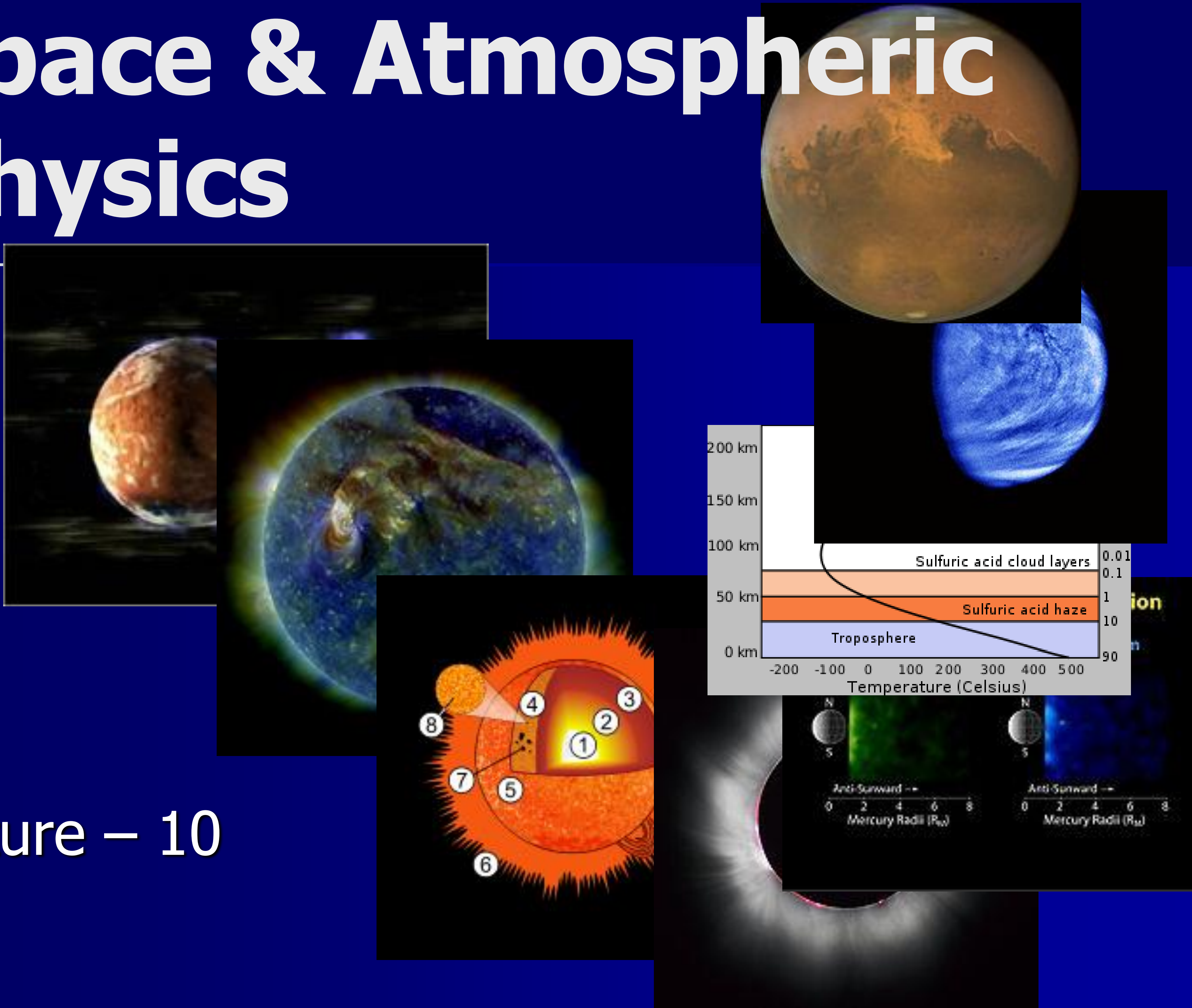
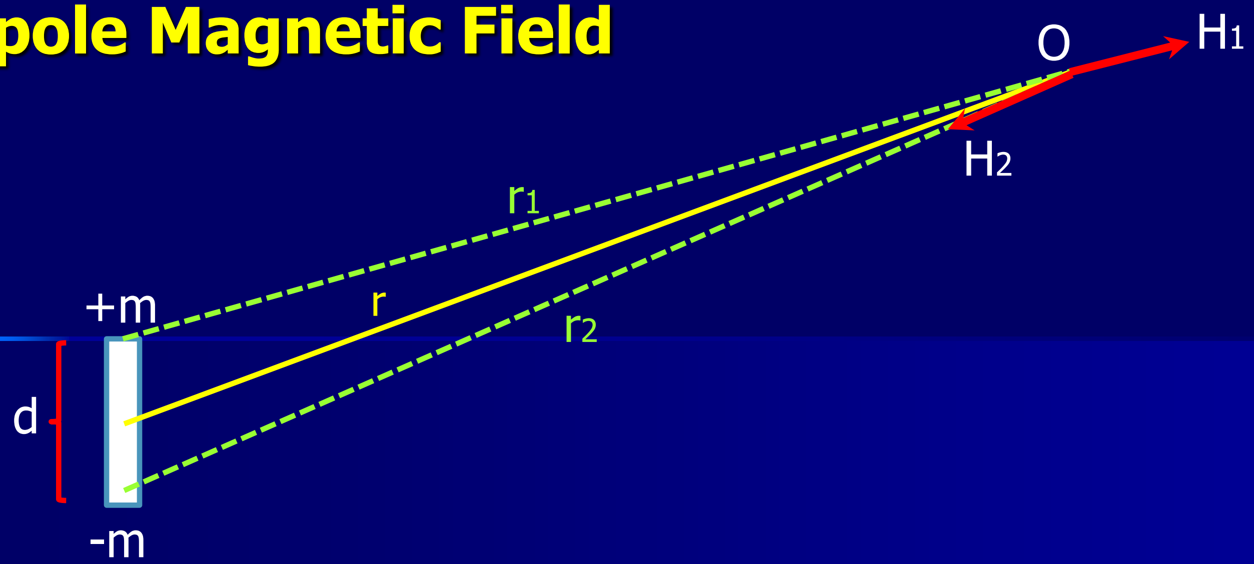
Space Physics

Space & Atmospheric Physics



Lecture – 10

The Dipole Magnetic Field

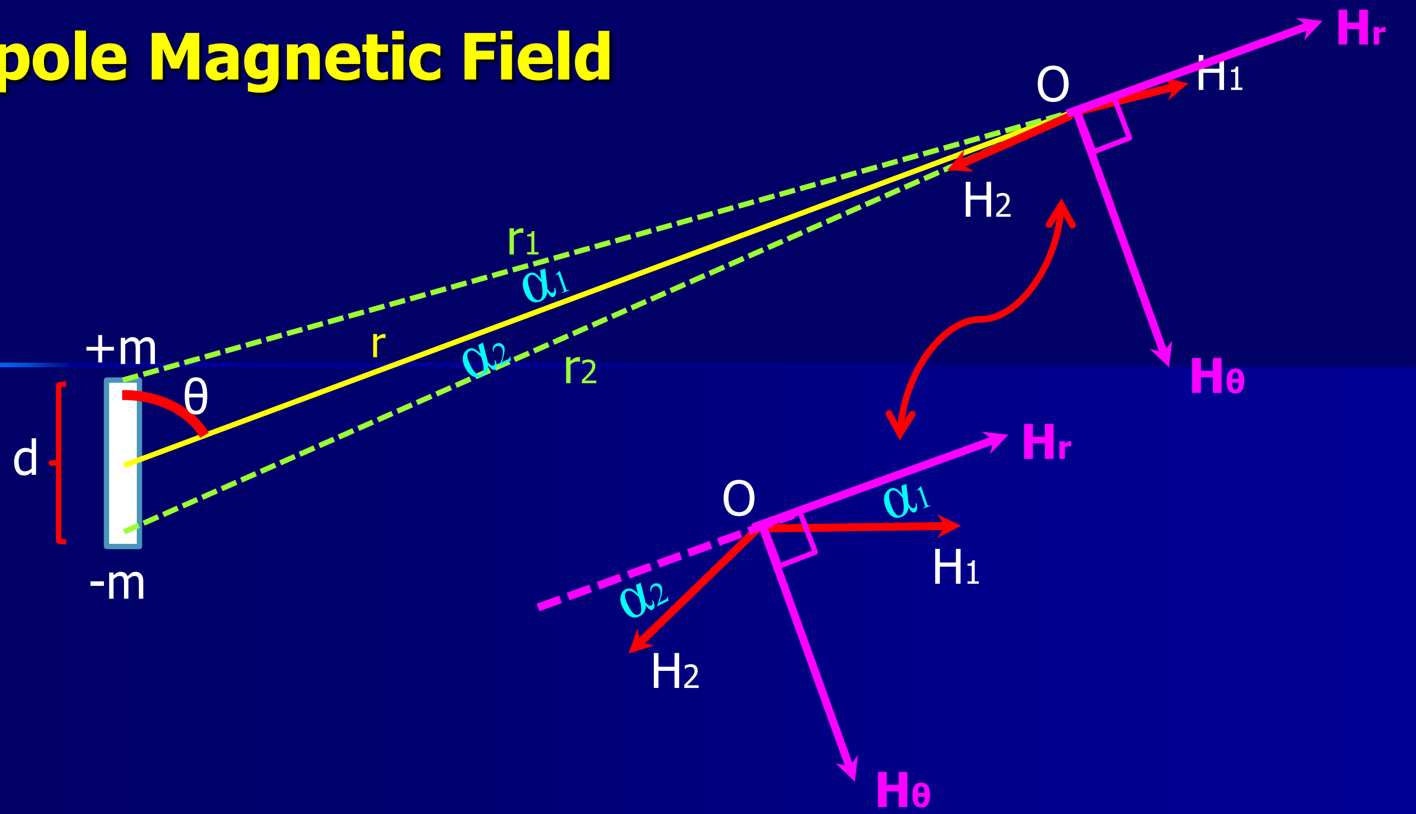


Let us consider the magnetic field at a point O, at distance r_1 and r_2 from the two poles of a magnetic dipole. Let m be the strength of each of the two poles and d the distance that separate them. The product $m\,d$ is called the Magnetic Dipole Moment (M).

The magnetic field at O will have the two components,

$$H_1 = \frac{\mu_o}{4\pi} \cdot \frac{m}{r_1^2} \quad \text{and} \quad H_2 = \frac{\mu_o}{4\pi} \cdot \frac{m}{r_2^2}$$

The Dipole Magnetic Field



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

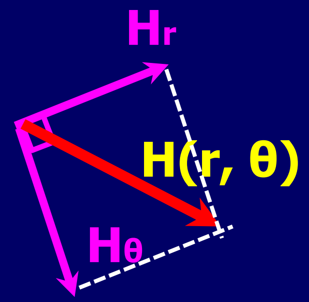
$$H_r = H_1 \cos\alpha_1 - H_2 \cos\alpha_2$$

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

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

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,

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

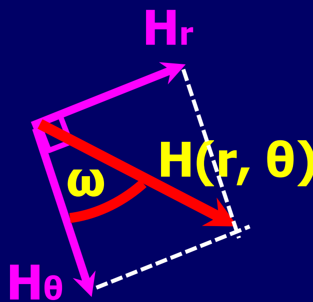
$$H = \left[\left(\frac{\mu_o}{4\pi} \cdot \frac{2M}{r^3} \cos\theta\right)^2 + \left(\frac{\mu_o}{4\pi} \cdot \frac{M}{r^3} \sin\theta\right)^2\right]^{1/2}$$

. . . .

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

The Dipole Magnetic Field

Total Magnetic Field



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

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

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.

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

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

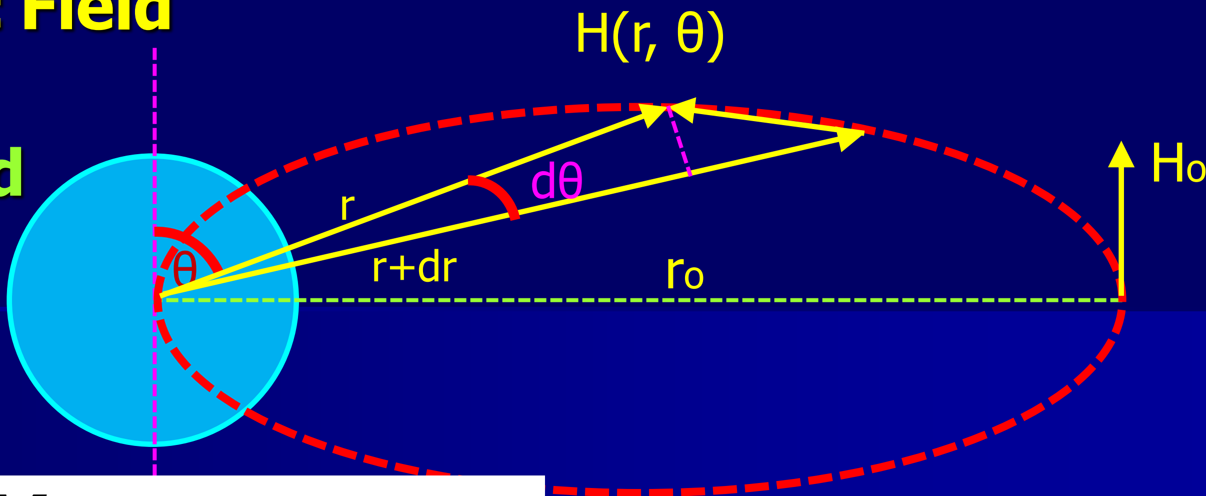
$$\Rightarrow \tan\omega = 2\cot\theta$$

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

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



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

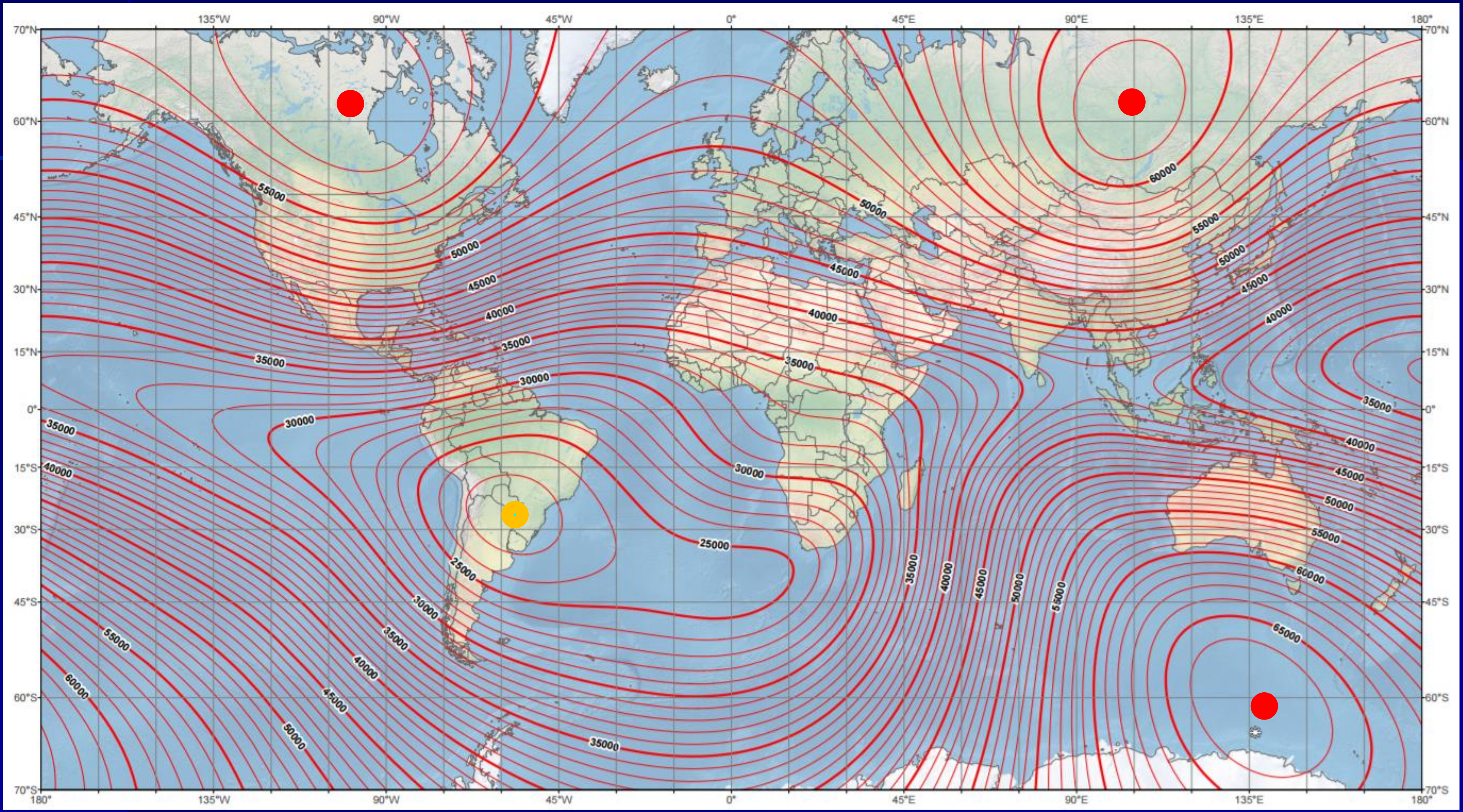
$$H(r,\theta) = \frac{\mu_o}{4\pi}\frac{M}{r_o^{\,3}}\frac{\left[1+3\cos^2\theta\right]^{1/2}}{\sin^6\theta}$$

