內磁層的結構與成因
Inner Magnetosphere

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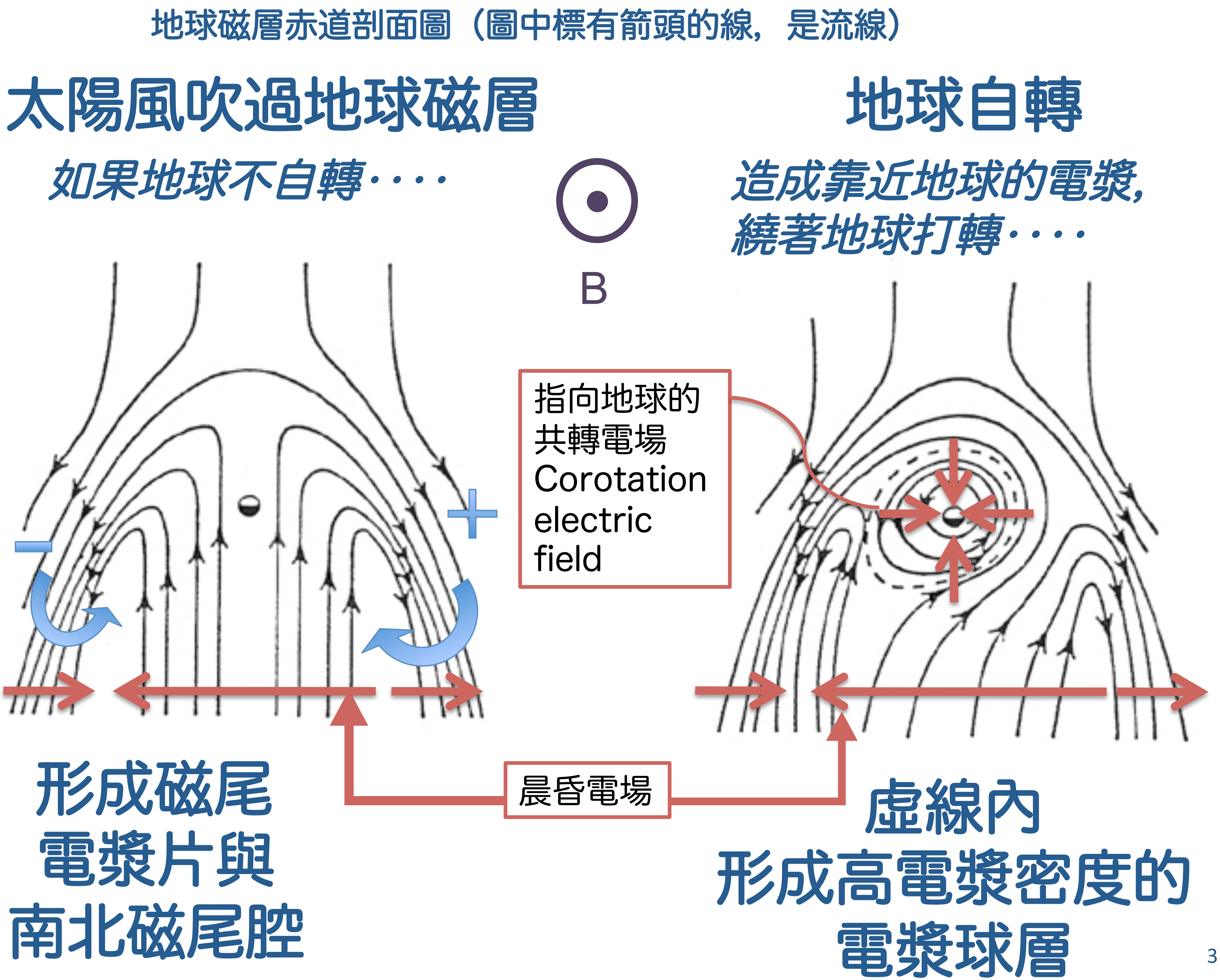
大綱

- 內磁層的結構與成因
- 內、外范愛倫輻射帶
- 簡介磁暴與磁副暴

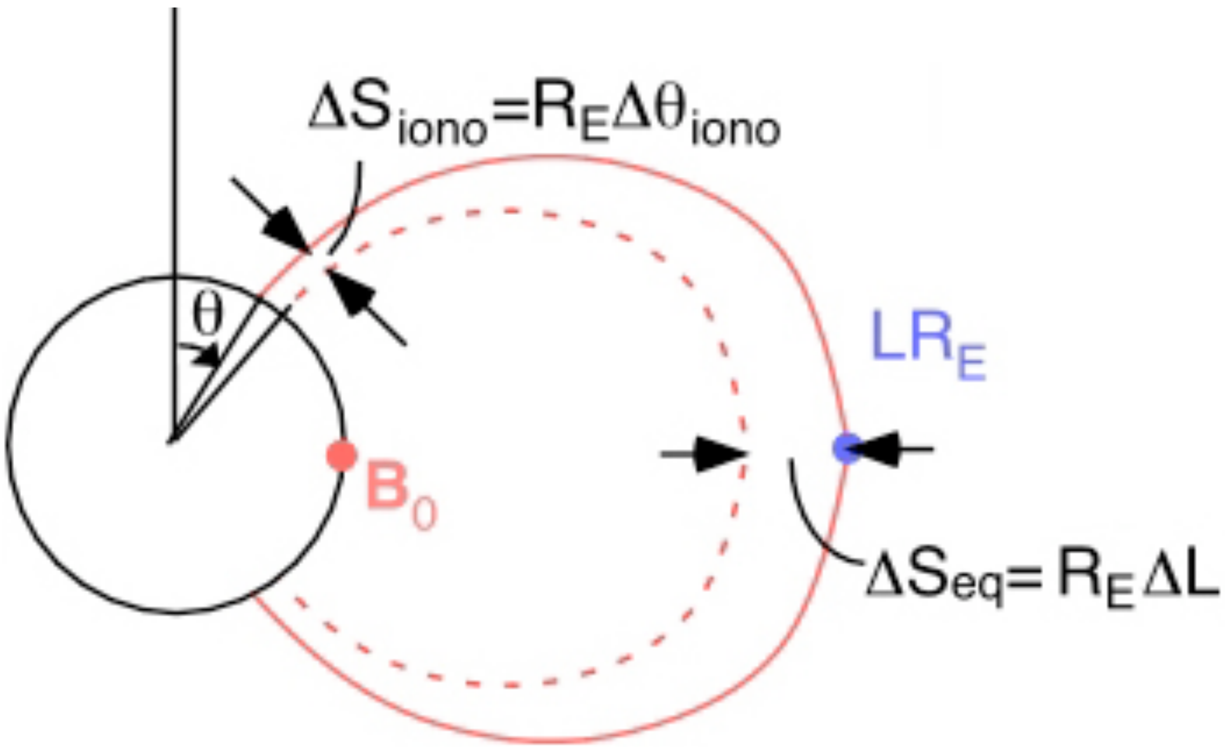


地球磁層赤道剖面圖（圖中標有箭頭的線，是流線）
太陽風吹過地球磁層
如果地球不自轉····
B
地球自轉
造成靠近地球的電漿，
繞著地球打轉····
指向地球的
共轉電場
Corotation
electric
field
+
-
形成磁尾
電漿片與
南北磁尾腔
晨昏電場
虛線內
形成高電漿密度的
電漿球層

