

第八章

Magnetospheric Dynamics

程鑫

天文楼407

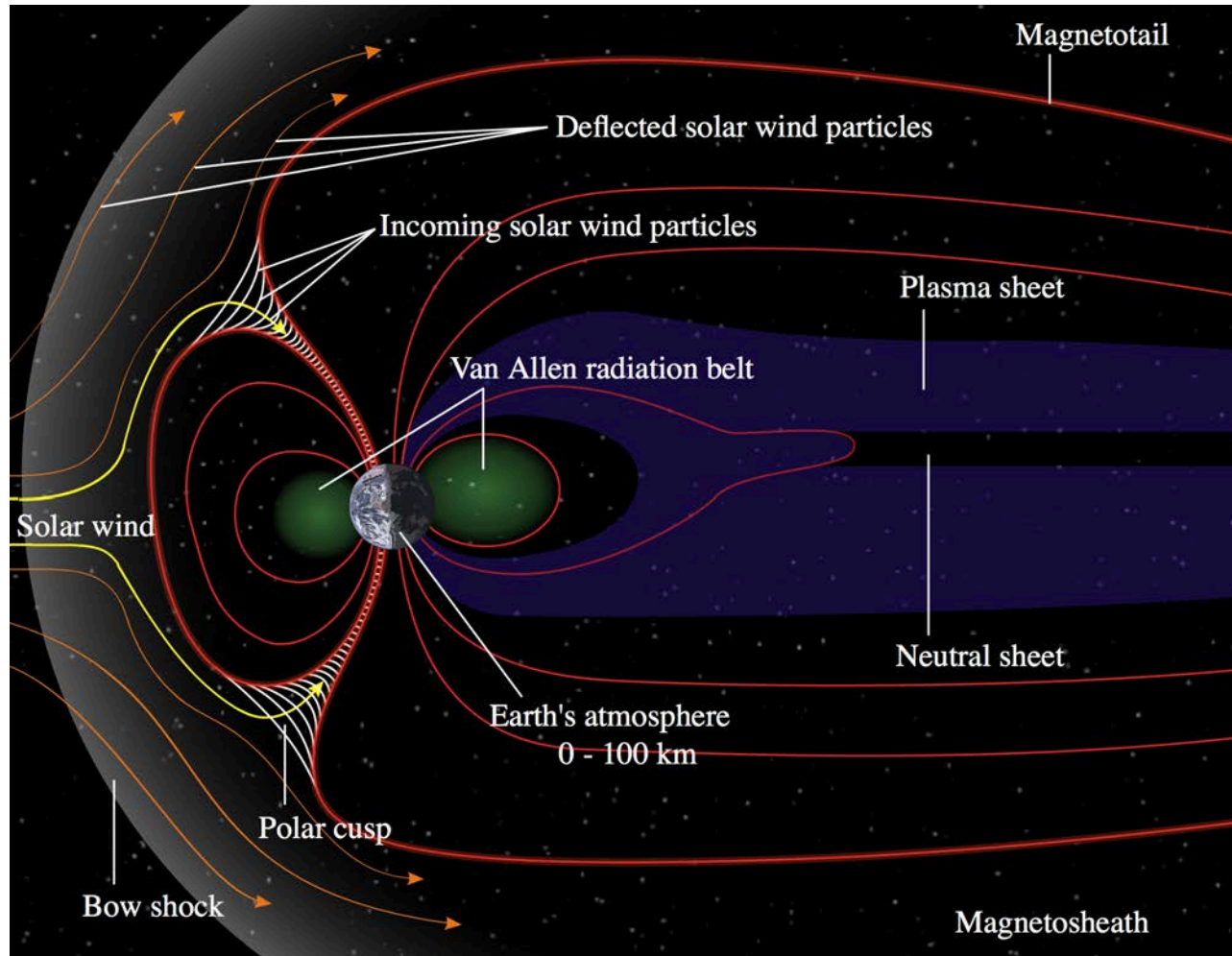
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主要内容

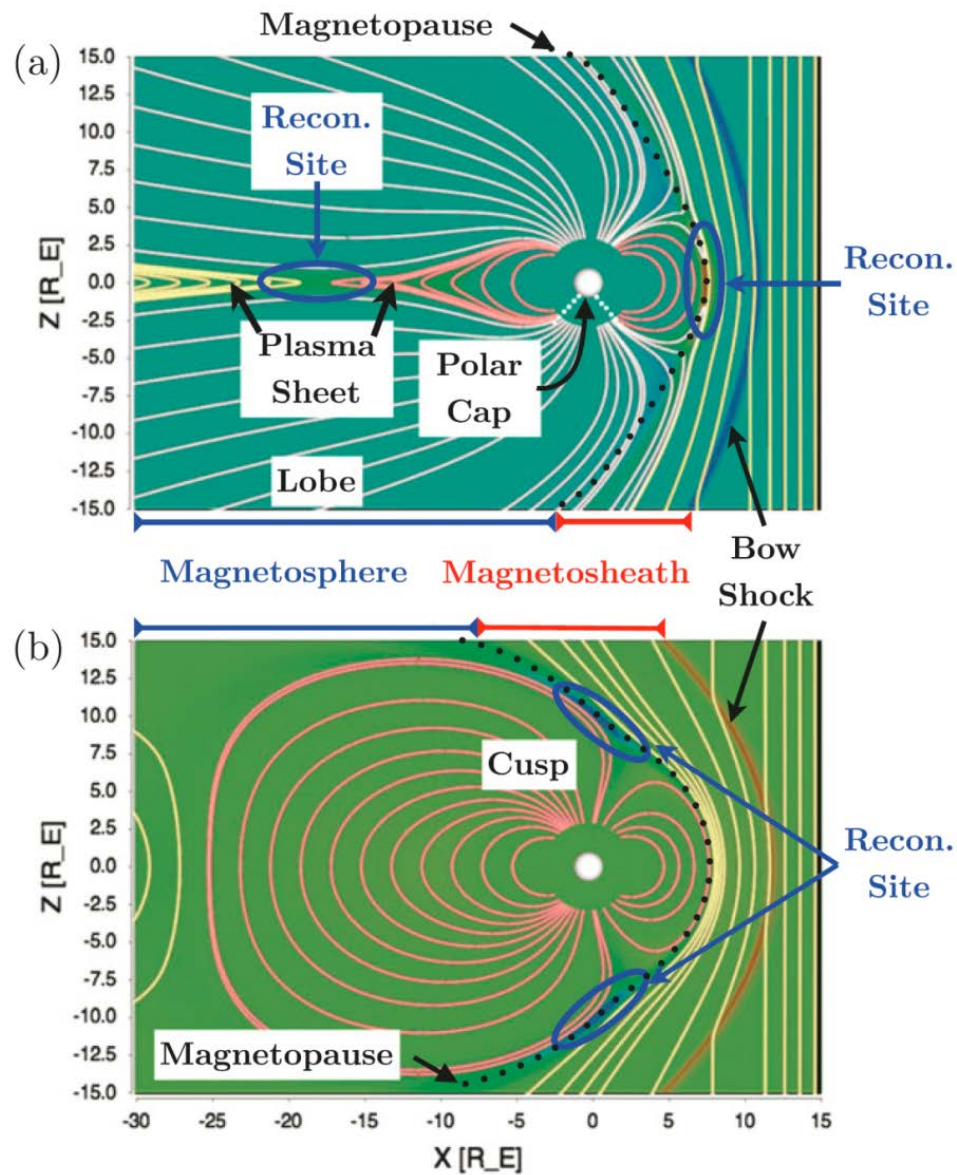
- 地球磁层（磁层电流）
- 地磁暴、磁层亚暴

➤ 地球磁层简介

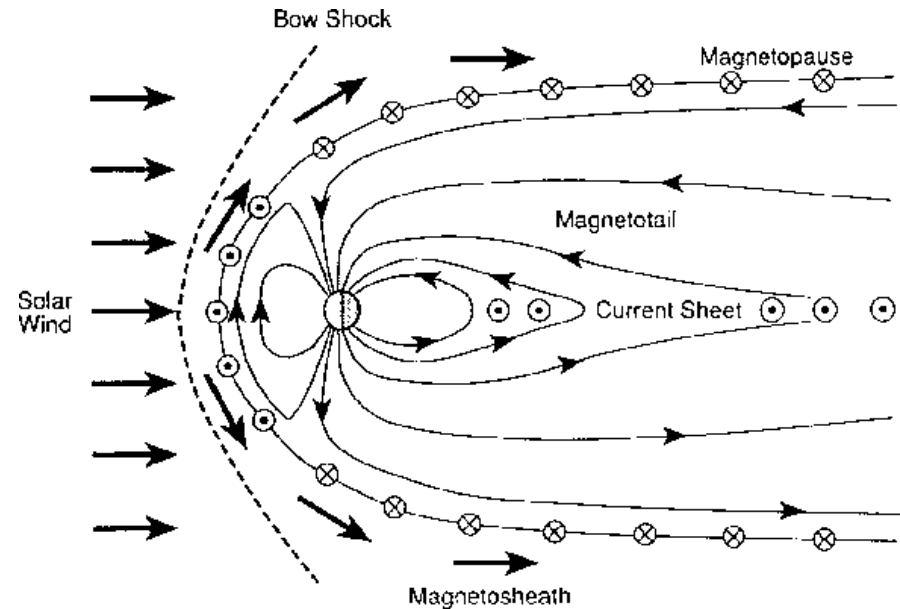
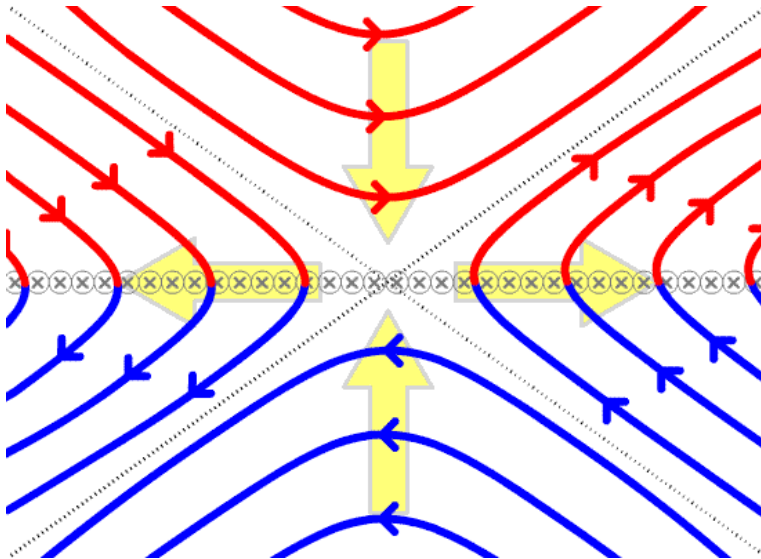
Magnetosphere



