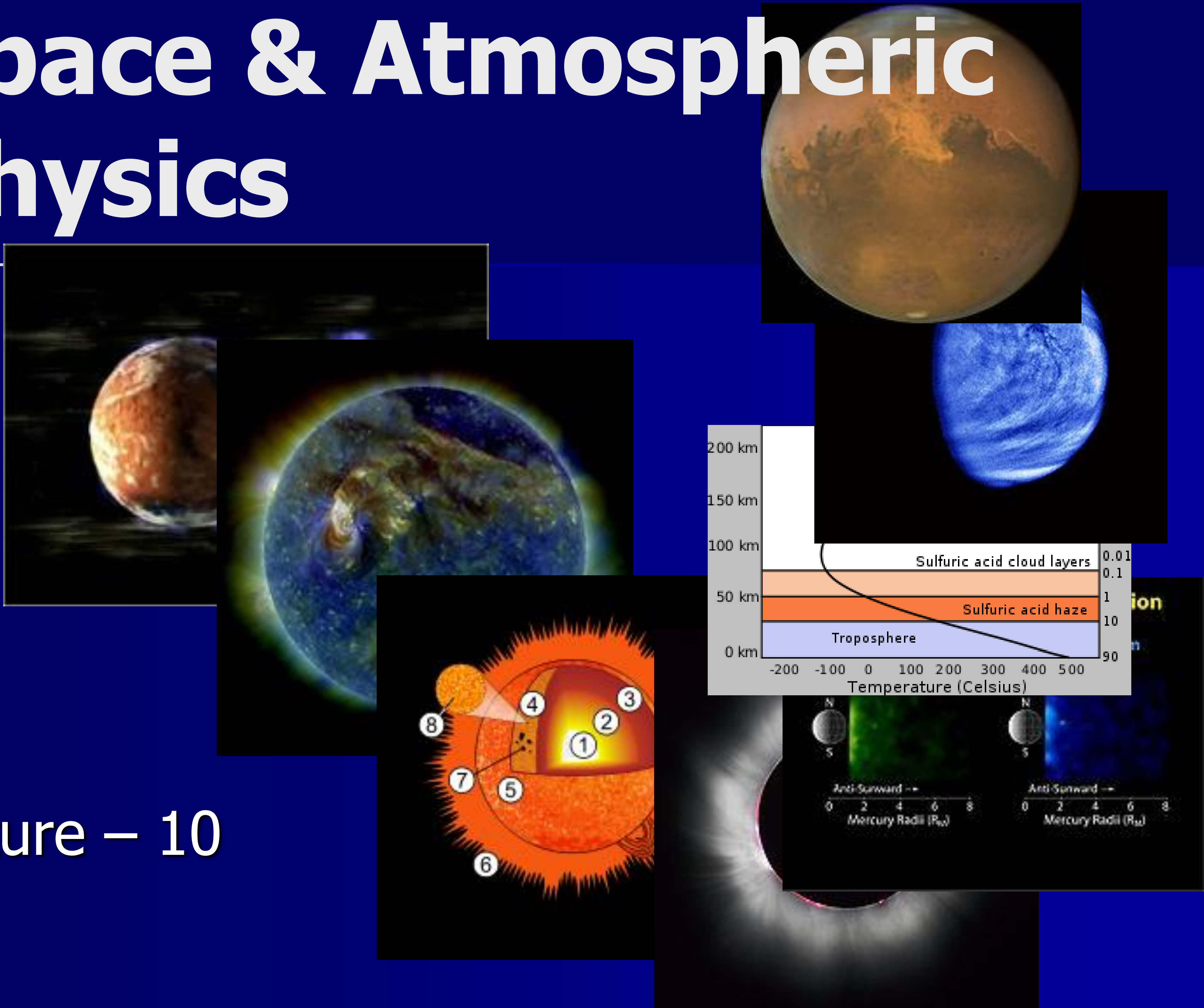
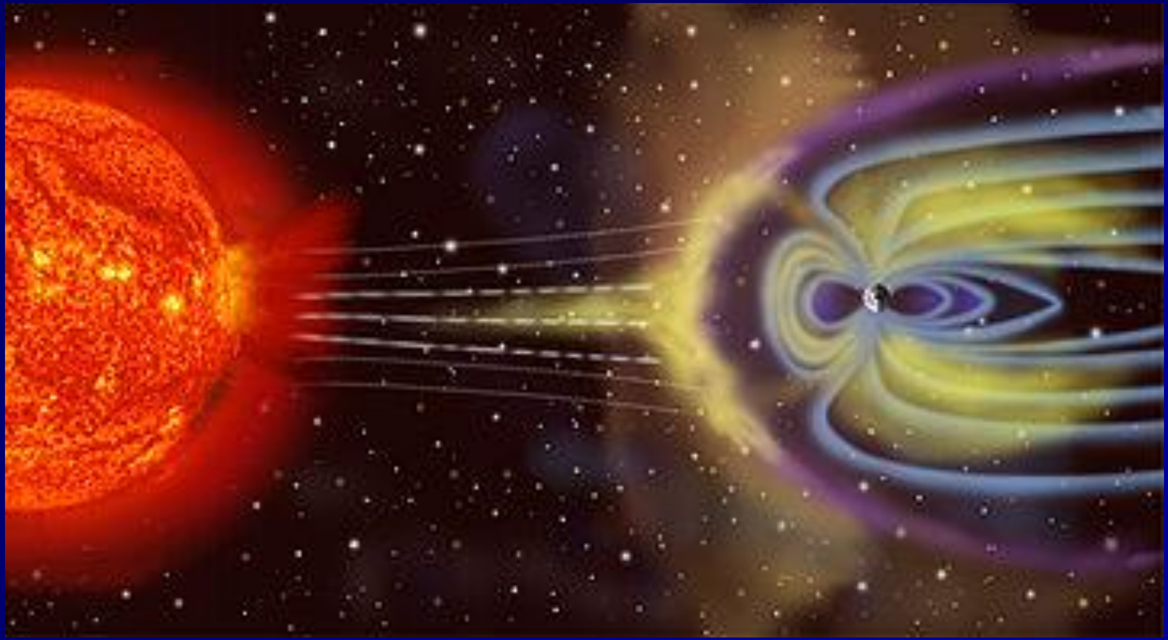
Space Physics

Space & Atmospheric Physics



Lecture – 10

The Magnetosphere



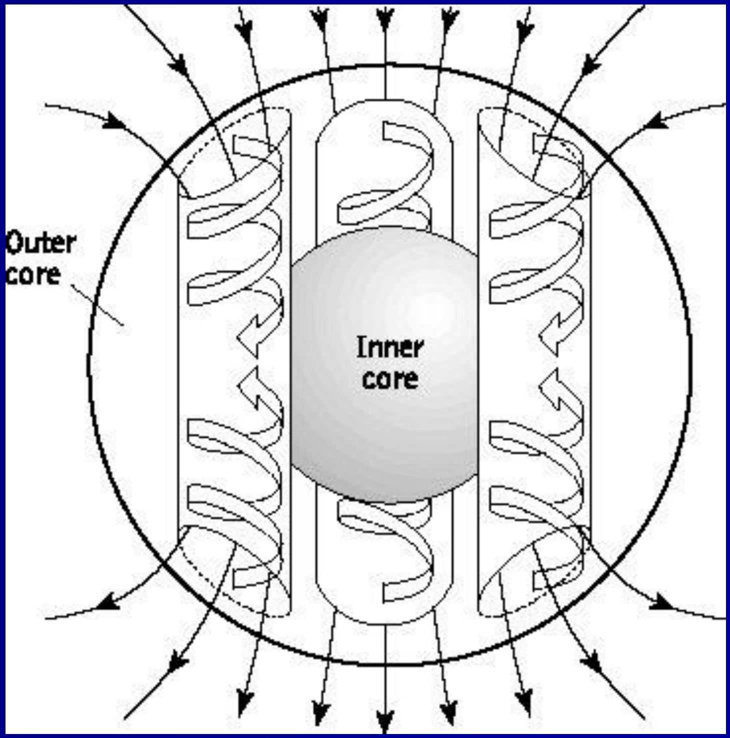
The Earth’s Magnetic Fields
The Dipole Magnetic Field
Motion of charged particles in a Dipole Magnetic Field
The Radiation Belts
The boundary and the tail of the Magnetosphere

The Earth’s Magnetosphere

NASA ScienceCasts : Earth's Magnetosphere

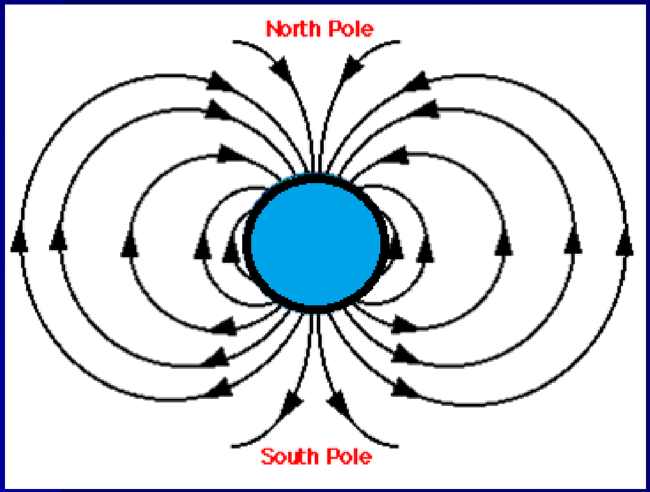
The Earth's Magnetic Field

Present theories believe that the Earth's magnetic field arises (appears) from electric currents flowing in the the molten metallic core of the planet, which has a radius approximately one-half the radius of the Earth

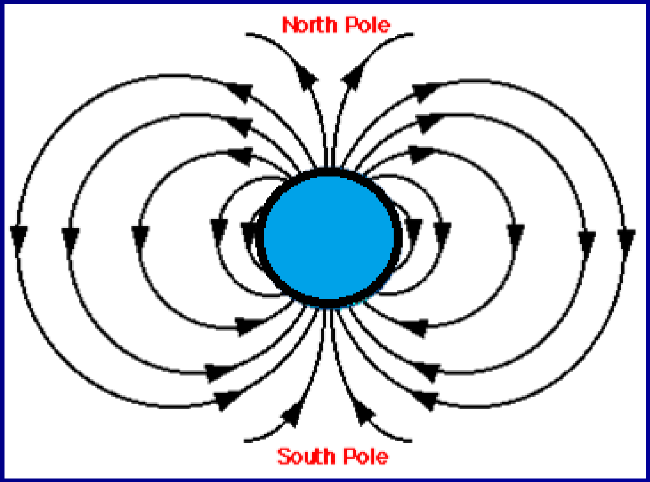


The Earth's Magnetic Field

The currents are attributed to a dynamo mechanism operating inside the core. Recent discoveries suggest that the strength and orientation of the terrestrial magnetic field have changed considerably over geological periods. There is also strong evidence that the Earth's magnetic field has reversed its direction several time during the life time of our planet.

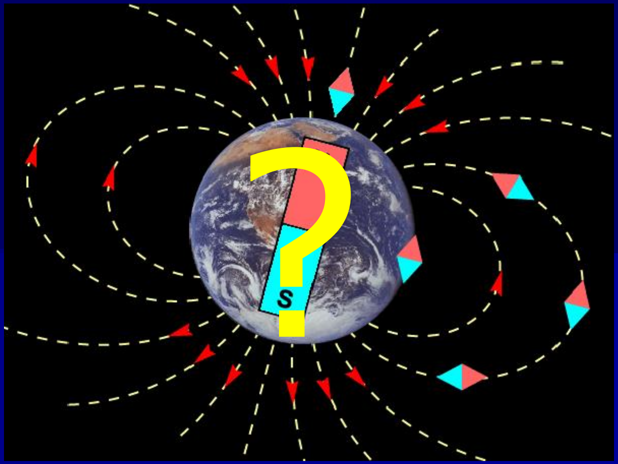


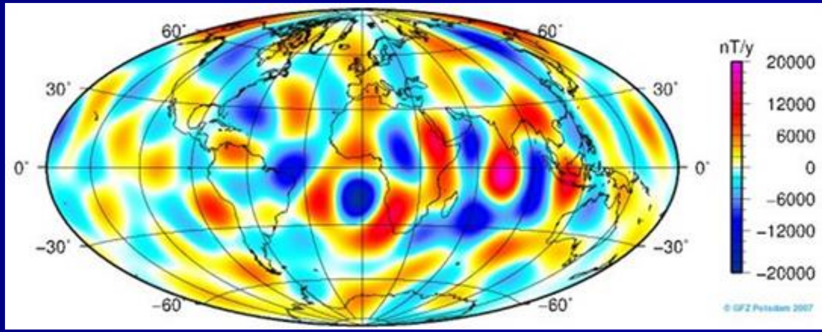
Million of years



The Earth's Magnetic Field

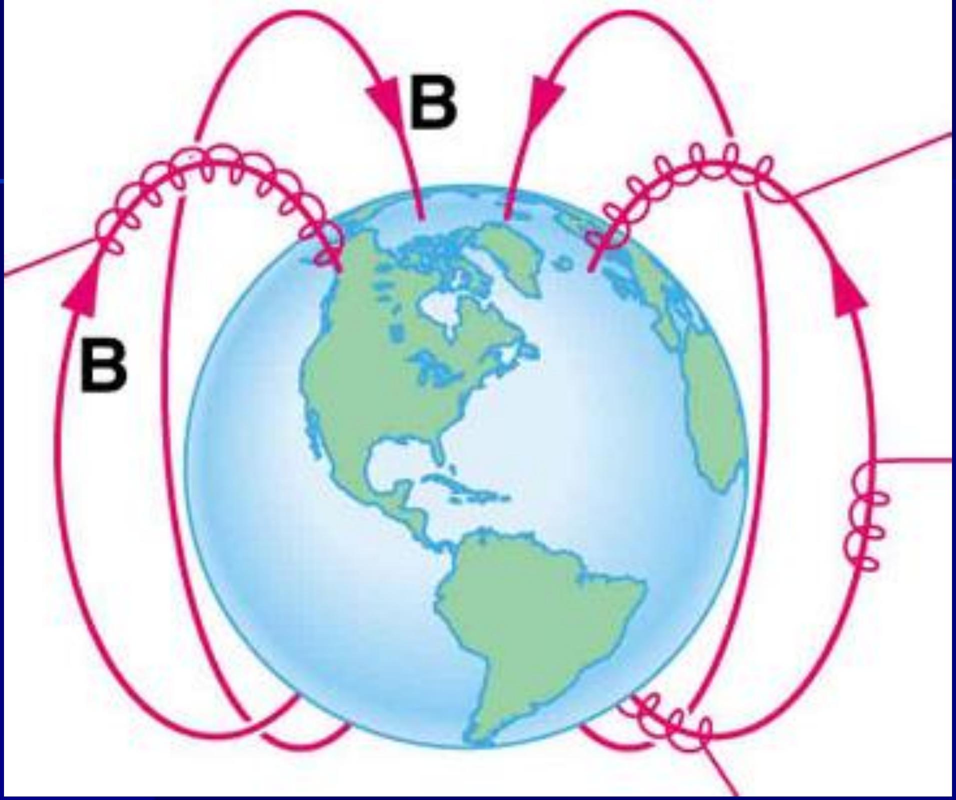
The Earth's magnetic field resembles a di-pole magnetic field. Large scale regional departures from the dipole field are called geomagnetic anomalies and are attributed to irregular or eddies in the dynamo current system.





There are also smaller size anomalies due to local mineral deposits which are called surface magnetic anomalies and are helpful in locating these deposits of ferromagnetic materials.

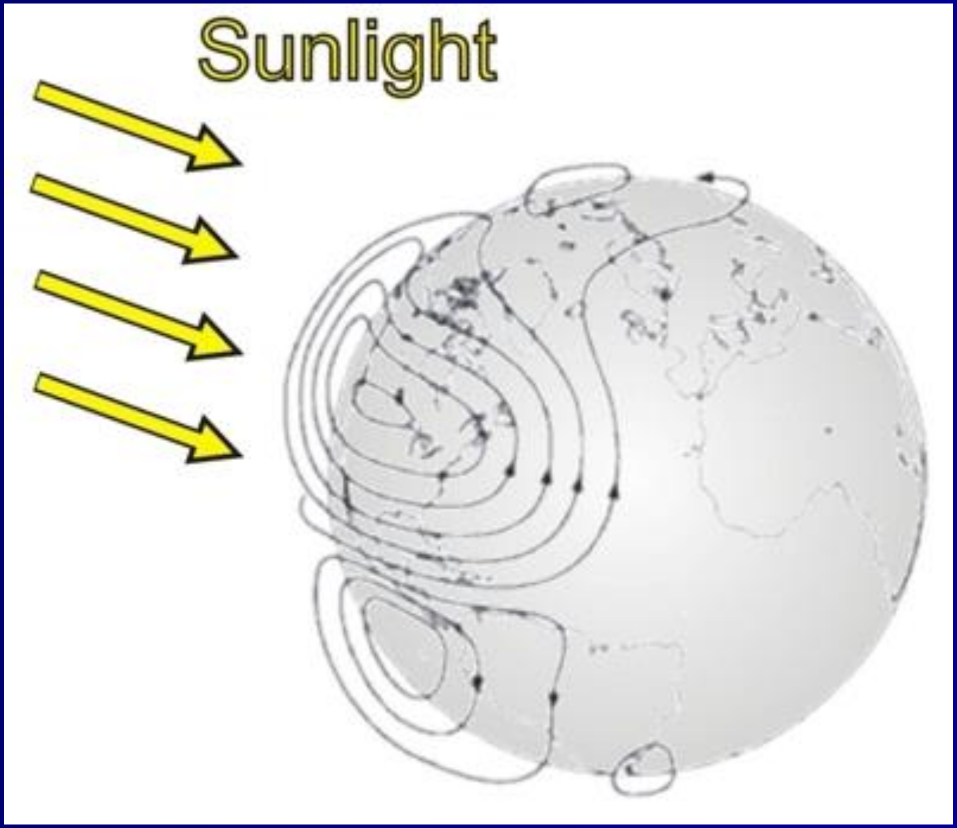
The Earth's Magnetic Field



A very small components (less than 0.1%) of the terrestrial magnetic field is due to currents of charge particles in the outer atmosphere of the Earth.

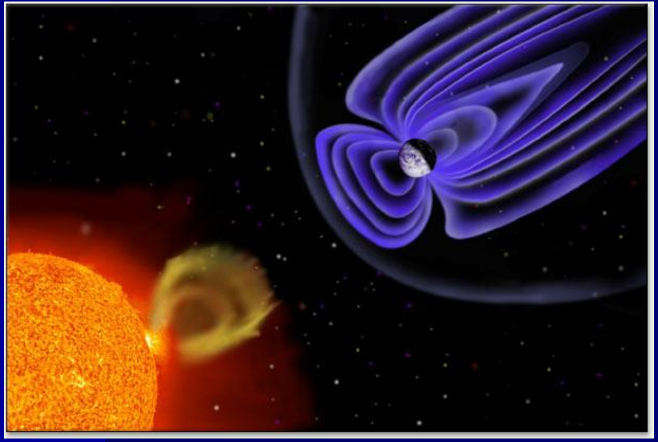
The Earth's Magnetic Field

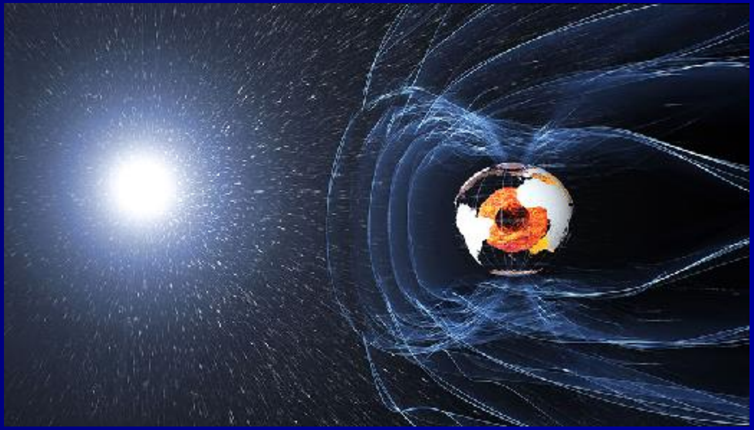
The sq-currents, eg: which circulates between the Sunlit and the dark hemisphere, is responsible for the small, regular diurnal (daytime) variations of the magnetic field observed on the ground.



The Earth's Magnetic Field

After a large solar flare, the enhanced flux of energetic particles from the Sun can produce strong ring currents of the charged particles around the Earth that can produce large fluctuations (occasionally as high as 3%) of the terrestrial magnetic field. These magnetic disturbances, which might last for several days, are described by the different indices of geomagnetic activity.