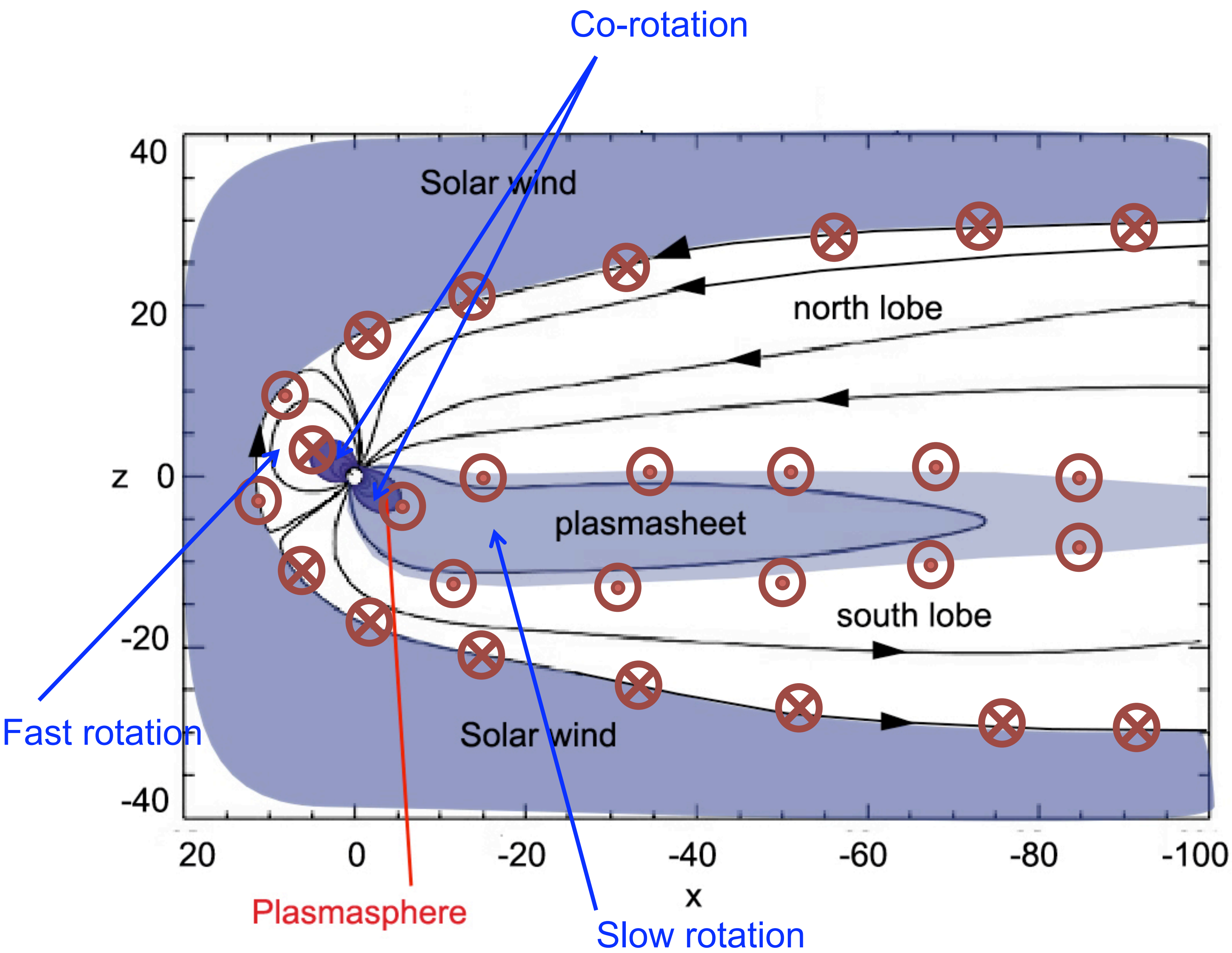
Co-rotating Electric Field

- 電離層中的電漿被中性風推著與地球一起自轉
- 電離層中電漿跨磁場運動會產生電場E=-VXB
- 若磁力線為等電位線，且磁場結構為dipole field，則當電離層中的電場沿著磁場線傳到磁赤道面時，其大小為 $\mathbf{E}_{eq} = -\hat{r}\omega_E R_E B_0 / L^2$
- 磁赤道面上的電漿速度 $\mathbf{V}_{eq} = \mathbf{E} \times \mathbf{B} / B^2 = \hat{\phi}\omega_E R_E L = \hat{\phi}\omega_E r_{eq}$ 因此這些電漿會同步繞著地球打轉 ω_E 。
- 若磁赤道面上，磁場強度比dipole field強，則該處電漿繞地球轉速也會比較大，反之亦然

Corotating Electric Field



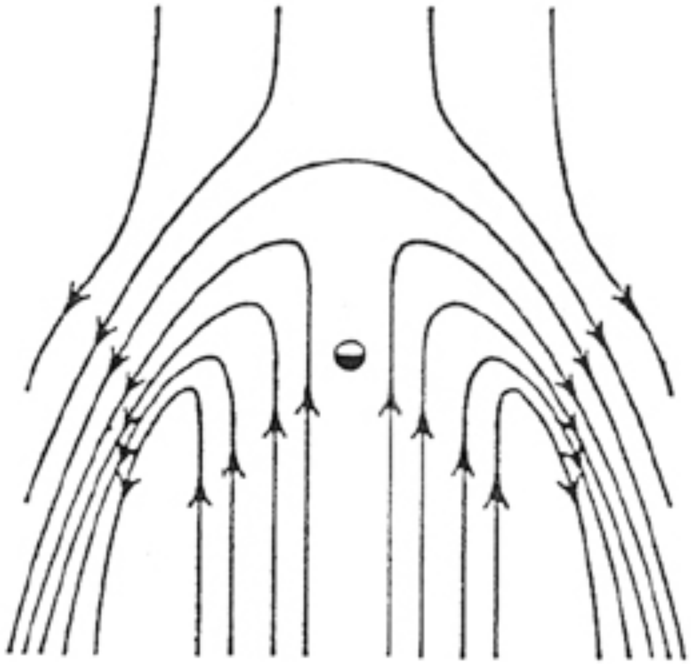
Diamagnetic Currents in the Magnetosphere



