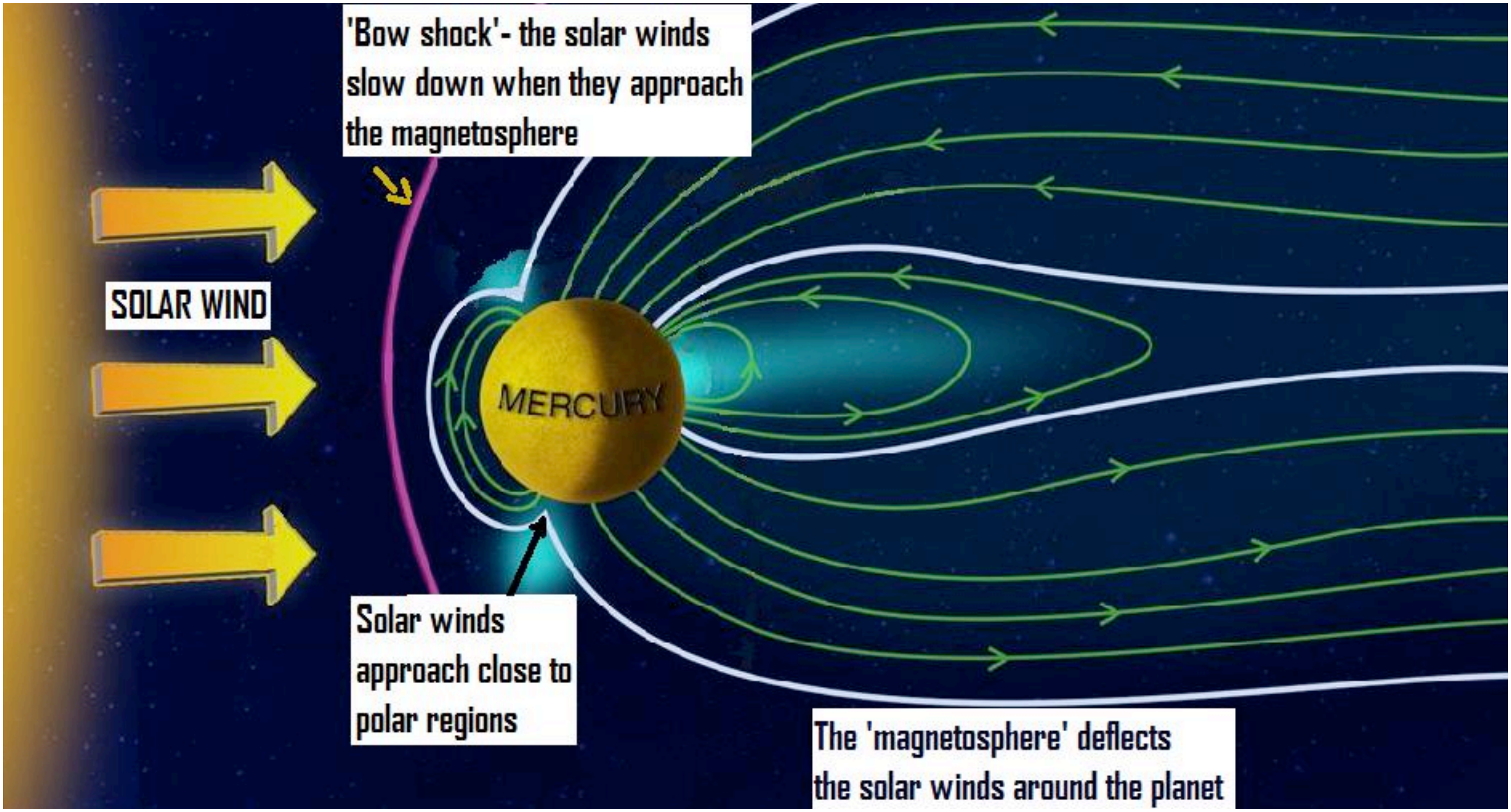
Fig. 5.43. Magnetotail current system (noon-midnight meridian)