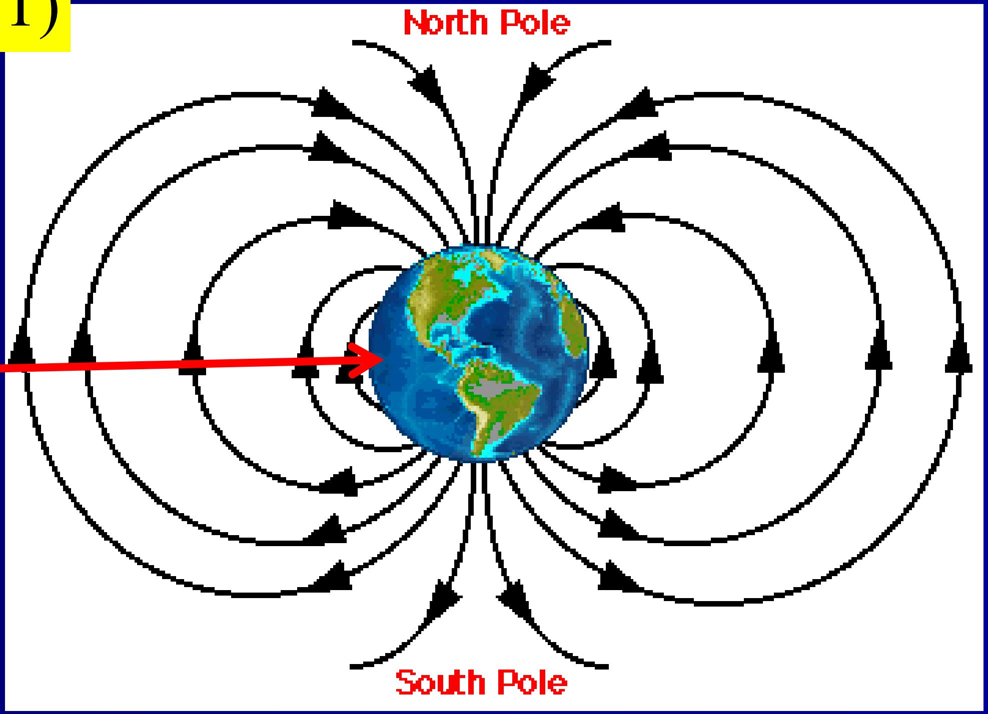


The Earth's Magnetic Field

The magnetic field of the Earth can be represented to a good approximation, by a **dipole-field** with a magnetic moment $M = 8.05 \pm 0.02 \times 10^{25}$ Gauss cm^3. The intensity of the field at the equator is ~0.3 Gauss and at poles ~0.6 Gauss.

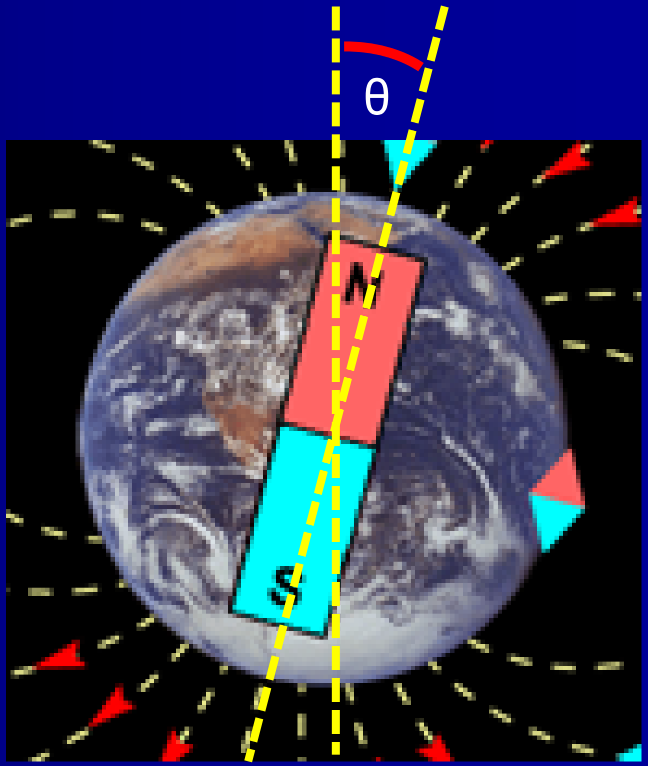
$$1 \text{ Gauss (G)} = \sim 1 \times 10^{-4} \text{ Tesla (T)}$$

The Earth magnetic field intensity at the equator ~40,000 nT.



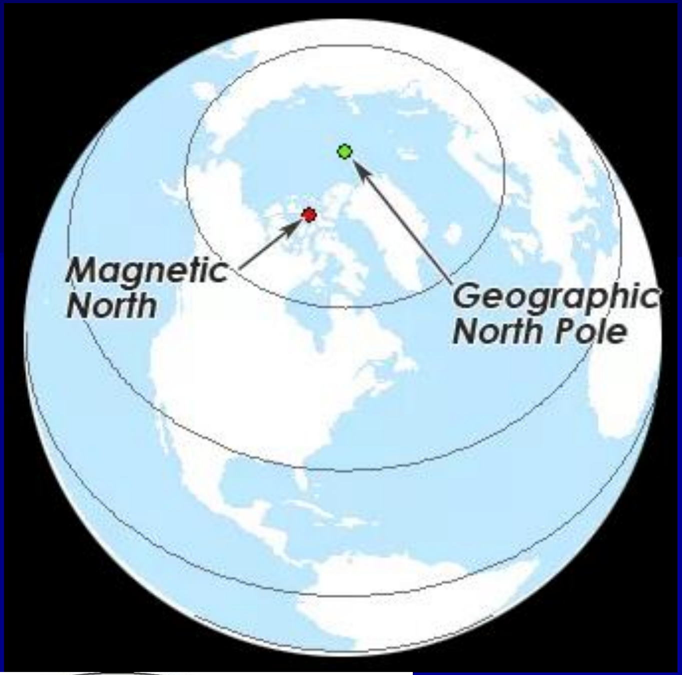
The Earth’s Magnetic Field

The centered dipole (its axis passes through the center of the Earth) which fits best the Earth’s magnetic field has its axis directed along the line (79°N, 290°E) to (79°S, 110°E). These are referred to respectively as the **north geomagnetic pole** and the **south geomagnetic pole**.

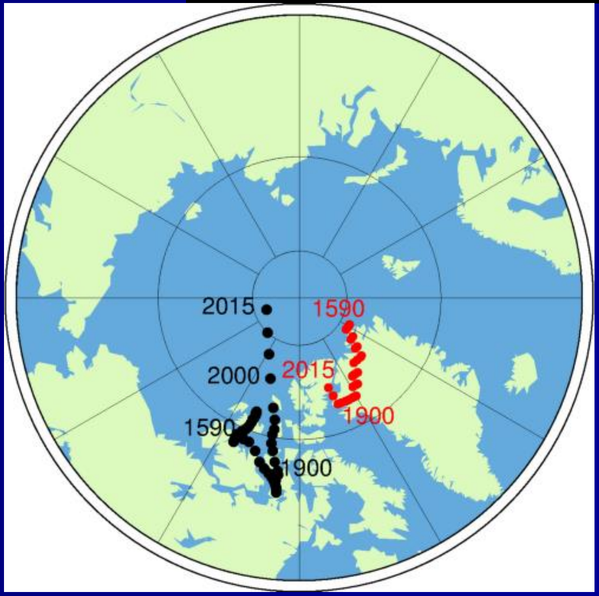


The Earth’s Magnetic Field

The **actual magnetic poles** are asymmetrically (unsymmetrically) located at (73°N, 262°E) to (68°S, 145°E).

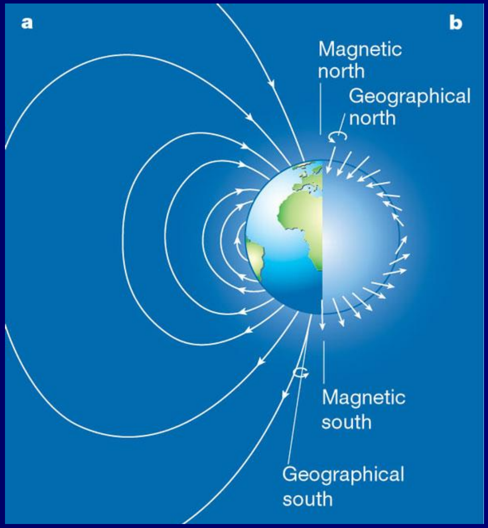


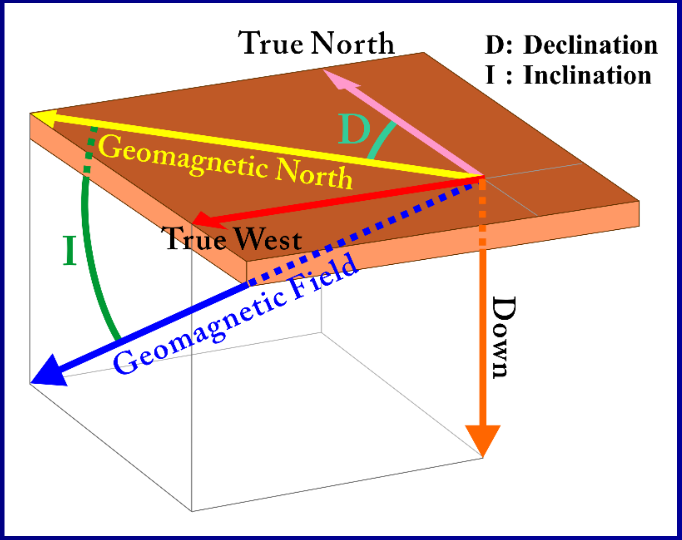
The **Earth magnetic poles** are changing with time !

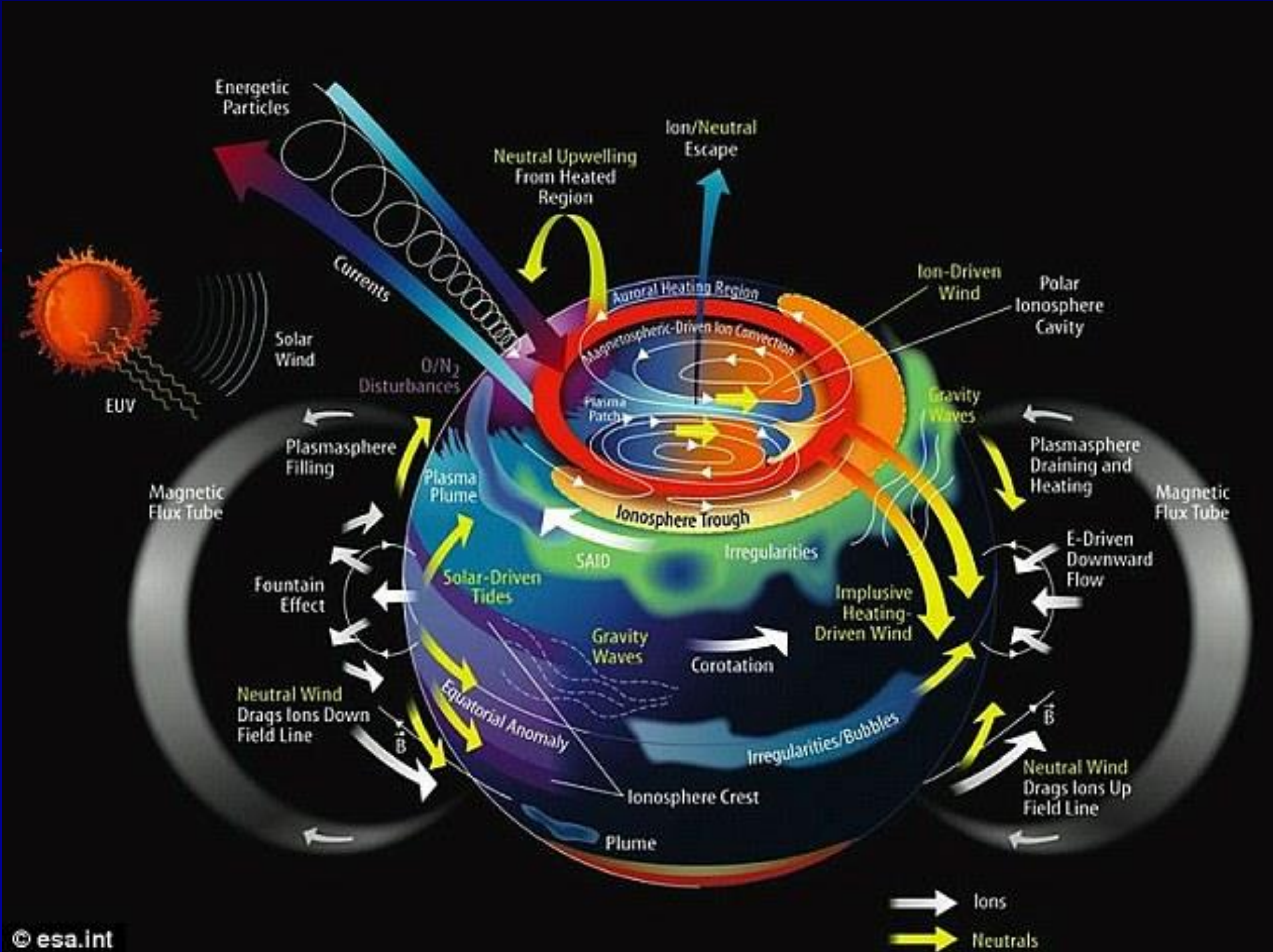


The Earth's Magnetic Field

The coordinates of the dipole field are called the geomagnetic latitude and the geomagnetic longitude. The angle the magnetic field makes with the horizontal is called the **inclination** or **dip** of the magnetic field, and the angle its horizontal component makes with the local geographic meridian (Earth Centre line from North Pole to South Pole) is called the **declination** (drop) of the magnetic field.







Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Currents
Auroral Heating Region
Ion-Driven Wind
Polar Ionosphere Cavity
Solar Wind
EUV
O/N2 Disturbances
Magnetospheric-Driven Ion Convection
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasmasphere Draining and Heating
Magnetic Flux Tube
Plasma Plume
Ionosphere Trough
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
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Ions
Neutrals
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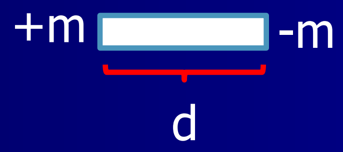
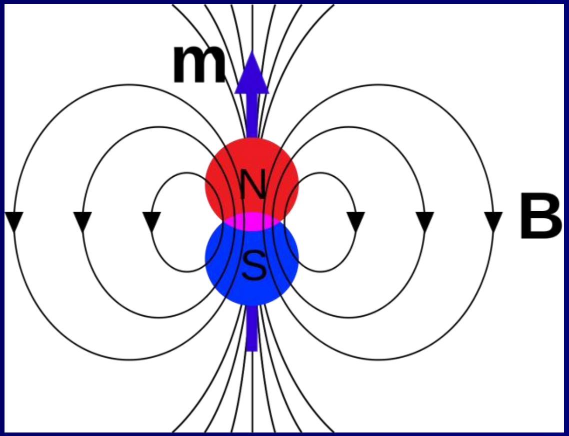
The Dipole Magnetic Field

Magnetic Dipole Moment



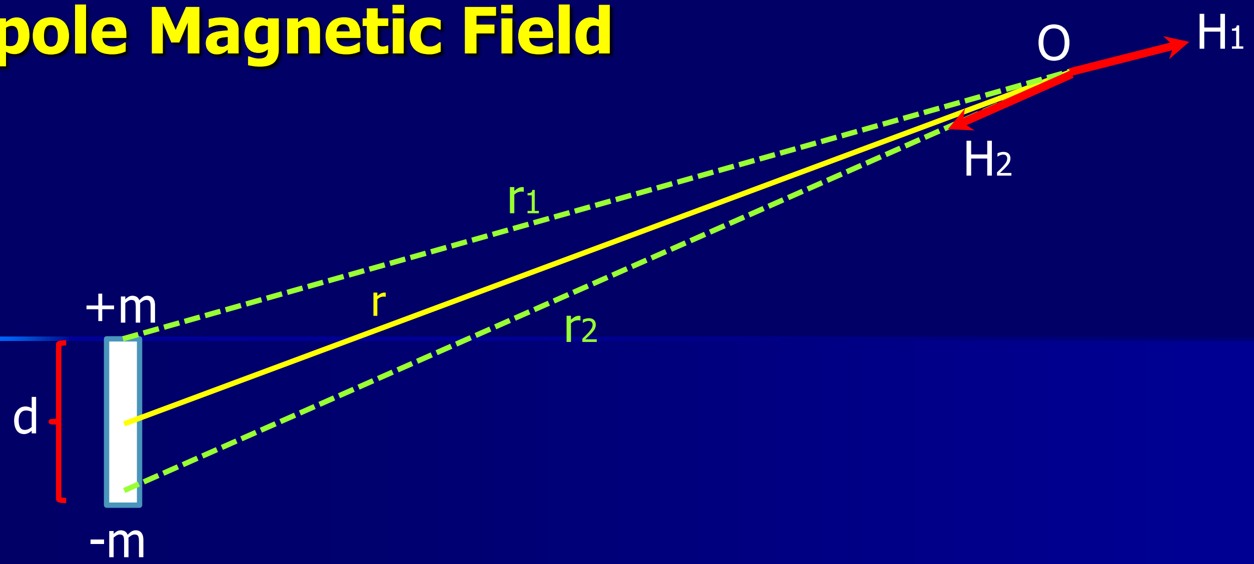
A measure of the magnetic strength of a magnet is set with its axes perpendicular to the magnetic field



Magnetic Dipole Moment, M

$$M = m \times d$$

The Dipole Magnetic Field



Let us consider the magnetic field at a point O, at distance r1 and r2 from the two poles of a magnetic dipole. Let m be the strength of each of the two poles and d the distance that separate them. The product m d is called the Magnetic Dipole Moment (M).

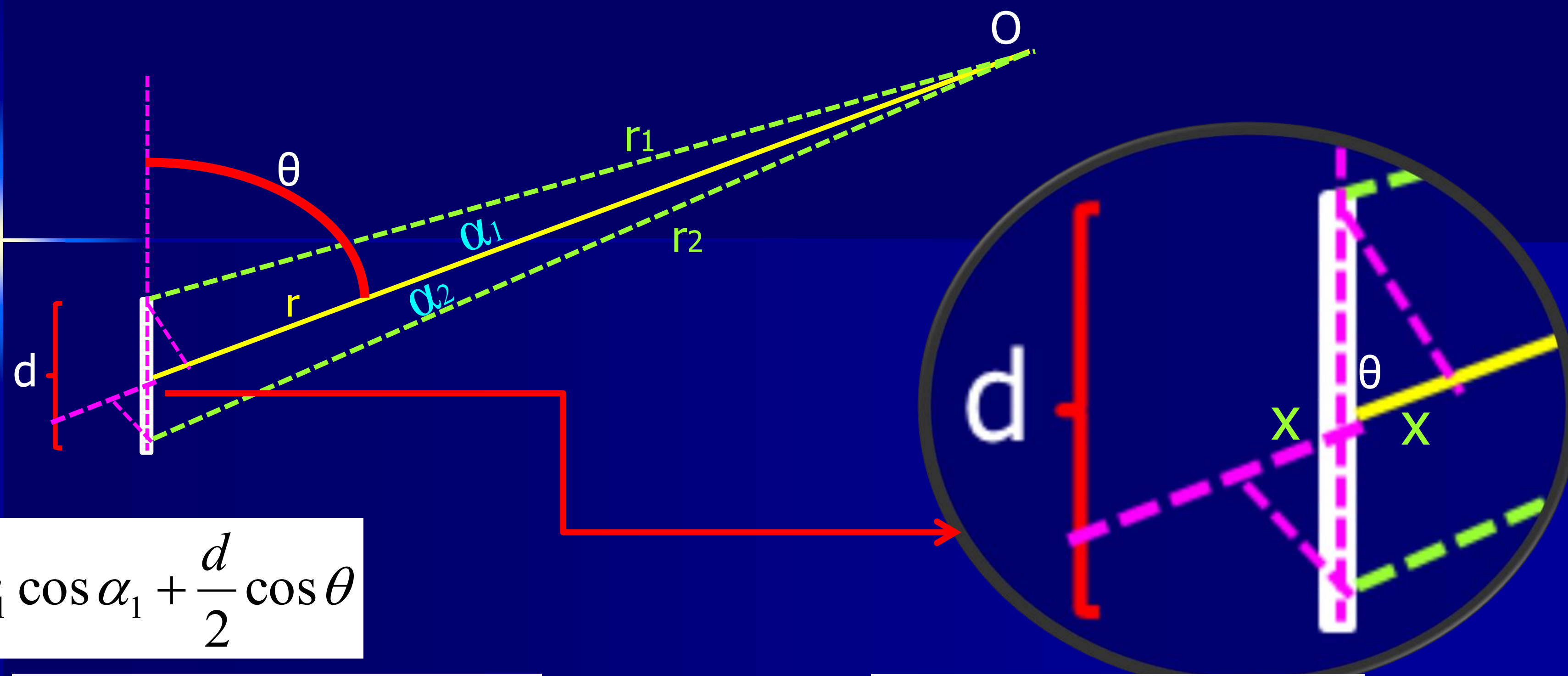
The magnetic field at O will have the two components,

$$H_1 = \frac{\mu_o}{4\pi} \cdot \frac{m}{r_1^2}$$

and

$$H_2 = \frac{\mu_o}{4\pi} \cdot \frac{m}{r_2^2}$$

The Dipole Magnetic Field



$$r = r_1 \cos\alpha_1 + \frac{d}{2}\cos\theta$$

$$\Rightarrow \quad r_1 = \frac{1}{\cos\alpha_1}\left(r - \frac{d}{2}\cos\theta\right)$$

$$\Rightarrow \quad \cos\alpha_1 = \frac{1}{r_1}\left(r - \frac{d}{2}\cos\theta\right)$$