地球磁層赤道剖面圖（圖中標有箭頭的線，是流線）

太陽風吹過地球磁層

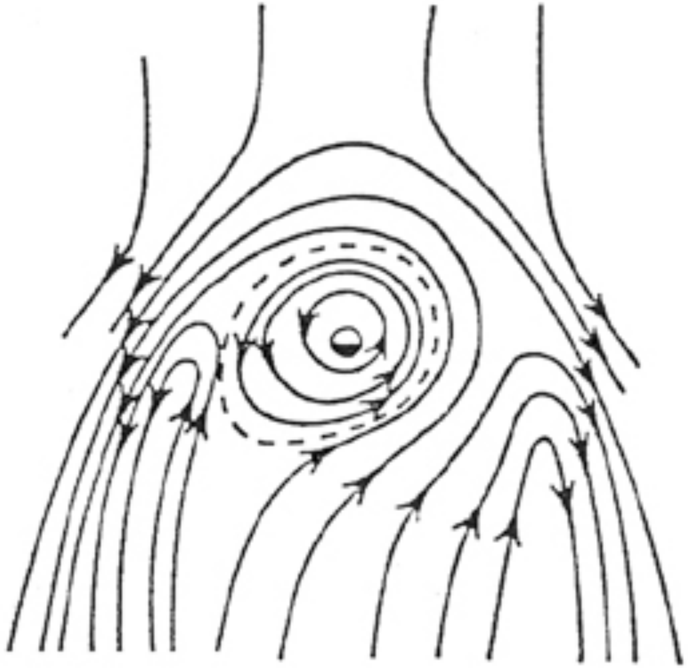
如果地球不自轉‧‥‥



形成磁尾
電漿片與
南北磁尾腔

地球自轉

造成靠近地球的電漿，
繞著地球打轉‧‥‥



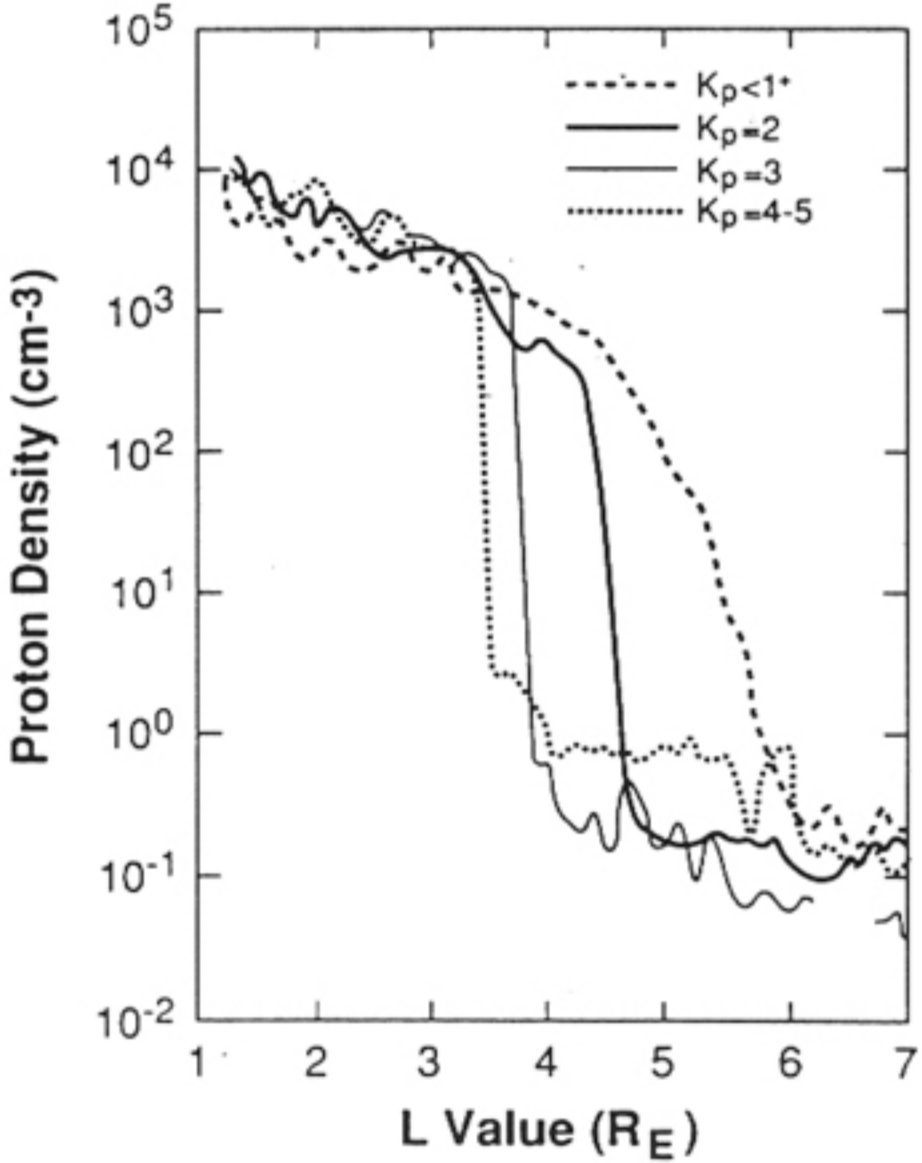
虛線內
形成高電漿密度的
電漿球層

內磁層中高密度電漿的成因

- 太陽風吹過地球磁層頂：造成晨昏電場
- 地球自轉：在磁赤道區造成指向地球的電場
  – 木星自轉：在磁赤道區造成指離木星的電場, why?
- “一同自轉電場”與“晨昏電場”兩者達到平衡點處，電場為零，決定低能帶電粒子飄移運動的Alfvén layer之位置。
- 內磁層中絕大多數的電漿（主要來自電離層）為這些沿著EXB的方向飄移的低能粒子
  – 內磁層的低能粒子電漿，繞著地球打轉，不易溢出內磁層，造成高密度的電漿球層(plasmashpere)。（日冕亦如此）
  – 內磁層的外邊界為電漿球層頂(plasmapause)

“電漿球層”內外，電漿密度的差異有多大？

質子密度



“電漿球層頂”
plasmapause
附近，電漿密度
相差超過一千倍

FIG. 10.15. Variation of the nightside plasmasphere to varying levels of geomagnetic activity as measured by *OGO 5*. (Adapted from Chappell, 1972.)

Drift Motion and Alfvén Layer

- Drift motion of the low-energy particle is mainly in the E X B direction.
- Drift motion of the energetic particle (高能粒子) is mainly governed by the grad-B drift and curvature drift.

$$\mathbf{v}_{\text{grad-B drift}} = \frac{mv_{gyro}^2}{2qB} \frac{(-\nabla_{\perp} B) \times \mathbf{B}}{B^2}$$

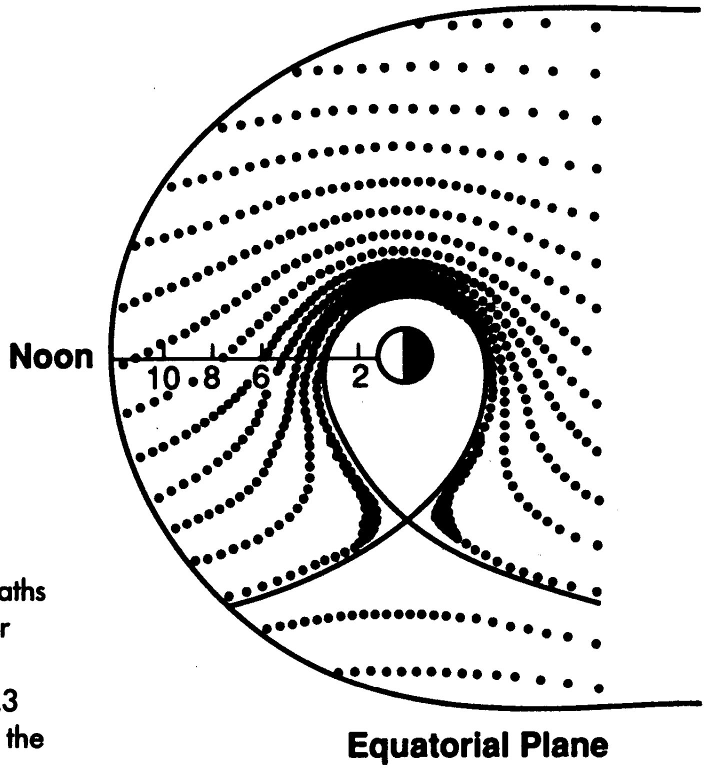
$$\mathbf{v}_{\text{curvature drift}} = \frac{mv_{\parallel}^2}{qB^2} \left(\frac{\hat{R}_B}{R_B} \times \mathbf{B}\right)$$

Alfvén Layer

- 請參閱課本, 第10.5節， 以及圖10.25, 10.26
  - 了解Alfvén layer的定義。
  - 了解磁層中“低能帶電粒子”的運動情形。以及“高能正電荷”與“高能負電荷”的飄移軌跡。了解三者之Alfvén layer之差異。

Alfvén Layer of Low-energy Particles

FIG. 10.16. Average shape of the plasmasphere, in the equatorial plane, as determined from whistler measurements. The diagram represents an observational average for moderate and steady magnetic activity ($K_p = 2–4$). The plot is based on whistler data recorded at Eights and Byrd, Antarctica, June–August 1963. (Adapted from Carpenter, 1970.)



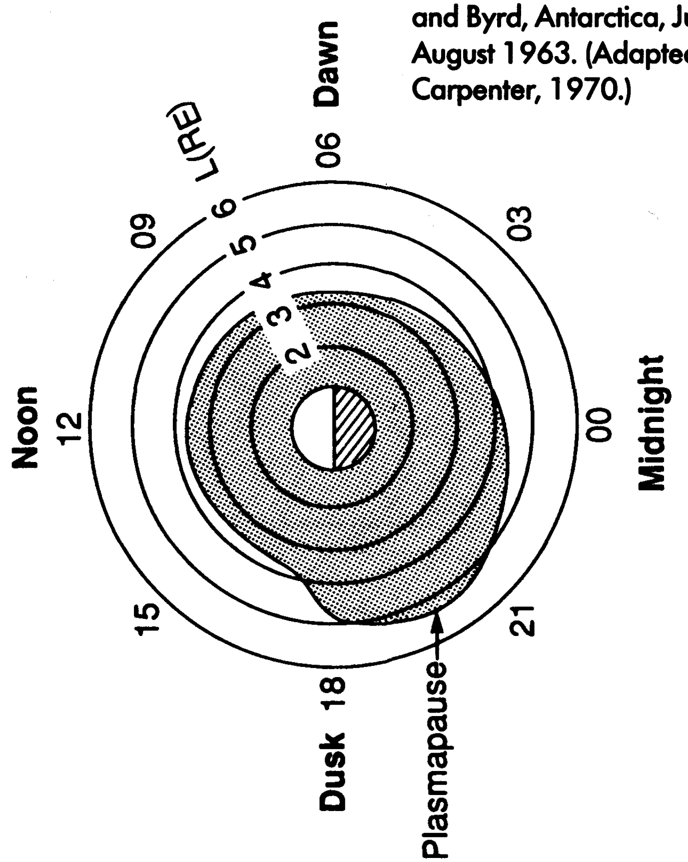


FIG. 10.25. Drift paths in the equatorial plane for particles with $\mu = 0$ and a uniform electric field of 0.3 $mV \cdot m^{-1}$. The positions of the magnetopause and the forbidden region are indicated by solid lines. The distance between successive dots is the distance a particle drifts in 10 min. (Adapted from Kavanagh et al., 1968.)