➤ 太阳和地球磁层的相互作用



重联电流片中电流方向再议！！



The Sweet–Parker model describes time-independent magnetic reconnection in the resistive MHD framework when the reconnecting magnetic fields are antiparallel (oppositely directed) and effects related to viscosity and compressibility are unimportant. The ideal Ohm's law then yields the relation

$$E_y = v_{in} B_{in}$$

where E_y is the out-of-plane electric field, v_{in} is the characteristic inflow velocity, and B_{in} is the characteristic upstream magnetic field strength. By neglecting displacement current, the low-frequency Ampere's law, $\mathbf{J} = \frac{\nabla \times \mathbf{B}}{\mu_0}$, gives the relation

$$J_y \sim \frac{B_{in}}{\mu_0 \delta},$$

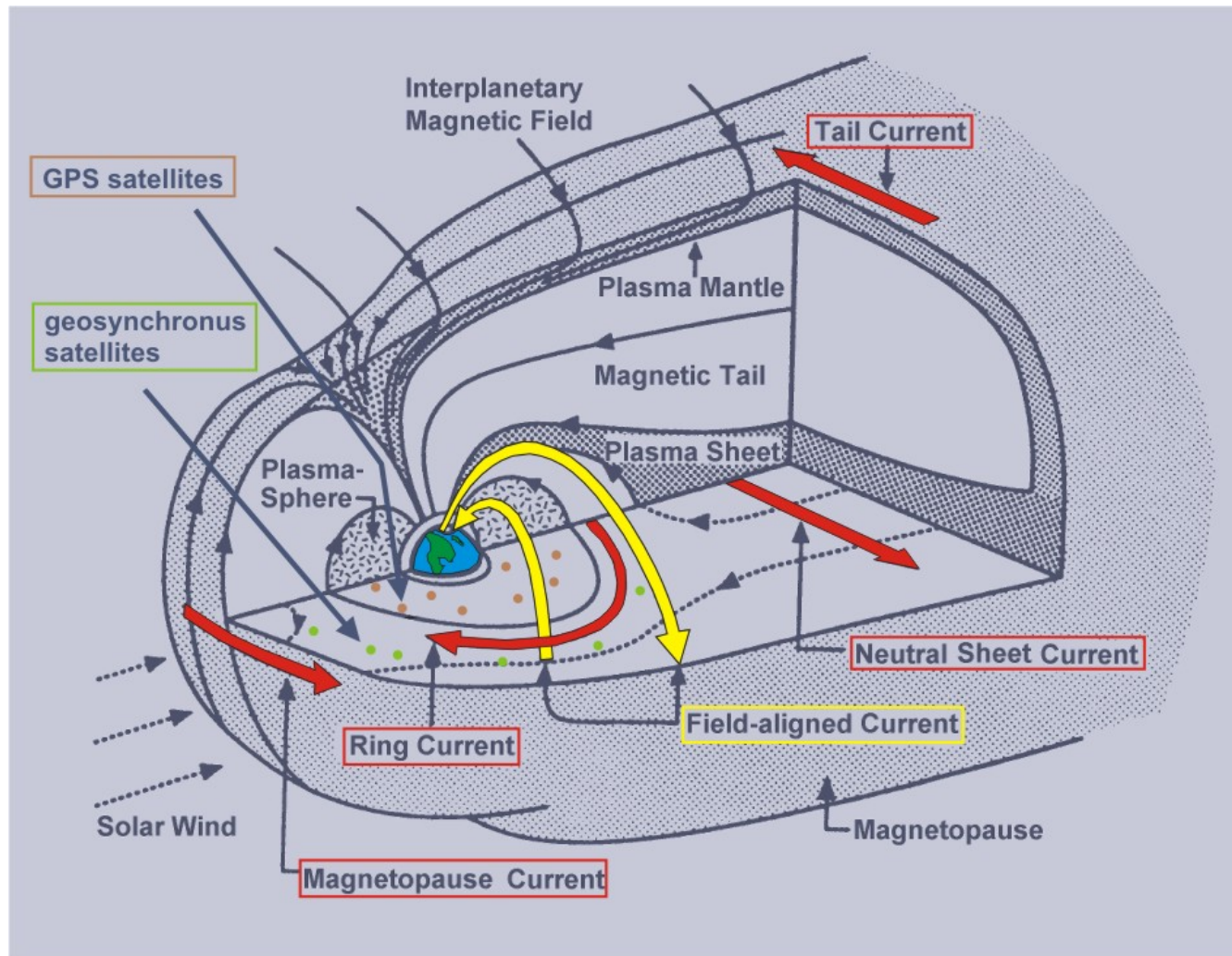
where δ is the current sheet half-thickness. This relation uses that the magnetic field reverses over a distance of $\sim 2\delta$. By matching the ideal electric field outside of the layer with the resistive electric field $\mathbf{E} = \frac{1}{\sigma} \mathbf{J}$ inside the layer (using Ohm's law), we find that

$$v_{in} = \frac{E_y}{B_{in}} \sim \frac{1}{\mu_0 \sigma \delta} = \frac{\eta}{\delta},$$

From Wiki

➤ 地球磁层简介

Electric Currents in Magnetosphere



➤ 地球磁层简介

磁层顶电流 (magnetopause current)

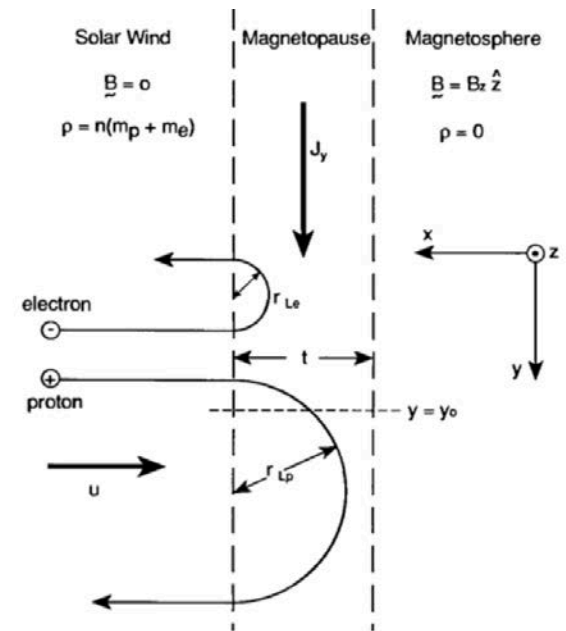
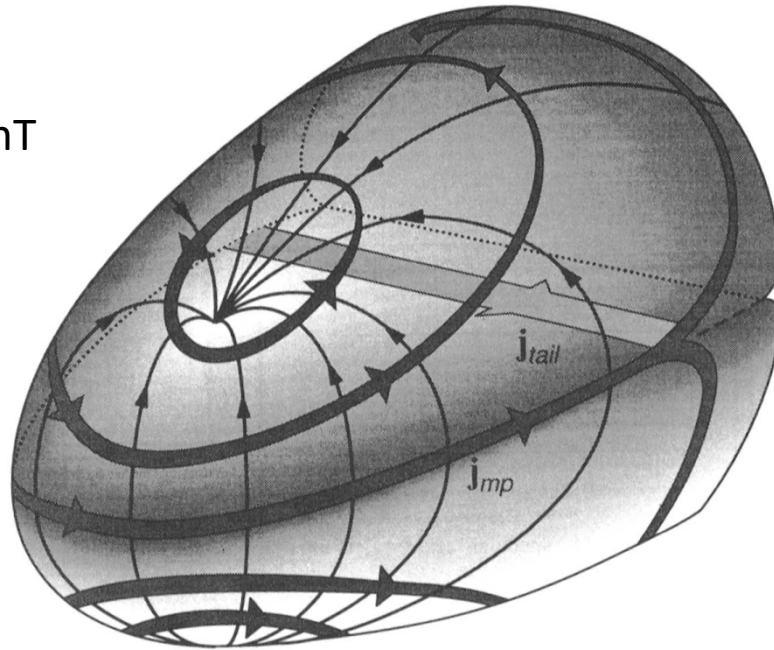
最早由Chapman 和Ferarro 于1931年开始研究，称C-F电流。它由向阳面磁层顶赤道南北两侧的两个电流涡组成，涡的中心位于磁层顶极隙区。

从太阳向地球看，北半球涡逆时针运动、南半球顺时针运动，赤道带形成自晨到昏的东向电流带。

平静日： $10 R_E$

$1.5 \times 10^6 \text{ A}$

产生的地面磁场几个nT



➤ 地球磁层简介

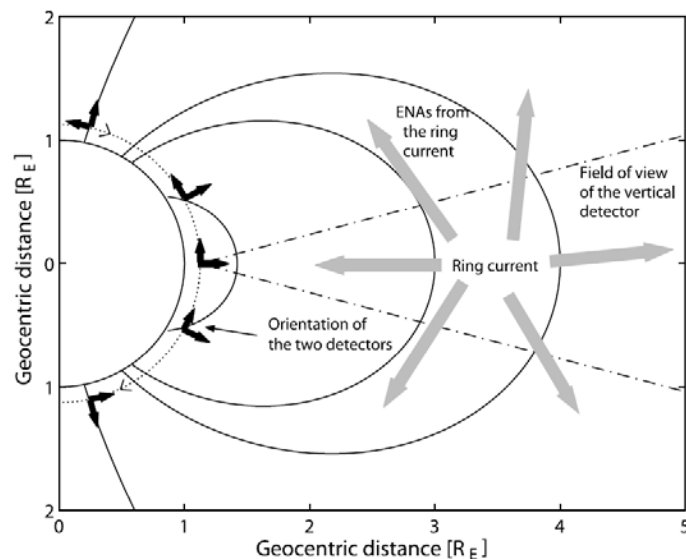
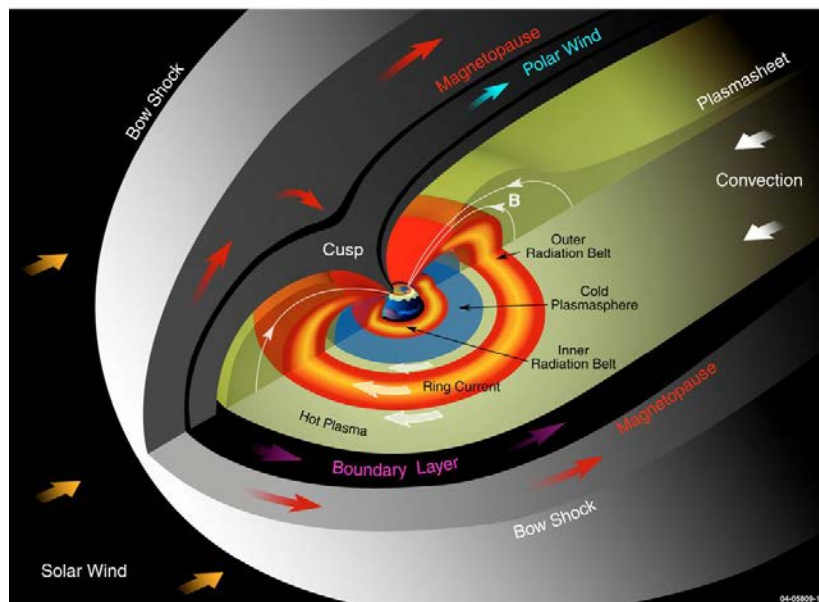
对称环电流 (symmetric ring current)