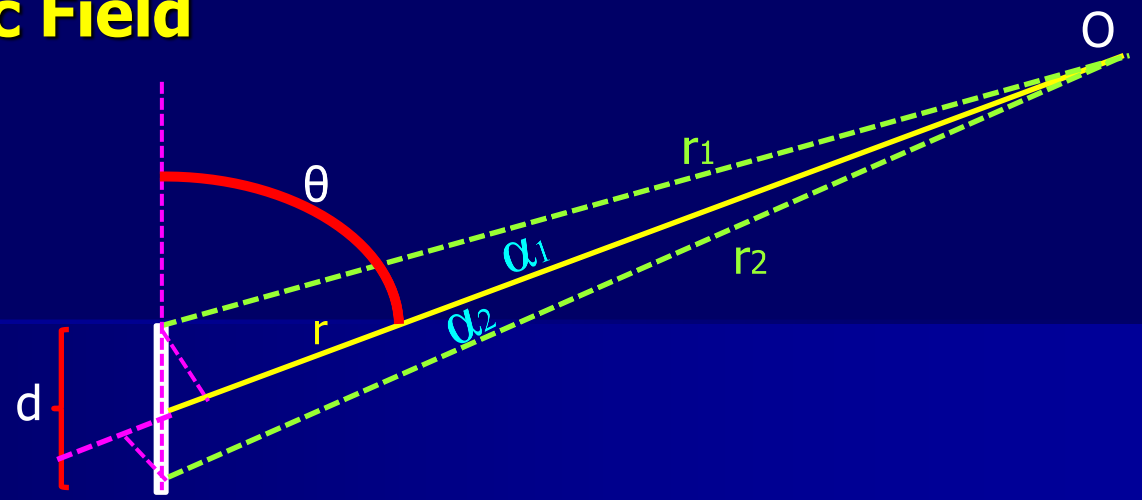
$$r = r_2 \cos\alpha_2 - \frac{d}{2}\cos\theta$$

$$\Rightarrow \quad r_2 = \frac{1}{\cos\alpha_2}\left(r + \frac{d}{2}\cos\theta\right)$$

$$\Rightarrow \quad \cos\alpha_2 = \frac{1}{r_2}\left(r + \frac{d}{2}\cos\theta\right)$$

(As seen from the above diagram, the distance r of the point O from the center of the dipole is given by the above expressions)

The Dipole Magnetic Field



Using the law of Sine for the above diagram :

$$\frac{\sin\alpha_1}{d/2} = \frac{\sin\theta}{r_1} \quad \text{and} \quad \frac{\sin\alpha_2}{d/2} = \frac{\sin\theta}{r_2}$$

$$\Rightarrow \frac{d}{2}\sin\theta = r_1 \sin\alpha_1 \quad \text{and} \quad \frac{d}{2}\sin\theta = r_2 \sin\alpha_2$$

$$\Rightarrow \frac{d}{2}\sin\theta = r_1 \sin\alpha_1 = r_2 \sin\alpha_2$$

$$\Rightarrow \sin\alpha_1 = \frac{d\sin\theta}{2r_1} \quad \text{and} \quad \sin\alpha_2 = \frac{d\sin\theta}{2r_2}$$

The Dipole Magnetic Field

When r1 ≈ r2 » d, the angles α1 and α2 tend to zero and the respective cosines to unity.

i.e.; d « r1, r2 and r1 ≈ r2

sin α1 → 0 and sin α2 → 0

cos α1 → 1 and cos α2 → 1

When, α1 → 0 and α2 → 0

$$r_2^3 - r_1^3 = \left(\frac{1}{\cos\alpha_2}\left(r + \frac{d}{2}\cos\theta\right)\right)^3 - \left(\frac{1}{\cos\alpha_1}\left(r - \frac{d}{2}\cos\theta\right)\right)^3$$

. . . .

$$r_2^3 - r_1^3 = 3\ r^2 d\cos\theta$$

$$r_1^3 + r_2^3 = \left(\frac{1}{\cos\alpha_1}\left(r - \frac{d}{2}\cos\theta\right)\right)^3 + \left(\frac{1}{\cos\alpha_2}\left(r + \frac{d}{2}\cos\theta\right)\right)^3$$

. . . .

$$r_2^3 + r_1^3 = 2\ r^3$$

The Dipole Magnetic Field

When $r_1 \approx r_2 \gg d$, the angles α_1 and α_2 tend to zero and the respective cosines to unity.

i.e.; $d \ll r_1, r_2$ and $r_1 \approx r_2$

$\sin\alpha_1 \rightarrow 0$ and $\sin\alpha_2 \rightarrow 0$

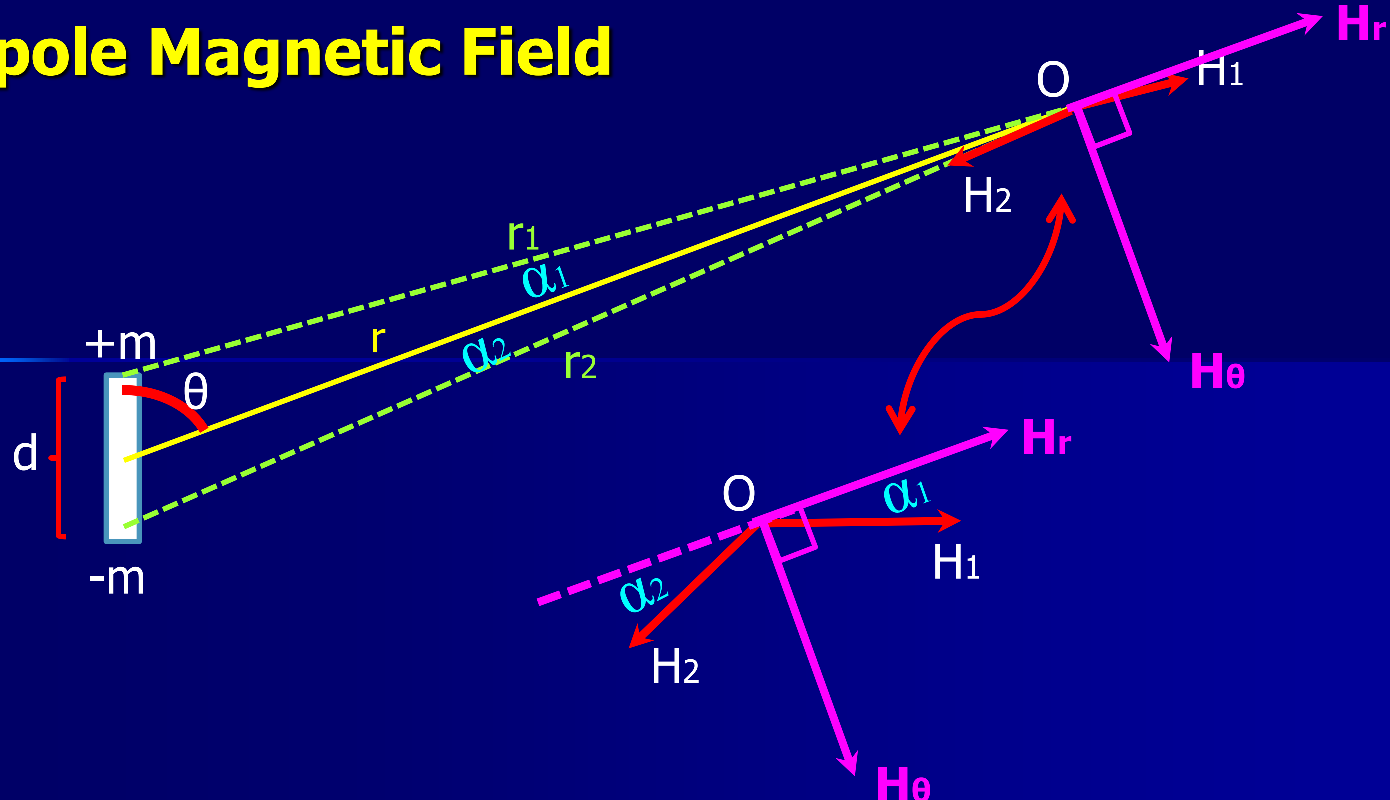
$\cos\alpha_1 \rightarrow 1$ and $\cos\alpha_2 \rightarrow 1$ When, $\alpha_1 \rightarrow 0$ and $\alpha_2 \rightarrow 0$

$$r_1^3 . r_2^3 = \left(\frac{1}{\cos\alpha_1}\left(r - \frac{d}{2}\cos\theta\right)\right)^3 \times \left(\frac{1}{\cos\alpha_2}\left(r + \frac{d}{2}\cos\theta\right)\right)^3$$

• • • •

$$r_1^3 . r_2^3 = r^6$$

The Dipole Magnetic Field



The radial component **Hr** of the magnetic field at a point O a large distance from the dipole is given by :

$$H_r = H_1 \cos\alpha_1 - H_2 \cos\alpha_2$$

And the tangential component **Hθ** of the magnetic field at a point O is given by :

$$H_\theta = H_1 \sin\alpha_1 + H_2 \sin\alpha_2$$

$$H_r = H_1 \cos\alpha_1 - H_2 \cos\alpha_2$$

$$H_r = \left(\frac{\mu_o}{4\pi}\cdot\frac{m}{r_1^2}\right)\left(\frac{1}{r_1}\left(r - \frac{d}{2}\cos\theta\right)\right) - \left(\frac{\mu_o}{4\pi}\cdot\frac{m}{r_2^2}\right)\left(\frac{1}{r_2}\left(r + \frac{d}{2}\cos\theta\right)\right)$$

• • • •

$$H_r = \frac{\mu_o}{4\pi}\cdot\frac{2M}{r^3}\cos\theta$$

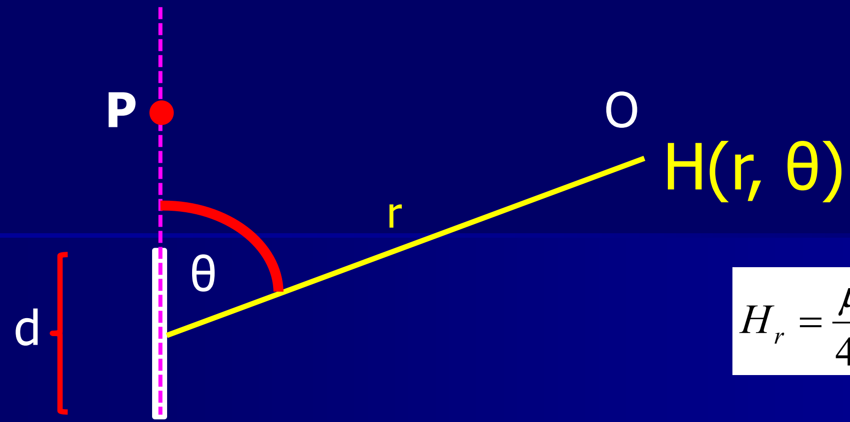
$$H_\theta = H_1 \sin\alpha_1 + H_2 \sin\alpha_2$$

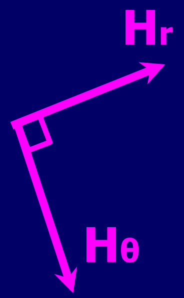
$$H_\theta = \left(\frac{\mu_o}{4\pi}\cdot\frac{m}{r_1^2}\right)\left(\frac{d\sin\theta}{2r_1}\right) + \left(\frac{\mu_o}{4\pi}\cdot\frac{m}{r_2^2}\right)\left(\frac{d\sin\theta}{2r_2}\right)$$

• • • •

$$H_\theta = \frac{\mu_o}{4\pi}\cdot\frac{M}{r^3}\sin\theta$$

The Dipole Magnetic Field





$$H_r = \frac{\mu_o}{4\pi} \cdot \frac{2M}{r^3} \cos\theta$$

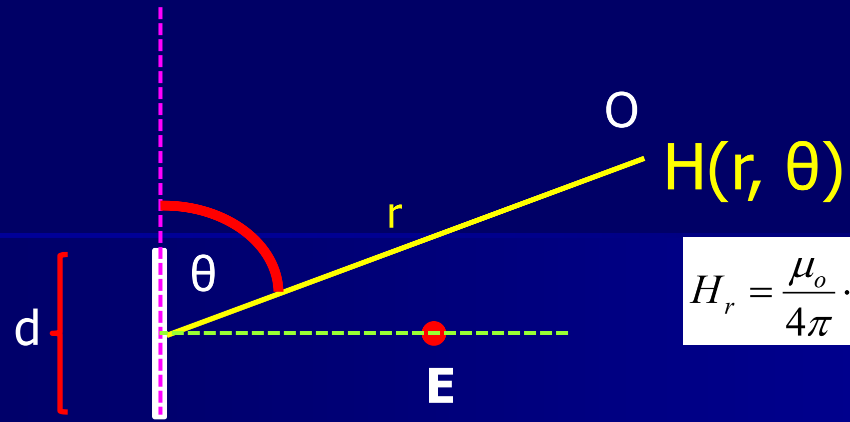
$$H_\theta = \frac{\mu_o}{4\pi} \cdot \frac{M}{r^3} \sin\theta$$

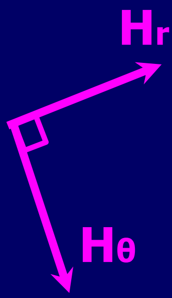
The line connecting the two poles of the dipole defines the axis of the north and south magnetic poles. Therefore, the angle θ represents the **geomagnetic co-latitude**. At the poles, where **θ=0**, the magnetic field **HP** is all in the **radial direction** and is given by the expression,

$$H_P = H_r\big|_{\theta=0}$$ Because, $$H_\theta\big|_{\theta=0} \rightarrow 0$$

$$\therefore \quad H_P = \frac{\mu_o}{4\pi} \cdot \frac{2M}{r^3}$$

The Dipole Magnetic Field





$$H_r = \frac{\mu_o}{4\pi} \cdot \frac{2M}{r^3} \cos\theta$$

$$H_\theta = \frac{\mu_o}{4\pi} \cdot \frac{M}{r^3} \sin\theta$$

While at the equator, where **θ=90°,** the magnetic field **HE** is entirely in the **tangential direction** and is given by the expression,

$$H_E = H_\theta \Big|_{\theta=90^o}$$ Because, $$H_r \Big|_{\theta=90^o} \rightarrow 0$$

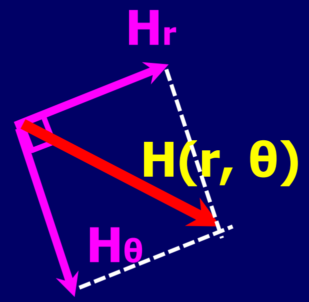
$$\therefore \; H_E = \frac{\mu_o}{4\pi} \cdot \frac{M}{r^3}$$

Thus the magnetic field at the poles has twice the intensity of the magnetic field at the equator !

i.e.; **HP = 2 HE**

The Dipole Magnetic Field

Total Magnetic Field



$$H_r = \frac{\mu_o}{4\pi} \cdot \frac{2M}{r^3} \cos\theta$$

$$H_\theta = \frac{\mu_o}{4\pi} \cdot \frac{M}{r^3} \sin\theta$$

Now we can compute the intensity of the total magnetic field at any **geomagnetic co-latitude, θ** from radial and the tangential components we have already obtained,

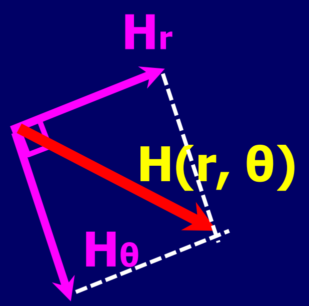
$$H = \left[H_r^2 + H_\theta^2\right]^{1/2}$$

$$H = \left[\left(\frac{\mu_o}{4\pi} \cdot \frac{2M}{r^3} \cos\theta\right)^2 + \left(\frac{\mu_o}{4\pi} \cdot \frac{M}{r^3} \sin\theta\right)^2\right]^{1/2}$$

. . . .

$$H(r,\theta) = \frac{\mu_o}{4\pi} \frac{M}{r^3} \left[1 + 3\cos^2\theta\right]^{1/2}$$

The Dipole Magnetic Field



Total Magnetic Field

$$H(r,\theta) = \frac{\mu_o}{4\pi}\frac{M}{r^3}\left[1+3\cos^2\theta\right]^{1/2}$$

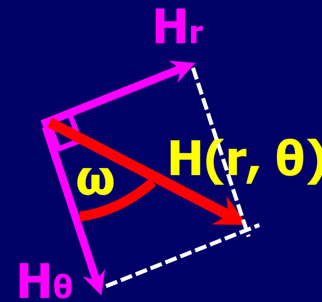
The above equation shows that the intensity of the dipole magnetic field decreases with distance as the third power (r^3) of the radial distance and for the same r varies, as we have seen already, by a factor of 2 from the poles to the equator. Using the above derived equations, we can express the total magnetic field at any given value of θ in terms of the equatorial magnetic field at the same radial distance.

$$H(r,\theta) = H_E\left[1+3\cos^2\theta\right]^{1/2}$$

Where, $H_E = \dfrac{\mu_o}{4\pi}\dfrac{M}{r^3}$

The Dipole Magnetic Field

Total Magnetic Field



$$H_r = \frac{\mu_o}{4\pi} \cdot \frac{2M}{r^3} \cos\theta$$

$$H_\theta = \frac{\mu_o}{4\pi} \cdot \frac{M}{r^3} \sin\theta$$

From the radial (vertical) and the tangential (horizontal) components of the magnetic field, we can also find the **inclination angle**, **ω** (dip) of the field.

$$\tan\omega = \frac{H_r}{H_\theta}$$

$$\tan\omega = \frac{\frac{\mu_o}{4\pi} \cdot \frac{2M}{r^3} \cos\theta}{\frac{\mu_o}{4\pi} \cdot \frac{M}{r^3} \sin\theta}$$

$$\tan\omega = \frac{2\cos\theta}{\sin\theta}$$

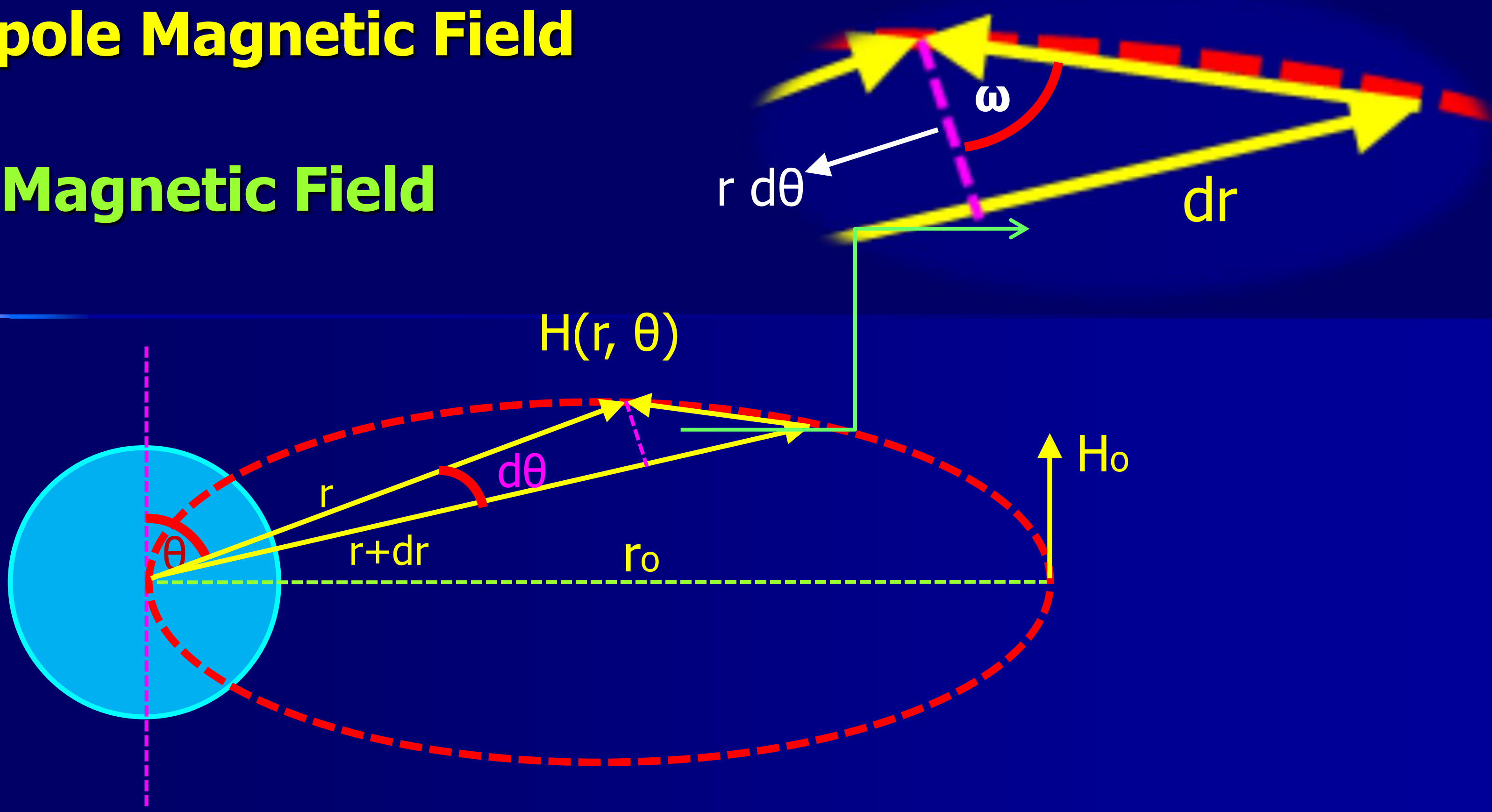
$$\tan\omega = 2\cot\theta$$

$$\omega = \omega(\theta) \neq \omega(r)$$

The above equation shows that the dip of the magnetic field is independent of the **radial distance** and therefore, the **magnetic field at any altitude above a given station will always be parallel to the magnetic field on the ground**.