$$\phi_{\text{eff}}^{\text{cold}} = -E_0 r \sin\varphi - \frac{\omega_E B_0 R_E^3}{r}$$

Alfvén Layers of Energetic Particles

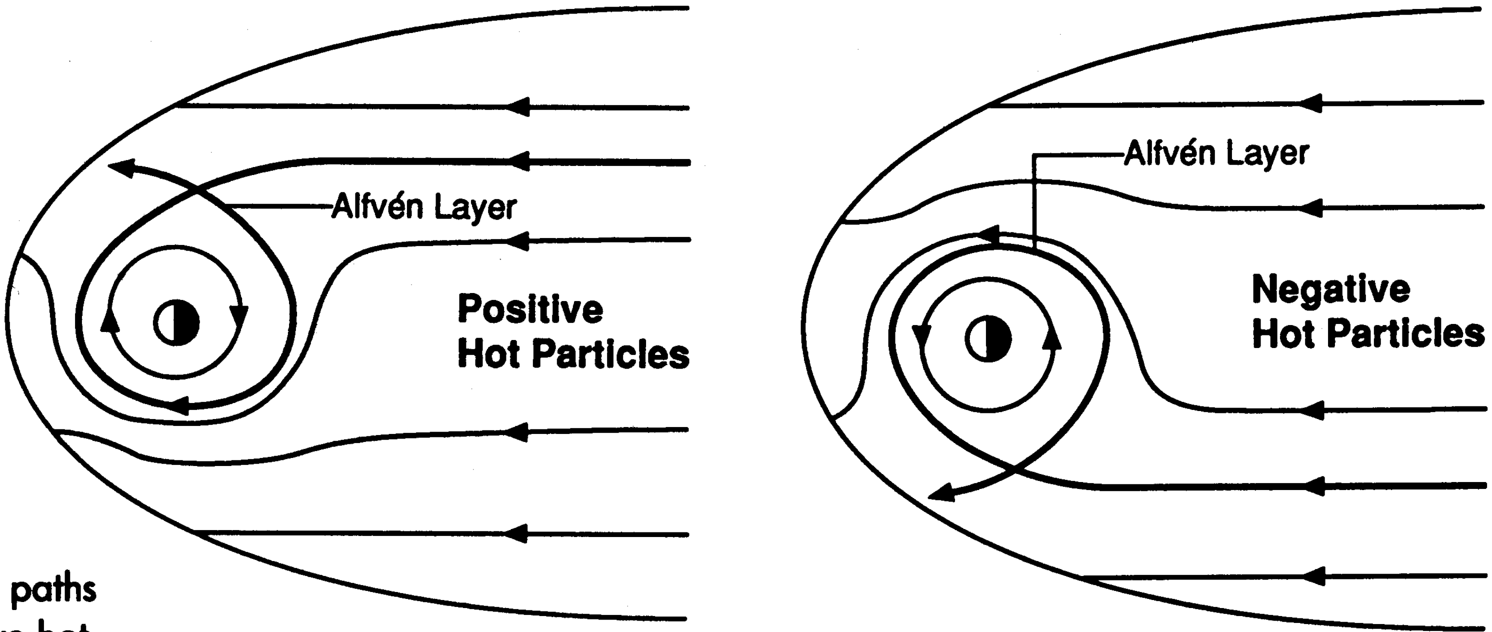


FIG. 10.26. Drift paths for positive and negative hot magnetospheric particles. The view is of the equatorial plane, with the sun to the left. The separatrix between the trajectories that lead from the magnetotail to the dayside magnetopause and those that circle the earth is called the "Alfvén layer."

$$\phi_{\mathrm{eff}}^{\mathrm{hot}} = -E_0 r \sin\varphi + \frac{\mu B_0 R_E^3}{q r^3}$$

內磁層中高能帶電粒子,源自何方?

- Cosmic Ray from Supernova & Solar Flare
- Storm time: Ionosphere –> magnetotail –> inner magnetosphere

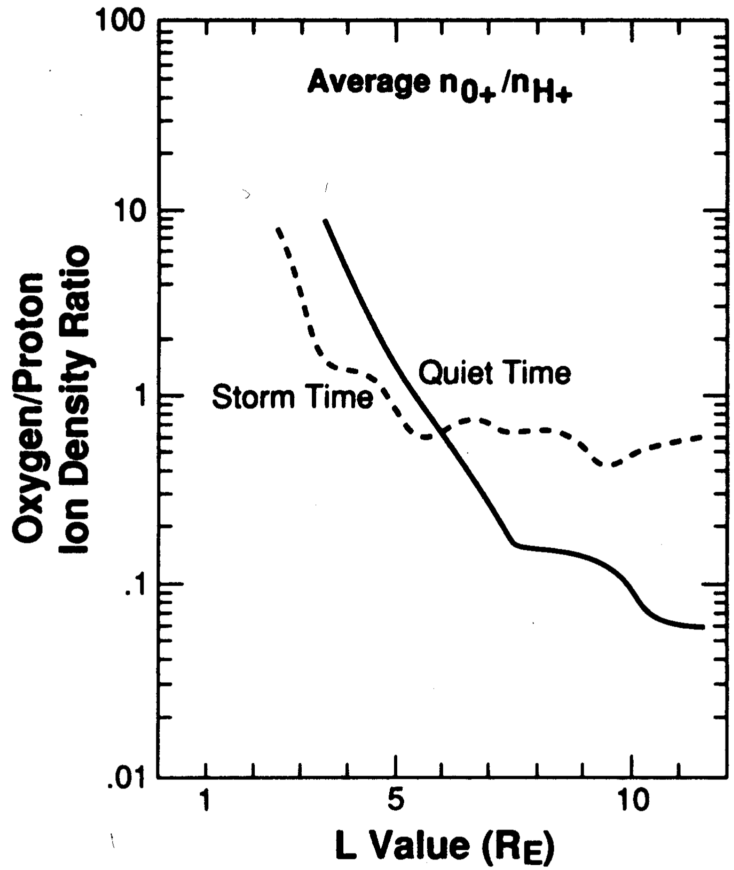
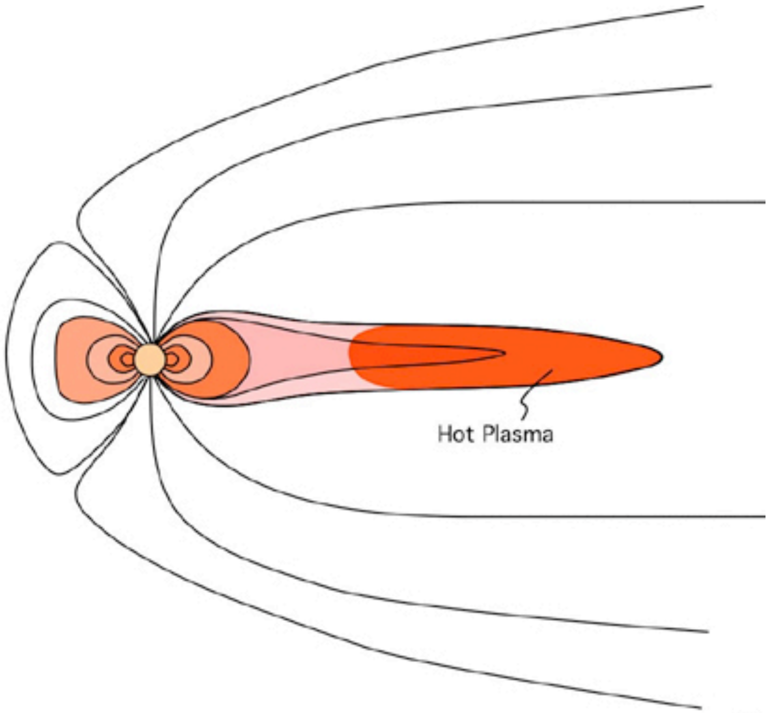
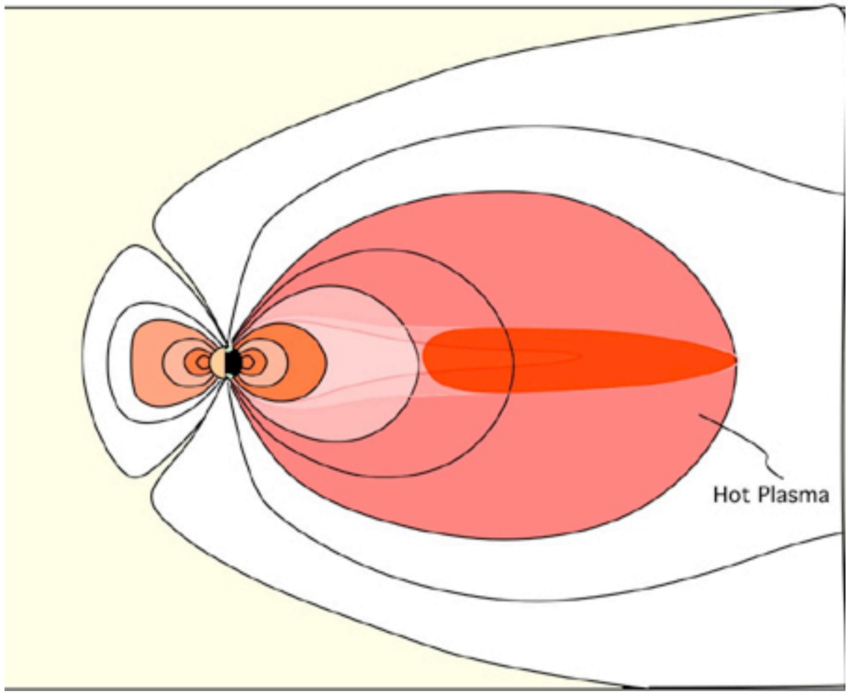
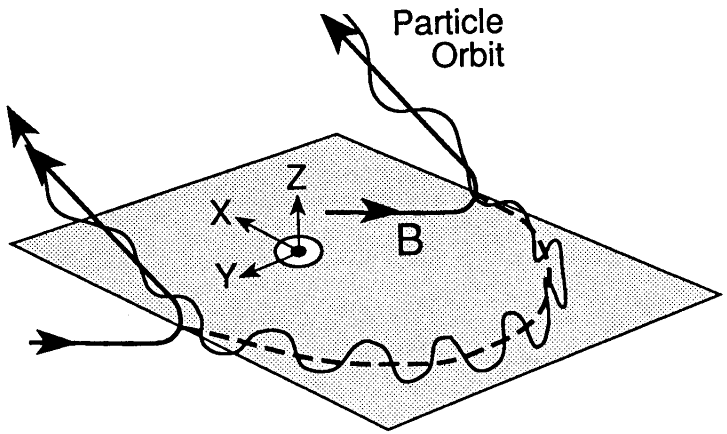
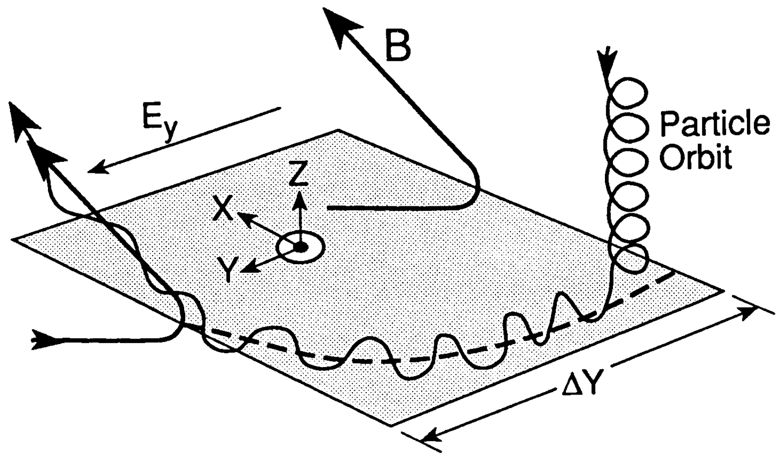