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

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

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

The Earth Magnetic Field



Min -

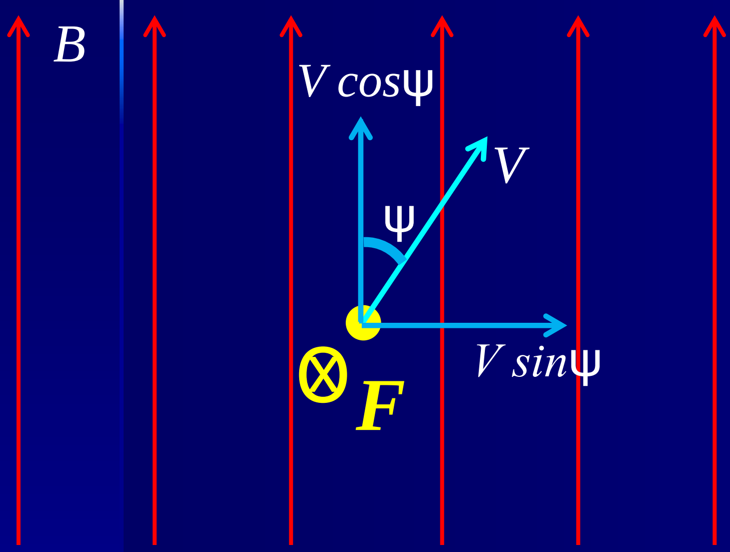
Max

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*.



Magnetic Force, F

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

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

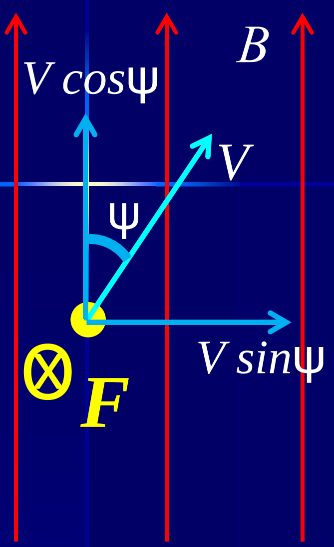
$$F = e\,(V \sin\psi)\frac{H}{c} \quad \otimes$$

Using Fleming's Left hand Law

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

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



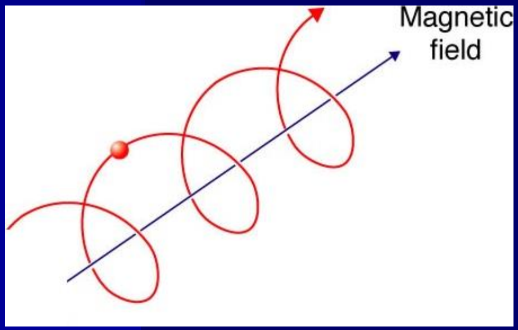
The Lorentz Force is balanced by the centrifugal force produced by the component $V_n = V \sin\psi$ of the particle's velocity which is normal to the magnetic field, i.e.;

$$\frac{e}{c} VH \sin\psi = \frac{m v_n^2}{r}$$

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

Gyro-radius

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



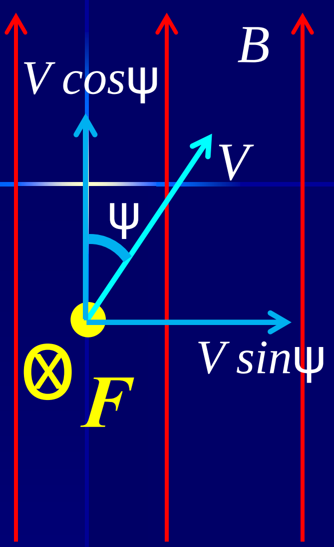
. . . .

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

or

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

Motion of Charged Particle in a Dipole Magnetic field



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

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

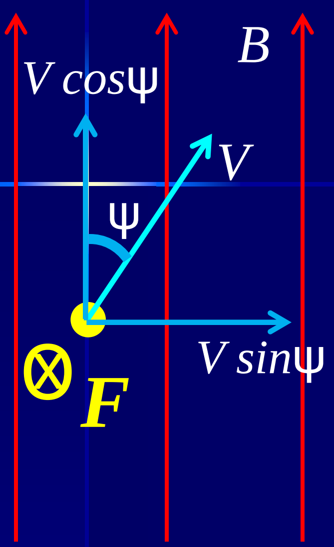
$$\omega_H = \frac{v_n}{R_H} \quad \text{because,} \quad V = r\,\omega$$

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

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

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

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 $$\frac{e}{2\pi\ m\ c} = \frac{1.6\times10^{-19} C}{2\pi\ 9.1\times10^{-31} kg\ \ 3\times10^{8} ms^{-1}}$$

$$= 93.28$$

$$\therefore \quad f_H = 93.28 \ \ H$$ or $$f_H = 93.28 \ \ Bc$$ or $$f_H = 2.8\times10^{10} B$$

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.

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

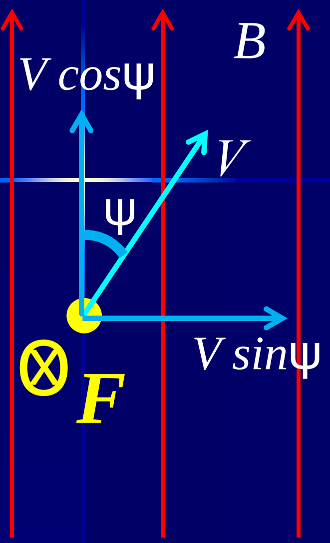
$$f_H = \left(2.8\times10^{10}\right)\times(60000\times10^{-9})$$

$$f_H = 1.68\times10^{6} Hz$$

or

$$f_H = 1.68 MHz$$

Motion of Charged Particle in a Dipole Magnetic field



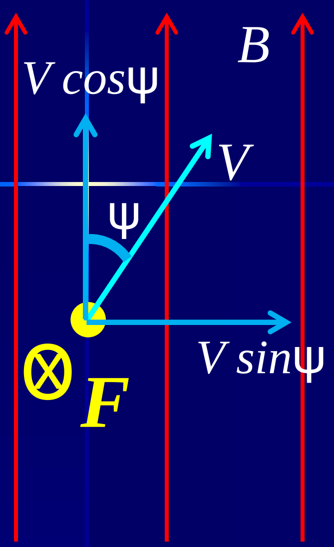
$$f_H = 2.8\times10^{10} B$$

In the numerical form of the above equation, **f_H** 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 **m_o** 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

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

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

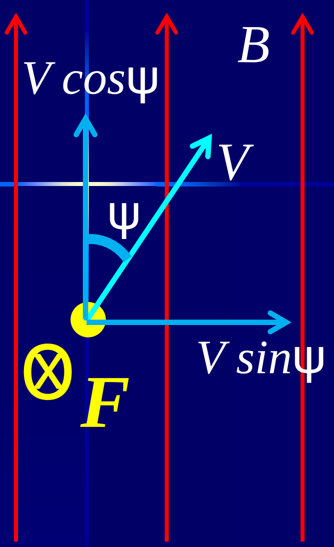
The **ion gyro-frequency** is determined by;

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

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

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.

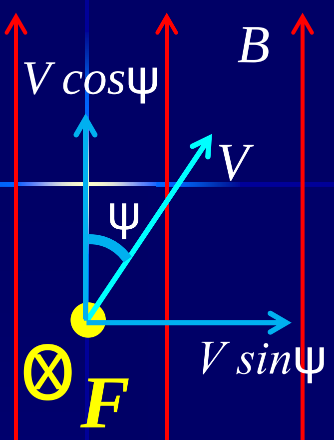
An example : For e^{n}s : $f_H = 1.68\,MHz$