主要由中能段粒子构成，质子的典型能量值 $1\sim 2000$ keV; 电子低一个能级

漂移形成了西向电流环带

高能粒子和低能粒子贡献小

环电流电子来自于磁尾等离子体片和电流层，粒子绕磁场运动，在磁场中的梯度和曲率漂移是两个主因。



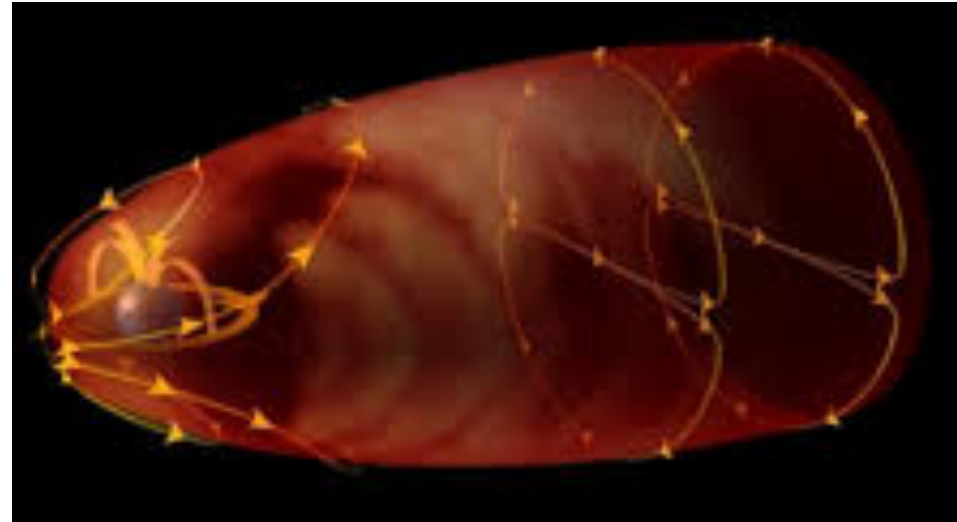
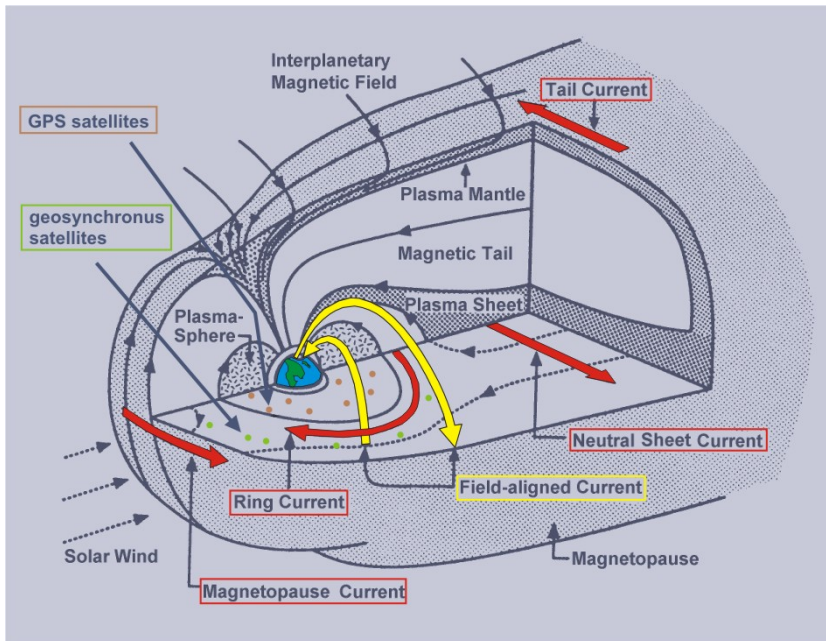
➤ 地球磁层简介

磁尾电流 (Magnetotail current)

磁尾中性片电流和磁尾磁层顶电流两部分组成，中性片电流是经由中性片从晨向昏流，磁尾磁层顶电流是中性片电流的闭合电流。

在磁层内部，磁尾电流片近地端和环电流相接

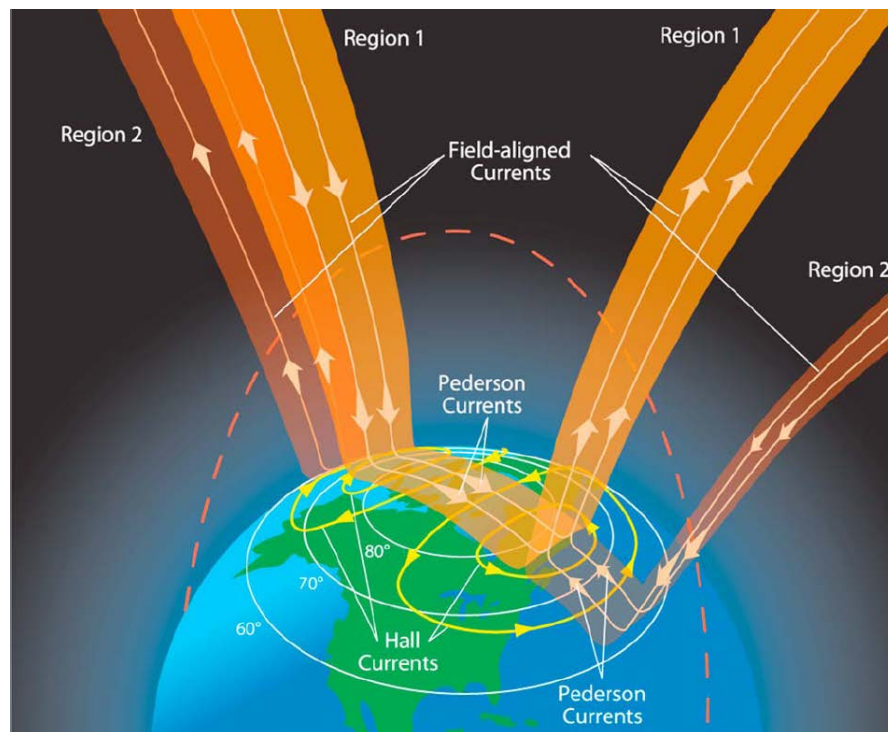
在磁层顶，磁尾电流体系的近地端和C-F电流体系相接。



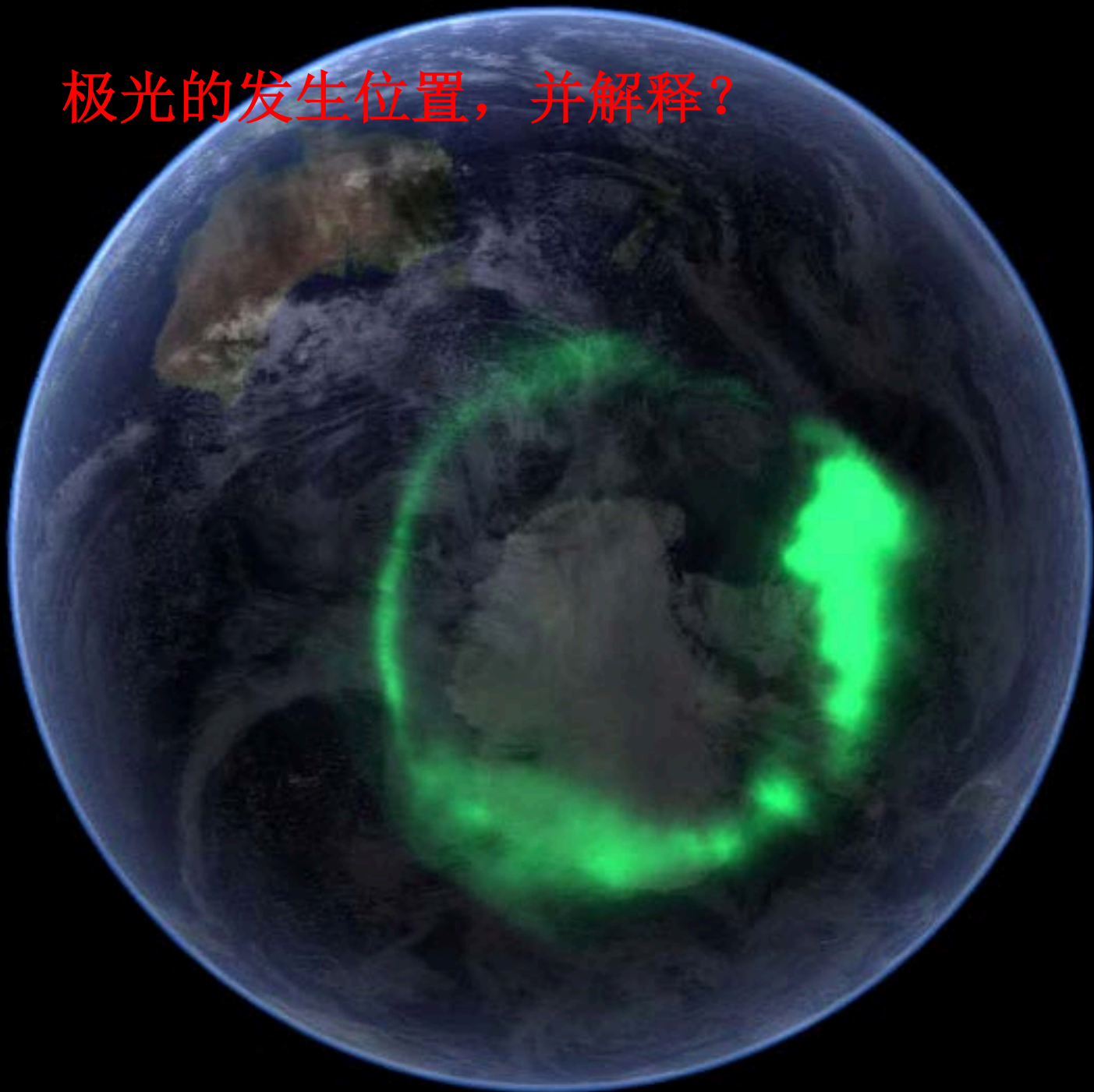
➤ 地球磁层简介

电离层电流（Ionosphere current）场向电流（field-aligned current）

行星际磁场南向时，地球磁层顶发生磁重联，等离子体向背阳面运动，尔后在极光卵区域回流形成2个电流涡



极光的发生位置，并解释？



Estimating the standoff distance to the magnetopause

The condition governing this position is that **the dynamic ram pressure from the solar wind is equal to the magnetic pressure from the Earth's magnetic field.**

$$\rho_{sw} u_{sw}^2 = B_{ms}^2 / (2\mu_0)$$

Chapman-Ferraro电流层的形成微观解释

左边为冷电子和离子束流，右边为均匀磁场。
 根据每单位时间通过某一特定 x - z 平面 ($y=y_0$)。任何进入2倍离子回旋半径区域的质子将跨越此平面。
 可求得电流：