The Dipole Magnetic Field

Total Magnetic Field



An imaginary line to which the **magnetic field is always tangential** is called a **line of force** or a **field line**. For such a line as seen from the above figure we have,

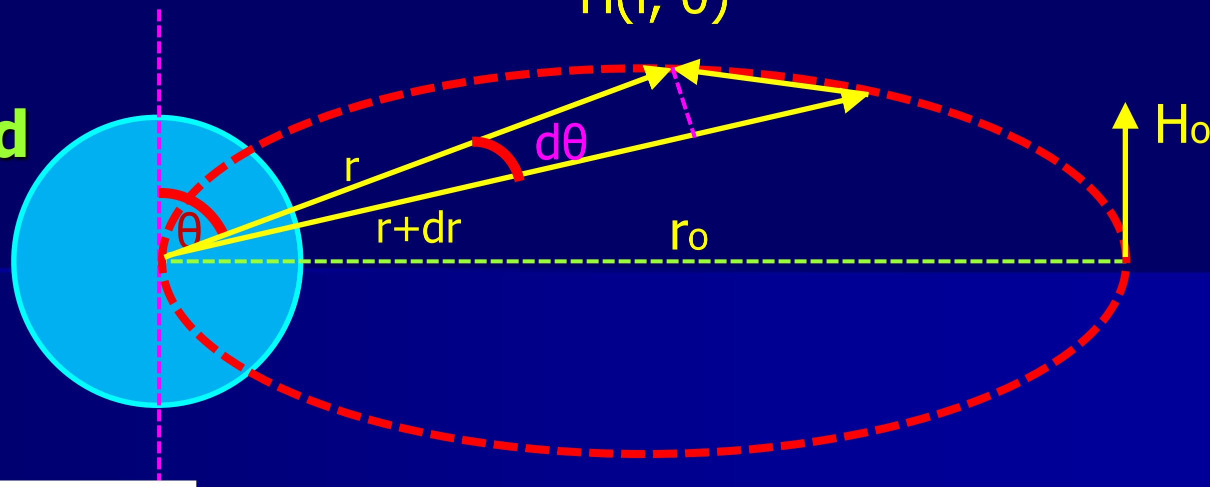
$$\tan\omega = \frac{dr}{rd\theta}$$

$$\therefore dr = rd\theta \tan\omega$$

$$\therefore dr = rd\theta .2\cot\theta$$

The Dipole Magnetic Field

Total Magnetic Field



$$\therefore dr = r d\theta .2\cot\theta$$

$$\int \frac{dr}{r} = 2\int \frac{\cos\theta}{\sin\theta} d\theta + c_1$$

$$\ln(r) = 2\ln(\sin\theta) + \ln(c)$$

$$\ln(r) = \ln(\sin^2\theta) + \ln(c)$$

$$\ln(r) = \ln(c.\sin^2\theta)$$

$$r = c.\sin^2\theta$$

Boundary Conditions :

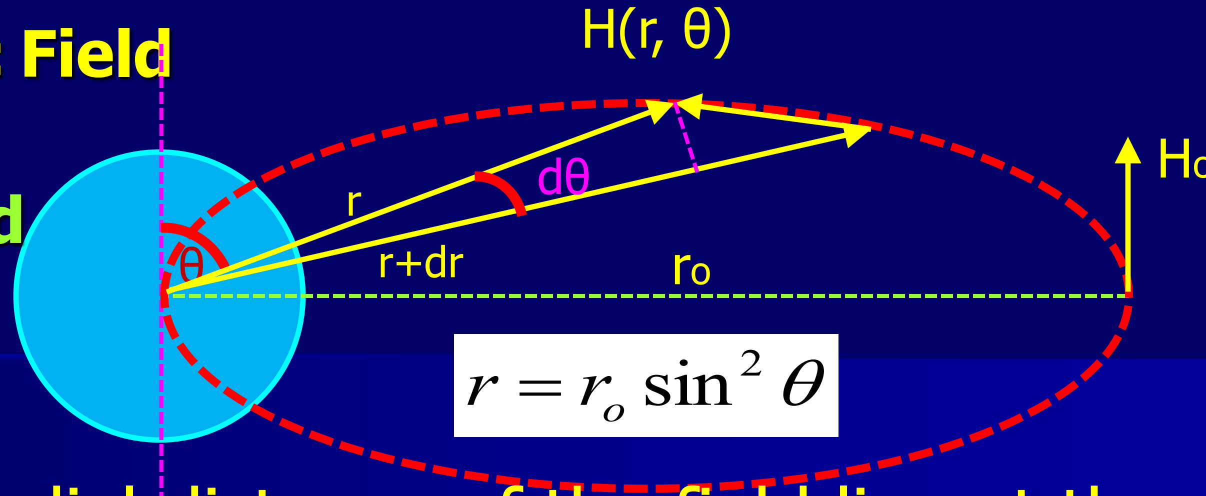
If θ=π/2 and r=ro

then c=ro

$$r = r_o \sin^2\theta$$

The Dipole Magnetic Field

Total Magnetic Field



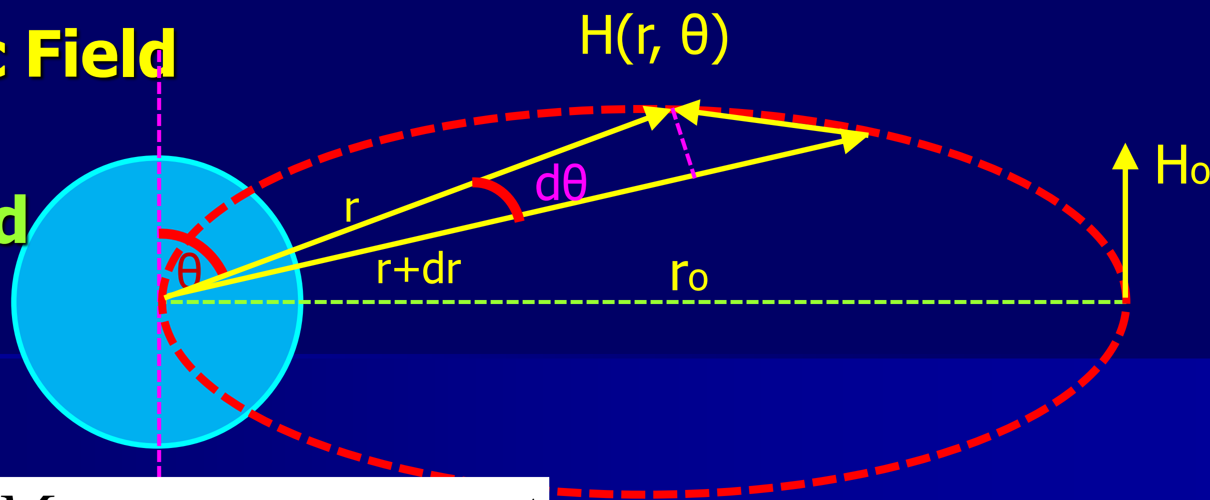
$$r = r_o \sin^2\theta$$

Where **ro** is the radial distance of the field line at the equator. The above equation is a very important relation because it gives the geometry of the field lines of the dipole field. The magnetic field at the equatorial crossing of a given field line is usually denoted by **Ho** and it is very important parameter because by knowing Ho we can determine the magnetic field at any point along this field line.

Using
$$H(r,\theta) = \frac{\mu_o}{4\pi}\frac{M}{r^3}\left[1+3\cos^2\theta\right]^{1/2}$$
and
$$r = r_o \sin^2\theta$$
$$r^3 = r_o^{\,3}\sin^6\theta$$

The Dipole Magnetic Field

Total Magnetic Field



$$H(r,\theta)=\frac{\mu_o}{4\pi}\frac{M}{(r_o{}^3\sin^6\theta)}\left[1+3\cos^2\theta\right]^{1/2}$$

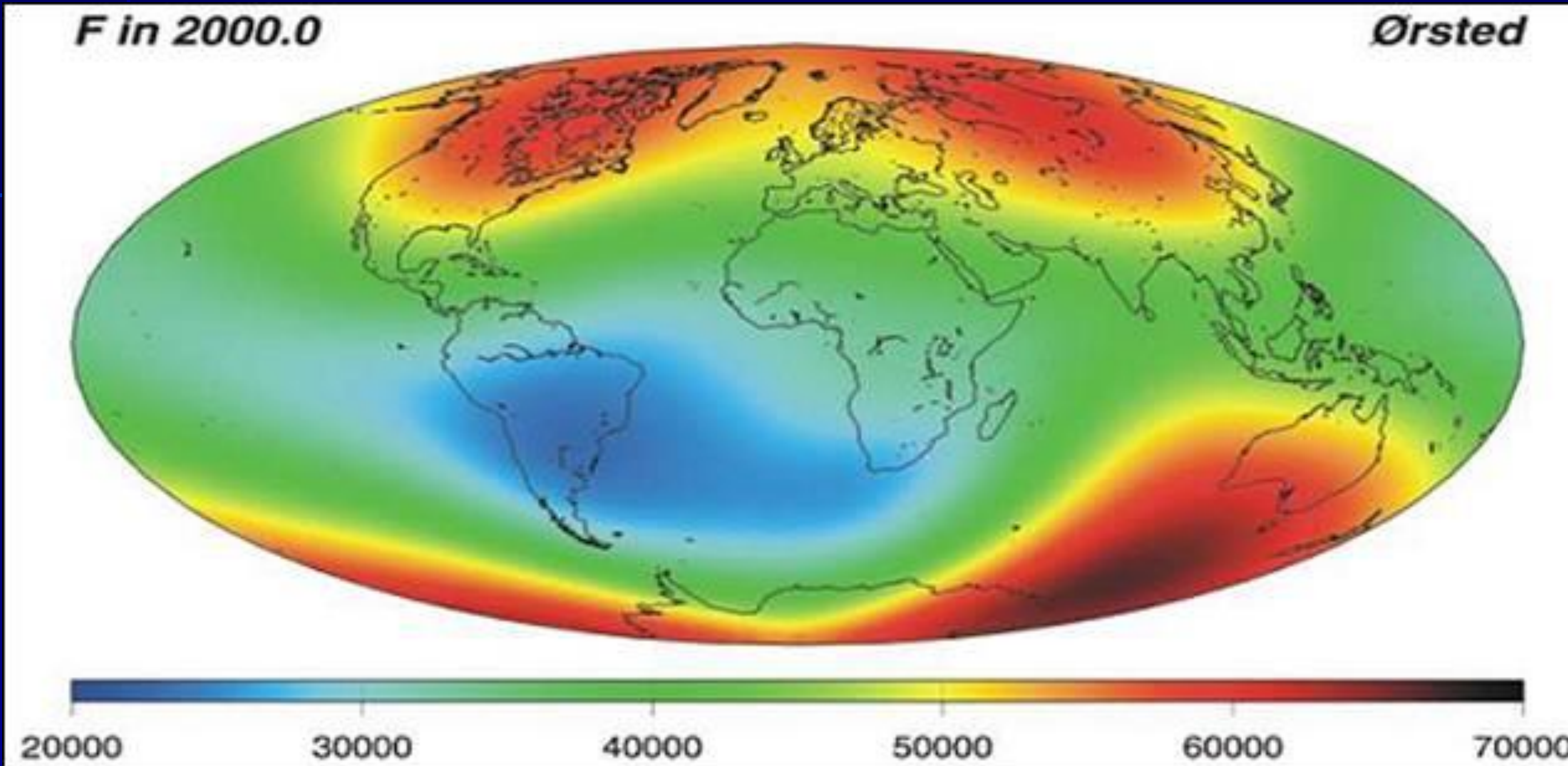
$$H(r,\theta)=\frac{\mu_o}{4\pi}\frac{M}{r_o{}^3}\frac{\left[1+3\cos^2\theta\right]^{1/2}}{\sin^6\theta}$$

$$H(r,\theta)=H_o\frac{\left[1+3\cos^2\theta\right]^{1/2}}{\sin^6\theta}$$

Where, $H_o=\frac{\mu_o}{4\pi}\frac{M}{r_o{}^3}$

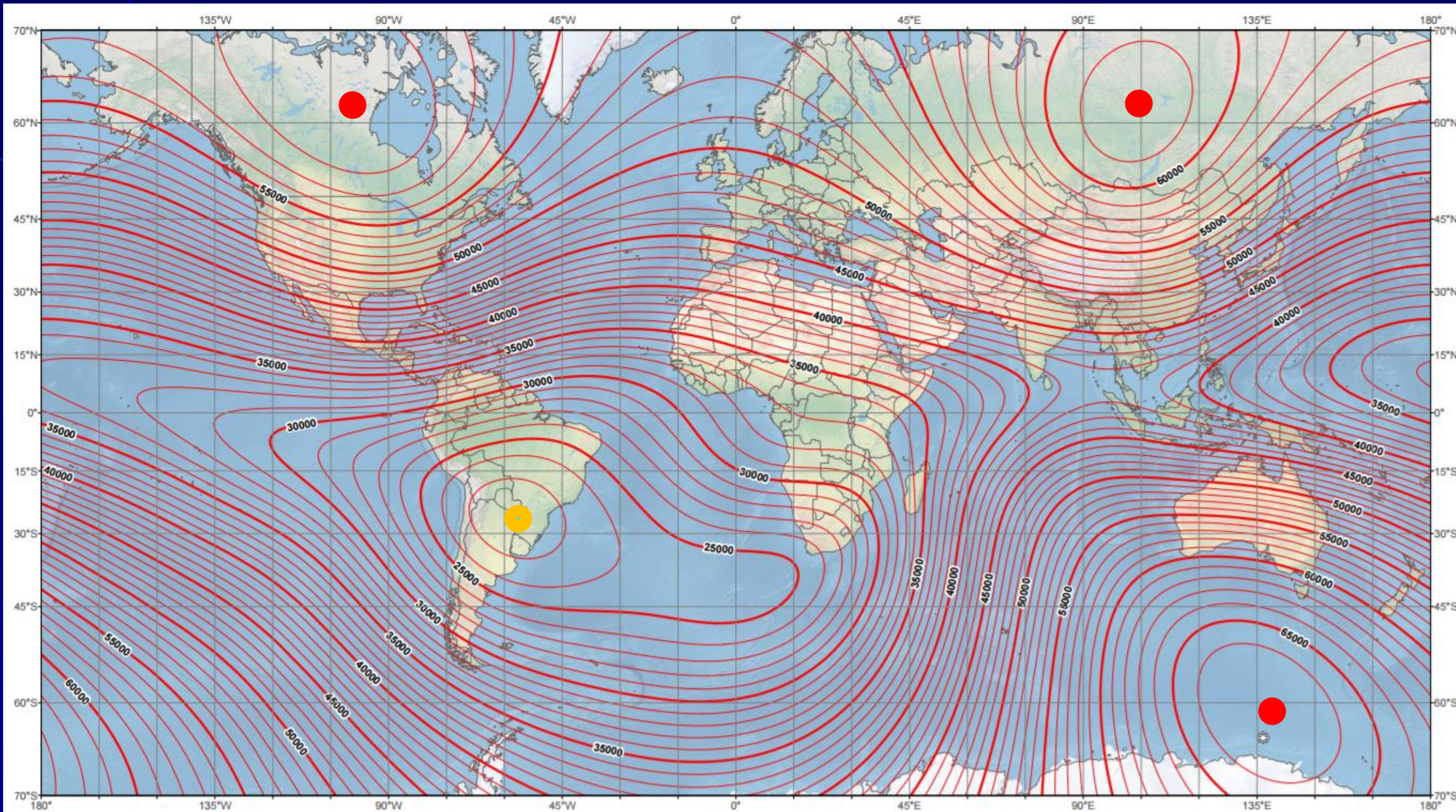
The above equation is probably the most useful expression in the **Mathematical description of the dipole magnetic field** !

The Earth Magnetic Field



The Earth's magnetic field ranges between approximately
~25,000 nT and ~65,000 nT (0.25–0.65 G).

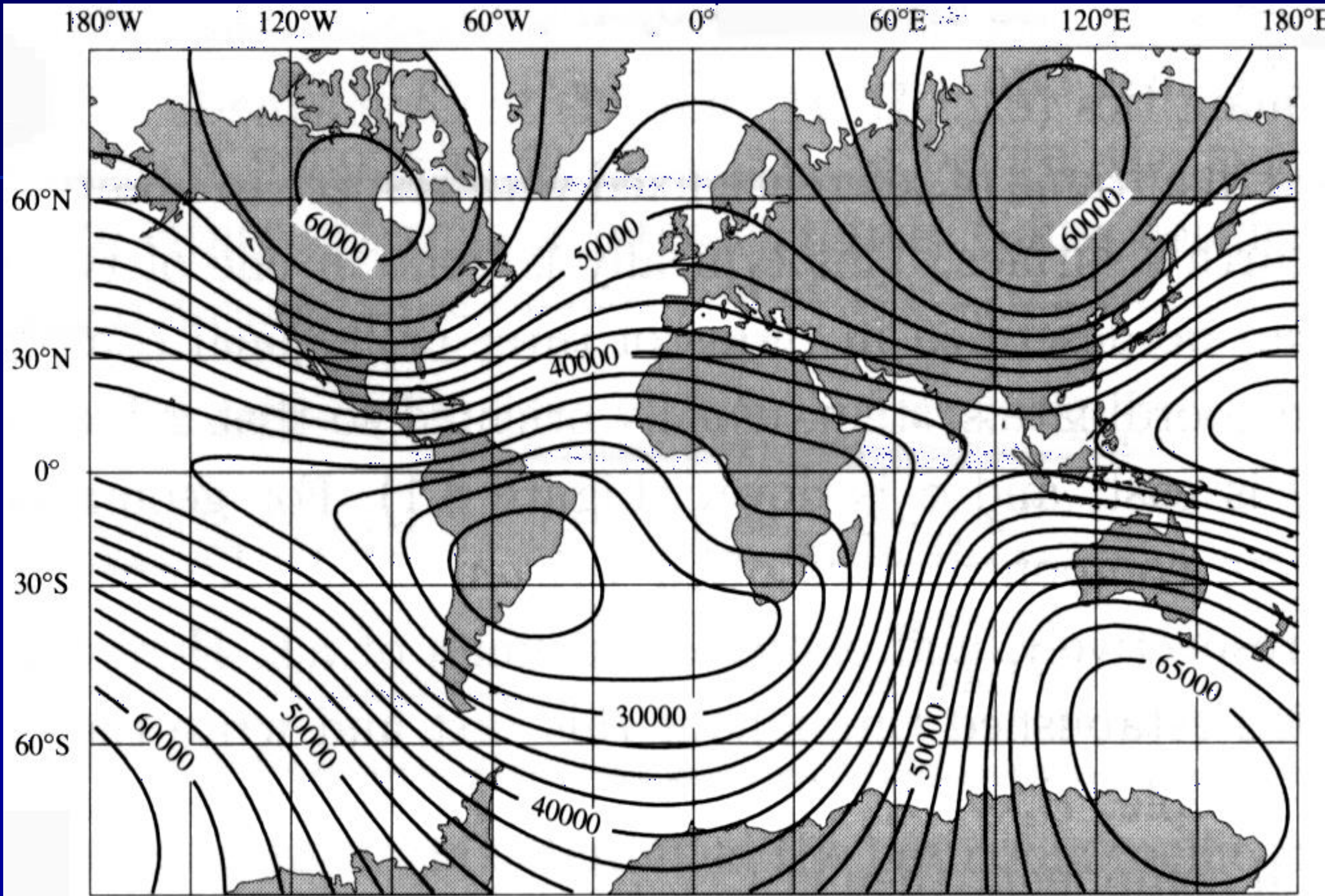
The Earth Magnetic Field



Min -

Max -

Earth magnetic Field

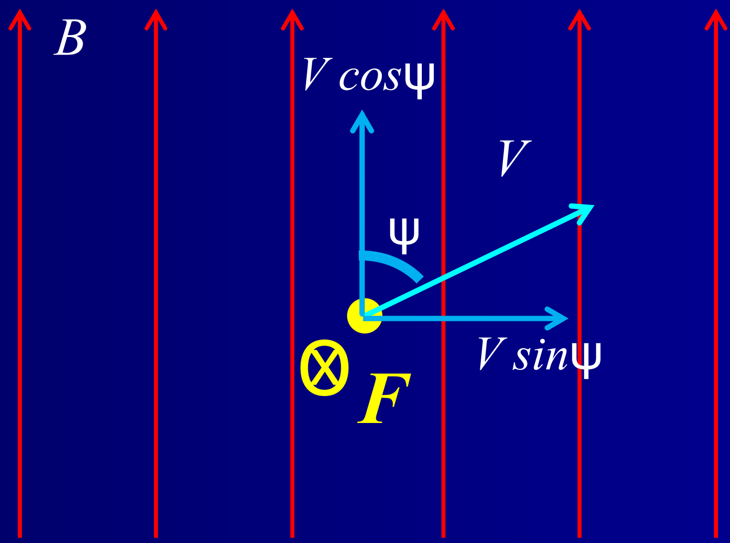


The Magnetosphere

The Earth's Magnetic Fields
The Dipole Magnetic Field
Motion of charged particles in a Dipole Magnetic Field
The Radiation Belts
The boundary and the tail of the Magnetosphere

Motion of Charged Particle in a Dipole Magnetic field

A charged particle moving with velocity *V* at an angle *ψ*, called **patch angle**, to a magnetic field will experience the **Lorentz Force** *F*.