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



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

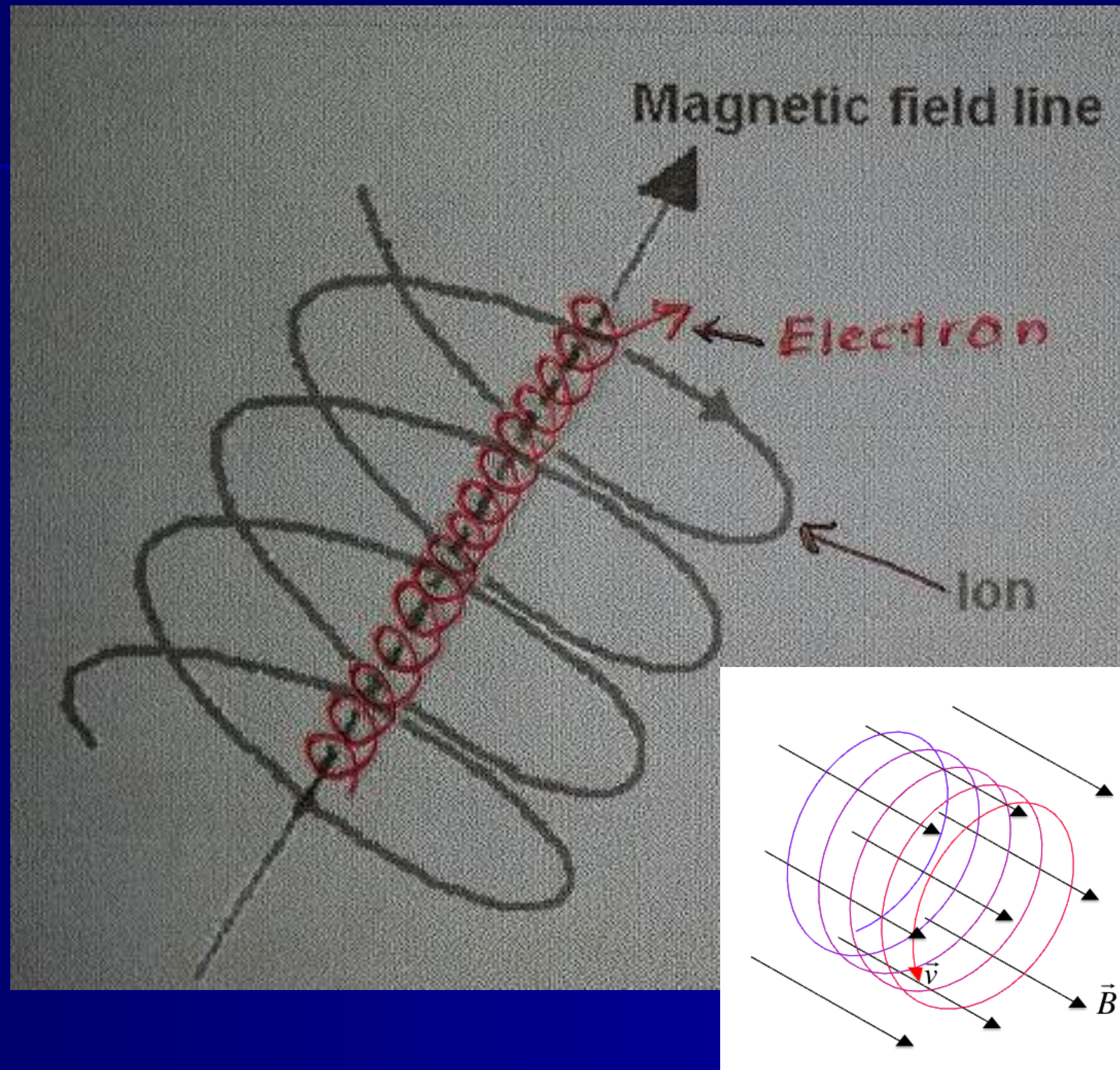
For e^ns

$$f_H = 1.68\,MHz$$

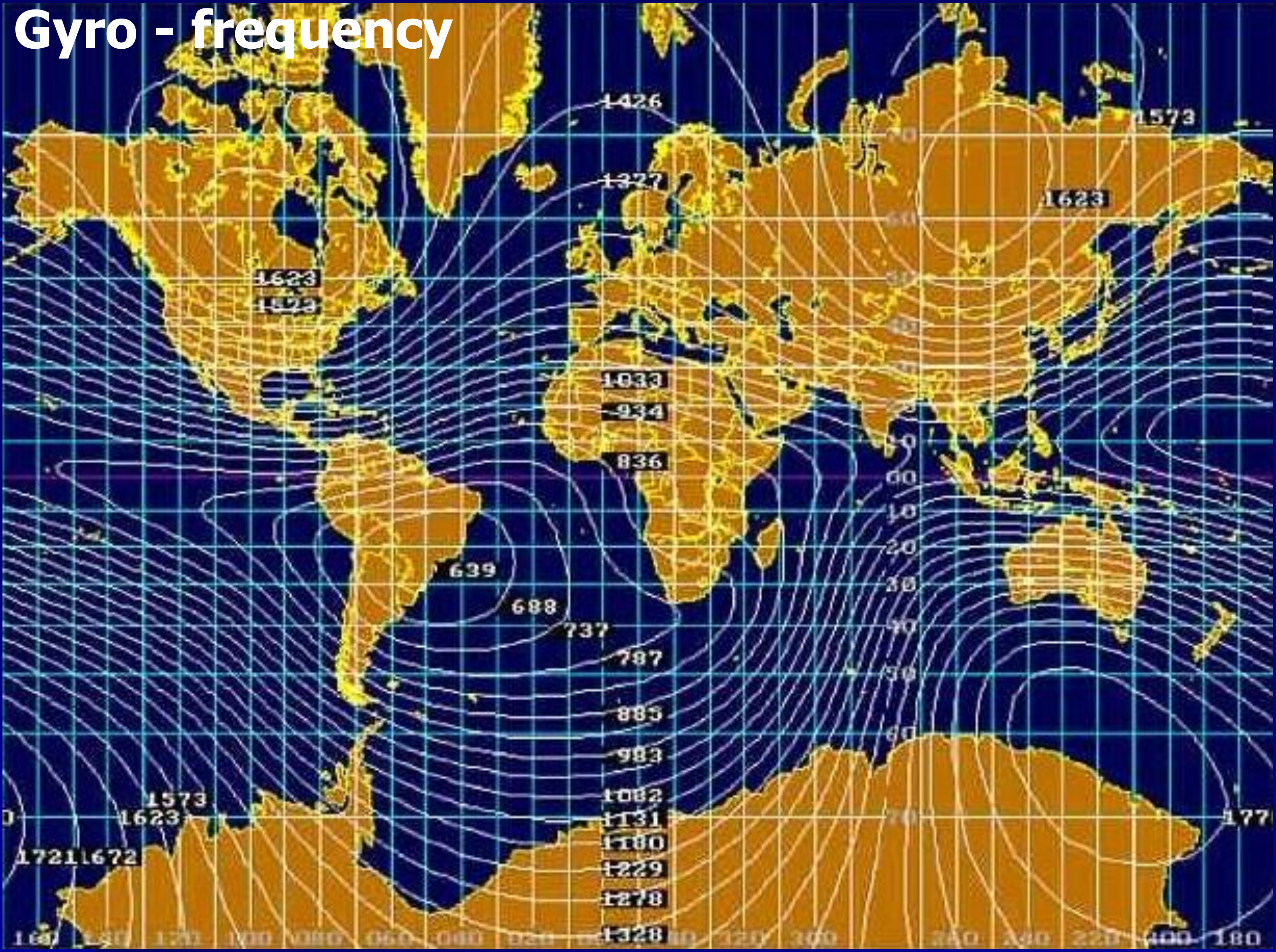
For O+ ions

$$f_H = 48\,Hz$$

Because, $M \gg m$



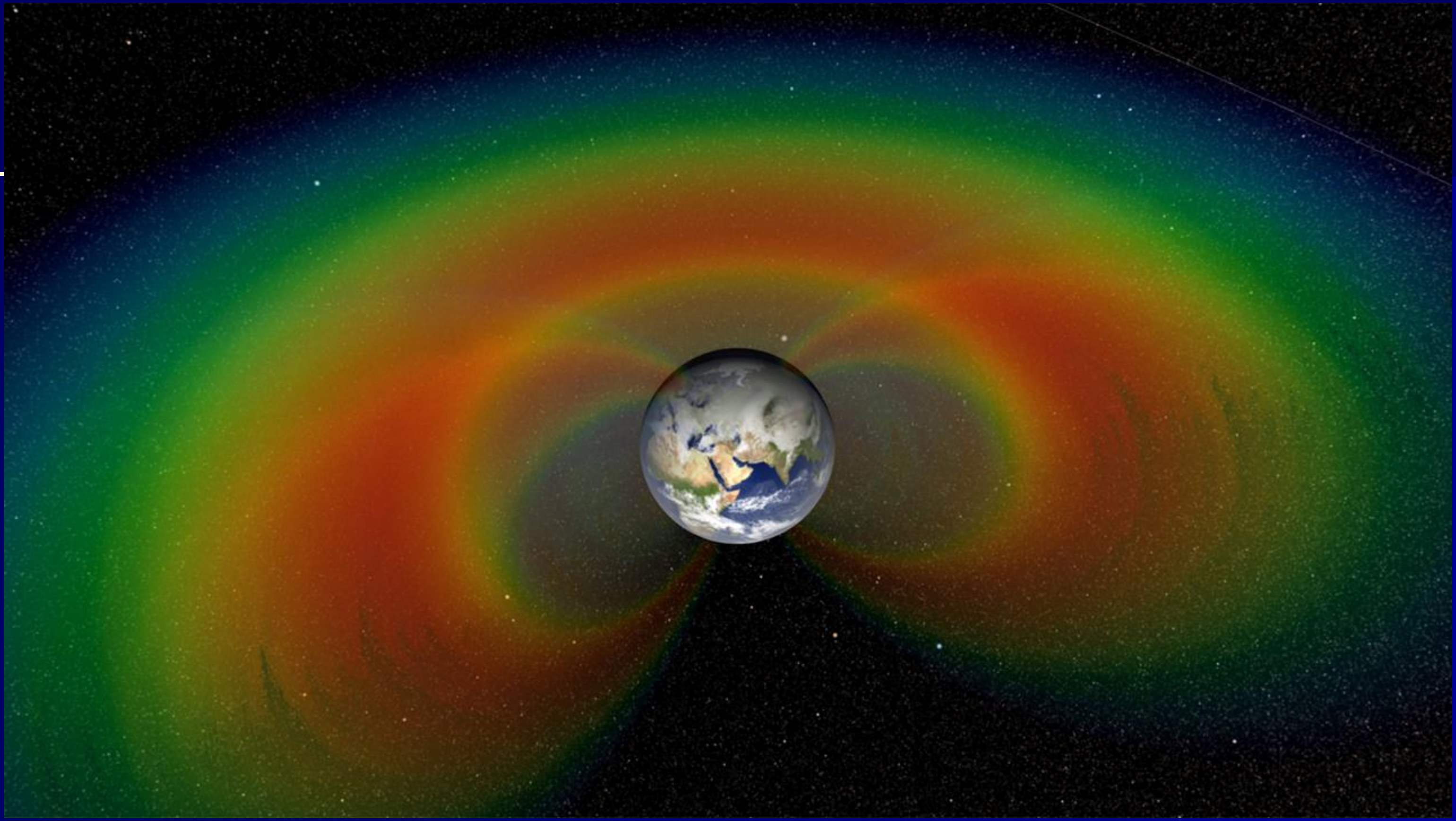
Gyro - frequency



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

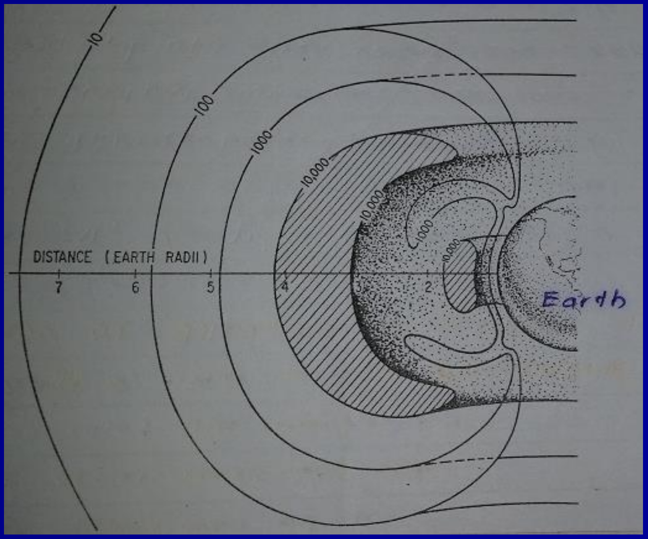
Reading from this counter were obtained only when the satellite passed above a small number of tracking stations. When the satellite pass was a low one, the counting rate was the one expected from the known cosmic ray flux when explorer-I was near apogee (very far place of the planetary orbit from the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

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**.

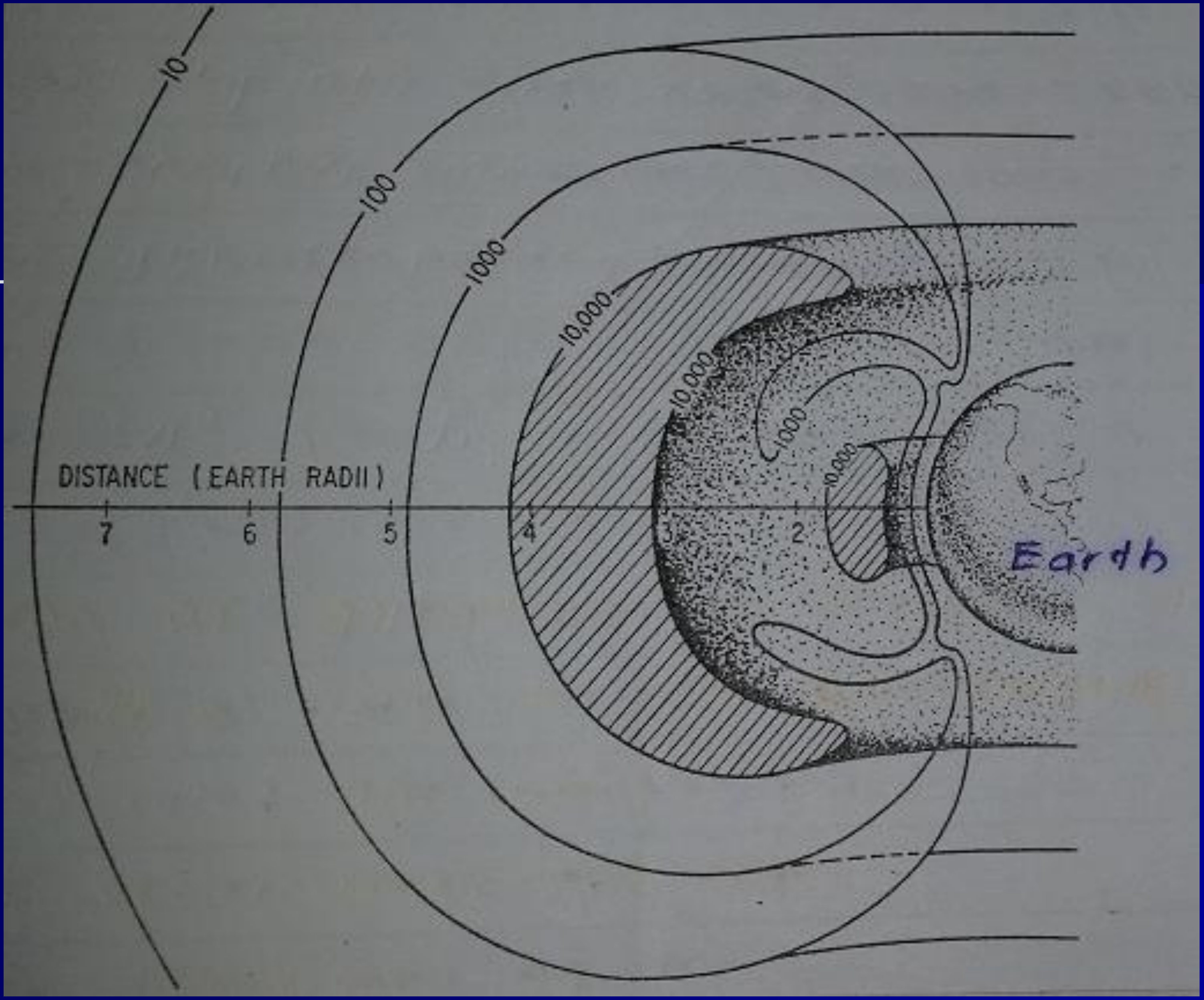
The Radiation Belts

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**.

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



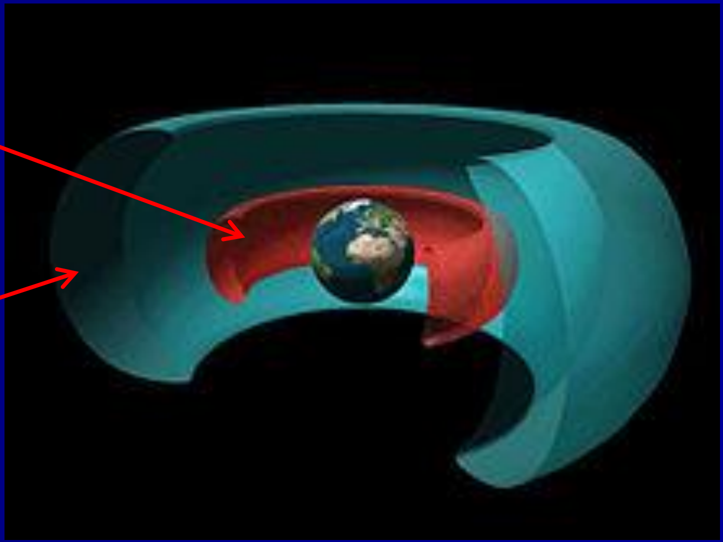
The inner and the outer radiation belts as they were first mapped by **Van Allen's group** of the University of Iowa (White, 1970)

The Radiation Belts

This diagram depicts counting rates of particles energetic enough to penetrate the shielding of 1.0 gr/cm² of lead which covered the approximately 1cm² 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 first counters could not differentiate between energetic protons and energetic electrons.

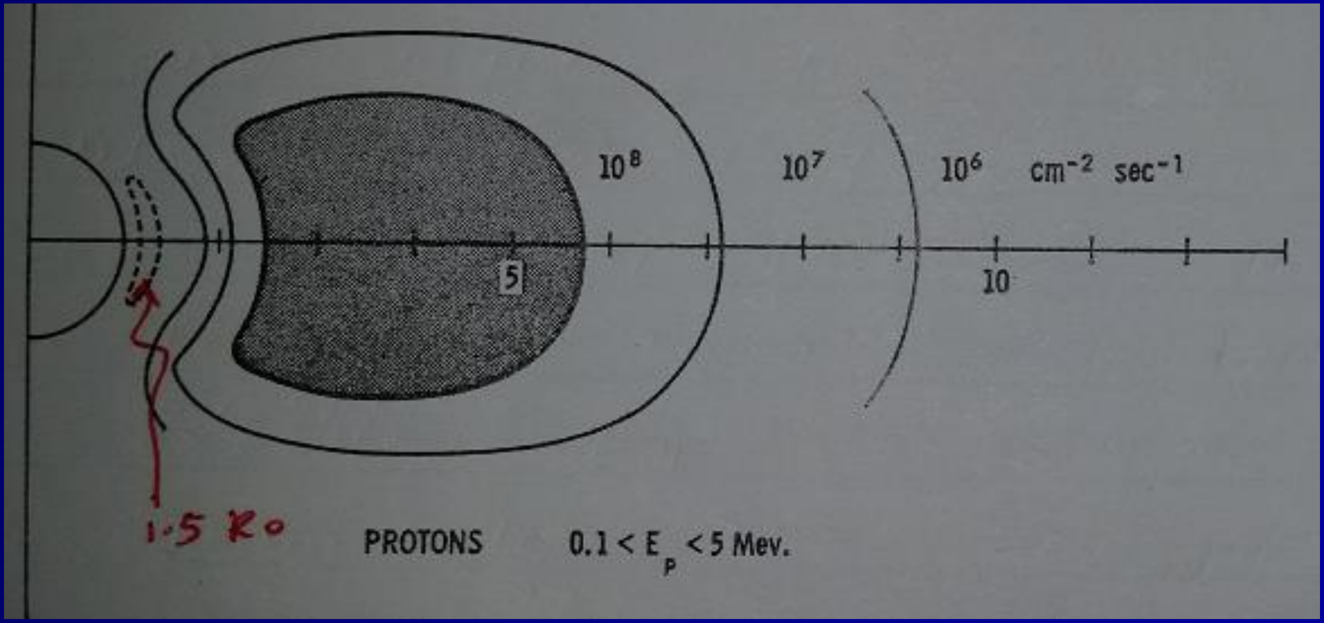
- Today we know that the high counting rates of the **inner belt are produced by energetic protons** with energies in the 10 to 100 MeV range, while the high counting rates of the **outer belt are produced by high energetic electrons** with energies in the 1 MeV range and above.



The Radiation Belts

- 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 R_o** but for protons of lower energies the peak of the belt moves farther out and the width of the belt increases considerably.