$$I = 2\rho_{cp} n u e = 2 n m_p u^2 / B_z$$

利用 $B_z = \mu_0 I$

可得

$$B_z^2 / 2\mu_0 = n m_p u^2 = \rho u^2$$

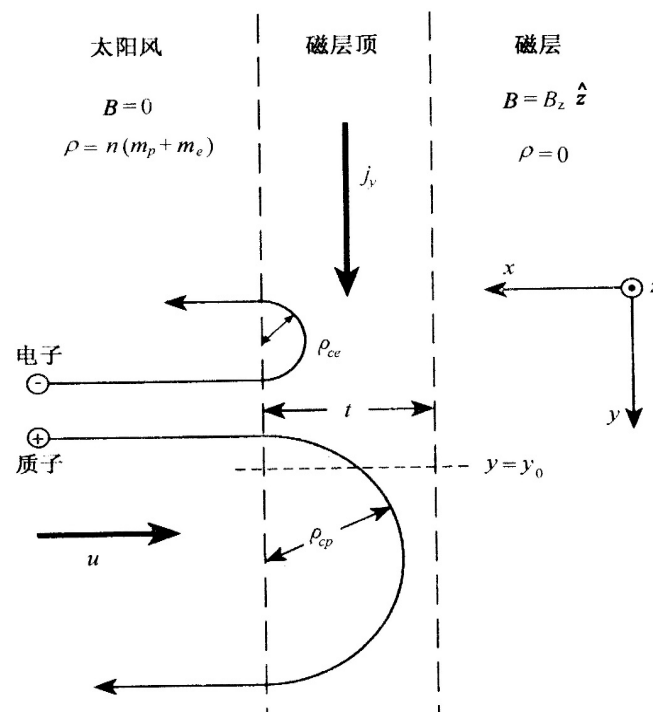


图 9.2

磁层顶平面简单模型, 将(左边)的非磁化太阳风和(右边的)没有等离子的磁层所隔开。太阳风粒子的集体回旋效应使得磁层顶电流向下流动, 每个粒子回旋半周后回到磁鞘

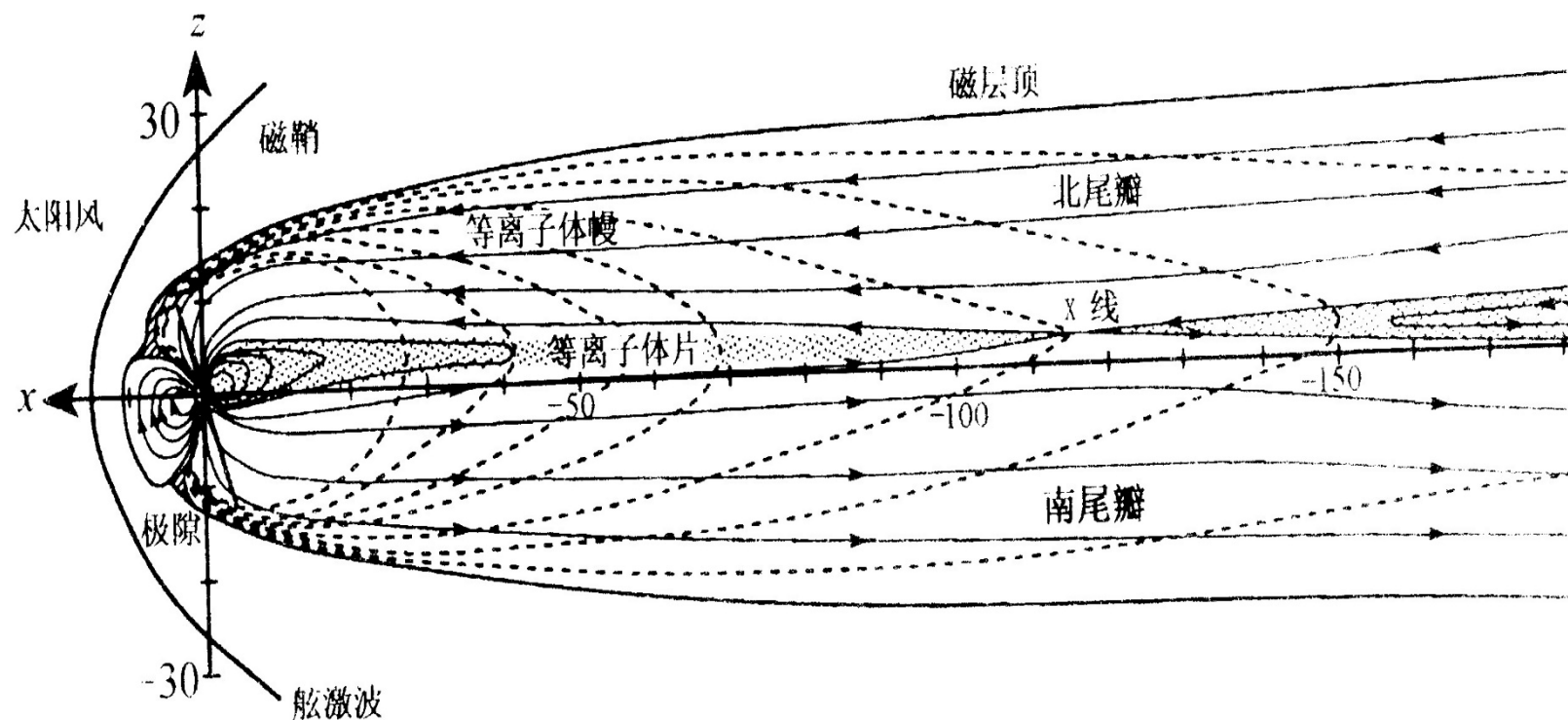


图 9.3 符合实际比例的磁层和磁尾中午-子夜截面图

月球轨道在图的中央附近。携带越尾电流片的等离子体片分成两个瓣区,在地球磁尾 115 个地球半径处有磁场 X 线或中性点。点线标明了等离子体慢粒子的轨迹

(参见 9.6.2 节, Pilipp and Morfill, 1978)

地球磁尾

极盖区上空磁场强度的垂直分量在极盖区的积分

$$\Phi_{PC} = 2\pi(R_E \sin \theta_{PC})^2 B_0$$

尾瓣磁场强度

$$\Phi_T = \pi R_T^2 B_T / 2$$

两者相等，可得

$$R_T / R_E = (4B_0 / B_T)^{1/2} \sin \theta_{PC}$$

如 $\theta_{PC} = 15^\circ$, $B_0 = 31000nT$, $B_T = 20nT$, 则 $R_T = 20R_E$

同时，根据稳态磁尾，尾瓣必须与等离子体片和太阳风之间保持压力平衡。可得

$$B_T^2 / 2\mu_0 = nk(T_i + T_e)$$

和尾瓣中的典型参数吻合

$$n \sim 0.3cm^{-3}, T_i \sim 4.2KeV, T_e = 0.6KeV$$

电流为 $\mu_0 I = \Delta B = 2B_T$

水星

Magnetic Field
Strength (nT)