Motion of Charged Particle in a Dipole Magnetic field

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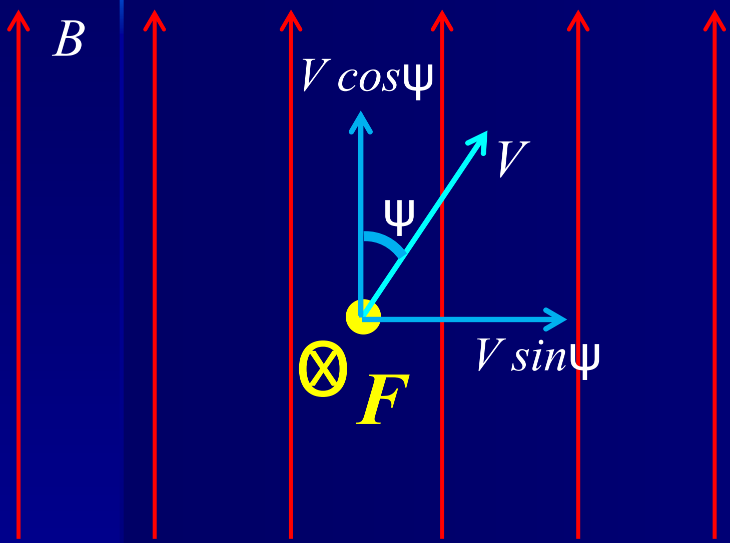


Magnetic Force, F

$$F = q\, V \times B$$

$$\Rightarrow F = q\, V \times \frac{H}{c}$$

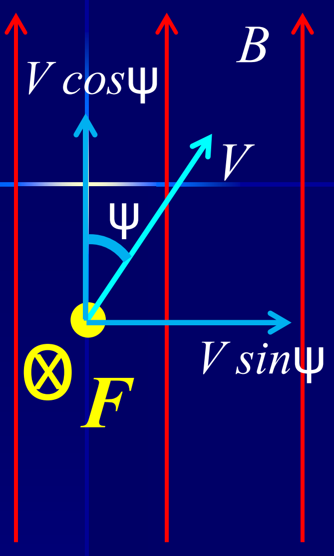
$$\Rightarrow F = e\, (V \sin\psi) \frac{H}{c} \quad \otimes$$

Using Fleming's Left hand Law

$$\Rightarrow F = \frac{e}{c} V H \sin\psi$$

Which will set the particle in a **helical** (spiral) **motion** around a line of force of the magnetic field.

Motion of Charged Particle in a Dipole Magnetic field

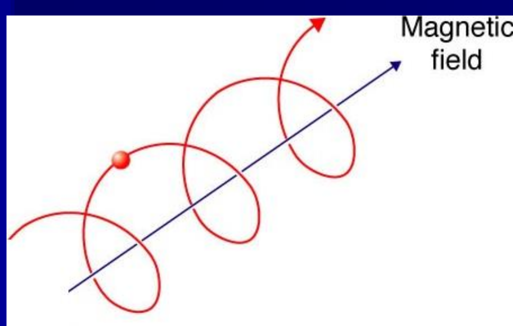


The Lorentz Force is balanced by the centrifugal force produced by the component *Vn = V sinψ* of the particle's velocity which is normal to the magnetic field, i.e.;

$$\frac{e}{c} VH \sin\psi = \frac{m v_n^2}{r} \Rightarrow \frac{e}{c} VH \sin\psi = \frac{m(V \sin\psi)^2}{R_H}$$

Gyro-radius

Where *RH* is the **radius of gyration** around the field line which is called the **Gyro-Radius** of the **Cyclotron Path**. . . . .

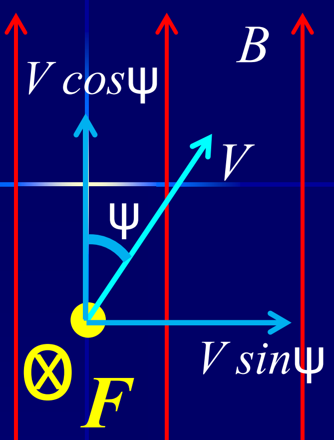


$$\Rightarrow R_H = \frac{mcV \sin\psi}{eH}$$

or

$$R_H = \frac{m\ c\ v_n}{eH}$$

Motion of Charged Particle in a Dipole Magnetic field



$$R_H = \frac{mcV\sin\psi}{eH}$$ or $$R_H = \frac{m\,c\,v_n}{eH}$$

The above equation defined also the angular cyclotron frequency, **ωH** which is given by the relation,

$$\omega_H = \frac{v_n}{R_H}$$

because,

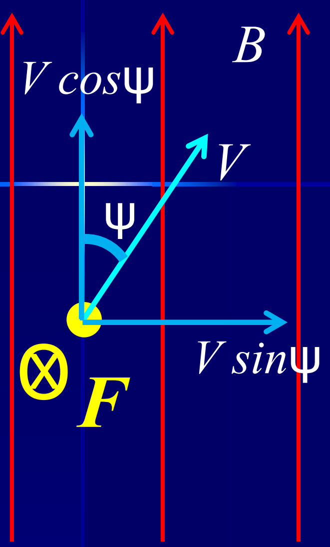
$$V = r\;\omega$$

$$\Rightarrow \omega_H = \frac{e\,H}{m\,c}$$ because, $$\frac{v_n}{R_H} = \frac{e\,H}{m\,c}$$

From which we obtain also the expression for the **Gyro-Radius** or **cyclotron frequency**, ***fH***,

$$f_H = \frac{\omega_H}{2\pi} \Rightarrow f_H = \frac{e\,H}{2\pi\;m\,c} \Rightarrow f_H = \frac{e}{2\pi\;m\,c}H$$

Motion of Charged Particle in a Dipole Magnetic field



Gyro-frequency

$$f_H = \frac{e}{2\pi\, m\, c} H$$

or

$$f_H \ \alpha \ H$$

The value of

$$\frac{e}{2\pi\, m\, c} = \frac{1.6\times 10^{-19}\, C}{2\pi\ 9.1\times 10^{-31}\, kg\ \ 3\times 10^{8}\, ms^{-1}}$$

$$= 93.28$$

$\therefore$

$$f_H = 93.28 \ H$$

or

$$f_H = 93.28 \ Bc$$

or

$$f_H = 2.8\times 10^{10}\, B$$

An example : When the strength of the Earth Magnetic Field is 60,000 nT at a certain point, then find the **electron gyro-frequency** at that point.

$$f_H = 2.8\times 10^{10}\, B$$

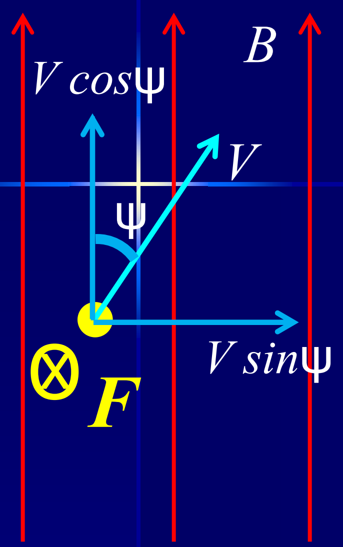
$$f_H = (2.8\times 10^{10})\times (60000\times 10^{-9})$$

$$f_H = 1.68\times 10^{6}\, Hz$$

or

$$f_H = 1.68 MHz$$

Motion of Charged Particle in a Dipole Magnetic field



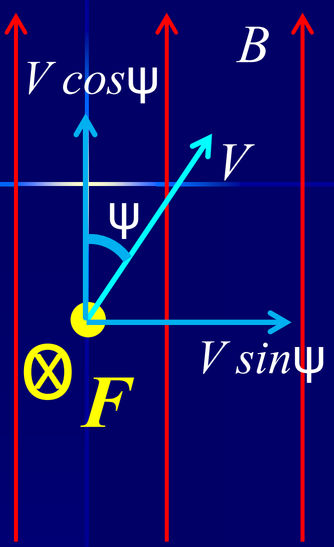
$$f_H = 2.8\times10^{10} B$$

In the numerical form of the above equation, **fH** is in MHz and H in Gauss (B in 40000 nT). For relativistic velocities the mass **m** in all the above formulae is related to the rest mass **mo** of the particle by the well known expression of the Special Theory of Relativity;

$$m = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}}$$

We should consider the above equation for substitute the value of mass because the velocities of charge particles in order of c.

Motion of Charged Particle in a Dipole Magnetic field



Gyro-frequency

$$f_H = \frac{e}{2\pi\, m\, c} H \quad \Rightarrow \quad f_H = \frac{e}{2\pi\, m\, c} Bc$$

$$\Rightarrow \quad f_{H e^n} = \frac{e}{2\pi\, m} B$$

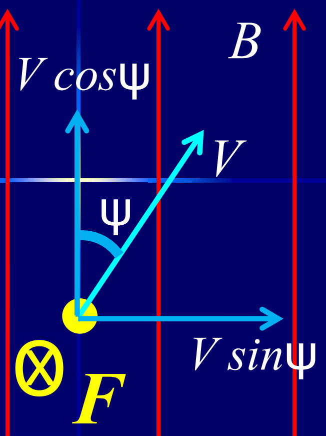
The **ion gyro-frequency** is determined by;

$$f_{H\,ion} = \frac{e}{2\pi\, M} B$$

$$\therefore \frac{f_{H\,ion}}{f_{H e^n}} = \frac{\frac{e}{2\pi\, M} B}{\frac{e}{2\pi\, m} B} \quad \Rightarrow \quad \frac{f_{H\,ion}}{f_{H e^n}} = \frac{m}{M} \quad \Rightarrow \quad f_{H\,ion} = \frac{m}{M} f_{H e^n}$$

When **m** is the mass of the electron and **M** is the mass of the ion.

Motion of Charged Particle in a Dipole Magnetic field



$$f_{H\,ion} = \frac{m}{M} f_{H\,e^n}$$

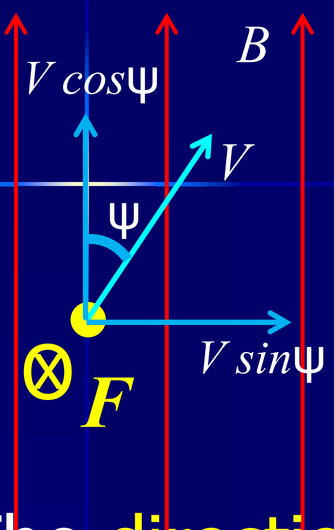
A close study of the above equation tells us that the much higher mass of the ions result in a much lower ion gyro-frequency compared to the electron gyro-frequency.

An example : For e^ns : $f_H = 1.68\,MHz$

For O+ ion : $f_H = 48\,Hz$

Because, $M >> m$

Motion of Charged Particle in a Dipole Magnetic field



$$f_{H\,ion} = \frac{m}{M} f_{H\,e^n}$$

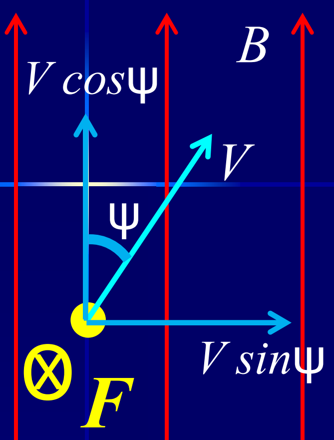
An example : For e^ns : $f_H = 1.68 MHz$

For O+ ion : $f_H = 48 Hz$

Because, $M >> m$

The direction of gyro-frequency is different for electrons and positive ions. This direction can be determine by using the **Simple Thumb Rule** : The direction of the rotation of electrons and negative ions is determined by the fingers of the right hand when the thumb point in the direction of the magnetic Field. The direction of the positive ions are opposite direction.

Motion of Charged Particle in a Dipole Magnetic field



$$f_{H\,ion} = \frac{m}{M} f_{H\,e^n}$$

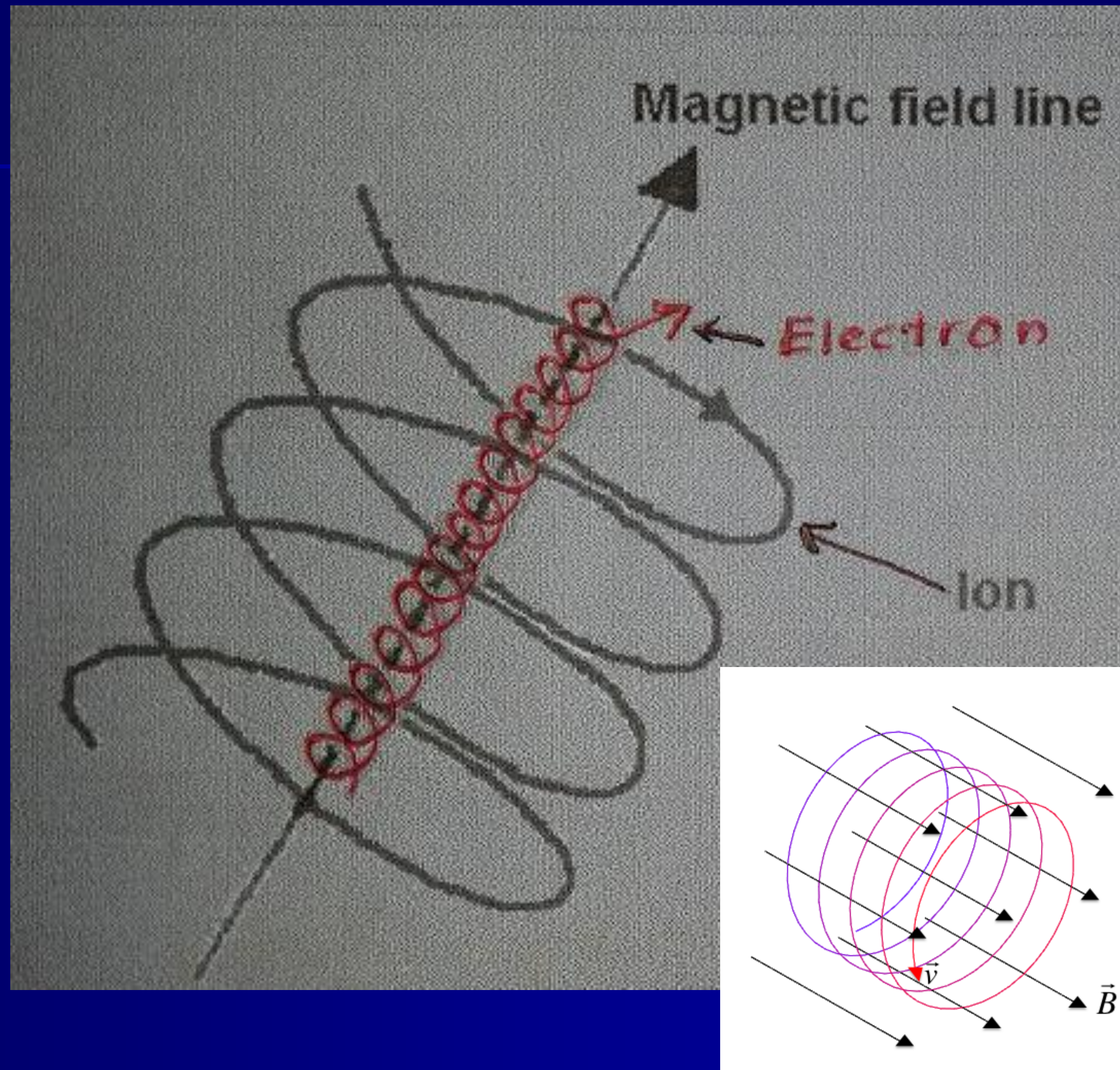
For e^ns

$$f_H = 1.68\,MHz$$

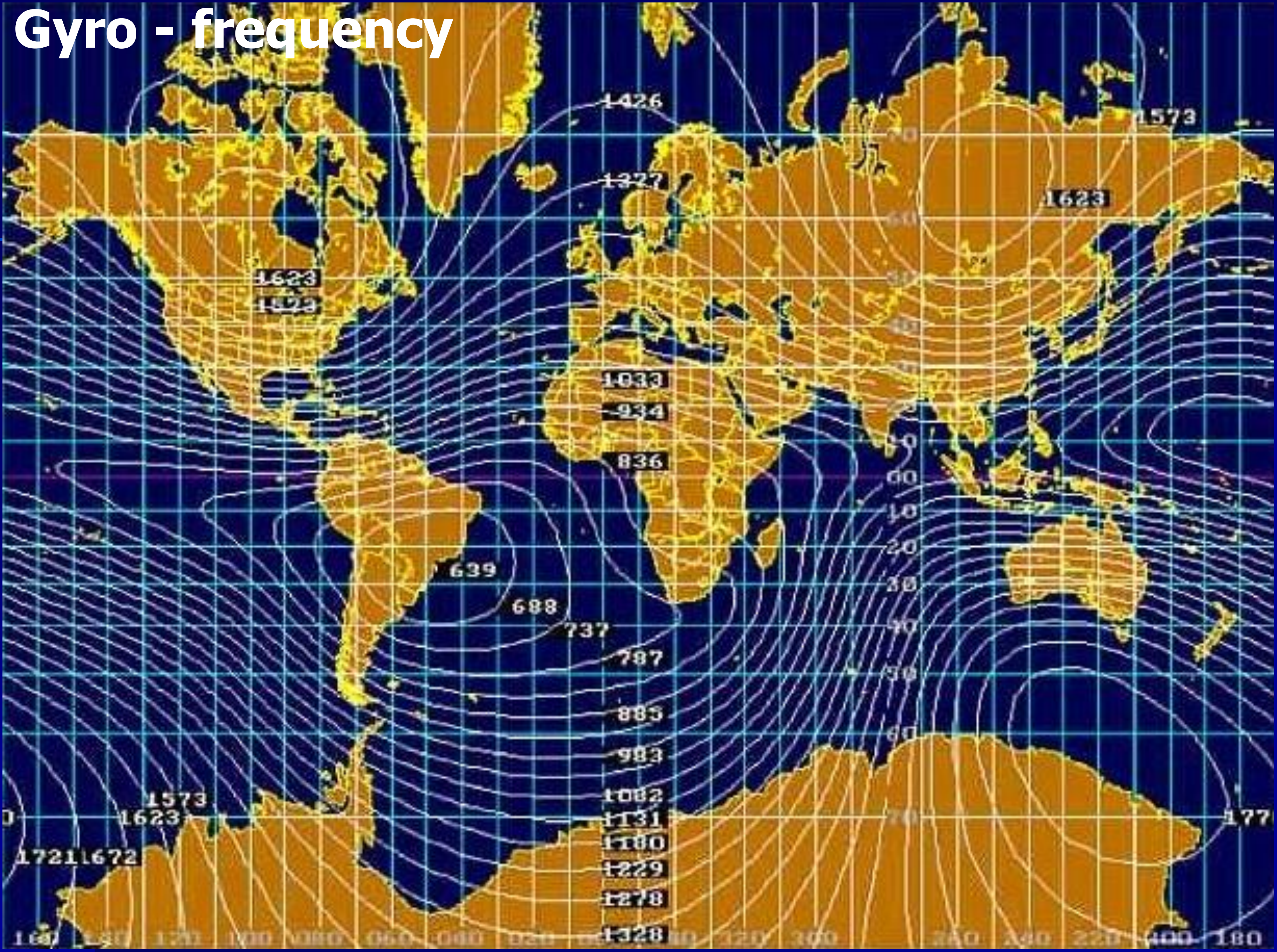
For O+ ions

$$f_H = 48\,Hz$$

Because, $M >> m$



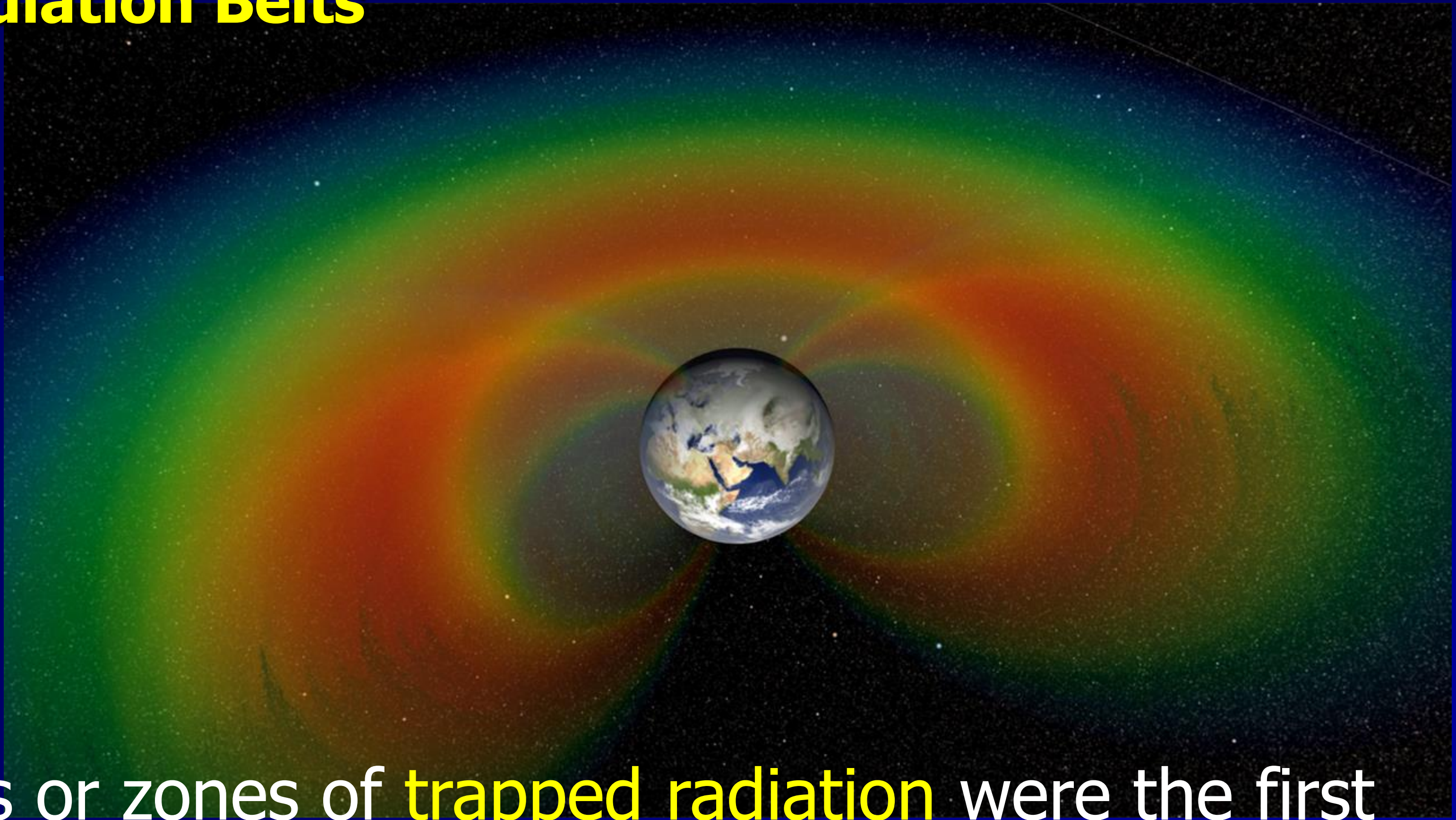
Gyro - frequency



The Magnetosphere

The Earth's Magnetic Fields
The Dipole Magnetic Field
Motion of charged particles in a Dipole Magnetic Field
The Radiation Belts
The boundary and the tail of the Magnetosphere