FIG. 10.5. Averaged radial profiles of O^+/H^+ density ratio, as measured from the *ISEE 1* spacecraft. (Adapted from Lennartsson and Sharp, 1982.)


Hot Plasma


Hot Plasma


Particle
Orbit
Z
X
Y
B


B
E_y
Particle
Orbit
Z
X
Y
ΔY

Grad B Drift & Curvature Drift of the Energetic Particles

- Grad-B drift and curvature drift of the energetic particles (高能粒子) in the dipole magnetic field can increase the ring current intensity and result in partial ring current.

$$\mathbf{v}_{\text{grad-B drift}} = \frac{mv_{gyro}^2}{2qB}\frac{(-\nabla_{\perp}B)\times\mathbf{B}}{B^2}$$

$$\mathbf{v}_{\text{curvature drift}} = \frac{mv_{\parallel}^2}{qB^2}\left(\frac{\hat{R}_B}{R_B}\times\mathbf{B}\right)$$

Partial Ring Current

- 請參閱課本, 圖10.1
  - 了解磁暴與磁副暴期間，Partial Ring Current 的成因。
  - 了解 Partial Ring Current 與Region-II Current System 之間的關係。

范艾倫輻射帶
Van Allen Radiation Belt

太空時代的來臨(Space Age)

- 德國火箭 V-2 rocket in 1942
- 俄國人造衛星“友伴一號”
  Sputnik 1 in 1957 (Oct. 4)
- 美國人造衛星“探險家一號”
  Explorer 1 in 1958 (Jan. 31)
- Explorer 1 的重大發現：
  Van Allen Radiation Belt 范艾倫輻射帶

Van Allen Radiation Belt 范艾倫輻射帶的發現過程

- Explorer 1 的科學酬載(payload)是一個由Iowa大學Van Allen教授所帶領的研究團隊所設計的宇宙射線(cosmic ray)探測儀，一種蓋格記數器(Geiger counter)。
- 科學家預期在太空中，每秒可以收到約30顆宇宙射線（高能的帶正電粒子）。由於Explorer 1以橢圓軌道運行，其遠地點據地面約2550公里，其近地點距離地面約358公里，因此可以分析軌道範圍中的宇宙射線分布。結果發覺，每當Explorer 1飛到約2000多公里的高空，就收不到任何訊號。等到Explorer 1 的軌道回到500公里高空就收到訊號。【地面觀測，宇宙射線flux，應該隨高度增加遞增】
- 為何會如此呢？原來是“太高”的宇宙射線flux,導致記錄器故障！

Explore 1 記者會

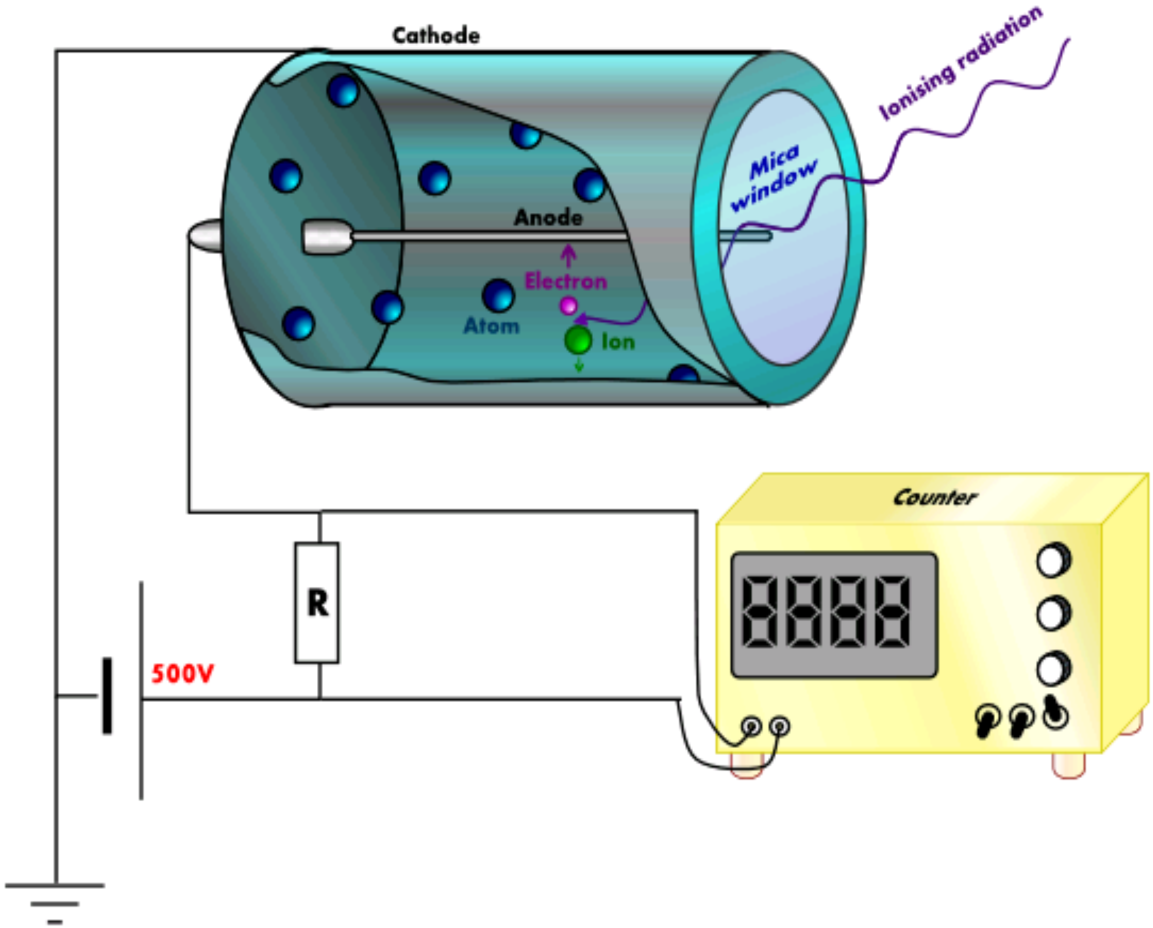
探險家一號衛星
Explore1 的外型為火箭一般的“長條型”衛“星”。後來證實，在逐漸失去動能後，它就不再依著長軸打轉，而會隨意翻覆打轉。從此以後，科學家就不再採用這種長條型的人造衛星了！