160
120
80
40
0

Magnetopause
Bow shock

Magnetopause

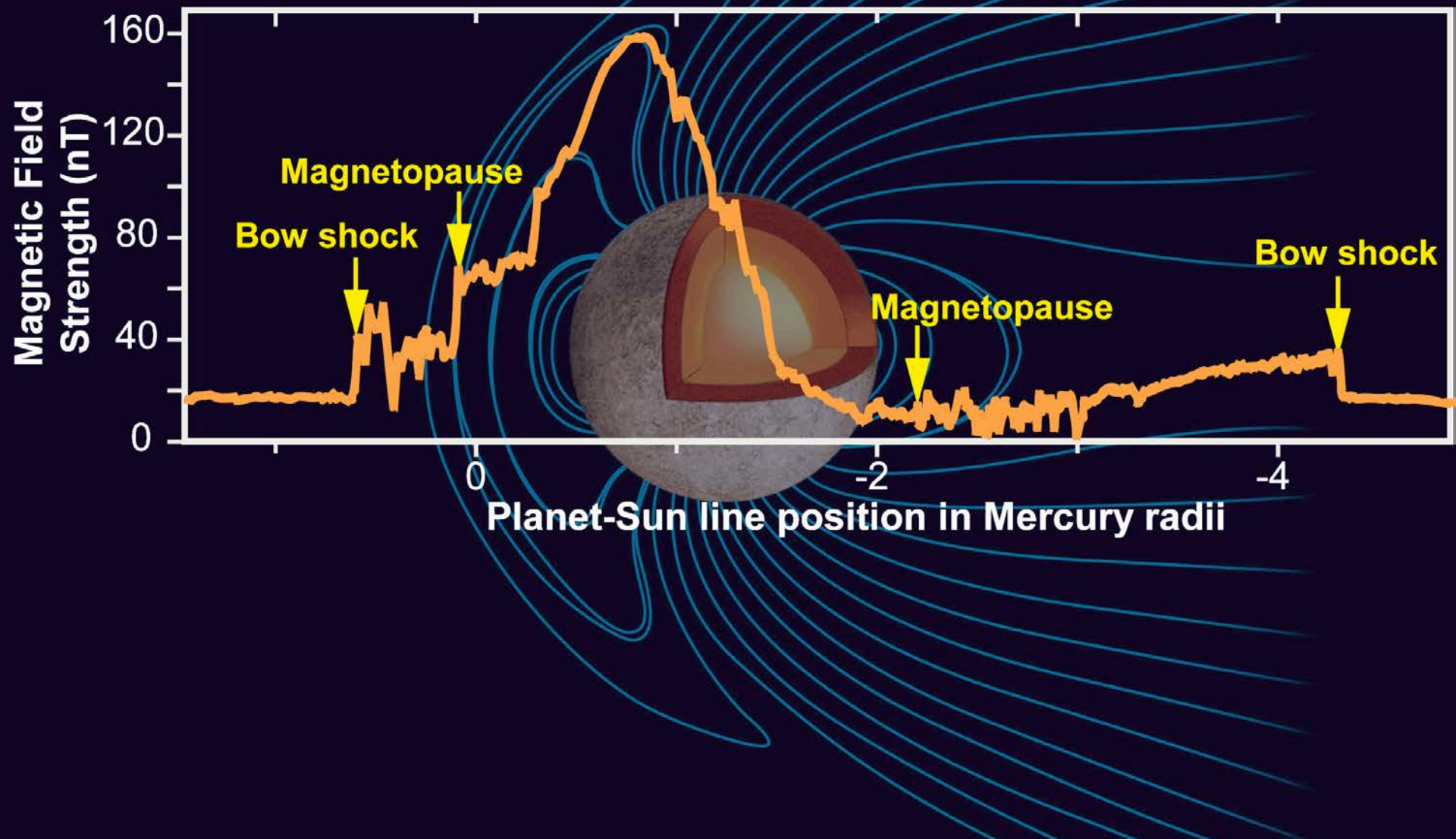
Bow shock

Planet-Sun line position in Mercury radii

0

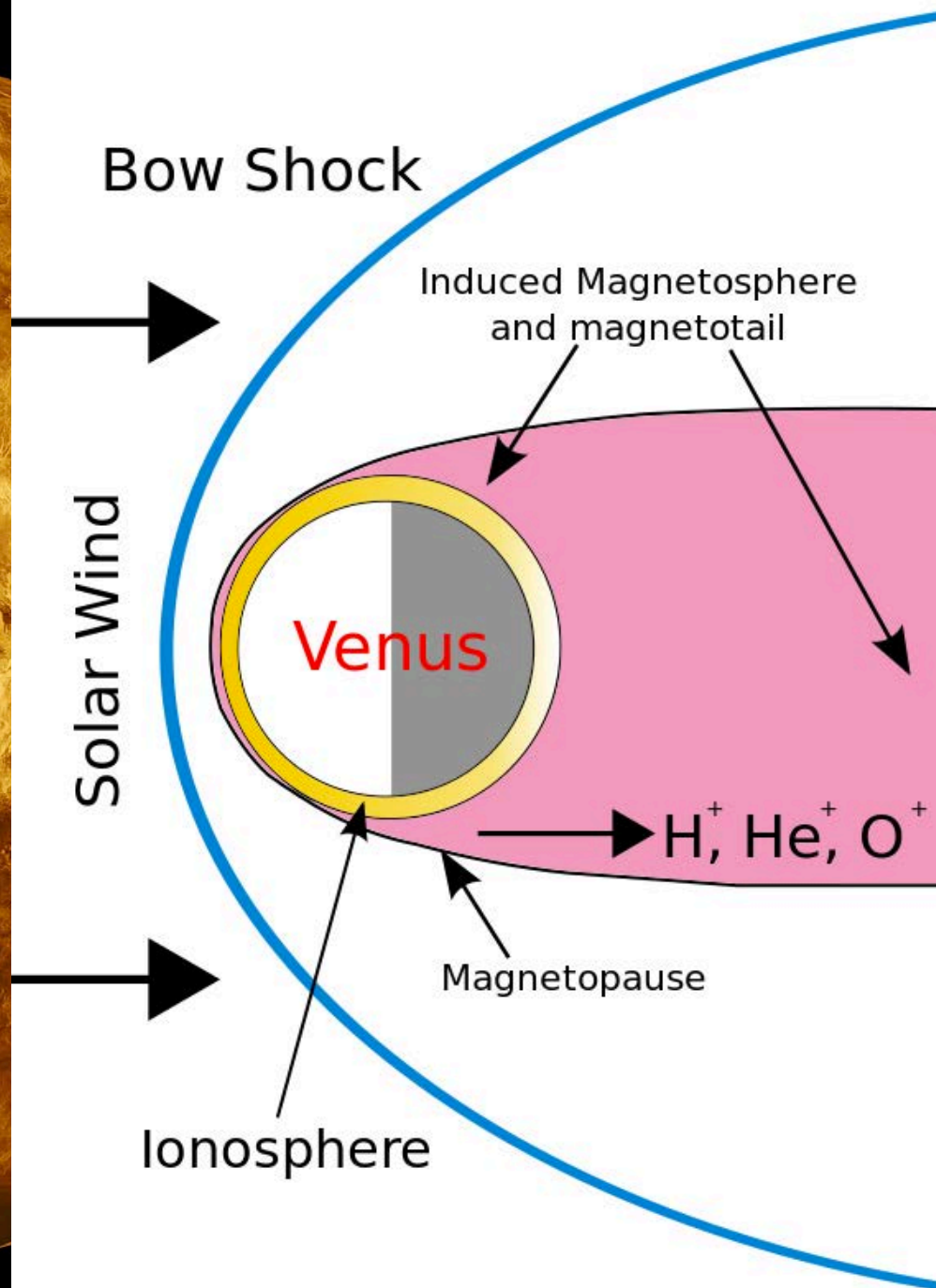
-2

-4



金星

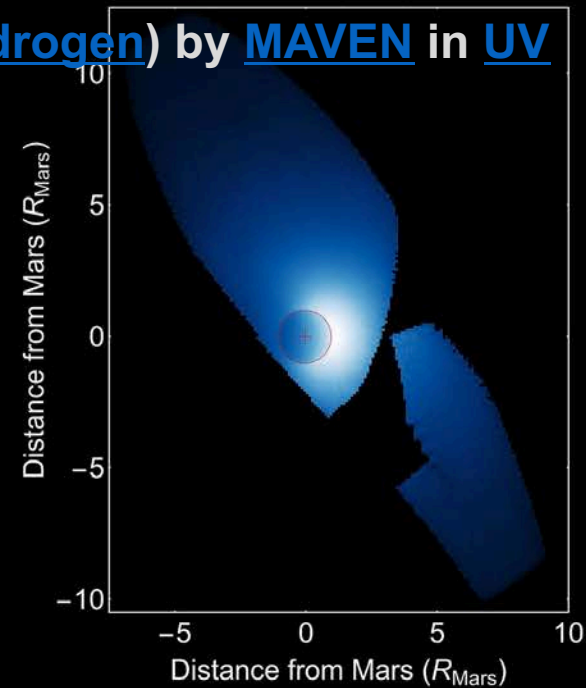
金星有没有磁层？
如何产生的？



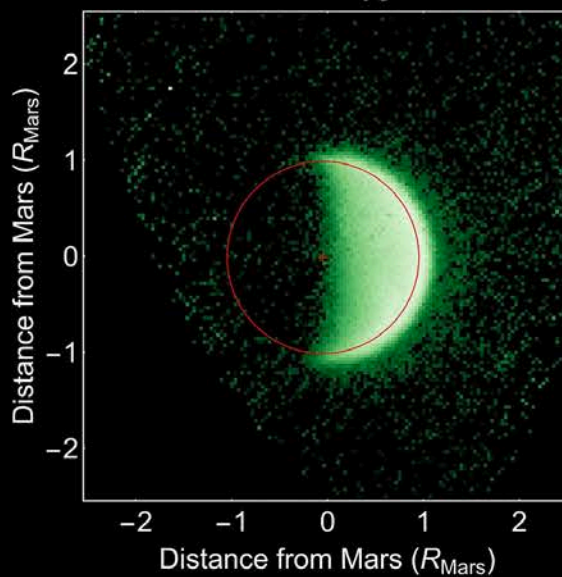
火星



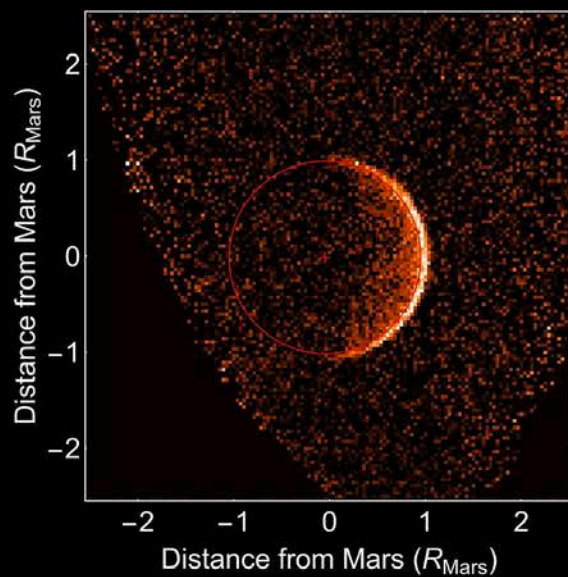
Atomic Hydrogen



Atomic Oxygen

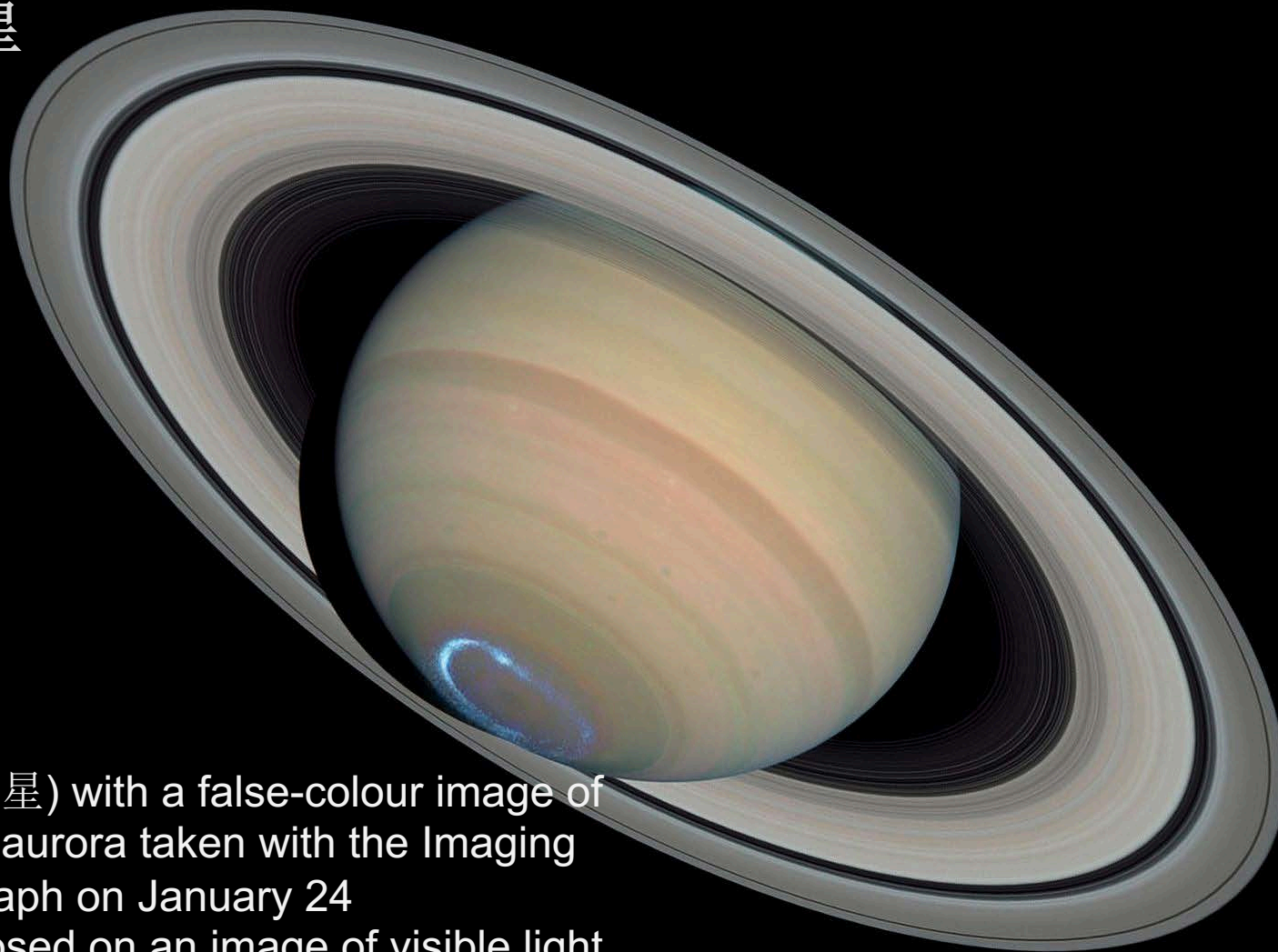


Atomic Carbon



Escaping atmosphere on Mars (carbon, oxygen, and hydrogen) by MAVEN in UV

土星



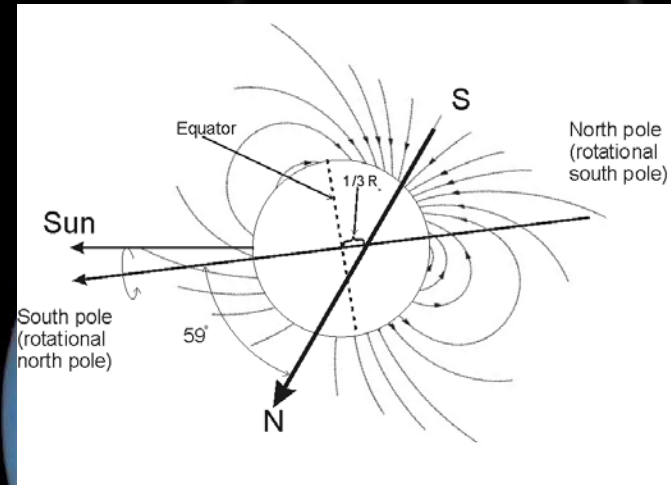
Saturn (土星) with a false-colour image of ultraviolet aurora taken with the Imaging Spectrograph on January 24 superimposed on an image of visible light taken with the Advanced Camera for Surveys on March 22, 2004 from NASA's [Hubble Space Telescope](#)

木星



The auroras were photographed during a series of Hubble Space Telescope Imaging Spectrograph far-ultraviolet-light observations taking place as NASA's Juno spacecraft approaches and enters into orbit around Jupiter

天王星



The magnetic field of
Uranus as observed
by *Voyager 2* in 1986!

Aurorae on Uranus taken by the Space Telescope Imaging Spectrograph (STIS) installed on [Hubble](#)

行星的磁场

磁层：行星磁场与太阳风相互作用
诱发磁层

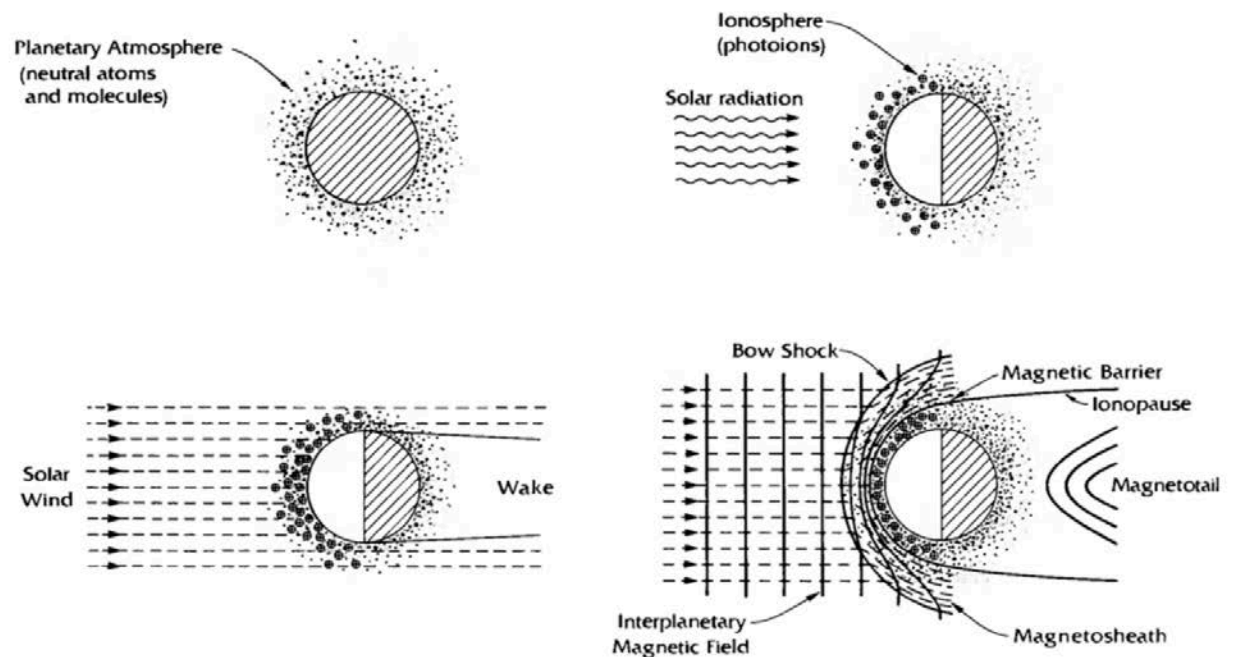


FIG. 8.5. Illustration of the steps that lead to the formation of an ionospheric planetary obstacle in a flowing plasma like the solar wind. Ionization by solar radiation, for example, is followed by diversion of the external plasma flow only if that flow is magnetized.