The Radiation Belts



The belts or zones of trapped radiation were the first major discovery of the space age. The first American satellite, **Explore-I**, was launched on **January 31,1958**, carrying among other instruments a **Geiger counter** provided by **Van Allen's group** of the university of Iowa.

The Radiation Belts

Reading from this counter were obtained only when the satellite passed above a small number of tracking stations. When the satellite pass was a low one, the counting rate was the one expected from the known cosmic ray flux when explorer-I was near apogee (very far place of the planetary orbit from the Earth), the corresponding ground station received the message that the counting rate of the Geiger counter had **dropped to zero**.

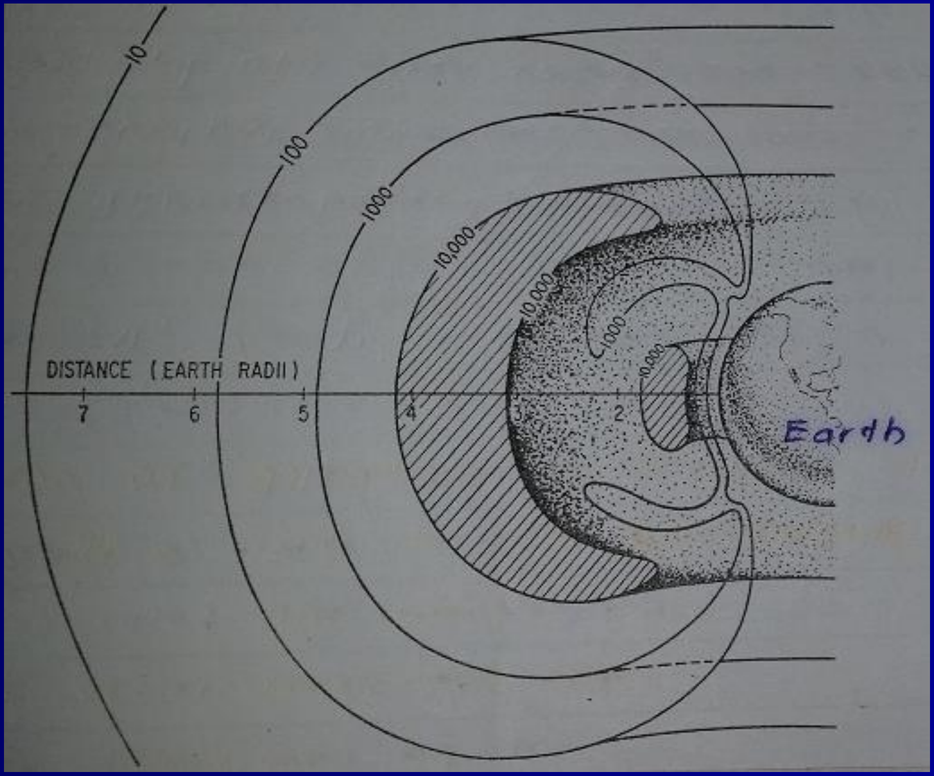
The Radiation Belts

This **unexpected result meant either that the counter was malfunctioning or that there was no radiation at higher attitudes**, which did not seem to make much sense. A third possibility was pointed out by **Carl McIlwain**, who suggested that the zero counting rate might be due to the saturation of the counter (dead-time effect) from a **very high flux** of **energetic particles**. McIlwain's suggestion was confirmed by **Explorer-III** after Explorer-II failed to reach an orbit. **The conclusion from these results was that at higher attitudes the satellites enter the region of trapped radiation were the counting rate is 1000 times higher than what it would have been due to the cosmic ray flux**.

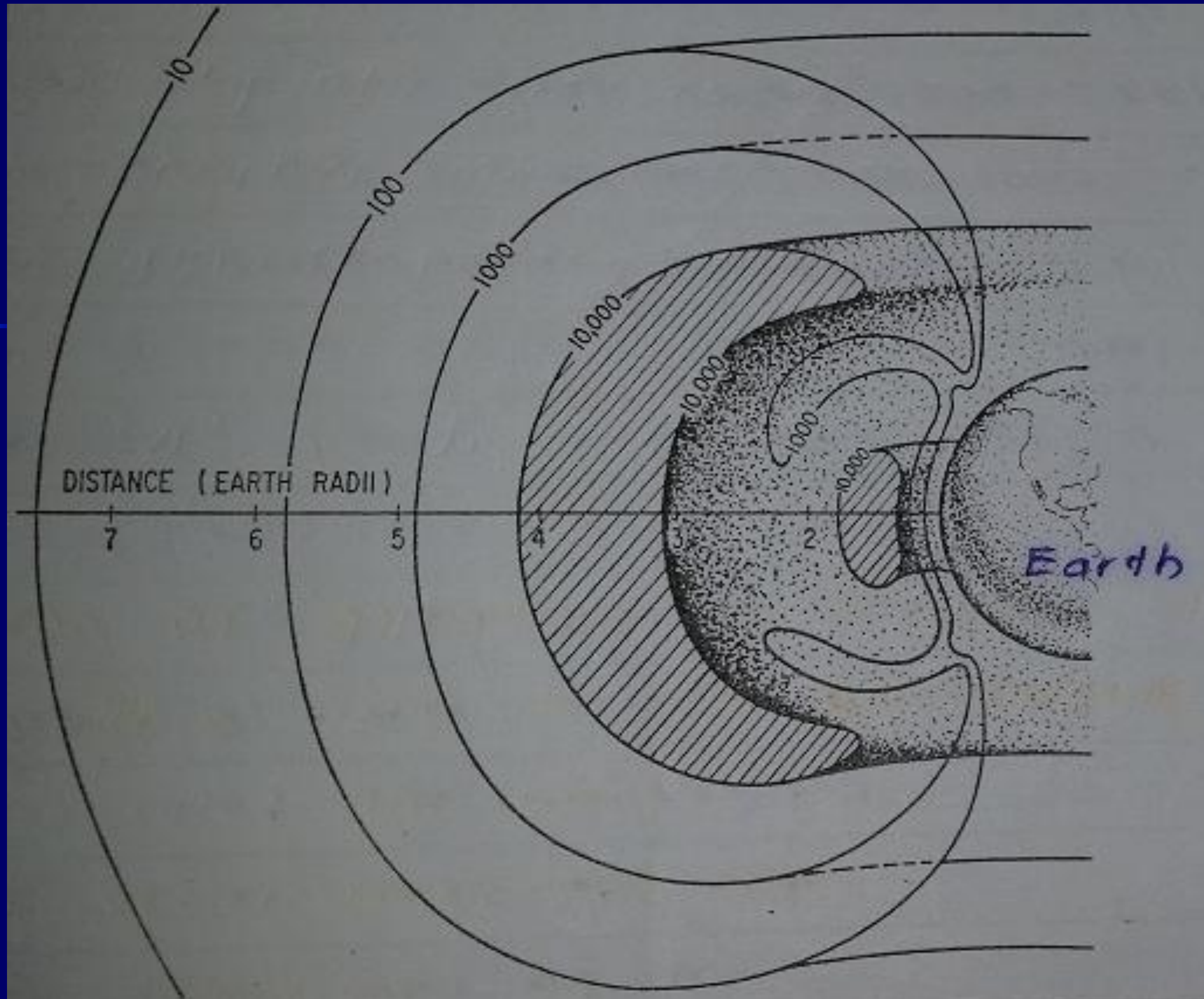
It is interesting to note parenthetically (with in bracket) that the **Russians** had placed Geiger counters on Sputnik-II, which was launched before Explorer-I and **therefore could have discovered the radiation belts before the Americans**. The Russian satellite happened to be always underneath the radiation belts (near perigee [nearest place of the planetary orbit from the Earth]) whenever the counter was monitored over the soviet union and the Russians missed a great opportunity. The discovery of the Iowa group was later confirmed by Sputnik-III, but the honor of discovering the radiation zones belongs to **Prof Van Allen and his group,** and for this reason **the belts of trapped radiation** are after often called **Van Allen Belts**.

The Radiation Belts

Following the **first satellite observations**, a great interest developed in exploring the morphology of the zones of **trapped radiation**. The first complete picture that emerged (came out) from the mapping of the belts is shown in the following figure.



The Radiation Belts



The inner and the outer radiation belts as they were first mapped by **Van Allen's group** of the University of Iowa (White, 1970)

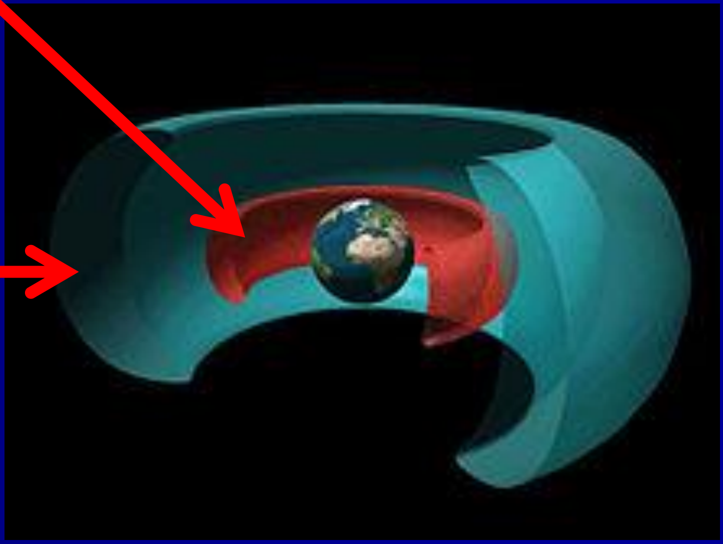
The Radiation Belts

This diagram depicts counting rates of particles energetic enough to penetrate the shielding of 1.0 gr/cm^2 of lead which covered the approximately 1cm^2 window of the Geiger counter.

As seen from the figure, the counting rates reached values higher than 10^4 counts/sec in two different regions. **This led** (PT of lead) **to the notion that there are actually two radiation belts which were named the inner and outer Van Allen belts.**

The Radiation Belts

- The first counters could not differentiate between energetic protons and energetic electrons.
- Today we know that the high counting rates of the **inner belt are produced by energetic protons** with energies in the 10 to 100 MeV range, while the high counting rates of the **outer belt are produced by high energetic electrons** with energies in the 1 MeV range and above.

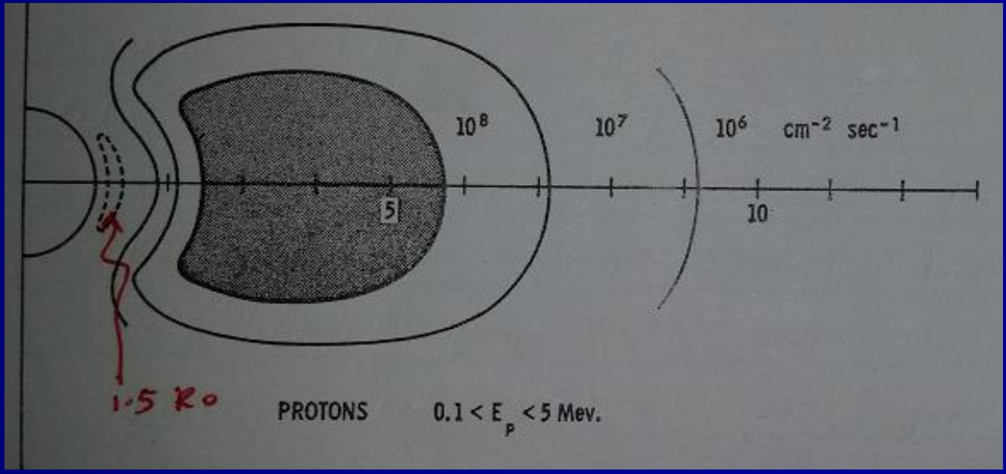


- This of course **does not mean that there are no energetic electrons in the inner belt or energetic protons in the outer belt.**

  More detailed studies have shown that the spatial distribution of the trapped electrons and protons varies with the energy of these particles.

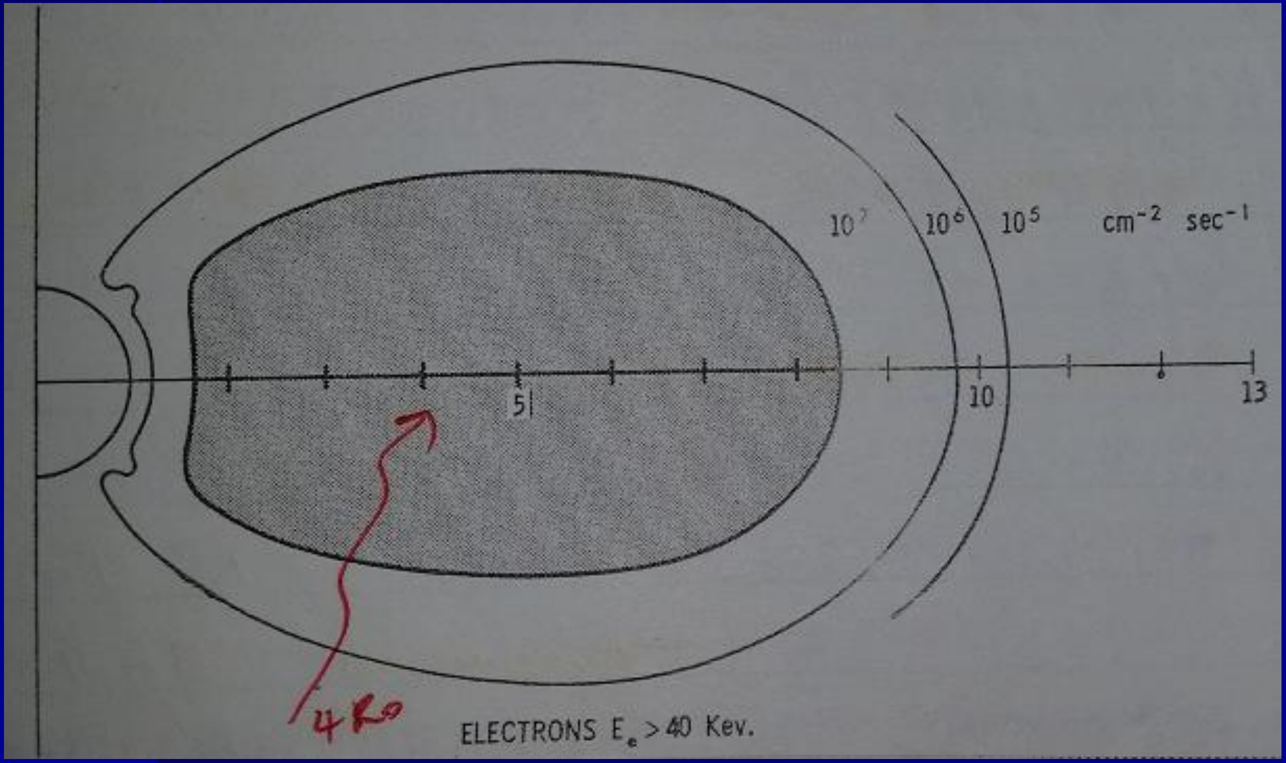
- The **highly energetic protons peak near 1.5 Ro** but for protons of lower energies the peak of the belt moves farther out and the width of the belt increases considerably.

The spatial distribution of **trapped protons** of different energies (Hess and Mead, 1968)



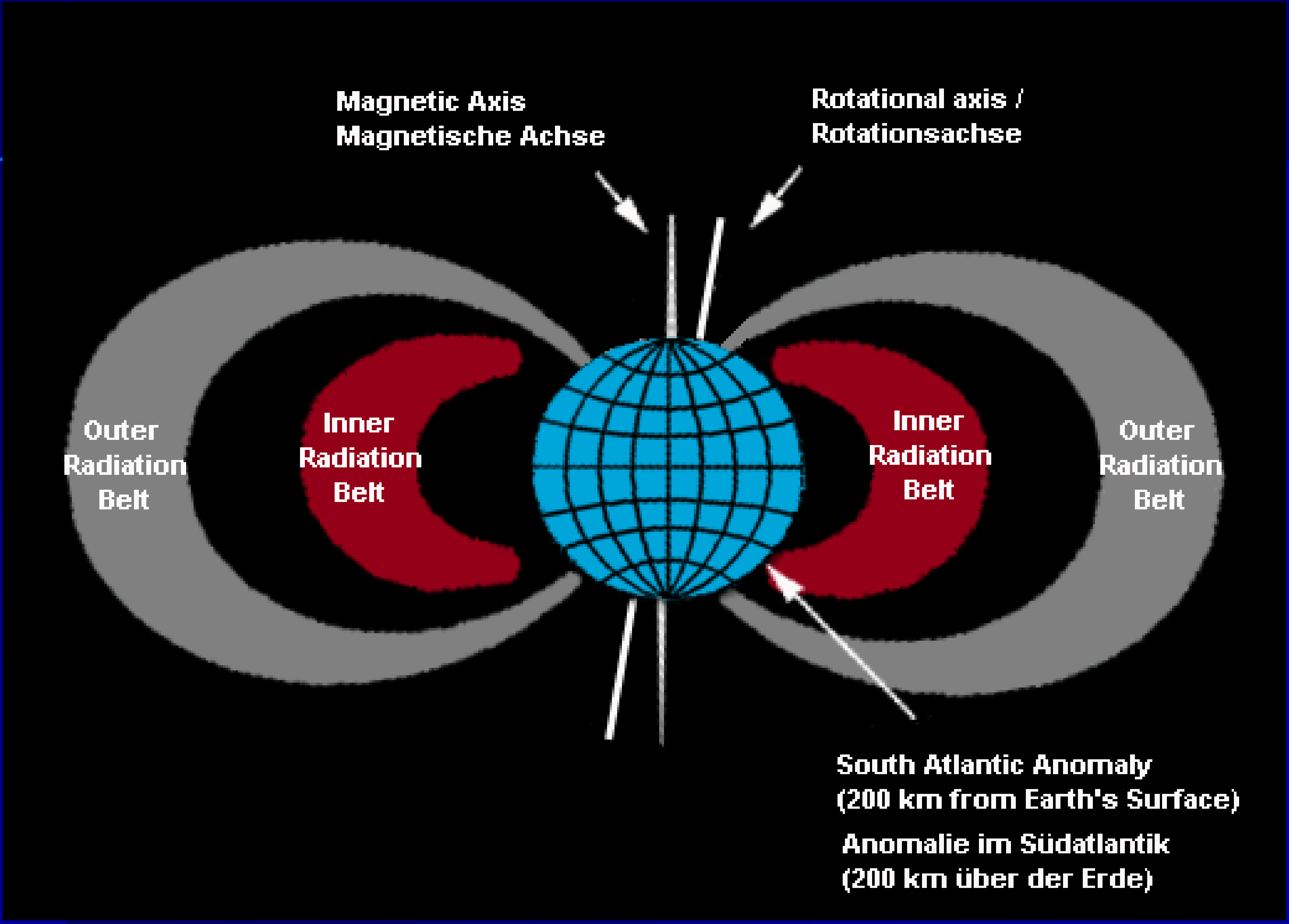
The same is also true for the **energetic electrons of the outer belt**.