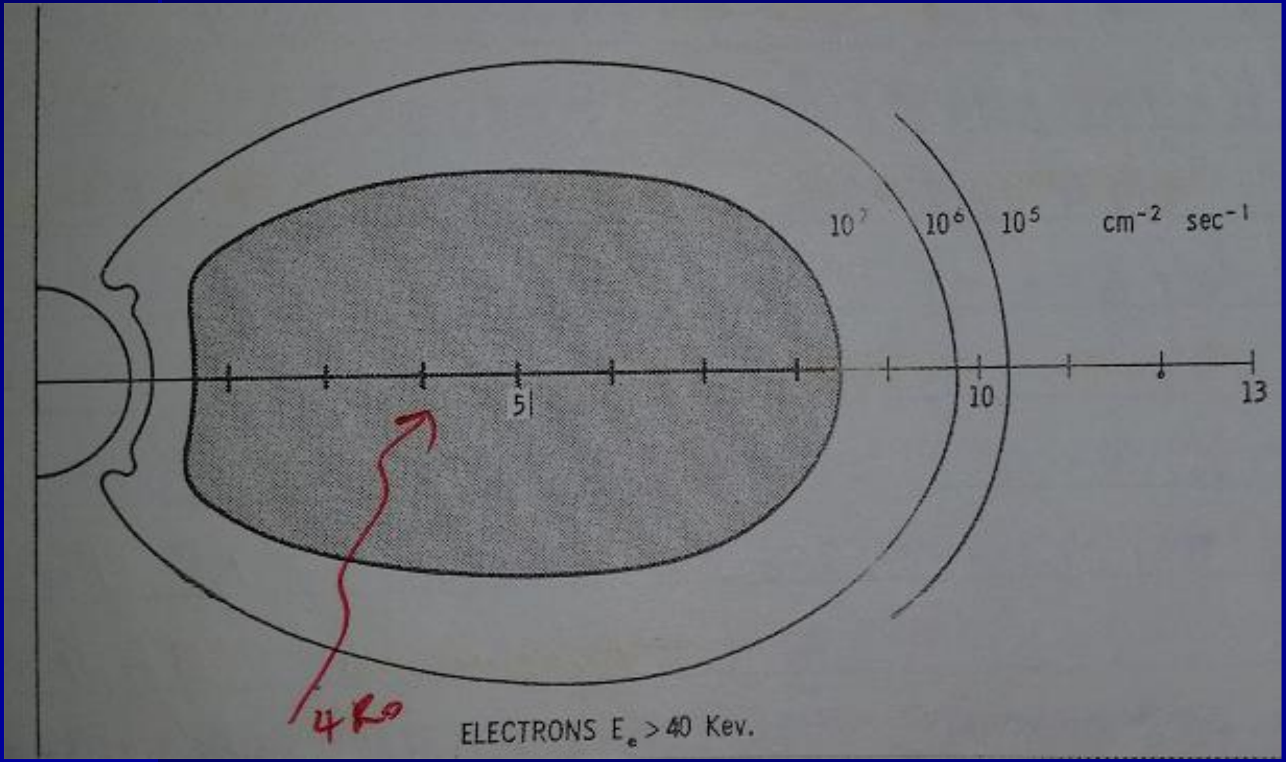


The spatial distribution of **trapped protons** of different energies (Hess and Mead, 1968)

The Radiation Belts

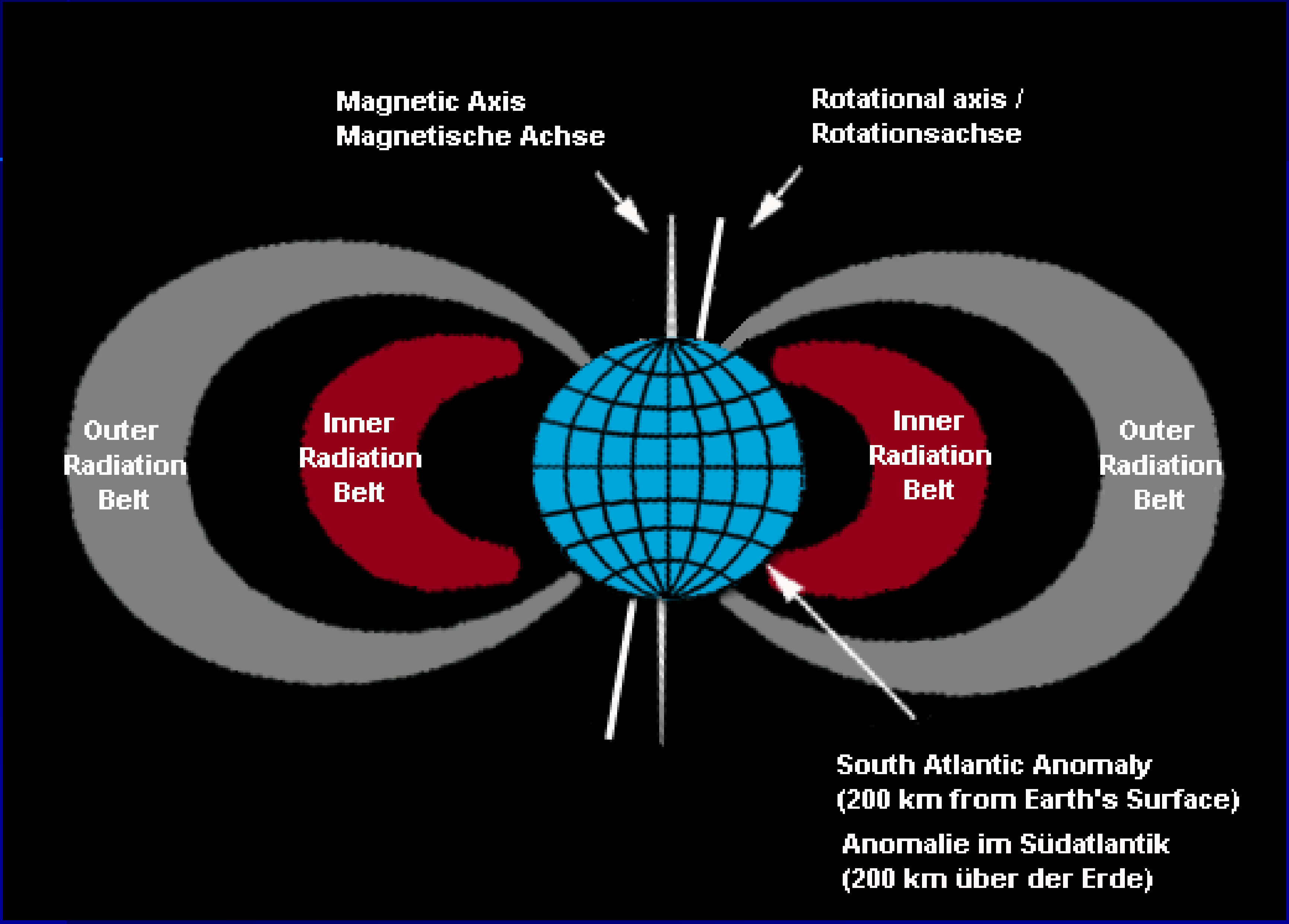
The same is also true for the **energetic electrons of the outer belt**.

- 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.

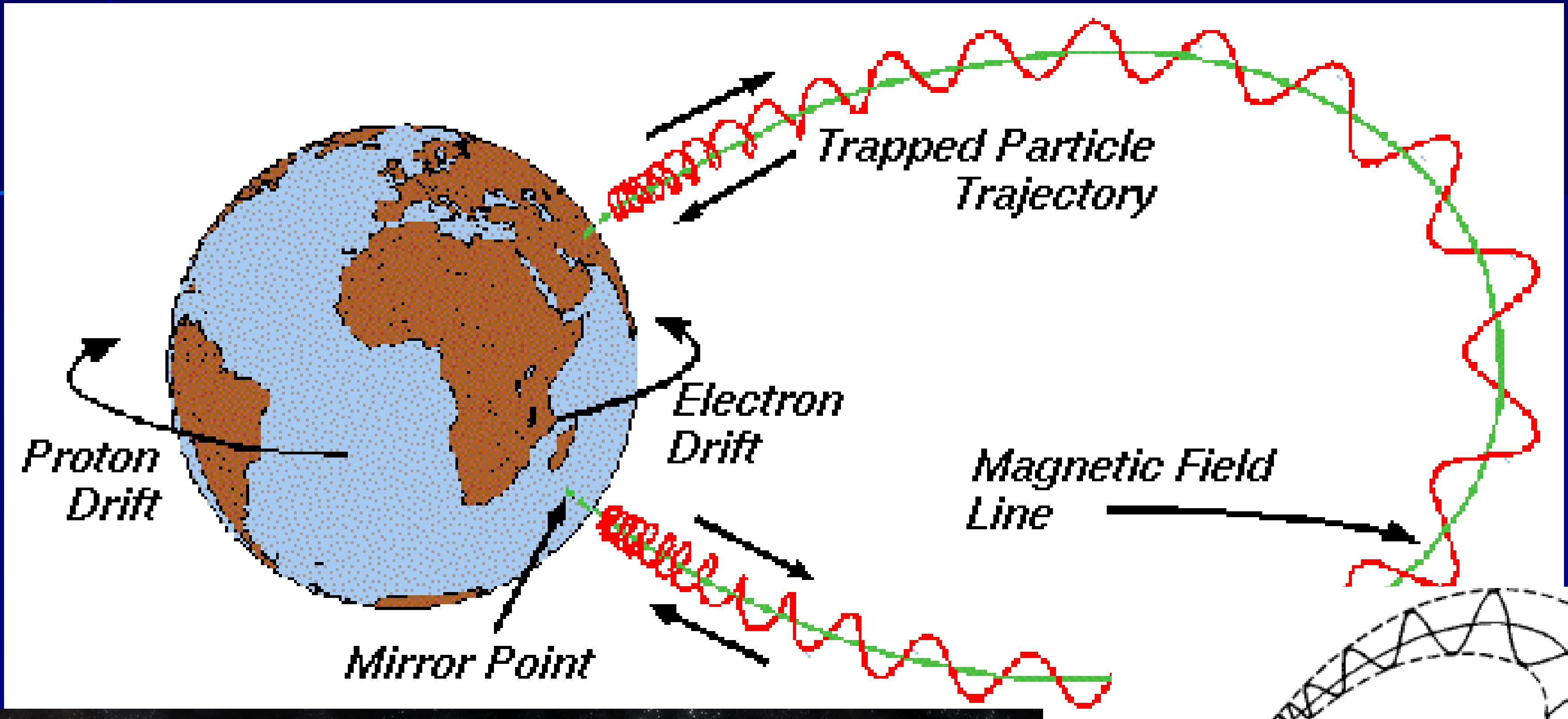


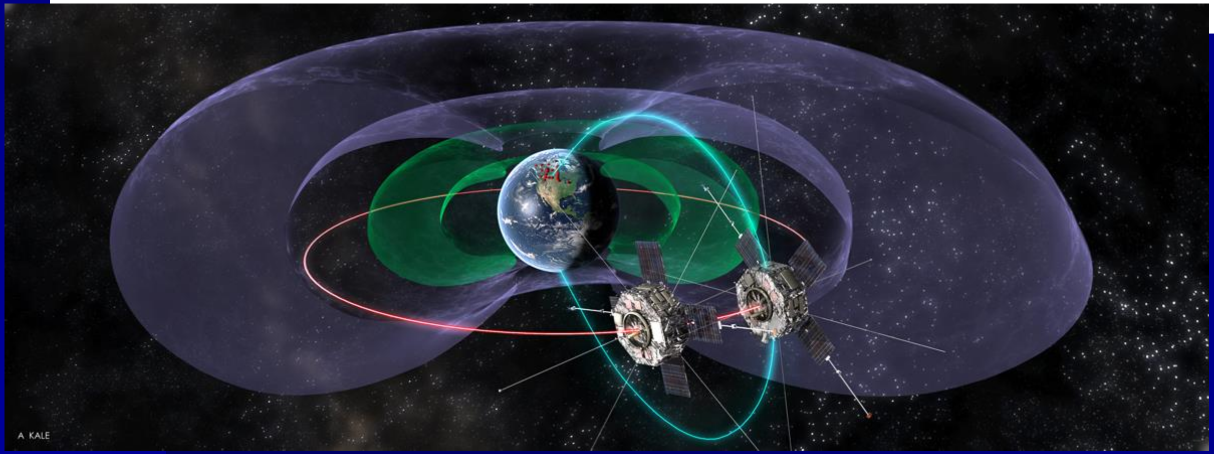
The spatial distribution of **trapped electrons** of different energies (Hess and Mead, 1968)