Estimating the standoff distance to the magnetopause

Solar System magnetopauses [\[edit \]](#)

Overview of the Solar System magnetopauses ^[11]					
Planet ↕	Number ↕	Magnetic moment [note 2] ↕	Magnetopause distance [note 3] ↕	Observed size of the magnetosphere ^[note 4] ↕	variance of magnetosphere ^[note 5] ↕
♿ Mercury	1	0.0004	1.5	1.4	0
♀ Venus	2	0	0	0	0
♁ Earth	3	1	10	10	2
♂ Mars	4	0	0	0	0
♃ Jupiter	5	20000	42	75	25
♄ Saturn	6	600	19	19	3
♅ Uranus	7	50	25	18	0
♆ Neptune	8	25	24	24.5	1.5

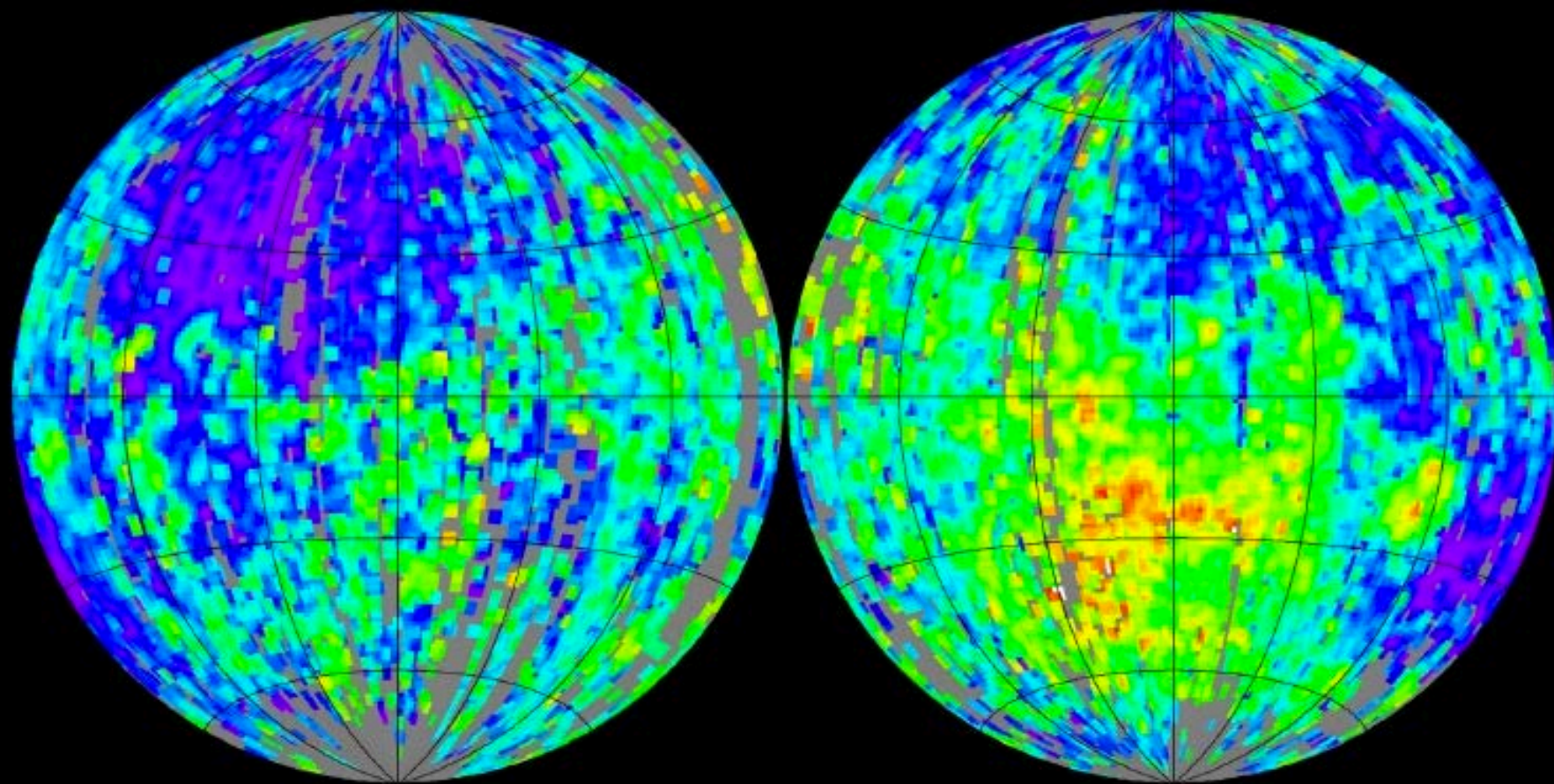
Research on the magnetopause is conducted using the LMN coordinate system (which is set of axes like XYZ). N points normal to the magnetopause outward to the magnetosheath, L lies along the projection of the dipole axis onto the magnetopause (positive northward), and M completes the triad by pointing downward.

Venus and Mars do not have a planetary magnetic field and do not have a magnetopause. The solar wind interacts with the planet's atmosphere^[12] and a void is created behind the planet. In the case of the Earth's moon and other bodies without a magnetic field or atmosphere, the body's surface interacts with the solar wind and a void is created behind the body.

月球

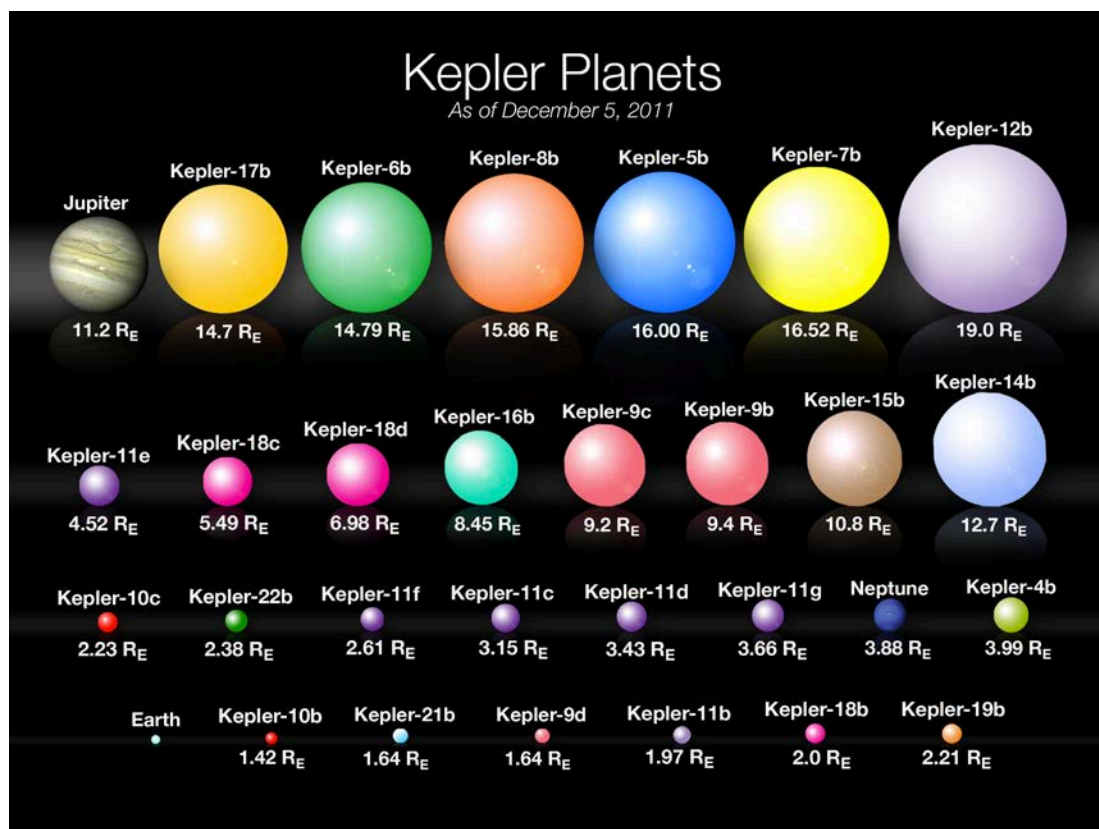
Near side

Far side



Total magnetic field strength, nT

讨论：宜居行星的必要条件



- 大小
- 距离
- 大气
- 磁场

地磁暴

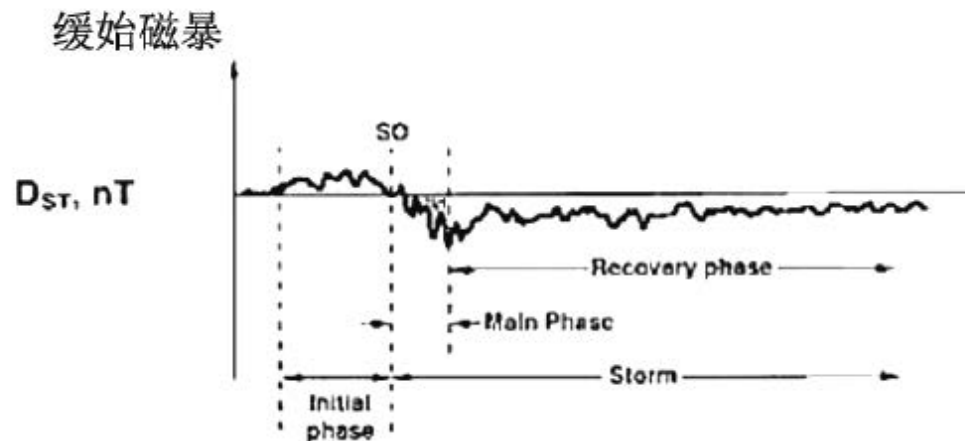
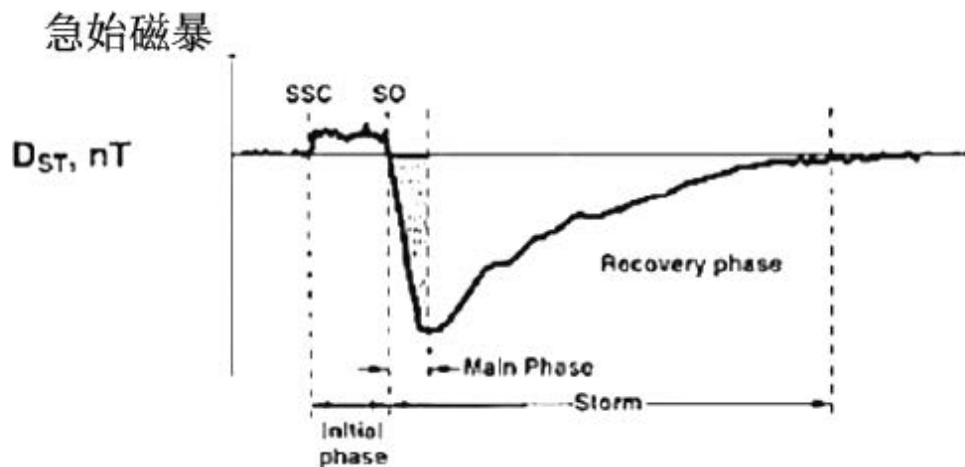
在中低纬台站经常观测到的地磁场水平分量大幅度减小，并且大约持续数天，这种现象叫做地磁暴。