Geiger counter
蓋格記數器

另一種測量宇宙射線的方法：兩銅箔的張角

高空張角大

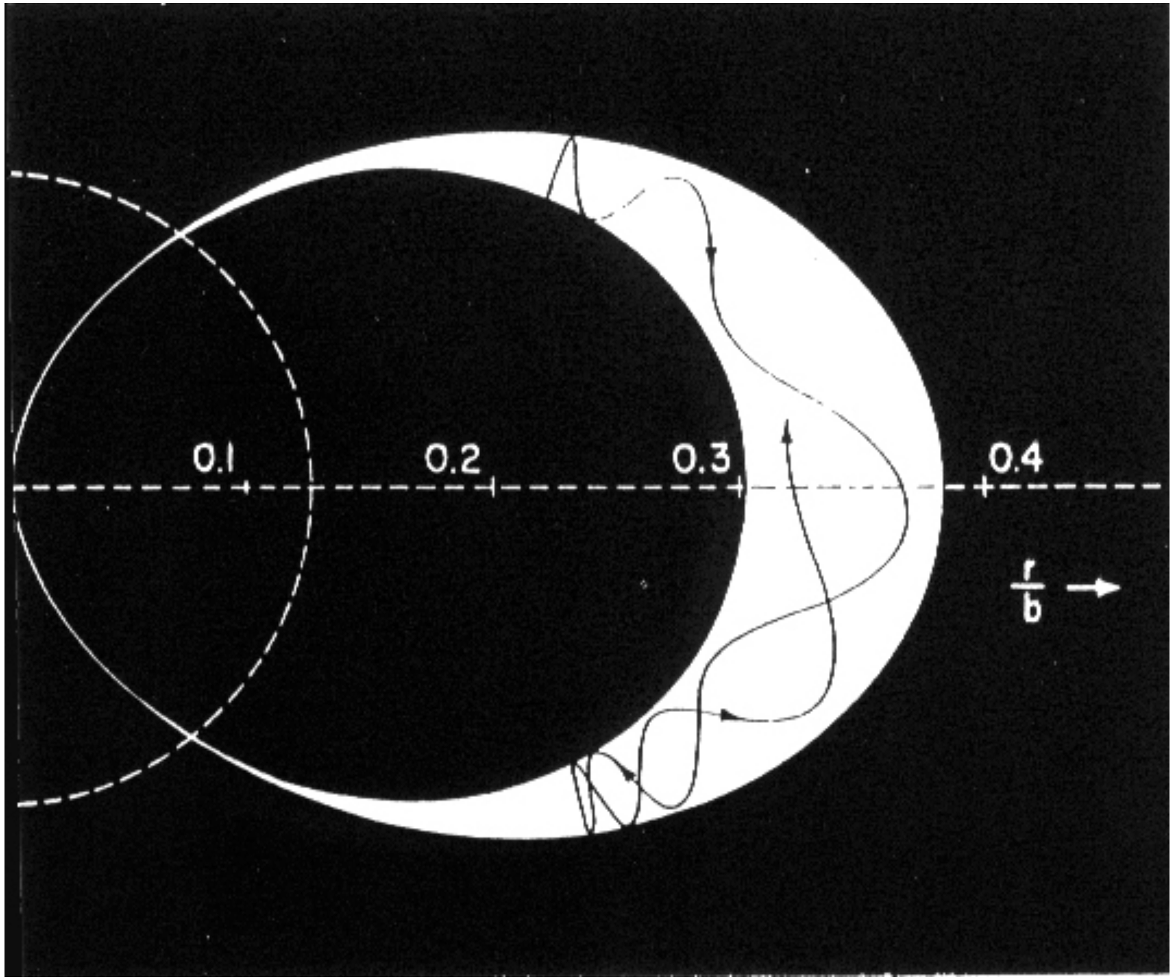
低空張角小



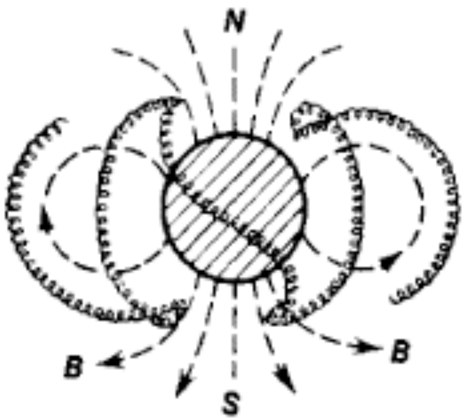
http://en.wikipedia.org/wiki/Geiger-Müller_tube