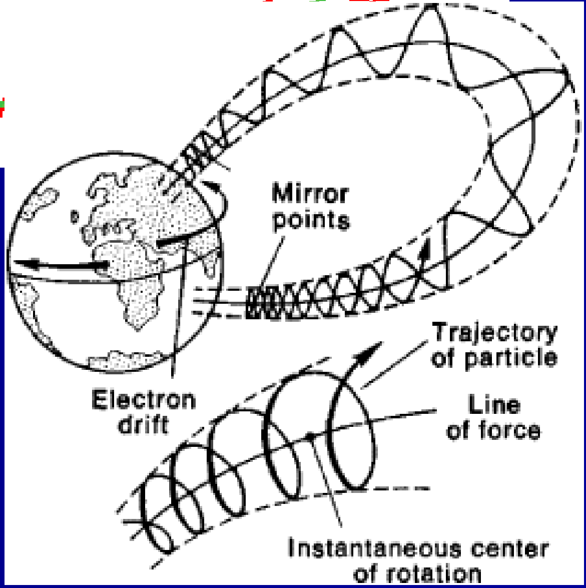
The Radiation Belt



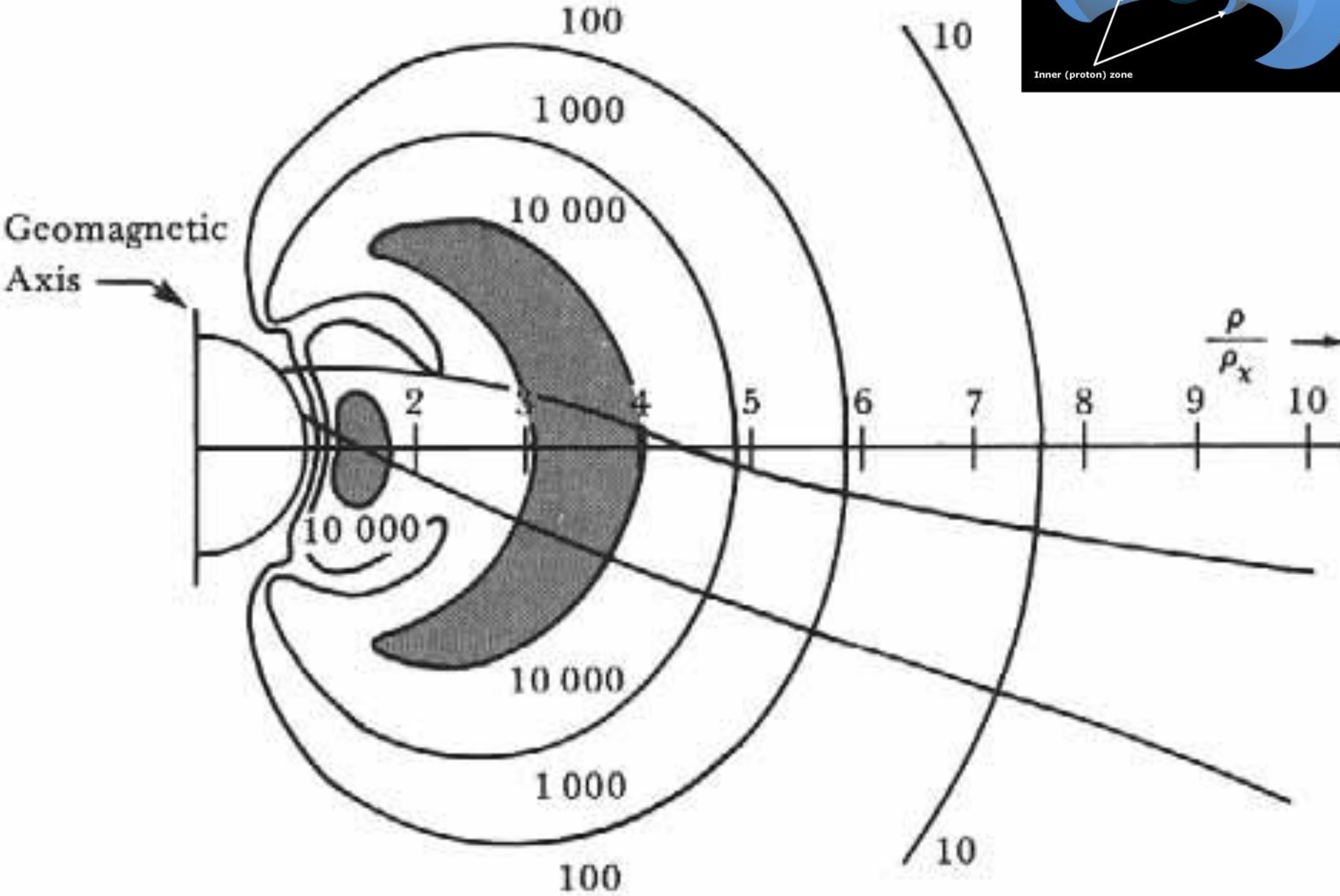
The Radiation Belts

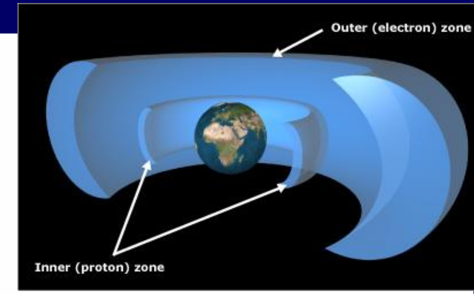






Radiation Belts

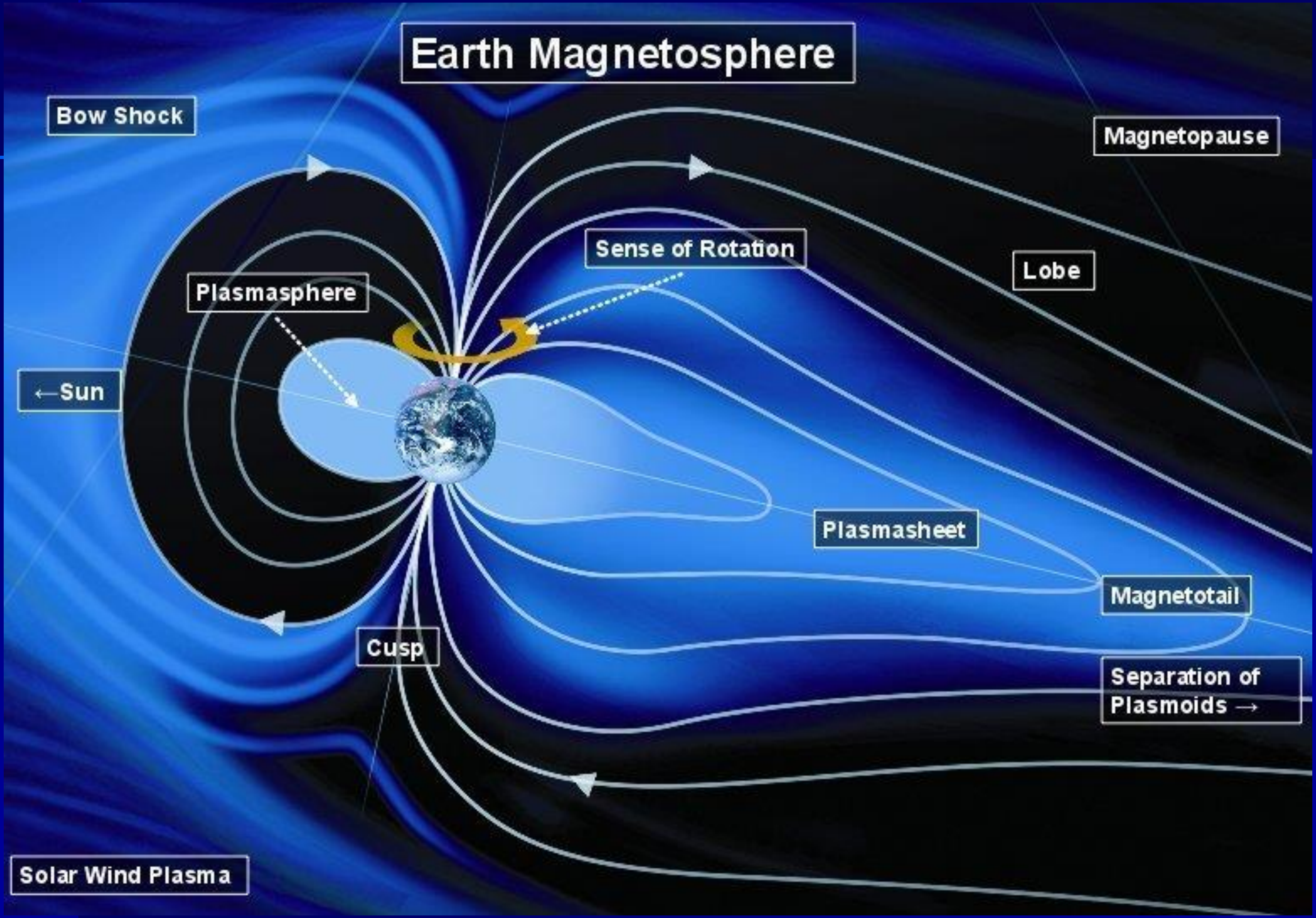




The Magnetosphere

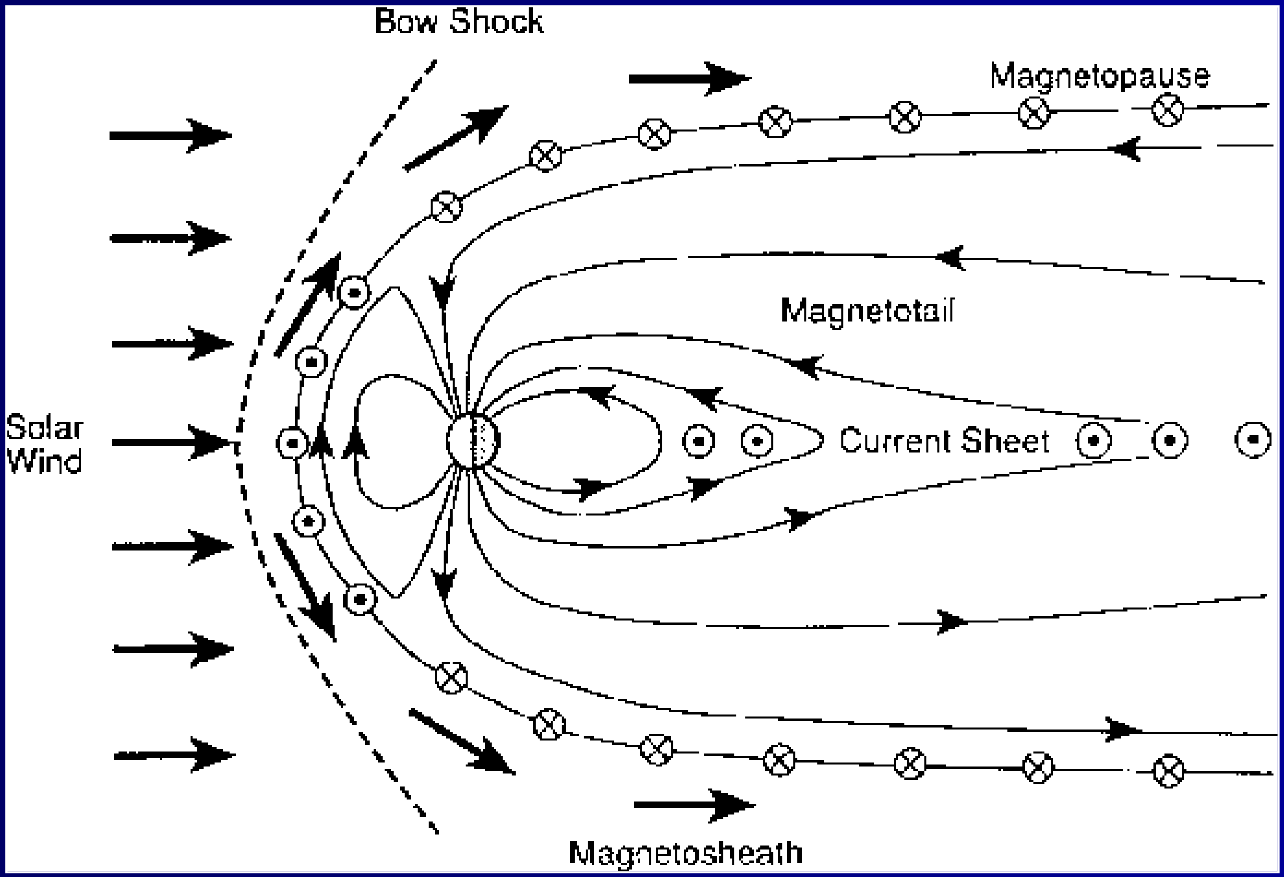
The Earth's Magnetic Fields
The Dipole Magnetic Field
Motion of charged particles in a Dipole Magnetic Field
The Radiation Belts
The boundary and the tail of the Magnetosphere

The 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.

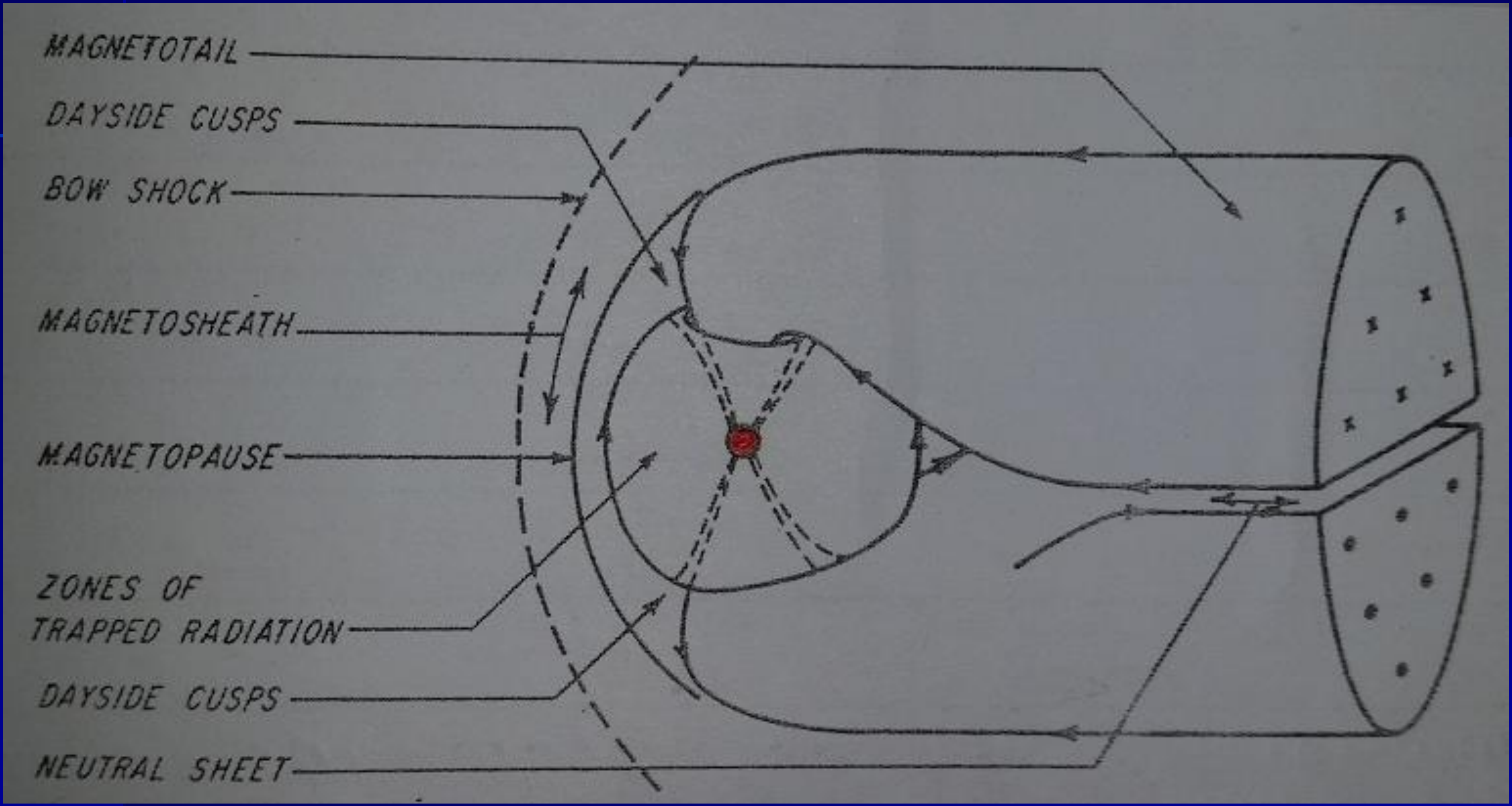


The Boundary and the Tail of the Magnetosphere

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.

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**.

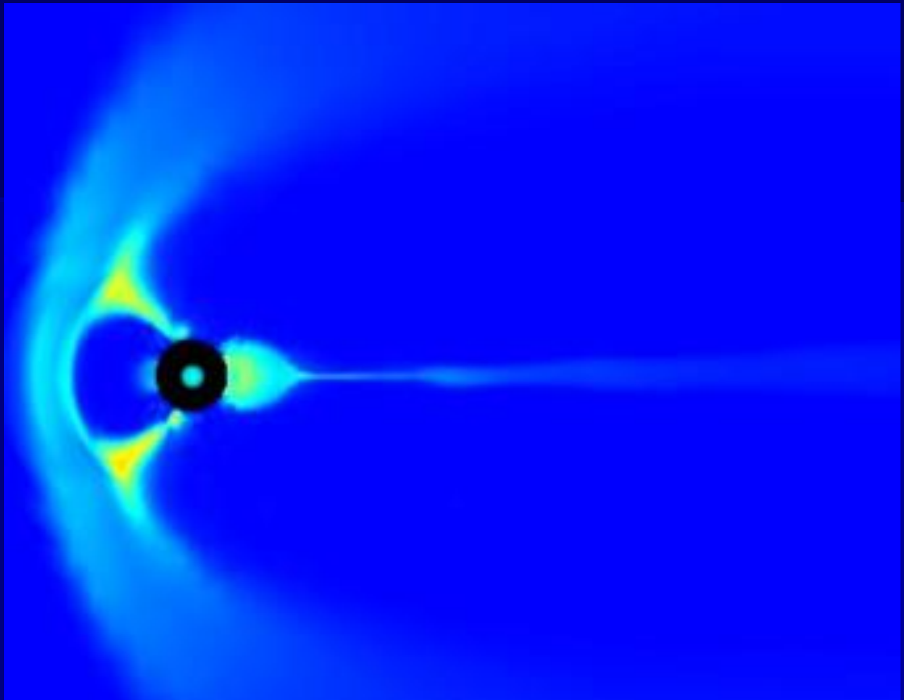
The Boundary and the Tail of the Magnetosphere



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 **R_t** is approximately **22 R_o** and remains the same for at least **100 R_o**.

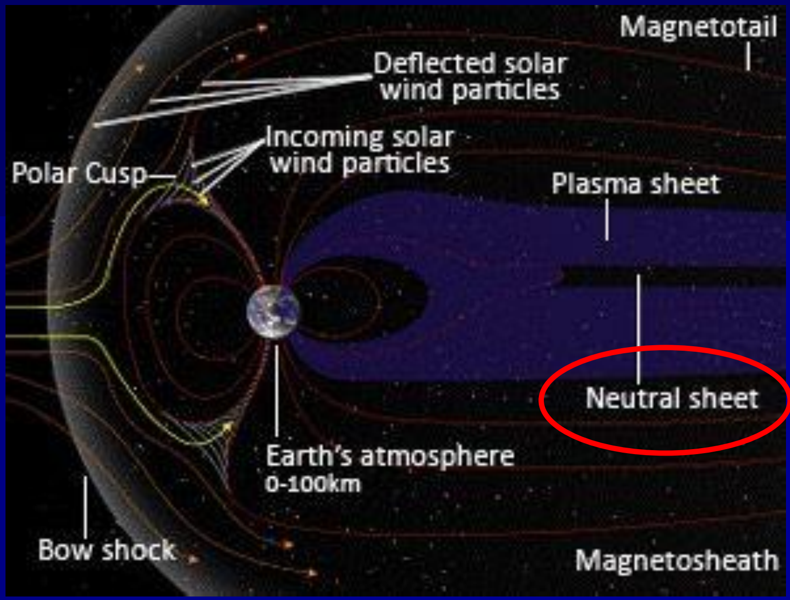


The formation of the geomagnetic tail from the magnetic field lines of the polar caps which are swept in the anti-solar direction by the solar wind.

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**.