磁暴急始 (ssc)

初相 (时段随意)

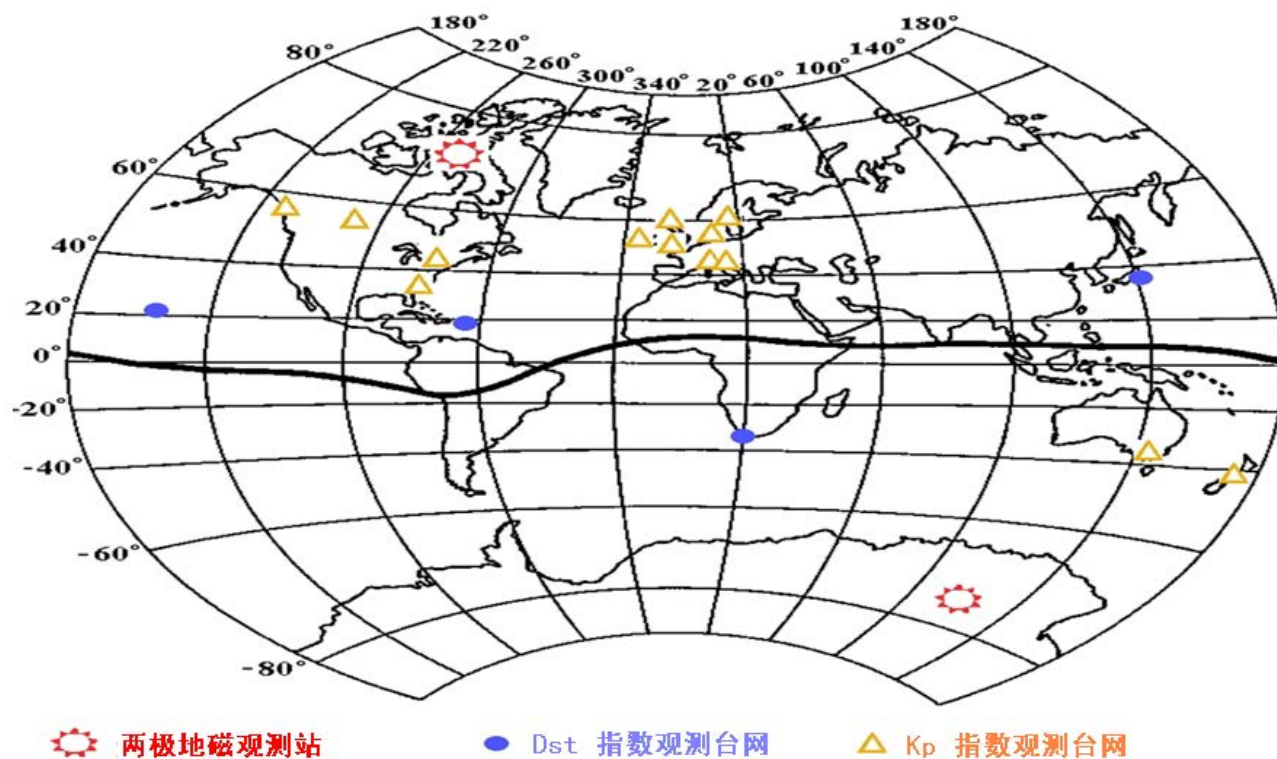
主相 (1-几个小时)

恢复相 (几个小时-十几个小时)



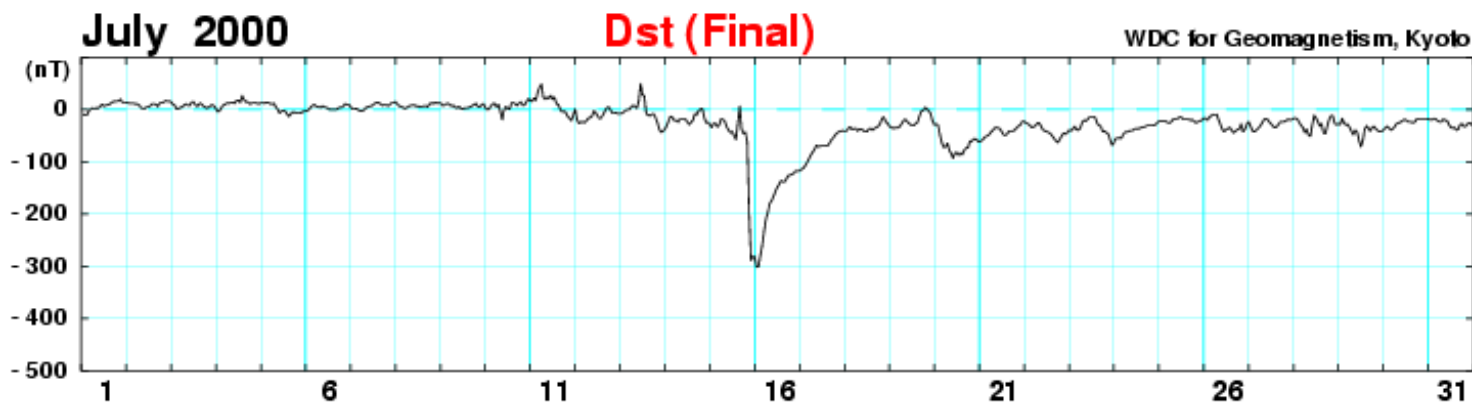
常用地磁指数

Dst指数、Kp指数、Ap指数



Dst指数

- ☑ **指数定义：**在地球赤道附近，按大致均匀的经度间隔选取四个地磁台站，这四个台站每小时地磁水平分量扰动值按一定权重平均即为Dst指数。
- ☑ **取值范围：**正几十纳特斯拉到负几千纳特斯拉。
- ☑ **指数意义：**描述了磁暴期间环电流的变化。
- ☑ **时间频率：**1小时。
- ☑ **更新情况：**由世界数据中心东京站（WDC-Kyoto[<http://wdc.kugi.kyoto-u.ac.jp/dstdir/>]）。包含初始数据（Preliminary），确定后发布最终数据（Final）。



Kp指数

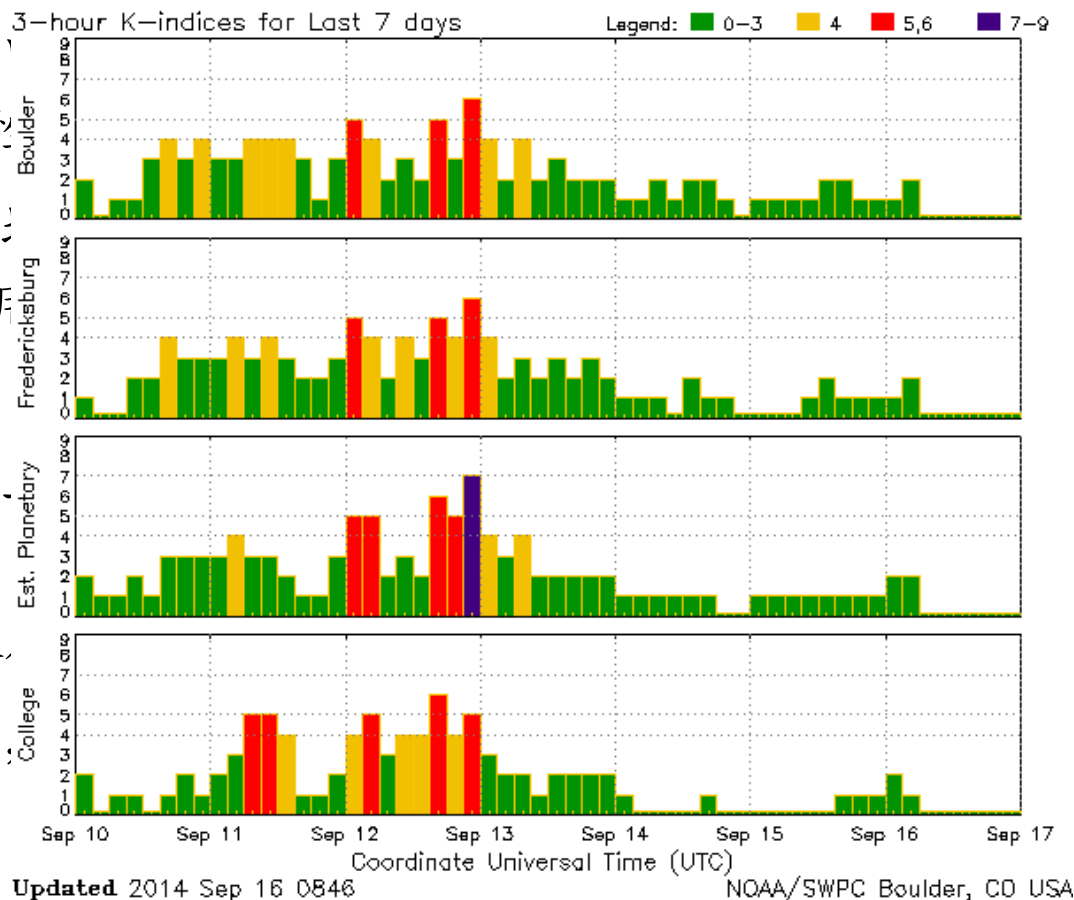
☑ K指数：描述单个地磁台站3小时时段内地磁扰动等级的指数，称为“三小时磁情指数”。取0到9共分10级，0表示地磁活动平静，9表示地磁扰动幅度最大。

☑ Kp指数：全球地磁台网，用于表示全球地磁活动性

☑ 指数意义：Kp描述全球地磁活动性，赋予其较强的业务实用性

☑ 时间频率：3小时。

☑ 更新情况：官方Kp指数由美国国家空间天气中心（SWPC，[index.html](http://www.swpc.noaa.gov/index.html)）通过全球合作台站发布，官方Kp指数一致性很高。



Ap指数

- ☑指数定义：首先按照换算表格由Kp对应得到ap指数，一天8个ap的平均即为Ap指数。
- ☑取值范围：0到400，值越大，地磁扰动越强。
- ☑指数意义：Kp指数与磁扰幅度是非线性的，是个等级，没有单位，转化后的Ap指数单位为2nT，可表征全球地磁扰动的幅度。
- ☑时间频率：1天。

☑更新情况：由国际地磁参考场中心（IGRF）提供

Kp指数和Ap
指数换算表

Kp = 0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+
ap = 0	2	3	4	5	6	7	9	12	15	18	22	27	32
Kp = 5-	5o	5+	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9o
ap = 39	48	56	67	80	94	111	132	154	179	207	236	300	400