- For energies above 1 MeV the belt is relatively narrow and peaks near **4 Ro** while the electrons of lower energies the belt spreads out fairly evenly over a much larger volume.

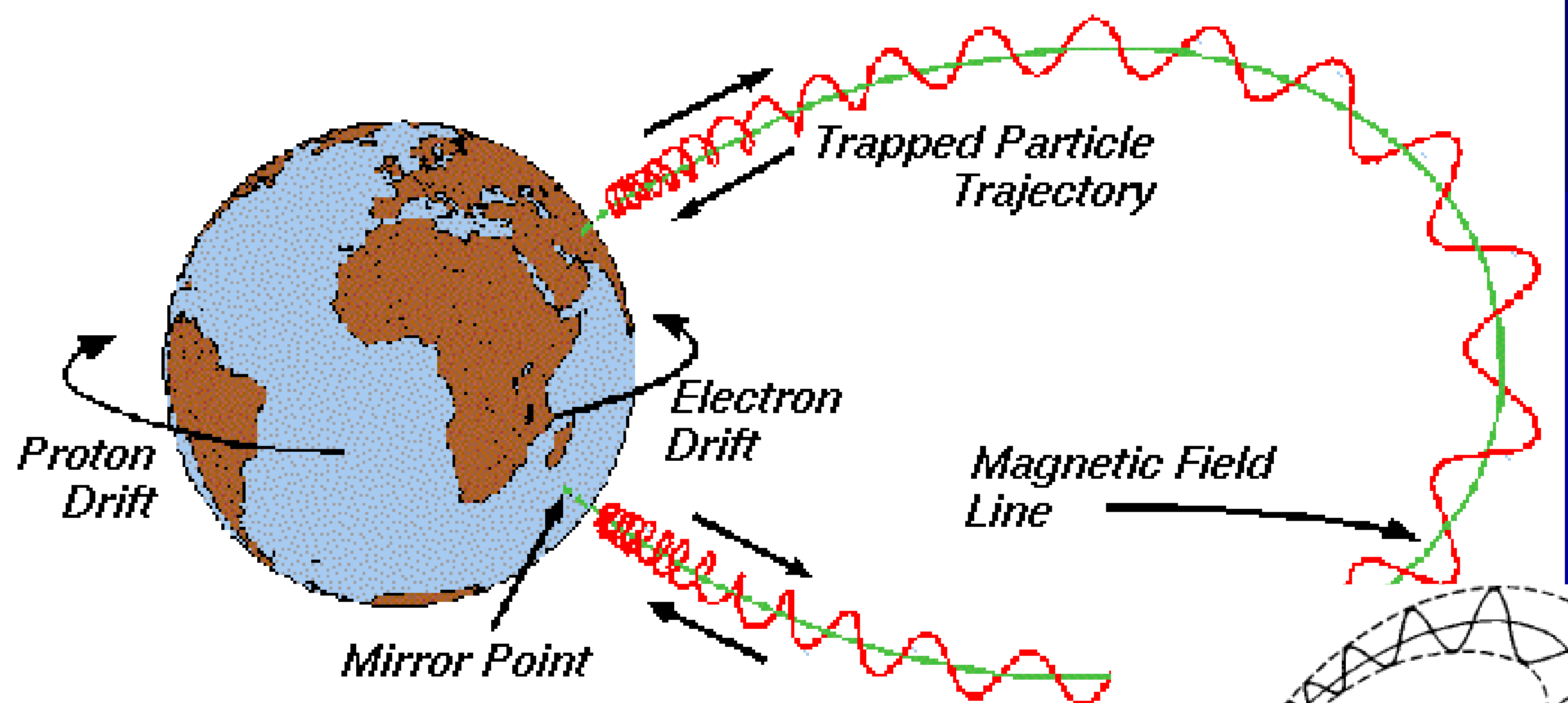


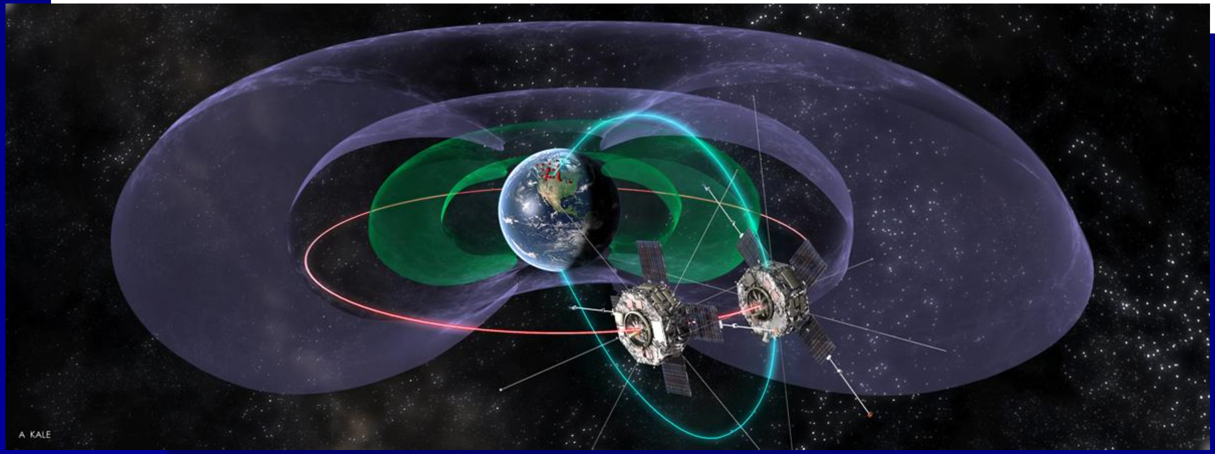
The spatial distribution of **trapped electrons** of different energies (Hess and Mead, 1968)

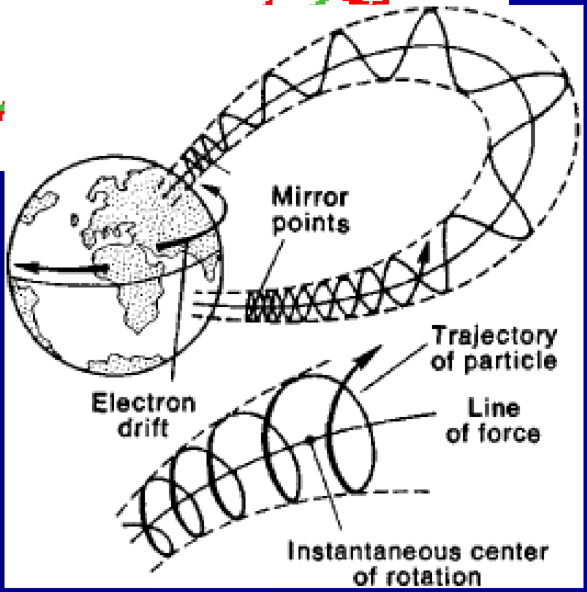
The Radiation Belt

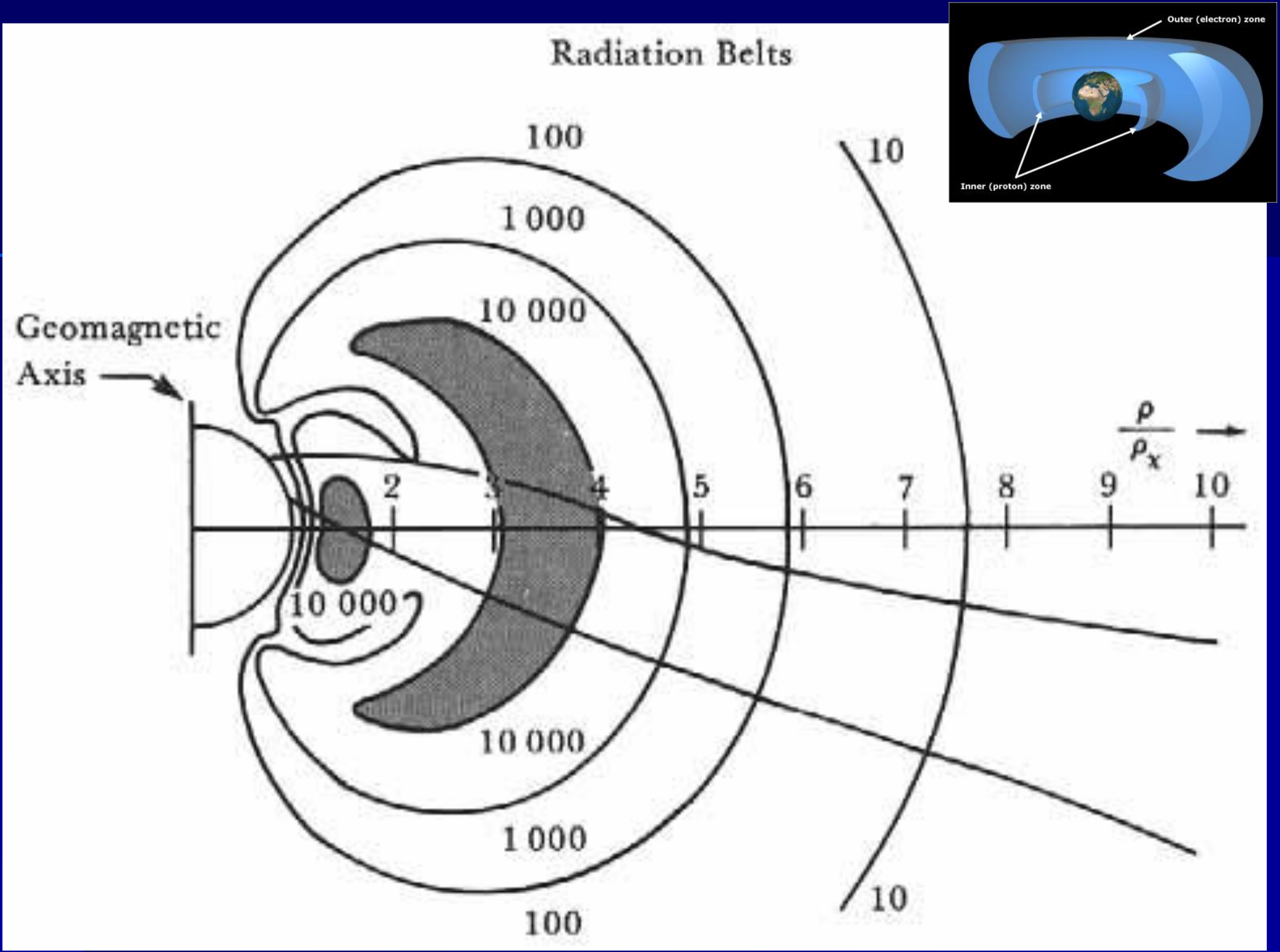


The Radiation Belts








Radiation Belts
100
10
1 000
10 000
Geomagnetic
Axis
$\frac{\rho}{\rho_x}$
2
3
4
5
6
7
8
9
10
10 000
10 000
1 000
10
100
Outer (electron) zone
Inner (proton) zone

The Magnetosphere

The Earth's Magnetic Fields
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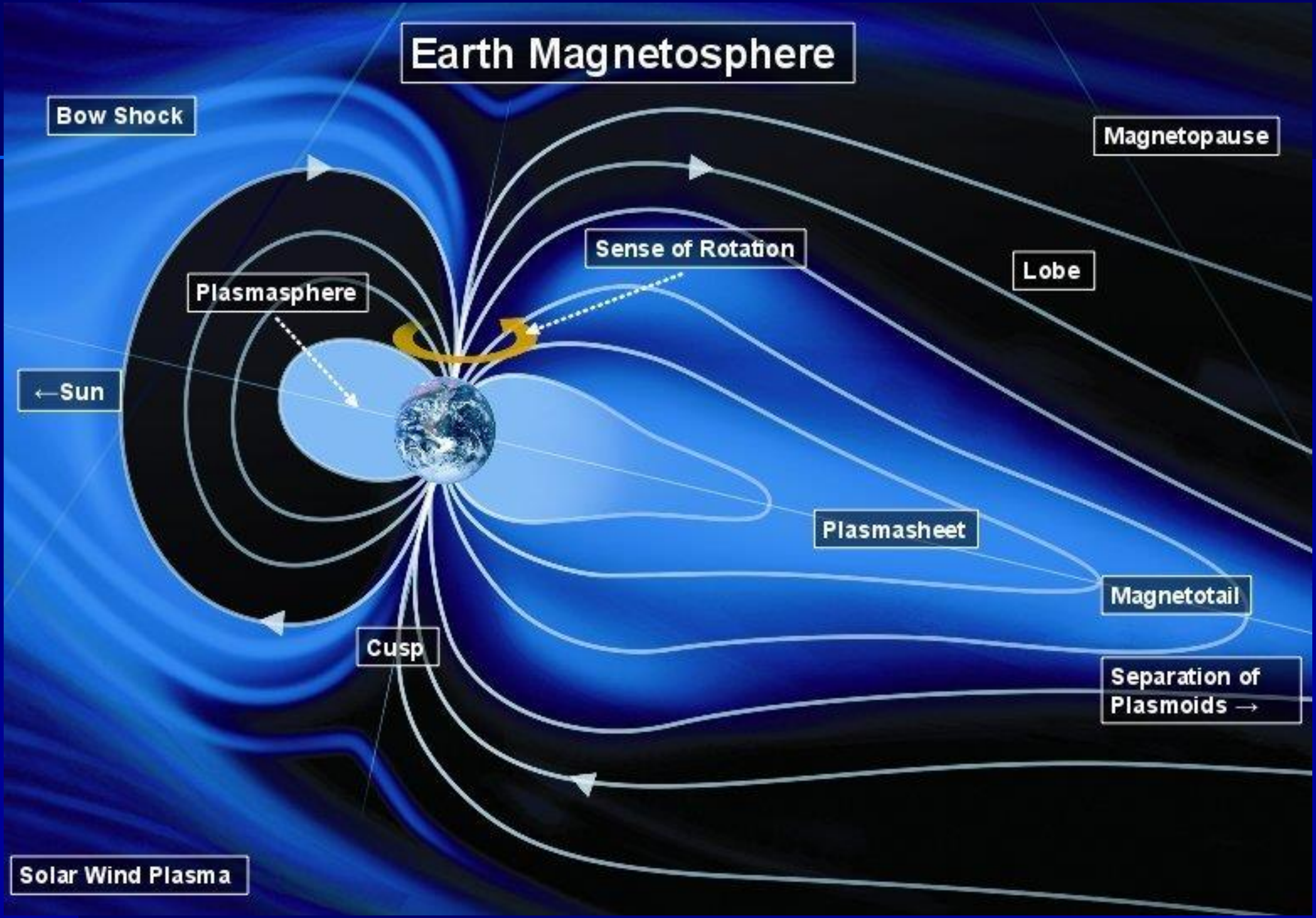
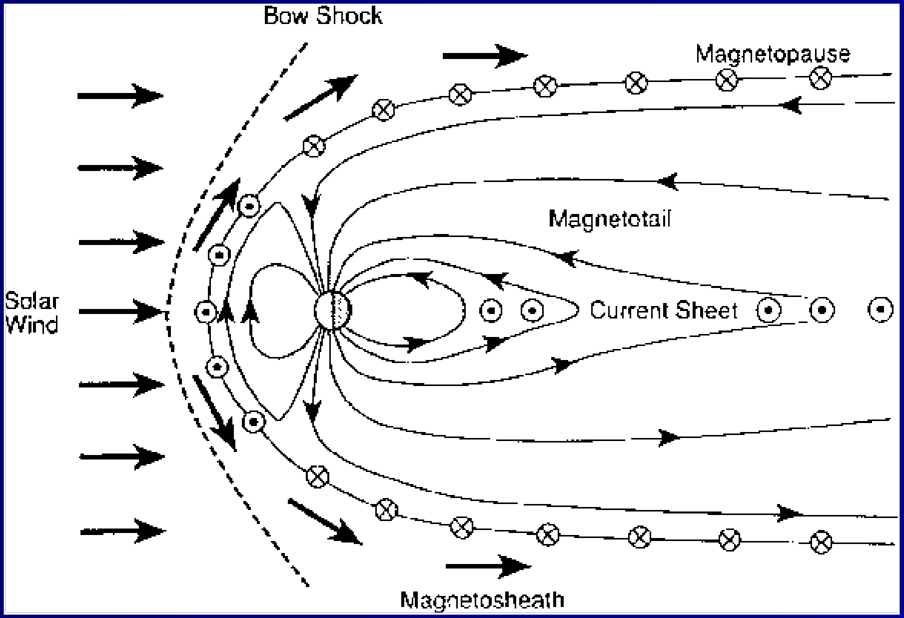
The boundary and the tail of the Magnetosphere

The Boundary and the Tail of the Magnetosphere



The Boundary and the Tail of the Magnetosphere

The magnetosphere is **the region where the motion of the charged particles is primarily governed by the Earth's magnetic field**. Originally it was thought that the terrestrial magnetic field extends way out into the interplanetary space, becoming weaker with distance and gradually merging into the emptiness of free space.



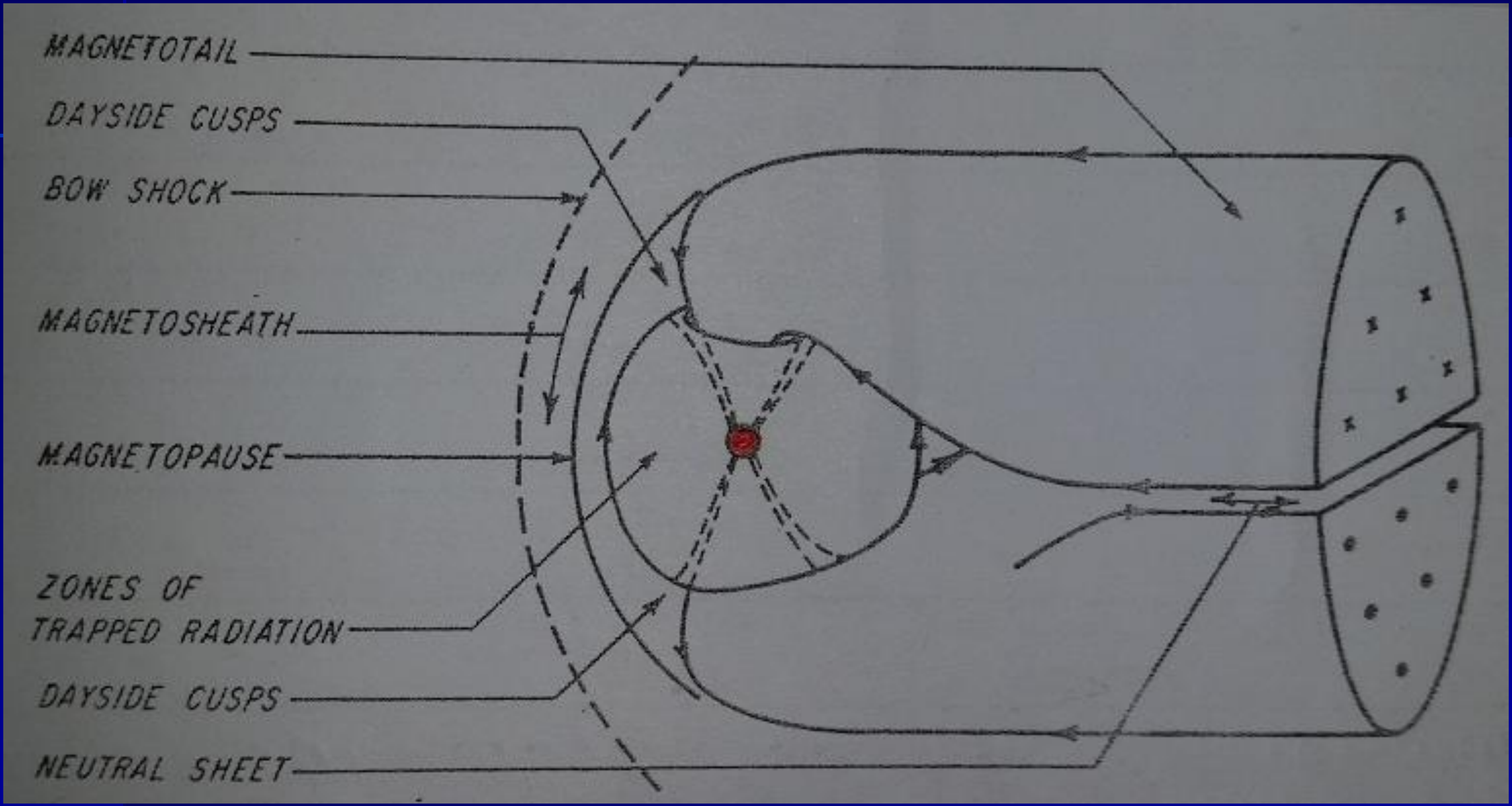
The Boundary and the Tail of the Magnetosphere

An alternative configuration for the Earth's magnetic field was discussed for the first time in **1931** by **Chapman and Ferraro**. In their effort to understand the mechanism of the magnetic storms and their relation to the solar flares, Chapman and Ferraro (1931) suggested that a large flare is accompanied by the ejection from the Sun of a big plasma cloud which reaches the Earth in approximately one day. As this cloud blows past the Earth, it exerts a pressure on the terrestrial magnetic field and sweeps it back in an aerodynamic configuration.