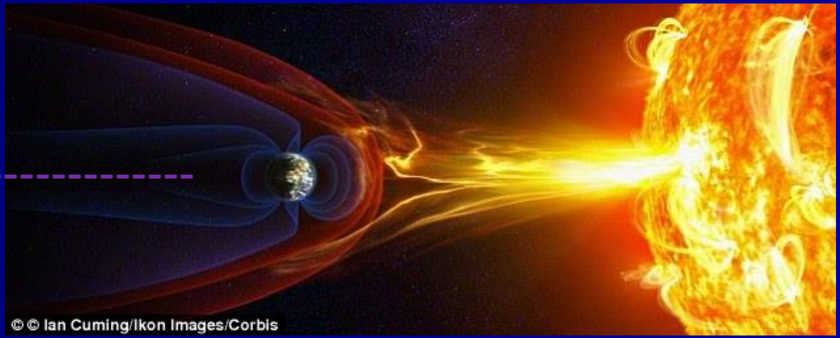
The Boundary and the Tail of the Magnetosphere

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**.



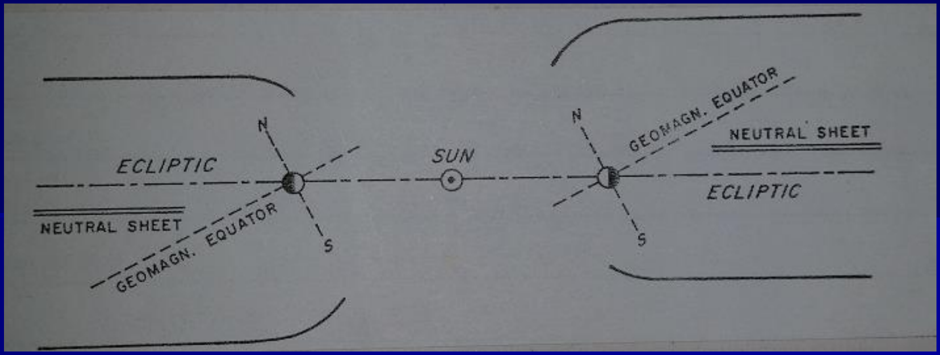
The **magnetic tail** of the Earth's magnetosphere has been detected with certainty by satellites orbiting the moon so that it definitely extends beyond **half a million kilometers**. Mariner-4 has found no evidence of the tail at **3,300 R_o**, whereas observations with Pioneer-7 near **1000 R_o** were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



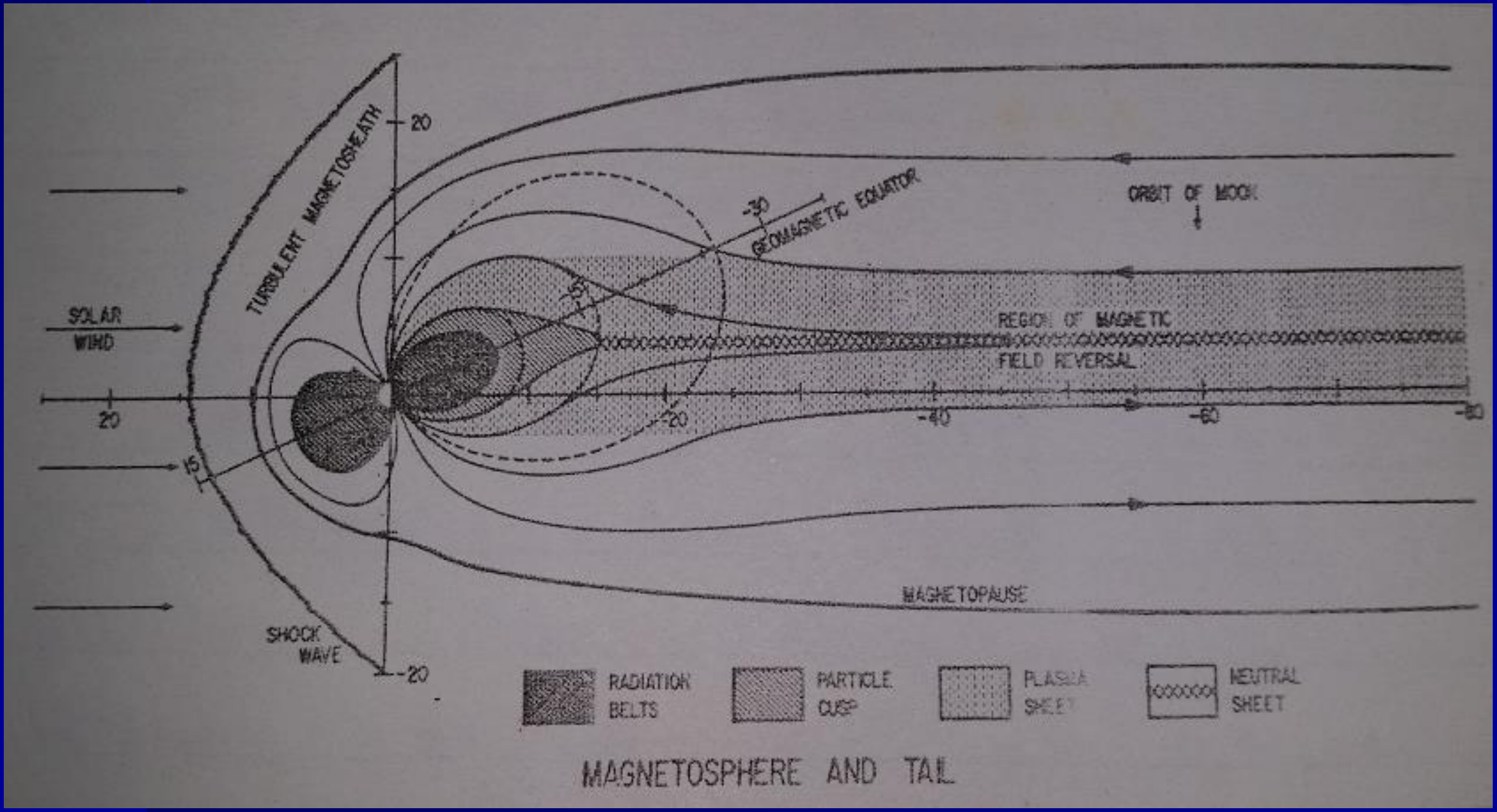


Fig-2 : The detail summary diagram of the Earths magnetic cavity (Ness, 1969)

The Boundary and the Tail of the Magnetosphere

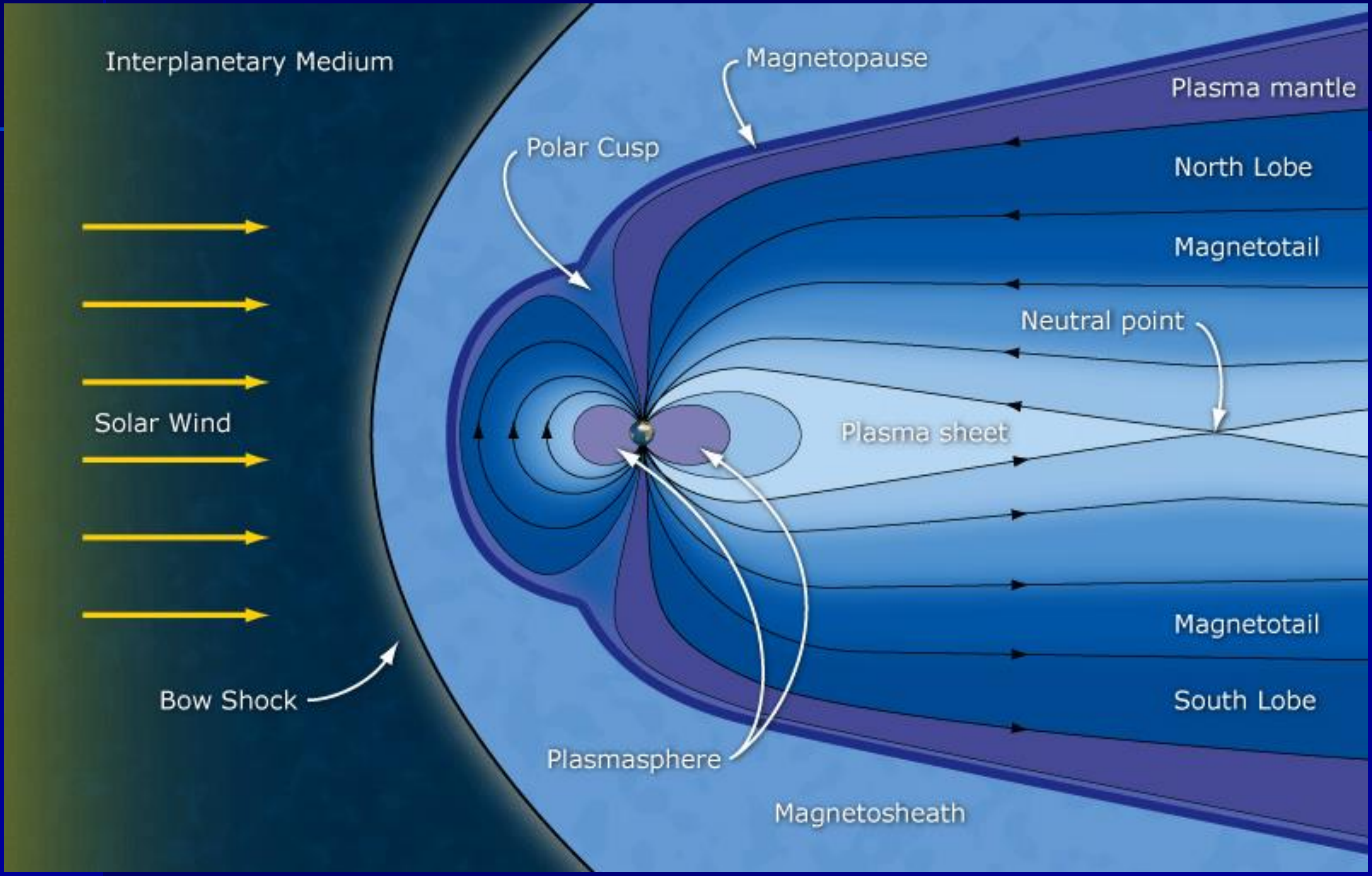
Thus it appears that the magneto tail, or a magnetosphere wake behind it after the field lines close extends for at least **several hundred Earth radii**. The plane of the neutral sheet is parallel to the plane of the ecliptic but, as seen from figure-1, it is displaced by a few Earth radii toward the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

On both sides of the natural sheet satellites have found **high fluxes** [10^8 - 10^9 en / (cm²)] 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 R_o.

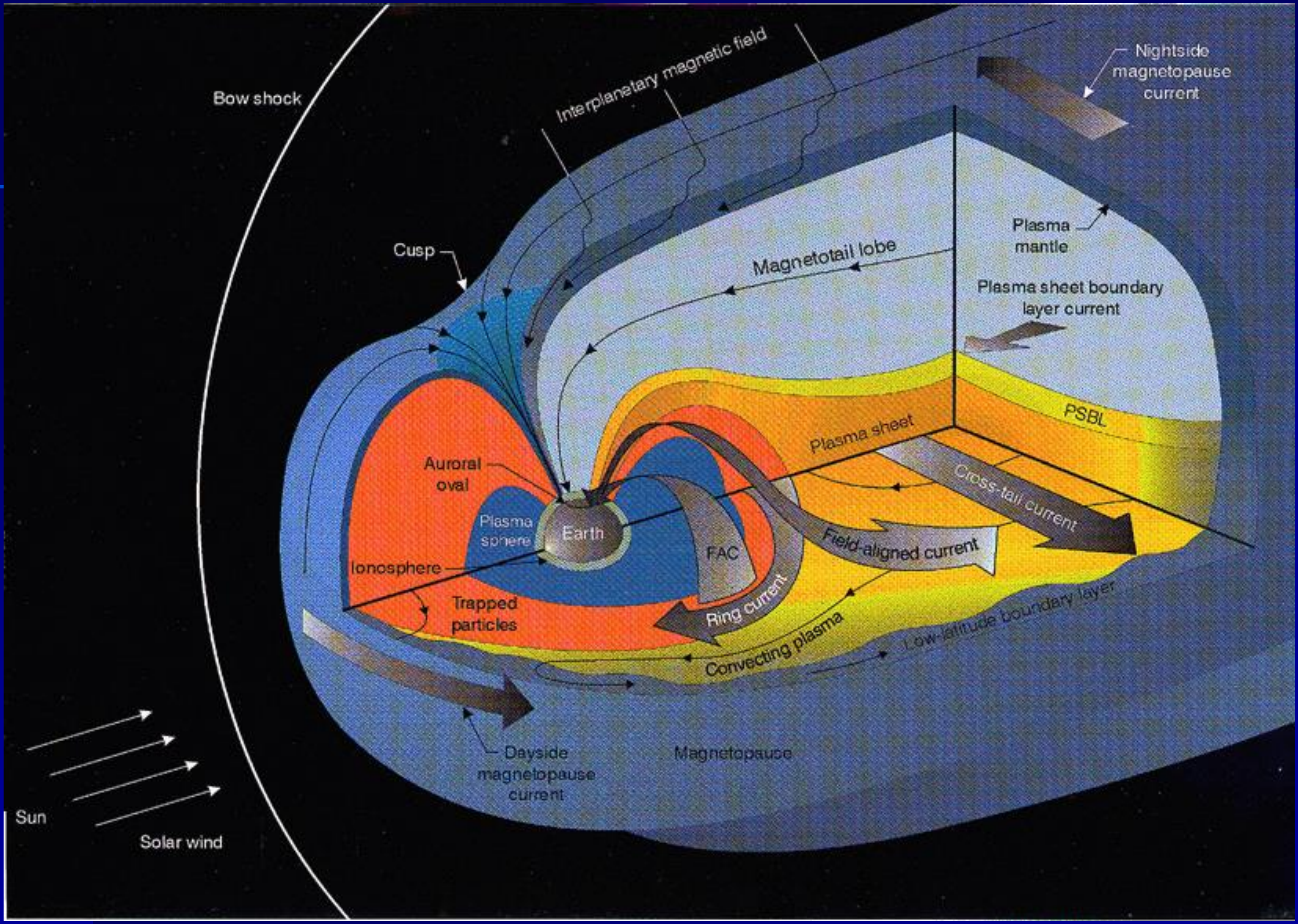
Anderson (1965) has also observed “ **islands** " of energetic particles inside the space of the **magnetotail**. The energies of the electrons in these islands are of the order of 100 keV and the fluxes measured reached 10^7 en en / (cm²).

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



PHY 497 2.0 – Space & Atmospheric Physics
Continuous Assignment – 10

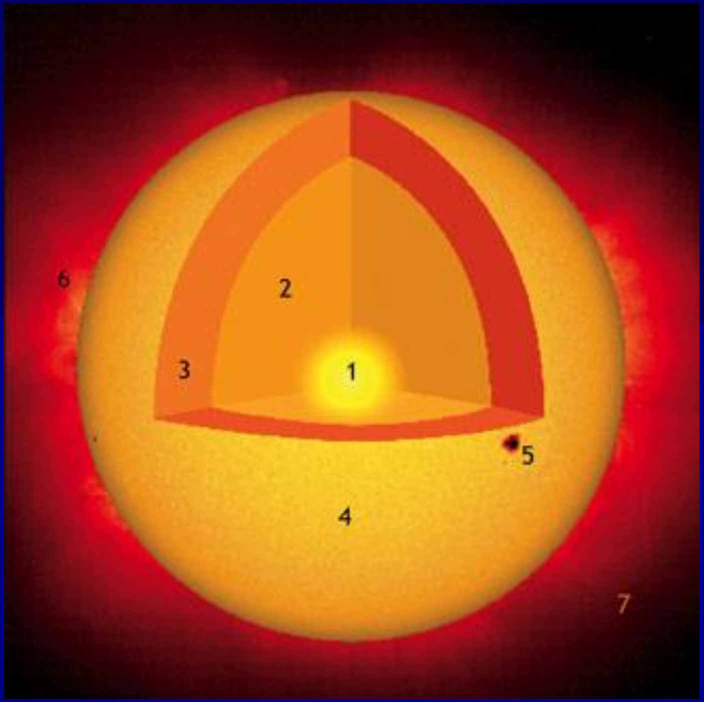
- The intensity of the Earth's Magnetic Field at the equator is 40,000 nT.