Proelss

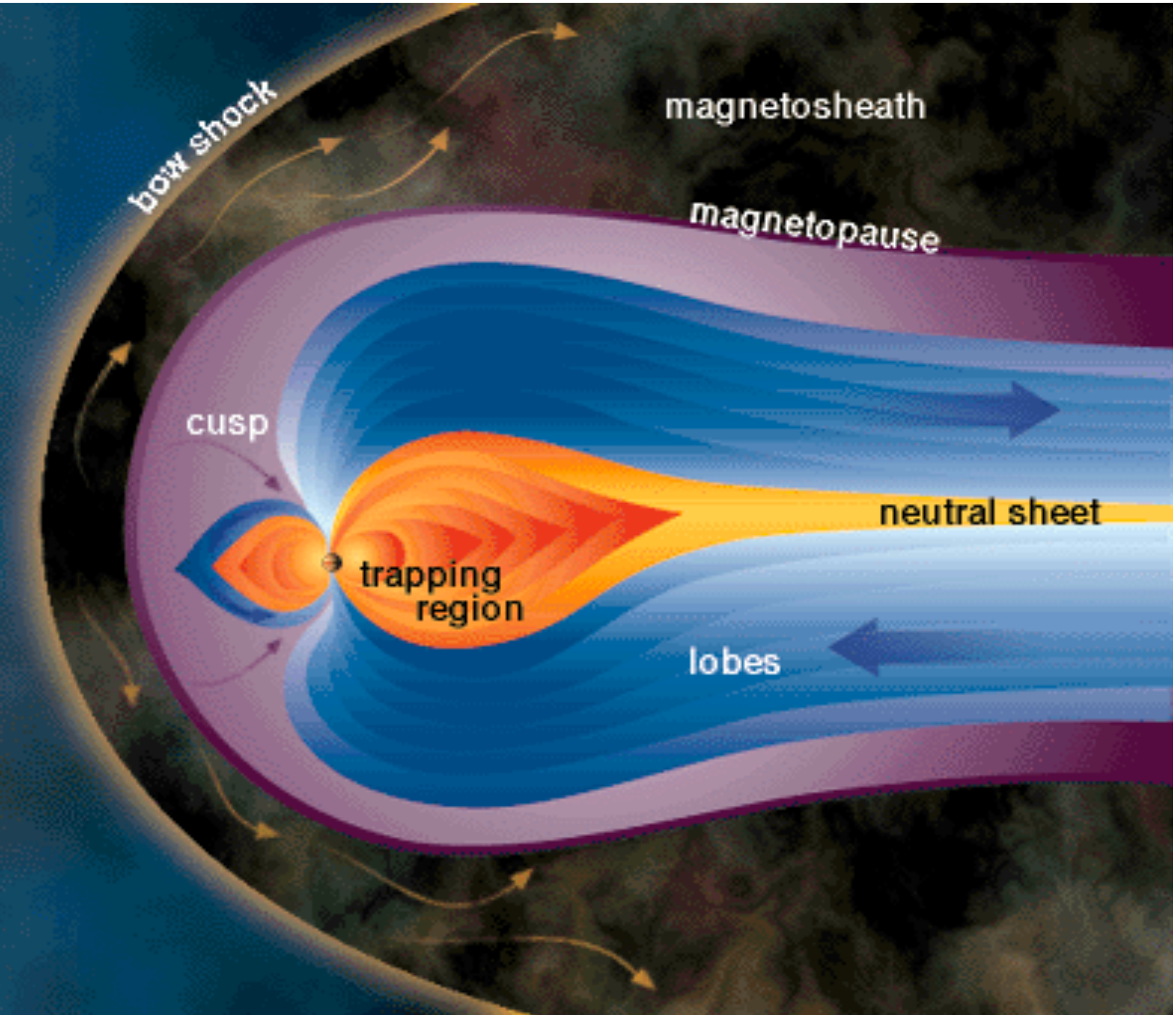


https://www.nasa.gov/sites/default/files/images/728490main_Magnetosphere-orig_full.jpg

Magnetosphere of other solar system bodies



Jupiter



http://www.odyssespace.fr/Images/Jupiter_magnetosphere.png