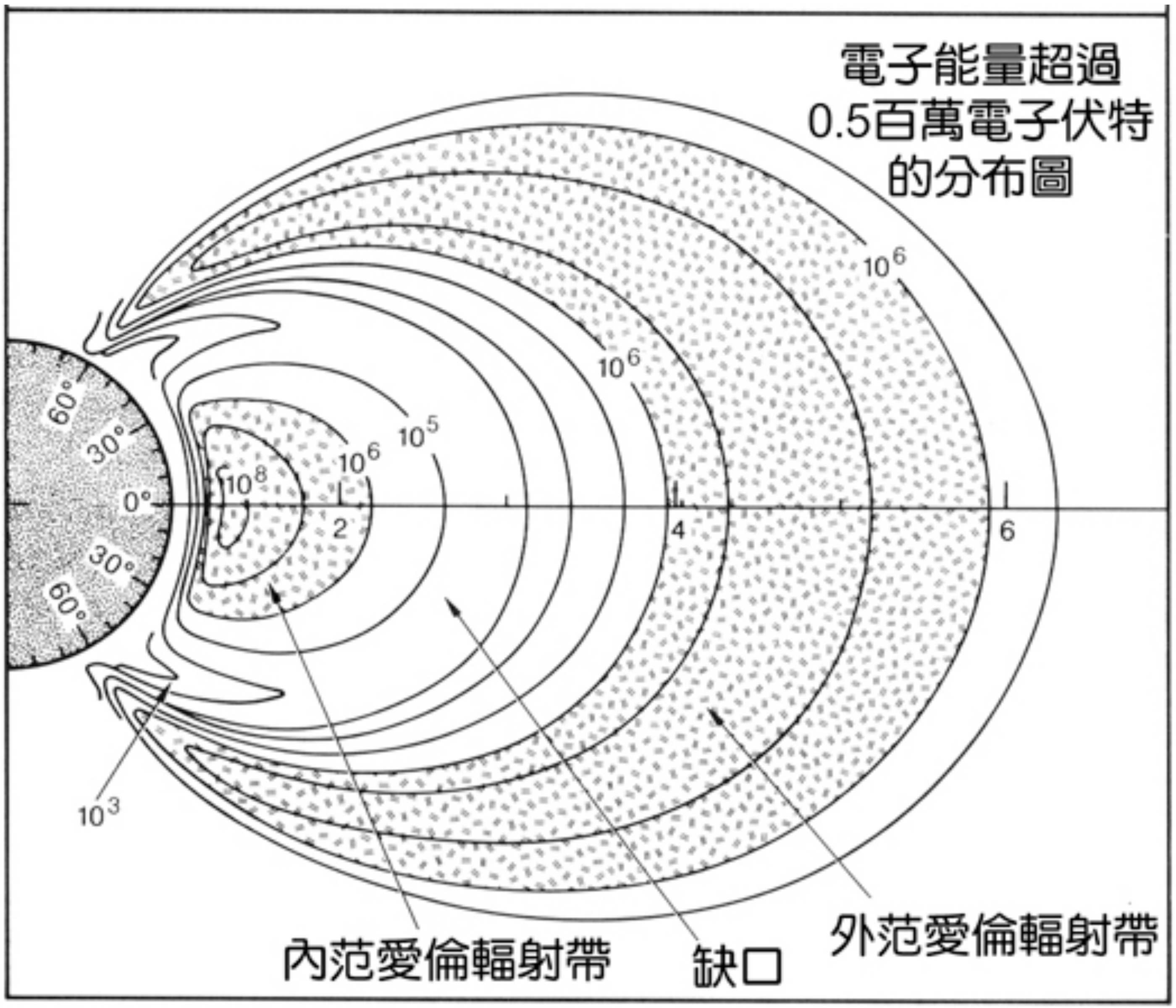
Van Allen Radiation Belt 范艾倫輻射帶的發現過程

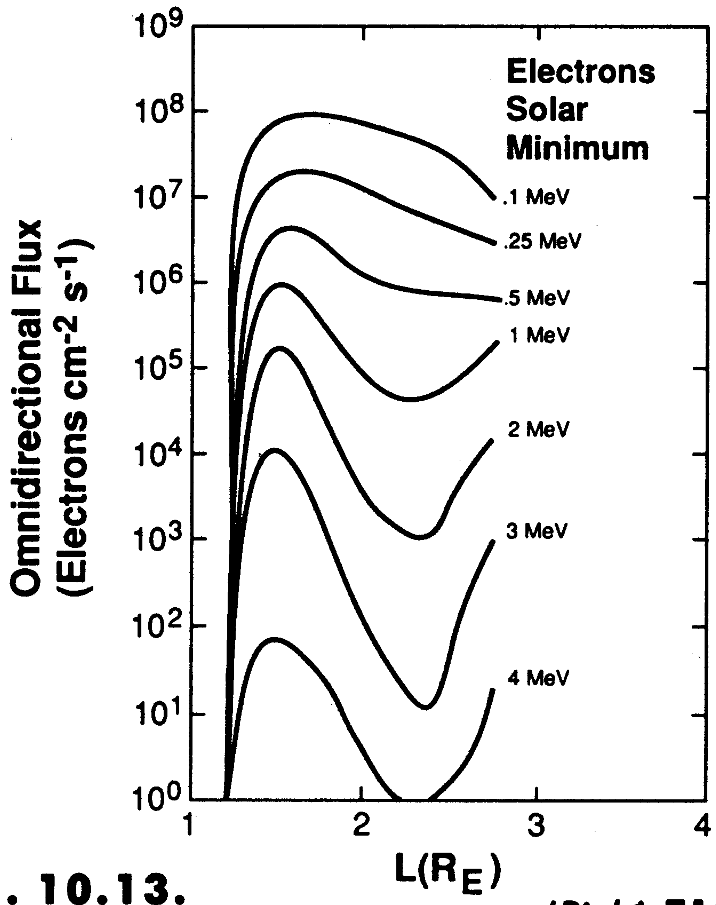
- Explorer 3 再度探測，確定了地球上空磁場線結構，可以像磁瓶一樣，抓住了高濃度的宇宙射線。這些宇宙射線可以把自己的一部份能量傳給四周的電子。這些獲得能量的電子，在磁場中以接近光速的速率快速打轉，就會放出X光，這就是范艾倫輻射帶的成因。