(a) Find the Earth Dipole Moment assuming the centered dipole which fits best the Earth's Magnetic Field. ($\mu_0 = 45\times10^{-7}$ Nm^2 wb^{-2} and the radius of the Earth is 6.4×10^6 m)

(b) Hence, Find the Magnetic Field intensity at the poles of the Earth.

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

The Active Sun



The Sun and Stars
Introduction of the Active Sun
The Photosphere
The Chromosphere and the Corona
Sunspots and the Solar Cycle
Faculae, Flares and Prominences
Radio and X-ray Bursts from the Sun
The Development of an Active Region on the Sun
Effect of the Solar Cycle
Life Cycle of the Sun

The Active Sun

Introduction

The sun is a star of mass $M = 1.99 \times 10^{30}$ kg, radius $R = 6.96 \times 10^{8}$ m and effective temperature $T = 5750$K. The total energy radiated by the Sun per second, i.e. its luminosity L is ,

$$L = 4\pi R^2 . \sigma . T^4$$

$$L = 4\pi (6.96 \times 10^{8})^2 . (5.67 \times 10^{-8}) . (5750)^4$$

$$L = 3.77 \times 10^{26}\ Js^{-1} (W)$$

Using Stephan's Law

$$E = \sigma\ T^4$$

Energy density per second

$$E = A\ \sigma\ T^4$$

Total Energy per second

The Sun is a main sequence **G2 star** (A star is between super giant and bright giant), approximately **5 billion years old**. In many ways it is a very representative star and it is estimated that it will remain essentially in its present state for at least another 5 billion years.

The Active Sun

The energy of the Sun is produced mostly **through the proton-proton nuclear reaction near its center** where the temperature is close to **10^7 K**. **The carbon nuclear cycle makes also a small contribution to the total energy produced**. In both of these processes the end result is that **4 Hydrogen atoms fuse together to form a Helium atom** with the release of approximately **25 MeV**. By comparing this number with the total luminosity of the Sun we see that nearly **10^{38} such fusions** must place **per second** which means that about **6.4 x 10^{11} kg of Hydrogen "burn" per second to Helium**. In this transmutation **0.7% of the mass becomes energy** ($E=mc^2$) and therefore about **4.5 million tons** of **solar matter are converted every second** into energy.

The Sun is a **gaseous sphere** rotating with an average period of **27 days**. The word "average" is used because the **Sun possesses a differential rotation, i.e., its rotational period varies with latitude**. The fastest rotation occurs at the equator where the **sidereal** (with respect to the stars) **period** is very close to **25 days**. The rotation slows down with increasing latitude becoming longer than **30 days near the poles**.

The Active Sun

An expression which gives to a good approximation the **daily sidereal rotation**, in degrees, for different solar latitudes, **λ** is,

The daily sidereal rotation

$$\emptyset = 14.4° - 2.8° \sin{}^{2}\lambda$$

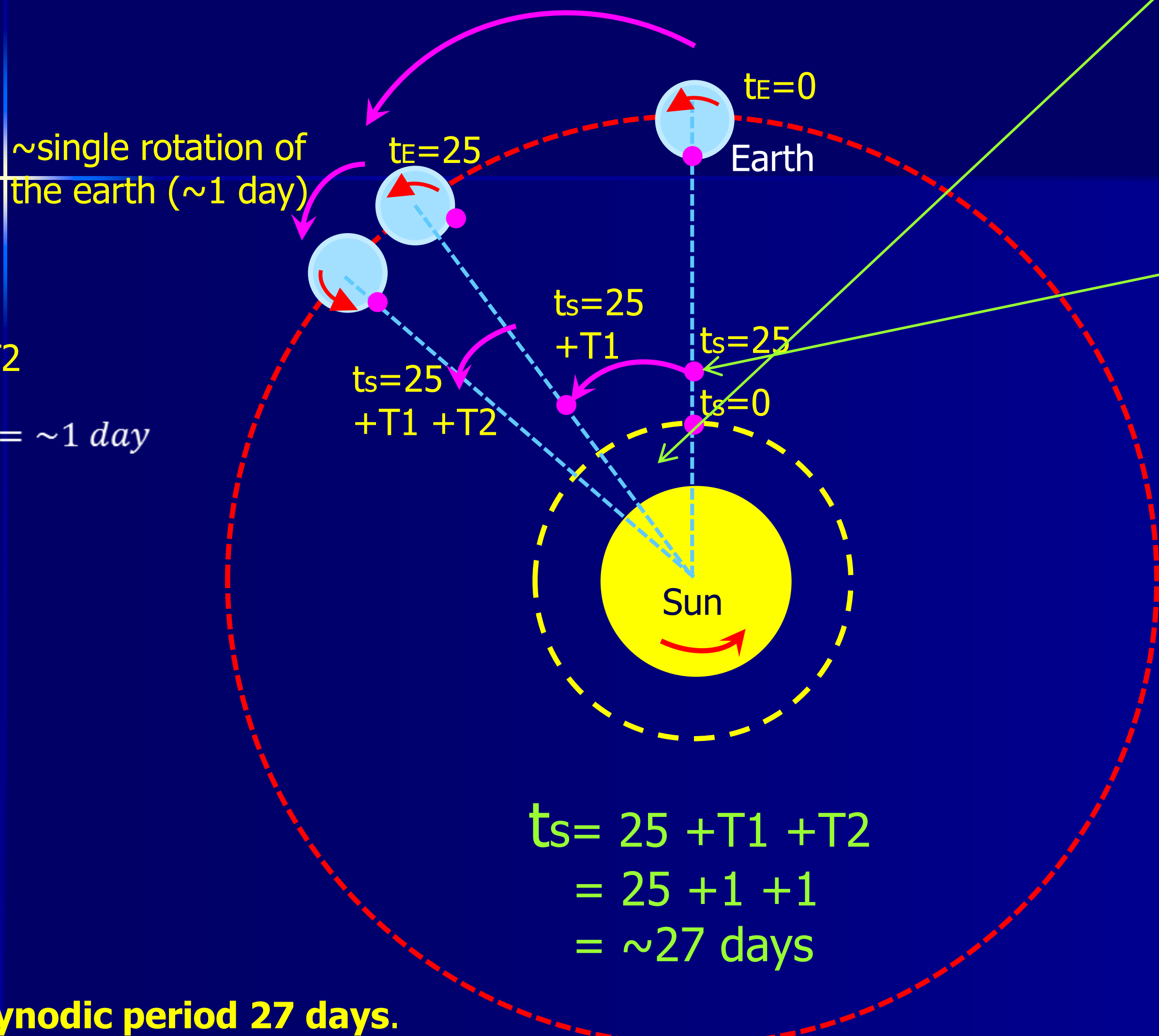
Solar latitudes

$$Rotation\ period\ at\ latitude \quad \lambda = \frac{\mathbf{360°}}{\emptyset} \quad (days)$$

It should be mentioned that for a terrestrial observer the Sun appears to rotate with a longer period, called the **synodic period** (moon month) which for the equatorial regions, is close to **27 days**. **The reason of course is that the Earth advances by approximately 1 degree per day in its orbit around the Sun and after 25 days a point near the equator of the Sun needs roughly two more days to reach the new angle of the Earth**. There is no generally accepted explanation on what causes and maintains the differential rotation of the Sun, but it is quite certain that it is responsible for the eleven year cycle of solar activity. Some scientists have suggested recently that the inner core of the Sun might rotate at a much faster rate, but this idea has not gained yet general acceptance.

The Active Sun

For Earth
1° (Sun) = 1 day (Earth)
25 days (Sun) = 25°



After single rotation of the Sun (~ 25 days)

Find T2

$$T2 = {\sim}1\ day$$

Find T1

$$\mathbf{360° = 25(\mathit{days})}$$

$$\mathbf{1° = \frac{25}{360°}}$$

$$\mathbf{25° = \frac{25}{360°}25°}$$

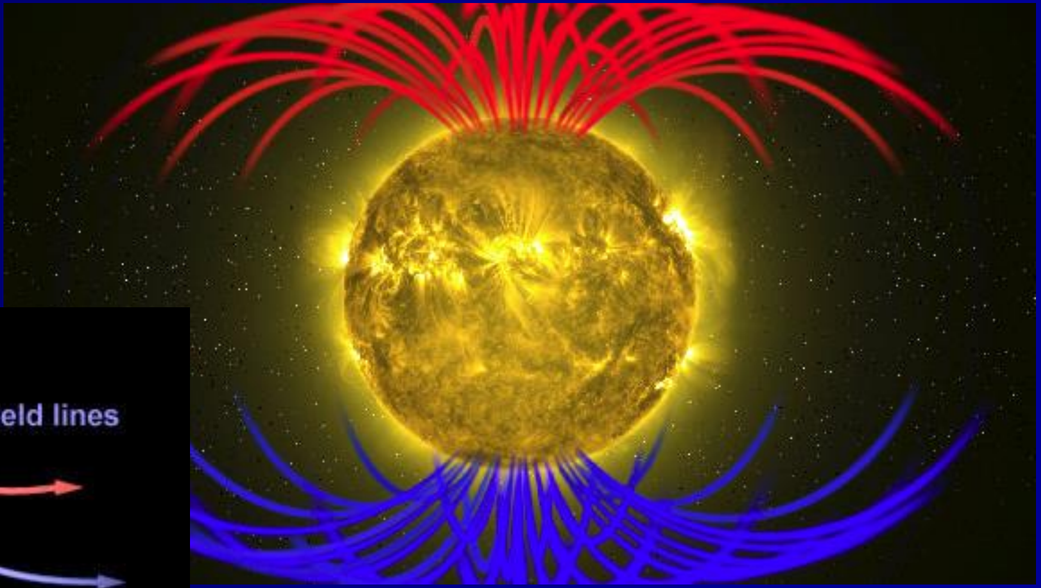
$$25° = {\sim}1\ day$$

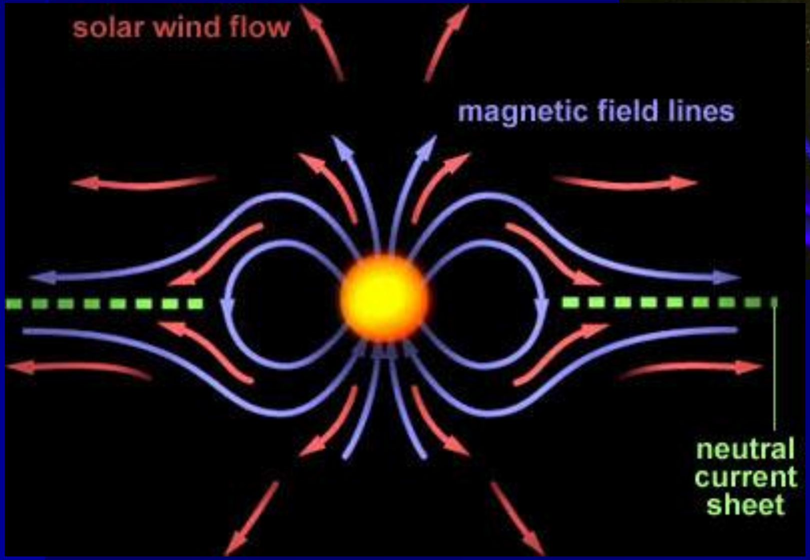
$$T1 = {\sim}1\ day$$

Sun - Synodic period 27 days.
The reason of course is that the Earth advances by approximately 1 degree per day in its orbit around the Sun and after 25 days a point near the equator of the Sun needs roughly two more days to reach the new angle of the Earth.

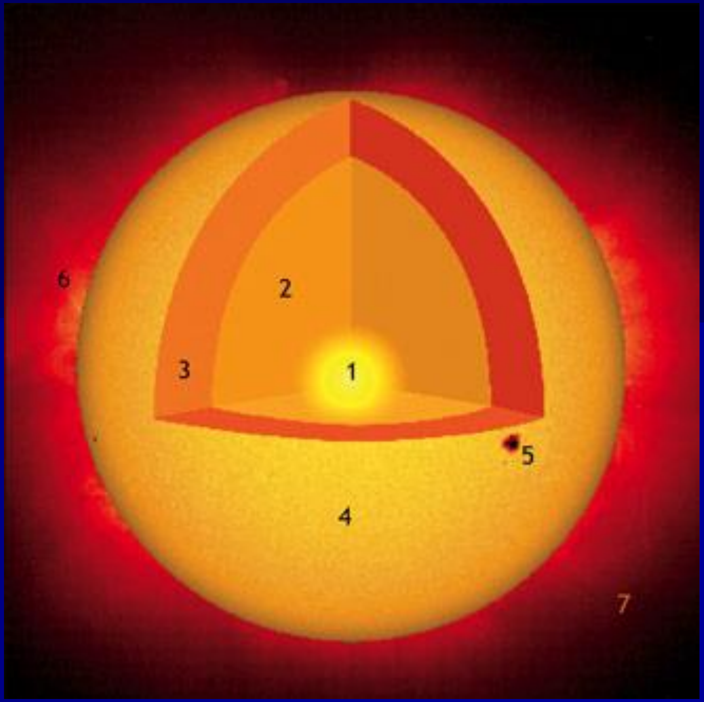
The Active Sun

The Sun possesses (with around) a rather **weak magnetic field** which reaches a typical value of a **few Gauss** on the surface on the Sun. Occasionally, the solar magnetic field displays transient (changeable) local enhancement where field intensities can reach values as high as several thousand Gauss.



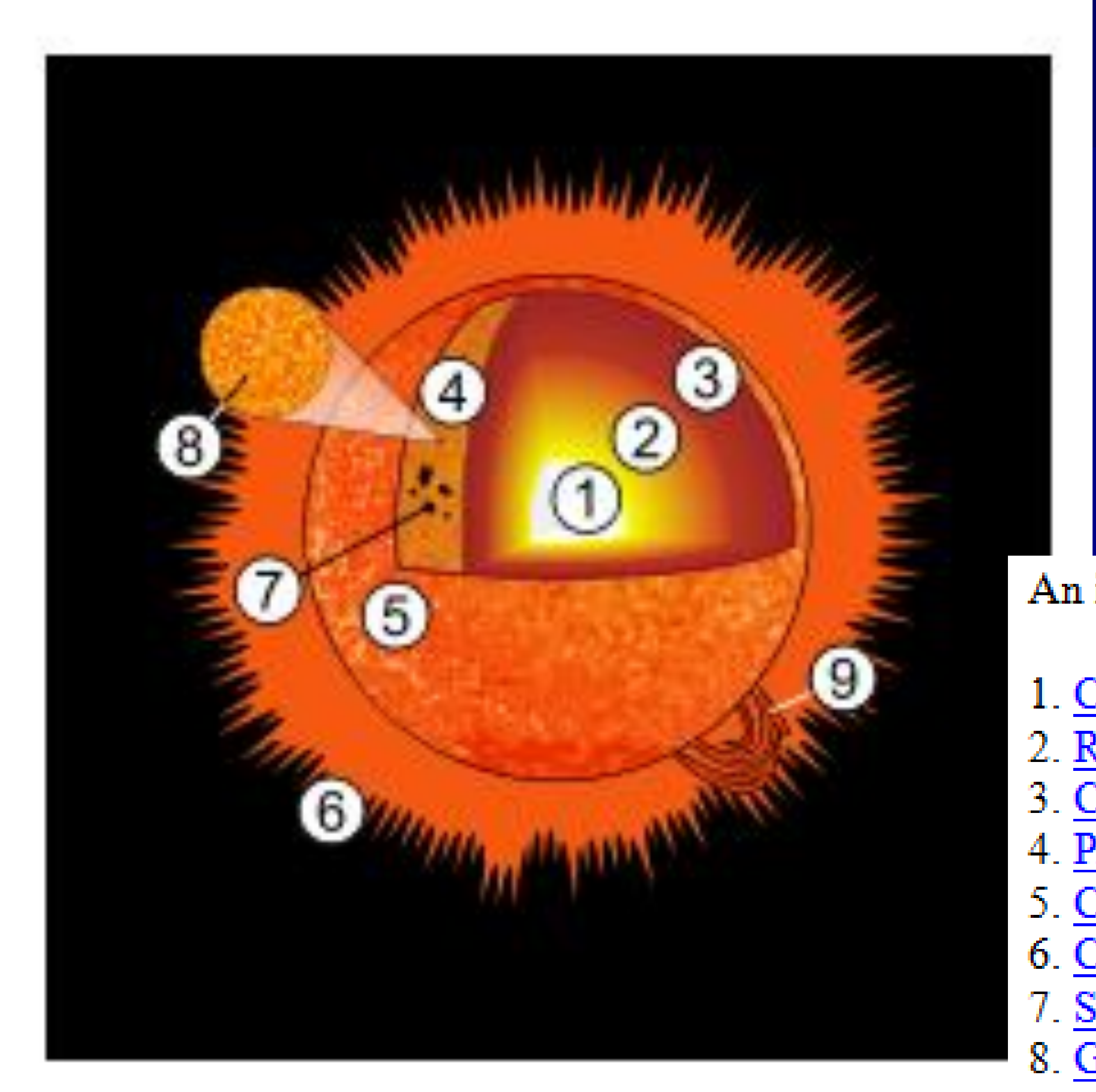


The Active Sun



The Sun and Stars
Introduction of the Active Sun
The Photosphere
The Chromosphere and the Corona
Sunspots and the Solar Cycle
Faculae, Flares and Prominences
Radio and X-ray Bursts from the Sun
The Development of an Active Region on the Sun
Effect of the Solar Cycle
Life Cycle of the Sun