The Boundary and the Tail of the Magnetosphere

Under the pressure of this cloud, the Earth's magnetic field is confined (restricted) inside a region which is called the **magnetic cavity**. The boundary of this cavity is called the **magnetopause** and marks the end of the magnetosphere. **At this boundary, the pressure of the compressed tubes of force of the Earth's magnetic field is equal and balance the pressure exerted** (employ) **by the stream of charged particles from the Sun.** The **pressure is exerted almost exclusively** (particularly) **by the protons**, which have approximately the same velocity, but are nearly 2000 times **heavier than the electrons**.

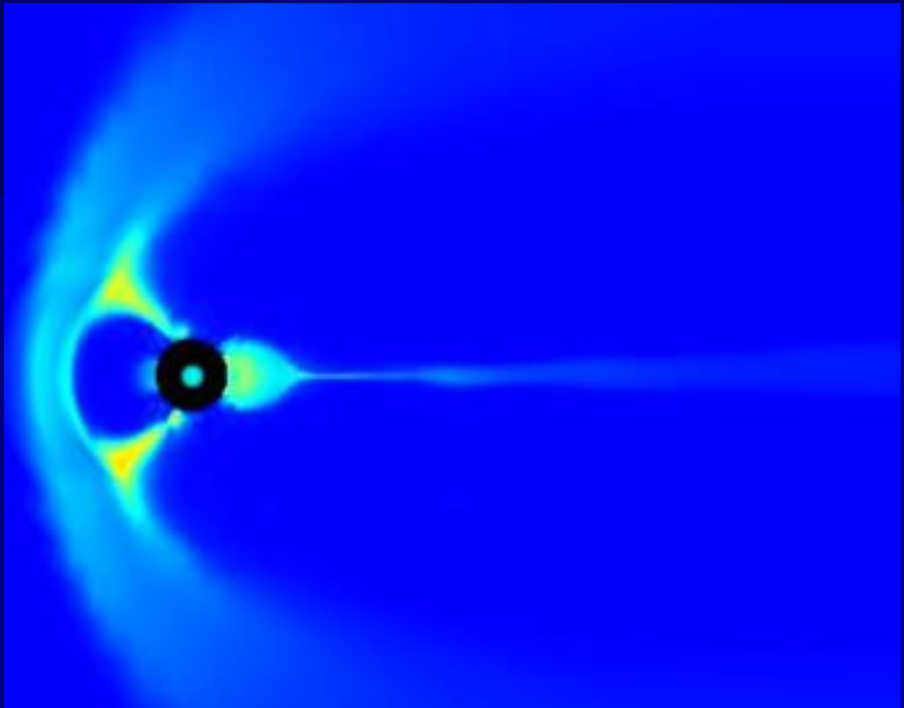
The Boundary and the Tail of the Magnetosphere



The formation of the magnetopause by the sweeping action of the solar wind

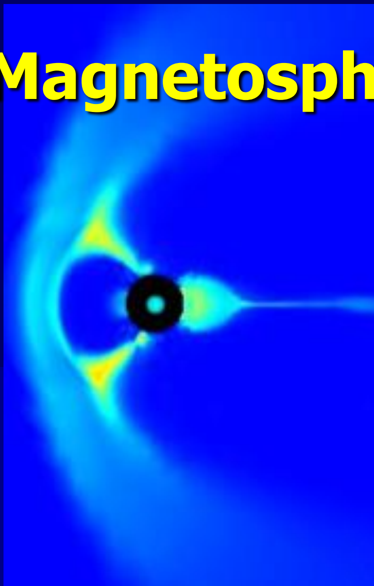
The Boundary and the Tail of the Magnetosphere

The magnetic field of the Earth under the sweeping action of the solar wind forms a **magnetic tail** in the anti-solar direction. Thus behind the Earth the magnetopause becomes a **cylindrical surface**. The radius of the magnetic tail **Rt** is approximately **22 Ro** and remains the same for at least **100 Ro**.



The formation of the geomagnetic tail from the magnetic field lines of the polar caps which are swept in the anti-solar direction by the solar wind.

The Boundary and the Tail of the Magnetosphere

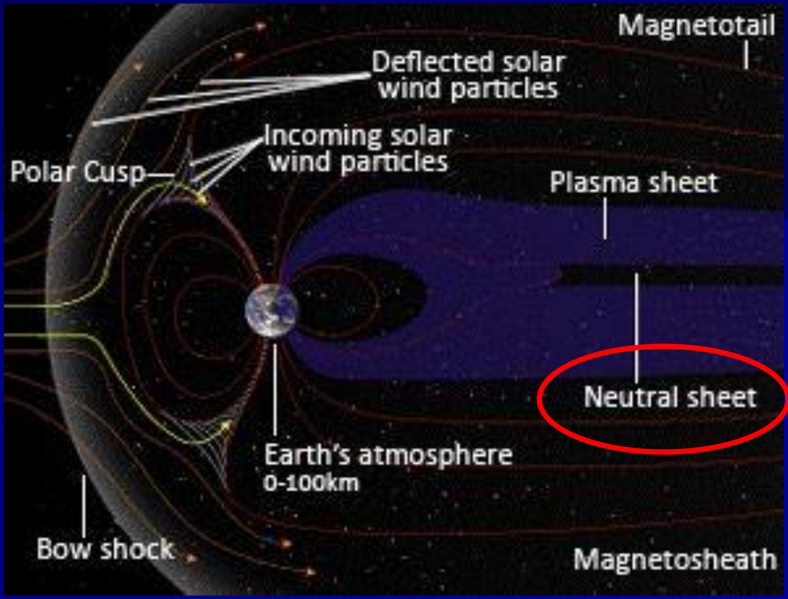


The formation of the geomagnetic tail from the magnetic field lines of the polar caps which are swept in the anti-solar direction by the solar wind.

As seen from the above figure, the magnetic field of the tail is actually the magnetic field of the polar caps which has been swept back by the solar wind. The incoming field lines in the northern half and the outgoing field lines in the southern half of the magnetic tail are separated by a plane layer where the intensity of the magnetic field drops essentially to zero. This neutral layer has thickness of about **1000 km** and is called the **neutral sheet**.

The Boundary and the Tail of the Magnetosphere

On several occasions satellites have detected in the neutral sheet weak magnetic fields normal to the neutral plane. This suggests that the parallel but opposite field lines on either side of the plane not only neutralize each other, but occasionally they combine to form loops, like the symbol of infinity, inside the **neutral sheet**.



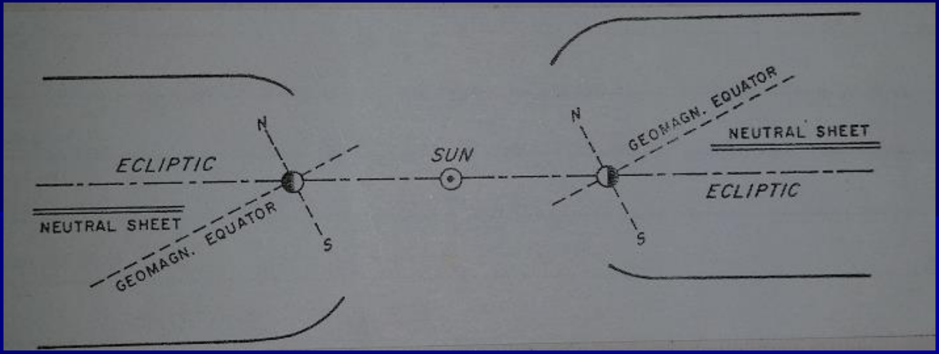
The Boundary and the Tail of the Magnetosphere

The **magnetic tail** of the Earth's magnetosphere has been detected with certainty by satellites orbiting the moon so that it definitely extends beyond **half a million kilometers**. Mariner-4 has found no evidence of the tail at **3,300 Ro**, whereas observations with Pioneer-7 near **1000 Ro** were rather ambiguous (doubtful).

magnetic tail

The Boundary and the Tail of the Magnetosphere

Fig-1 : The movement of the geomagnetic tail relatively to the plane of the ecliptic as the Earth orbits around the sure.



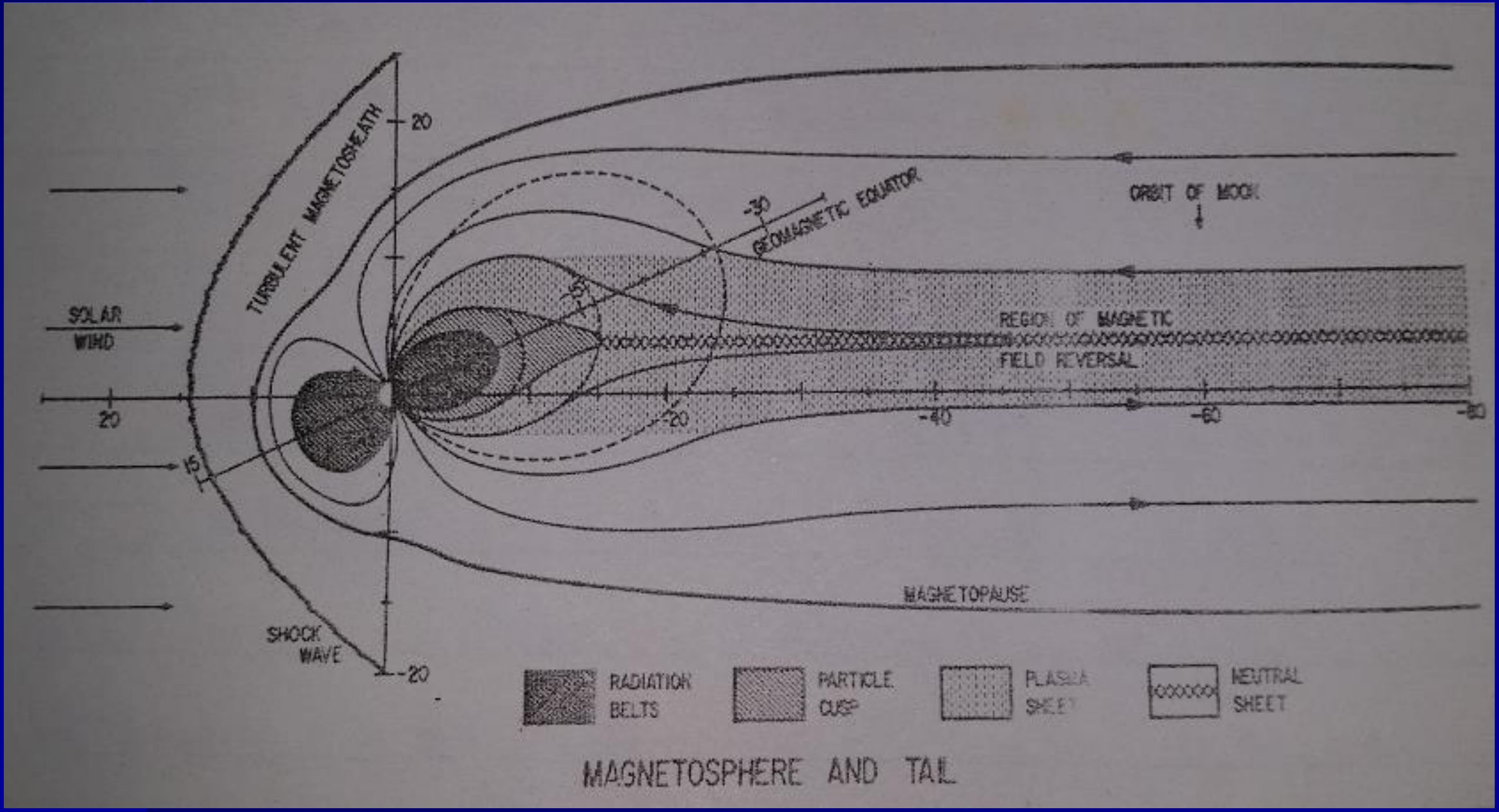


Fig-2 : The detail summary diagram of the Earths magnetic cavity (Ness, 1969)

The Boundary and the Tail of the Magnetosphere

Thus it appears that the magneto tail, or a magnetosphere wake behind it after the field lines close extends for at least **several hundred Earth radii**. The plane of the neutral sheet is parallel to the plane of the ecliptic but, as seen from figure-1, it is displaced by a few Earth radii toward the geomagnetic equator.

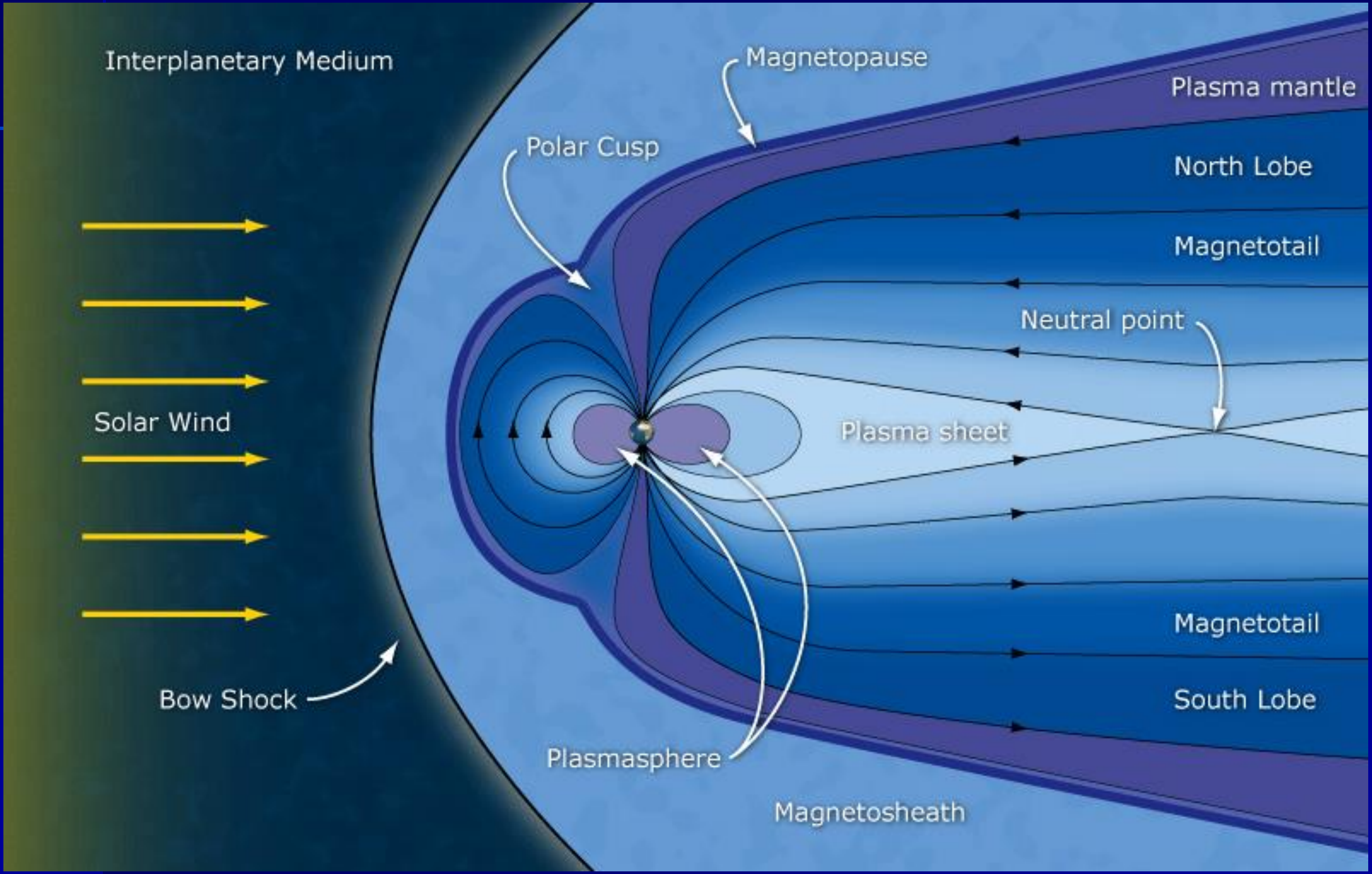
On both sides of the natural sheet satellites have found **high fluxes** [10^8 - 10^9 en / (cm^2)] of **low energy electrons** with energies typically of the order of a few keV. This region, which sandwiches the natural sheet, is called the plasma sheet and has a thickness of about 10 Ro.

The Boundary and the Tail of the Magnetosphere

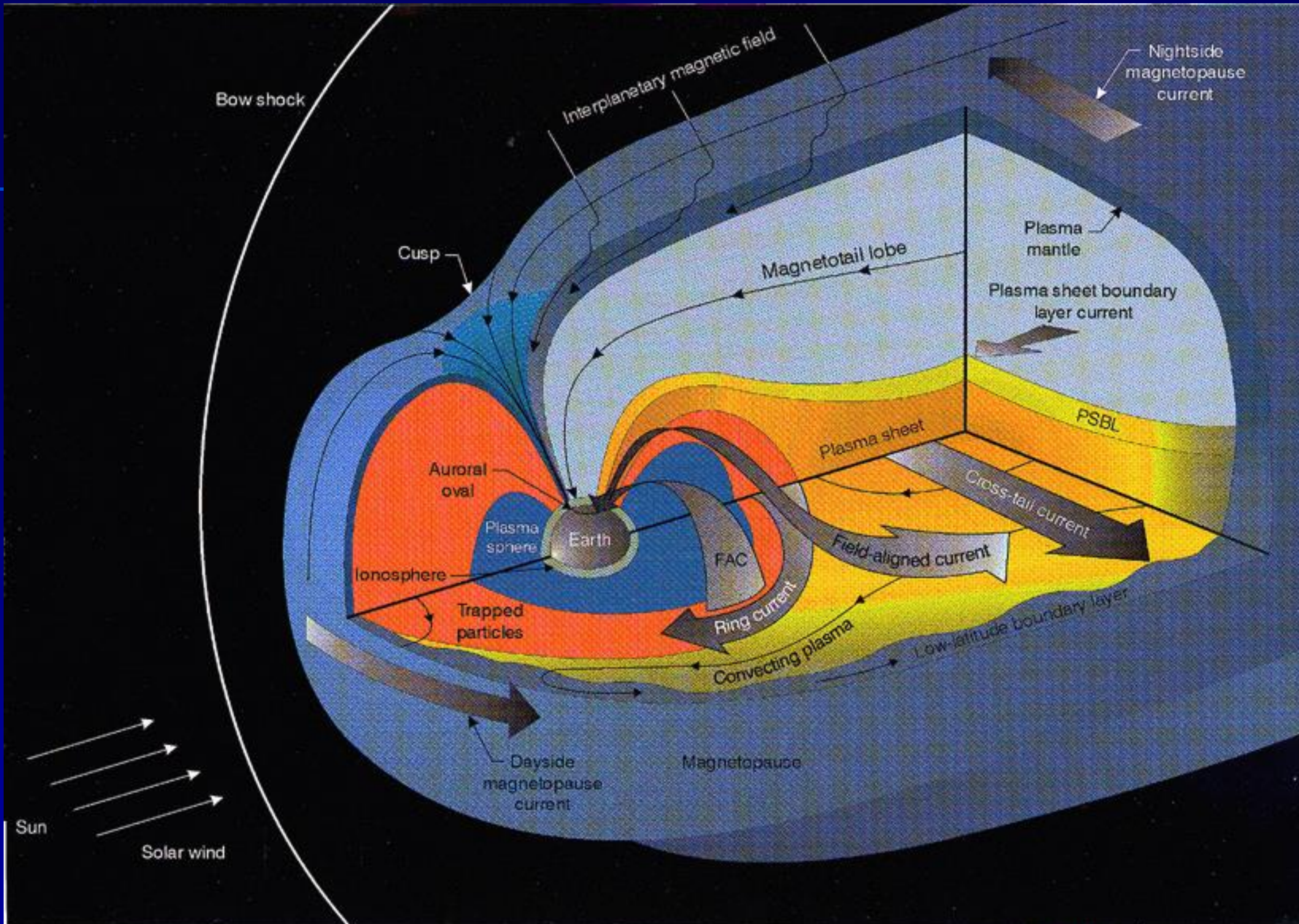
Anderson (1965) has also observed " **islands** " of energetic particles inside the space of the **magnetotail**. The energies of the electrons in these islands are of the order of 100 keV and the fluxes measured reached 10^7 en en / (cm^2).

A combined diagram of the magnetic sheath, the magnetosphere and the magnetic tail of the Earth, produced by Ness is shown in above figure-II

The Boundary and the Tail of the Magnetosphere



The Boundary and the Tail of the Magnetosphere



Thank You !