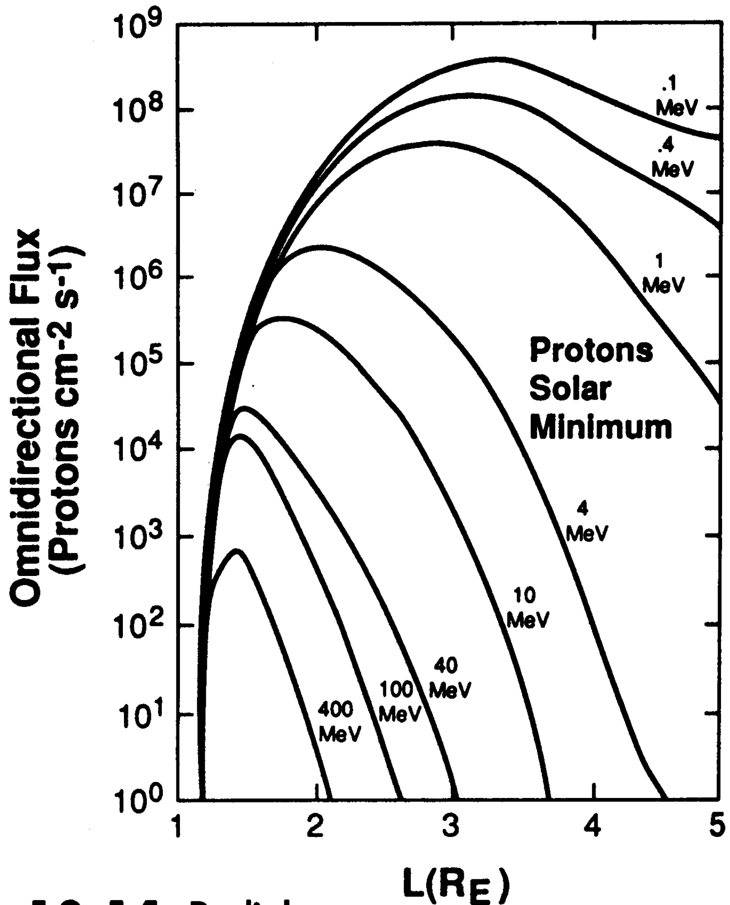


內、外范愛倫輻射帶分布情形







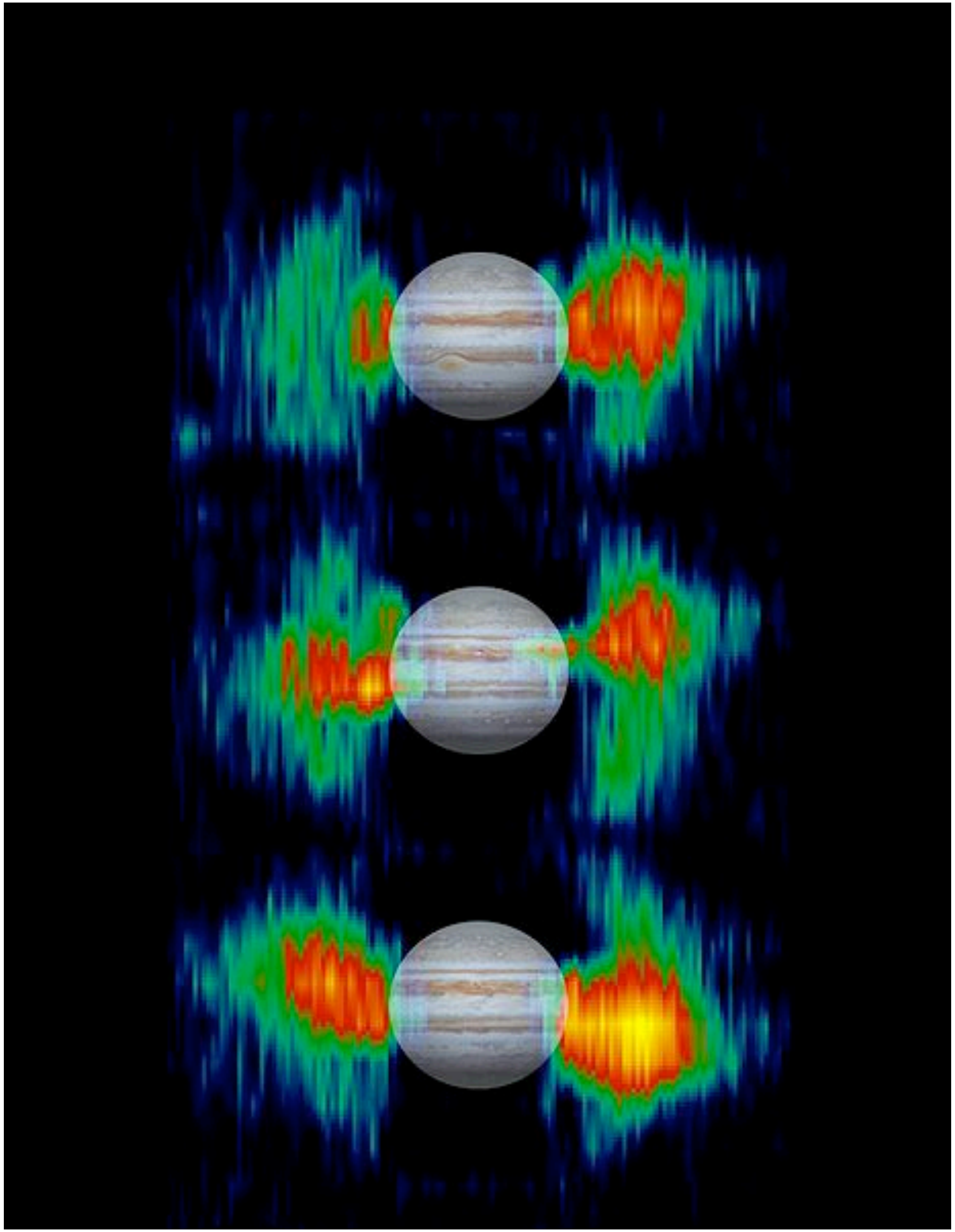


(*Left*) **FIG. 10.13.** Equatorial omnidirectional electron flux versus *L* shell for the AE5 solar-minimum radiation-belt model. The flux curves are labeled by threshold energy. Each curve gives the total electron flux above the specified threshold. (Adapted from Spjeldvik and Rothwell, 1983.)

(*Right*) **FIG. 10.14.** Radial distribution of proton omnidirectional fluxes in the equatorial plane, according to the AP8 solar-minimum radiation model. The curves give total fluxes above various threshold energies from 0.1 to 400 MeV. (Adapted from Spjeldvik and Rothwell, 1983.)

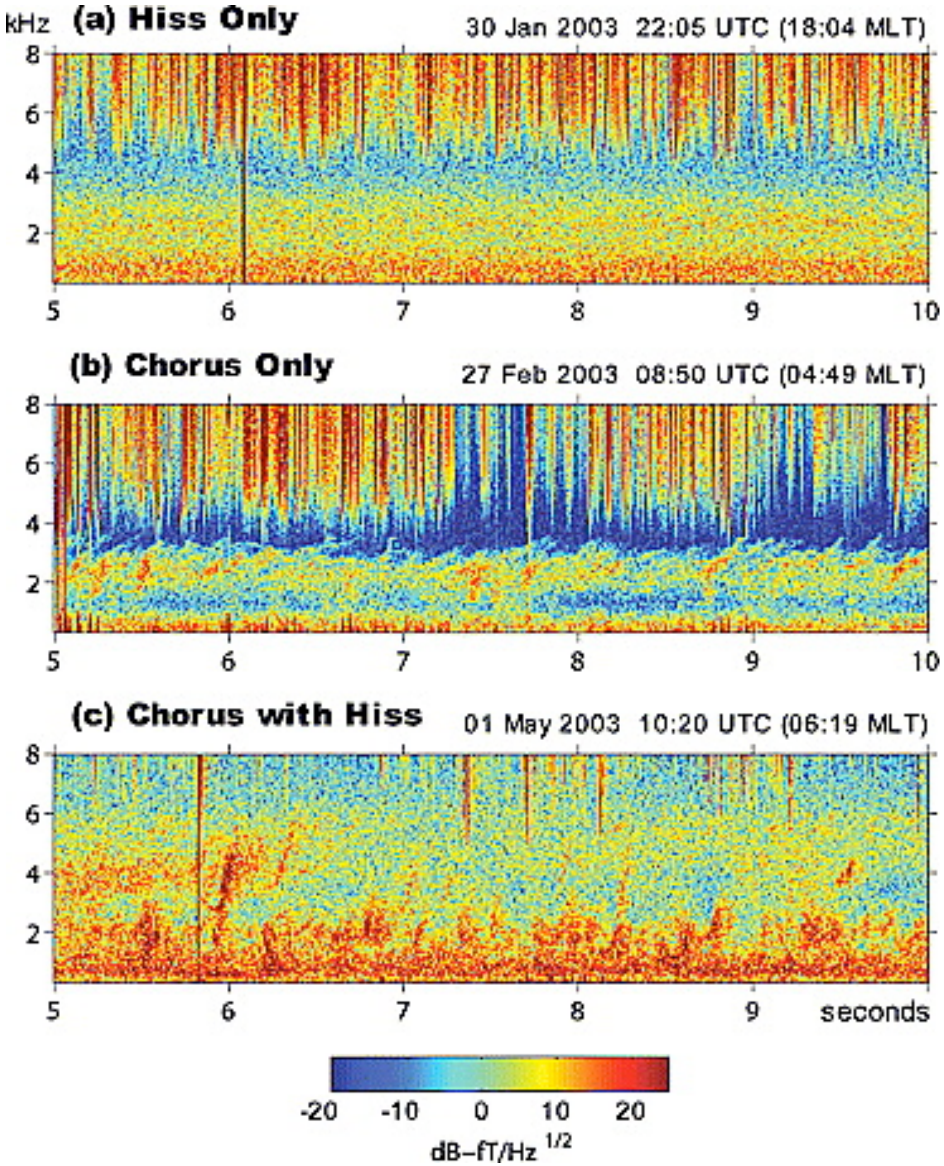
1994年
彗星撞木星，導致木星輻射帶的輻射強度不對稱的增加

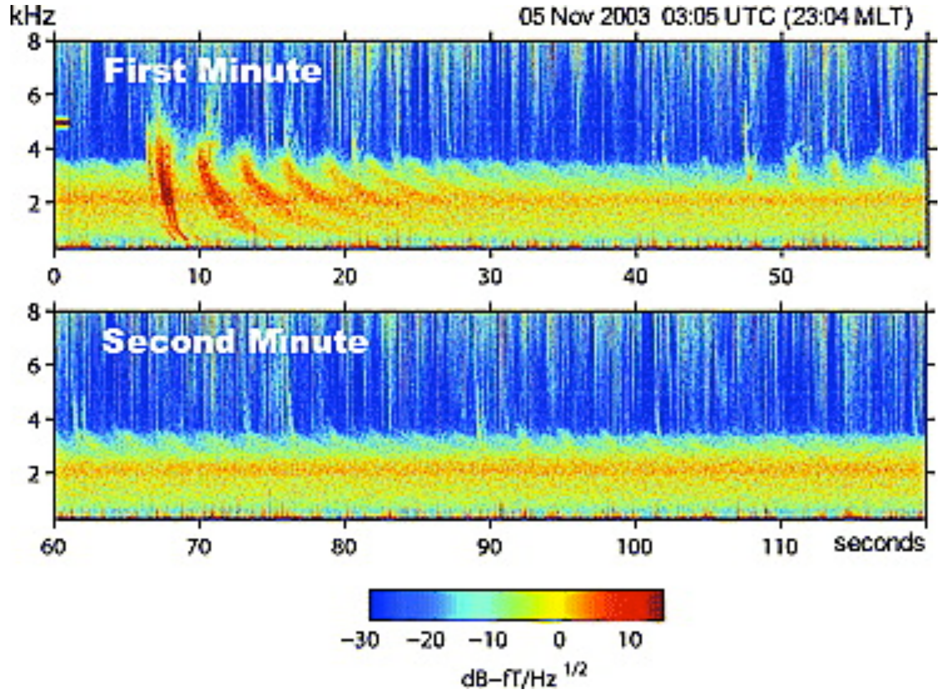
Comet Shoemaker-Levy 9 broke apart and collided with Jupiter in July 1994.



Waves in the Inner Magnetosphere

(Golden, Spasojevic & Inan, 2009 JGR)





Hiss (disperseless noise)
Chorus (low freq. to high freq.)
Whistler (high freq. to low freq.)

Waves in the Inner Magnetosphere

(Thorne, 20010 GRL)