The Structure of the Sun

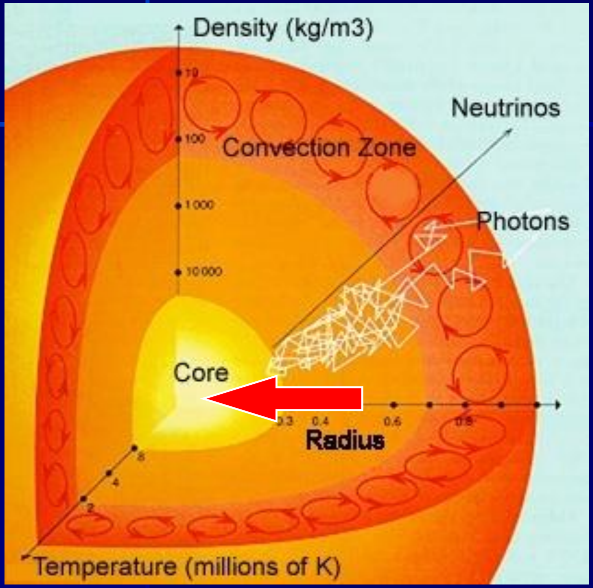


An illustration of the structure of the Sun:

1. Core
2. Radiative zone
3. Convective zone
4. Photosphere
5. Chromosphere
6. Corona
7. Sunspot
8. Granules
9. Prominence

The Structure of the Sun

Core



The core of the Sun is considered to extend from the center to about 20-25% of the solar radius. It has a **density** of up to **150,000 kgm^{-3}** and a **temperature** of close to **13.6 million Kelvin**.

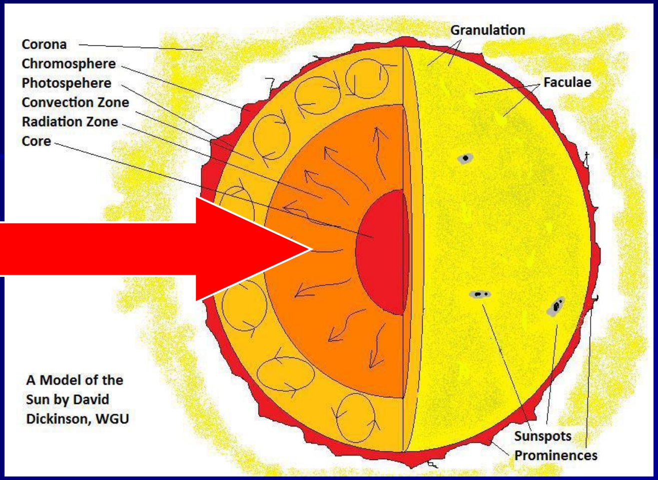
The core is the only region in the Sun that produces an appreciable amount of thermal energy through fusion; inside 24% of the Sun's radius, 99% of the power has been generated and by 30% of the radius, fusion has stopped nearly entirely.

The rest of the star is heated by energy that is transferred outward from the core and the layers just outside. The energy produced by fusion in the core must then travel through many successive layers to the solar photosphere before it escapes into space as Sunlight or kinetic energy of particles.

The proton-proton chain occurs around 9.2 x 10^{37} times each second in the core of the Sun.

The Structure of the Sun

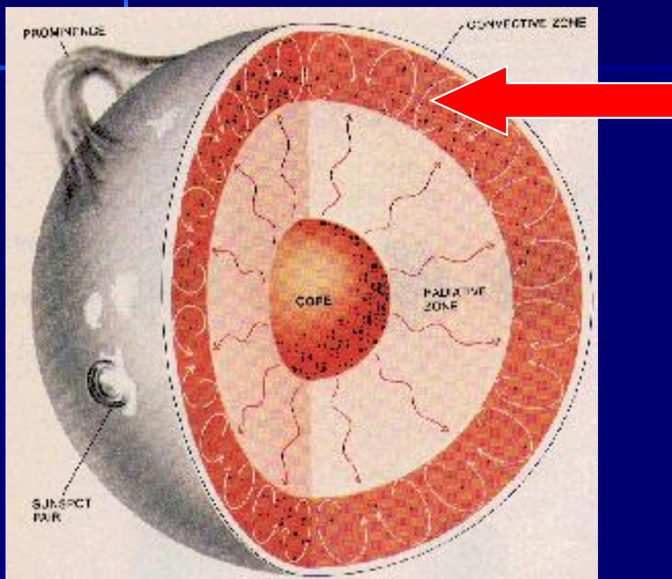
Radiative Zone



From about 0.25 to about 0.7 solar radii, **solar material is hot and dense enough that thermal radiation** is sufficient to transfer the intense heat of the core outward. This zone is free of thermal convention; while the material gets cooler from **7** to about **2 million Kelvin** with the increasing altitude, this temperature gradient is less than the value of the adiabatic lapse rate and hence can not drive convection. Energy is transferred by **radiation-ions** of **hydrogen** and **helium** emit photons, which travel only a brief distance before being reabsorbed by other ions. The **density drops from 20 x 10^3 kgm^{-3} to only 0.2 x 10^3 kgm^{-3} from the bottom to the top** of the radiative zone.

The Structure of the Sun

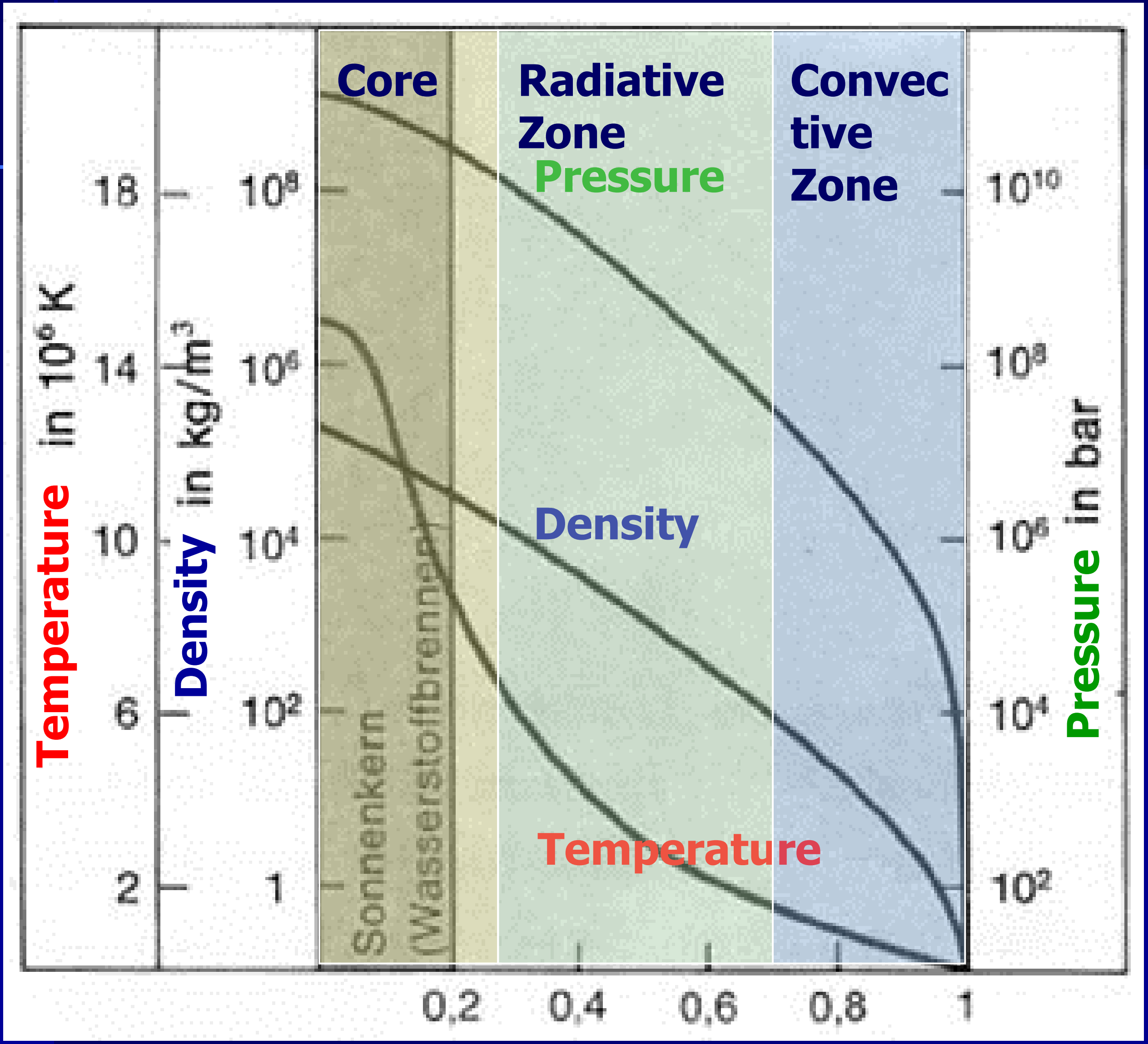
Convective Zone



In the Suns outer layer, from its surface down to approximately **200,000 km** (or 70% of the solar radius) the solar plasma is not dense enough or hot enough to transfer the thermal energy of the interior outward through radiation; in other words its opaque enough. As a result, thermal convection occurs as **thermal columns** carry hot material to the surface (photosphere) of the Sun.

Once the material cools off at the surface, it plunges (suddenly sink) **downward to the base of the convection zone, to receive more heat from the top of the radiative zone**. At the visible surface of the Sun, the temperature has dropped to **5750 K** and the density to only **0.2 g/m^3**.

Pressure, Density & Temperature Inside the Sun



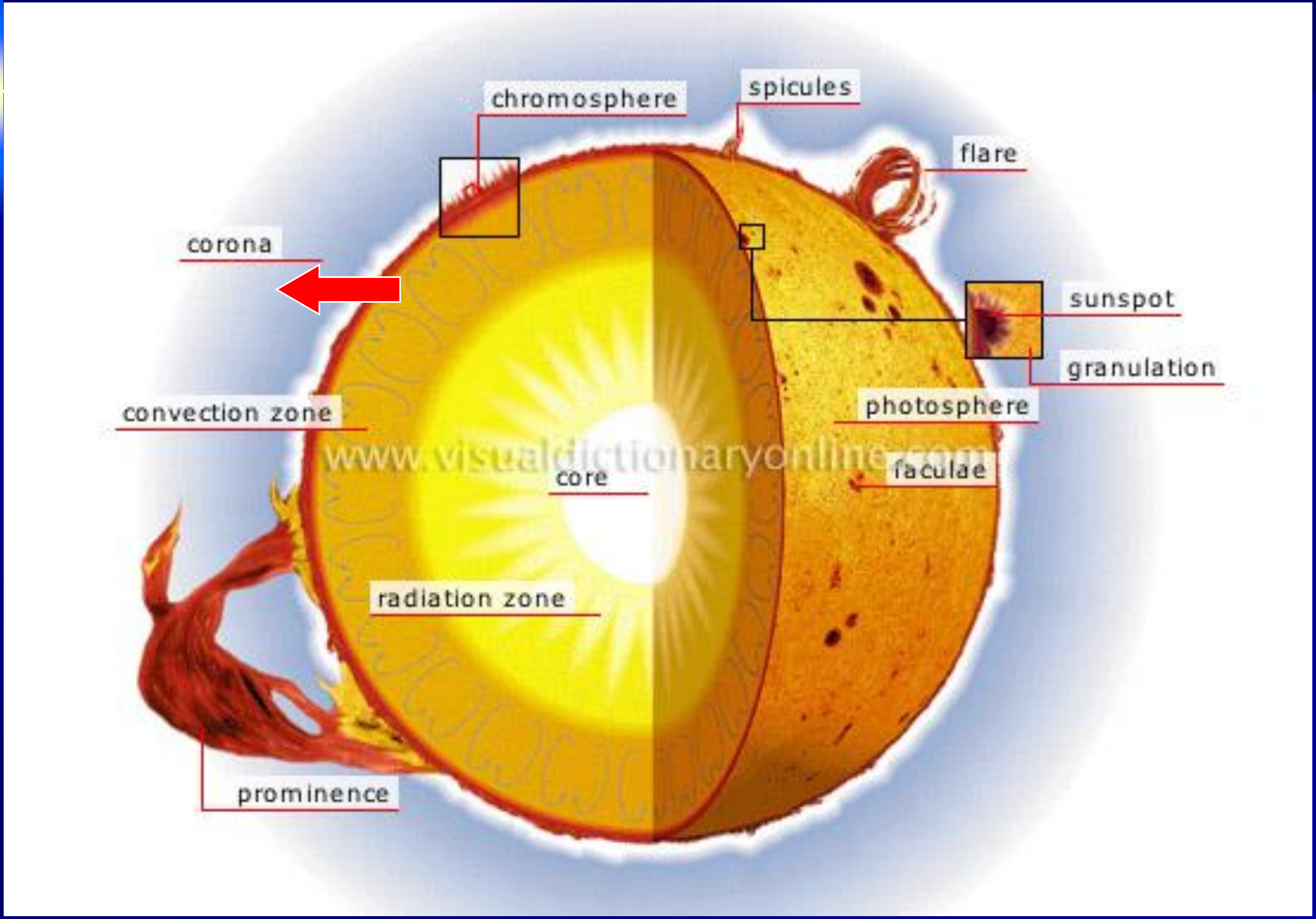
Center to ~20-25% Ro → Core

~25% to ~70% Ro → Radiative Zone

~70% to 100% Ro → Convective Zone

The Structure of the Sun

The photosphere



PHY 497 2.0 – Space & Atmospheric Physics
Continuous Assignment – 11 & 12

- **This assignment is to be completed using aiding the facts (sources) available in the internet.**
- Write down a **summarized description** on the following topic, both in **Sinhala/Tamil and English media** that would consist the related facts enough for a **half of an A4 paper** by each. The descriptions are essentially required to be written in your **own hand writings**.

01. " Short Wave Fade out in Radio Waves "
02. " Knife – Edge Diffraction in Radio Waves "
03. " Lightning Scattering in Radio Waves "
04. " Aero Plane Scattering in Radio Waves "
05. " Rain Scattering in Radio Waves "
06. " Tropospheric Ducting in Radio Waves "
07. " Tropospheric Scattering in Radio Waves "
08. " Auroral Reflection of Radio Waves "
09. " Meteor Scattering in Radio Waves "
10. " Sudden Cosmic Noise Absorption in Radio Waves "
11. " Sudden Ionospheric Disturbances in Radio Waves "
12. " Tropospheric Delay in Radio Waves "
13. " Polar Cap Absorption of Radio Waves "
14. " Polarization of Radio Waves "

- **15. " Ionospheric Storms " – Absent Boy**

16. " Absorption of Radio Waves " – Absent Girl

Thank You !