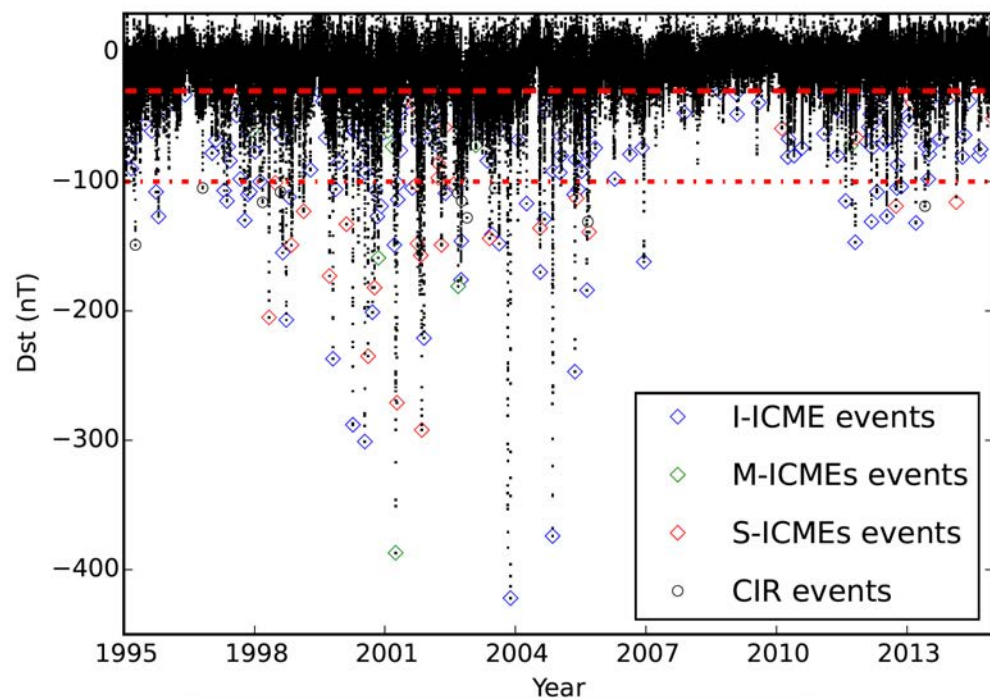
地磁暴的分类

$Dst_{min} \leq -30\text{nT}$: 地磁暴

$-50\text{nT} \geq Dst_{min} > -100\text{nT}$:
中等地磁暴

$Dst_{min} \leq -100\text{nT}$: 强地磁暴

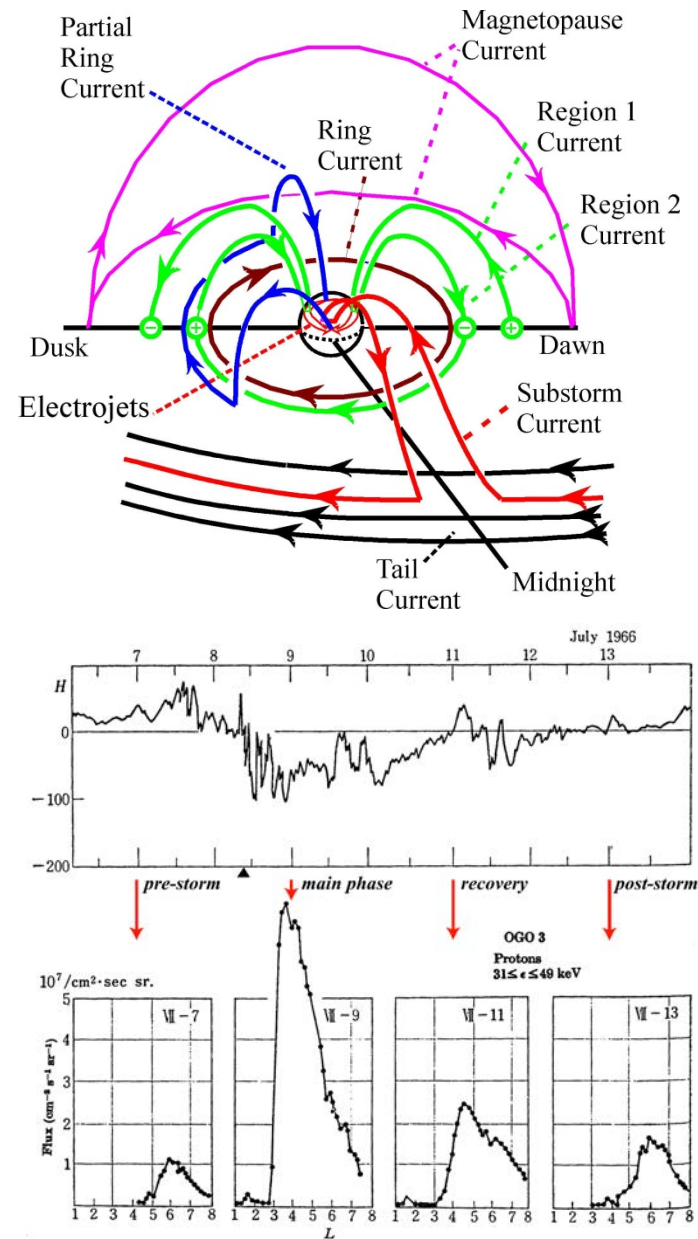
$Dst_{min} \leq -200\text{nT}$: 超强地磁暴



地磁暴起源

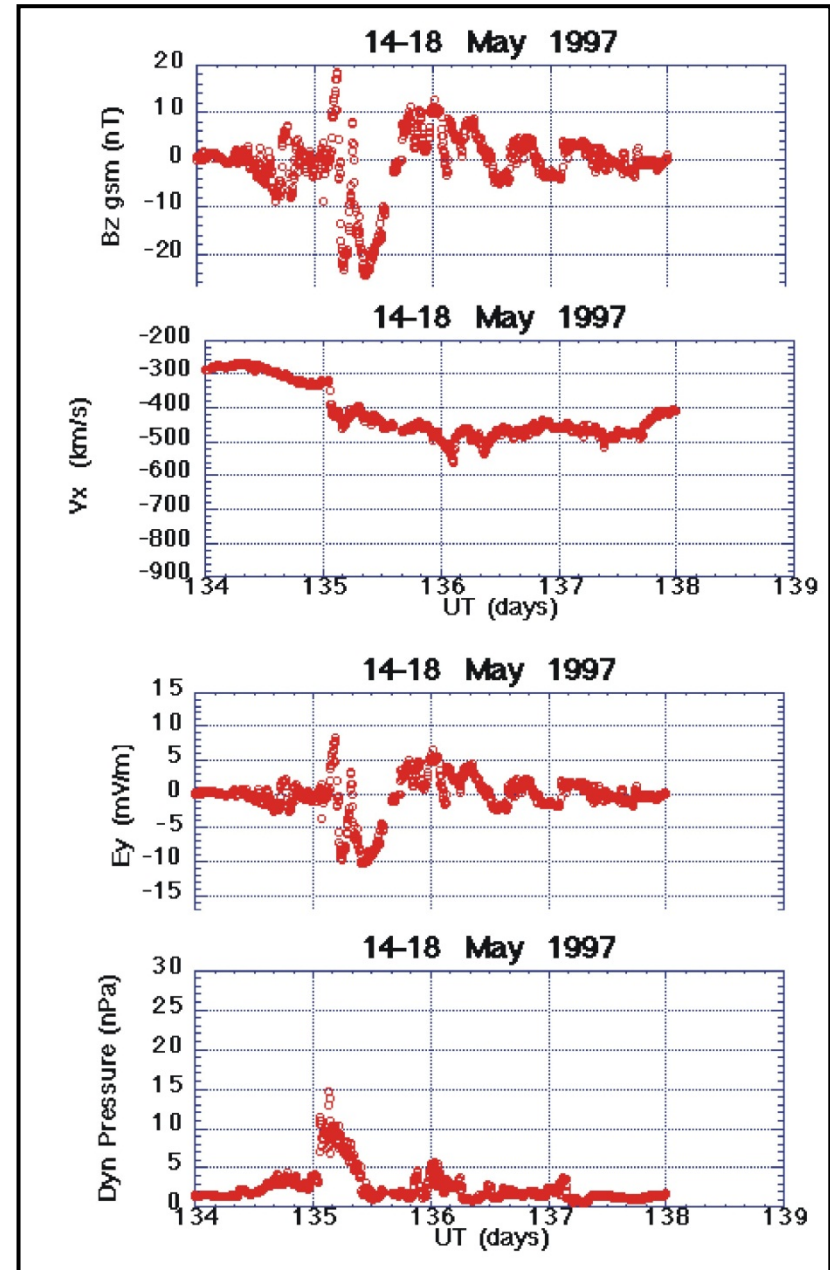
The **ring current** decreases the horizontal component of the magnetic field at the Earth's surface. (You can use a right hand rule to check this – Place your thumb along the direction of the current. Your bent fingers will give the direction of the change in the magnetic field.)

The disturbance storm time (Dst) index measures these differences. A stronger ring current causes Dst to decrease.



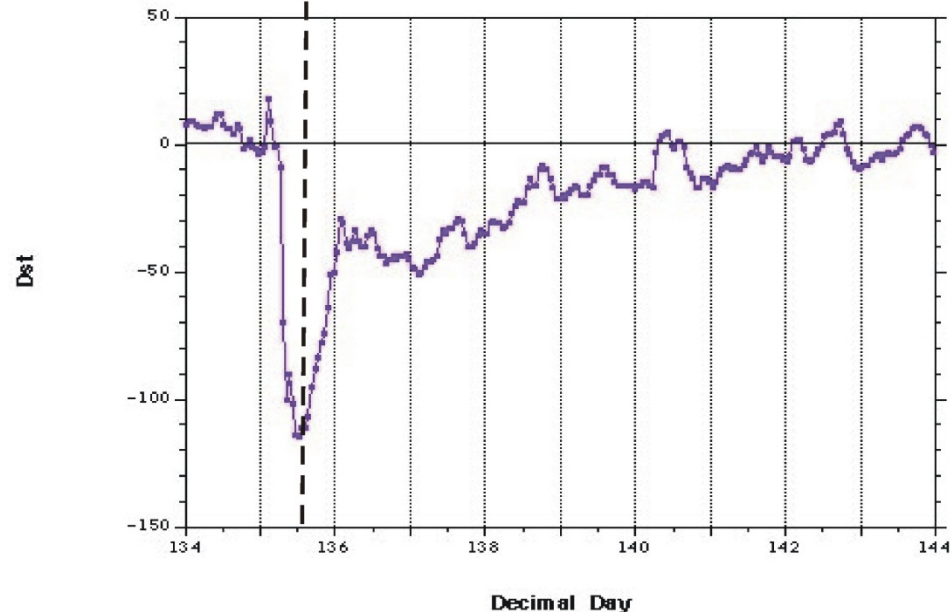
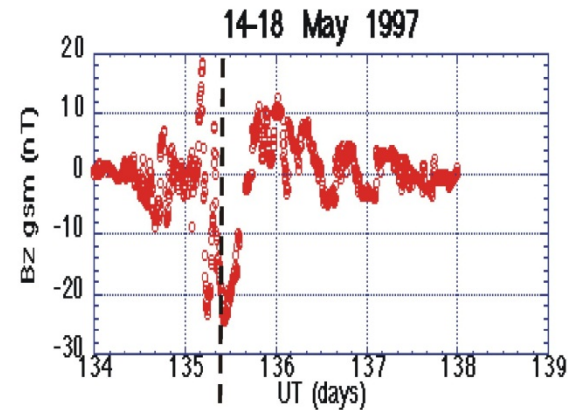
The Solar Wind During a CME Driven Storm

- Extended periods (several hours) of southward IMF lead to the *main phase* of the magnetic storm.
 - **Southward IMF** leads to magnetic reconnection.
 - Northward IMF has only minimal dayside reconnection.
- The increased dayside reconnection increases the penetration of the solar wind into the magnetosphere, increased convection and ring current injection.



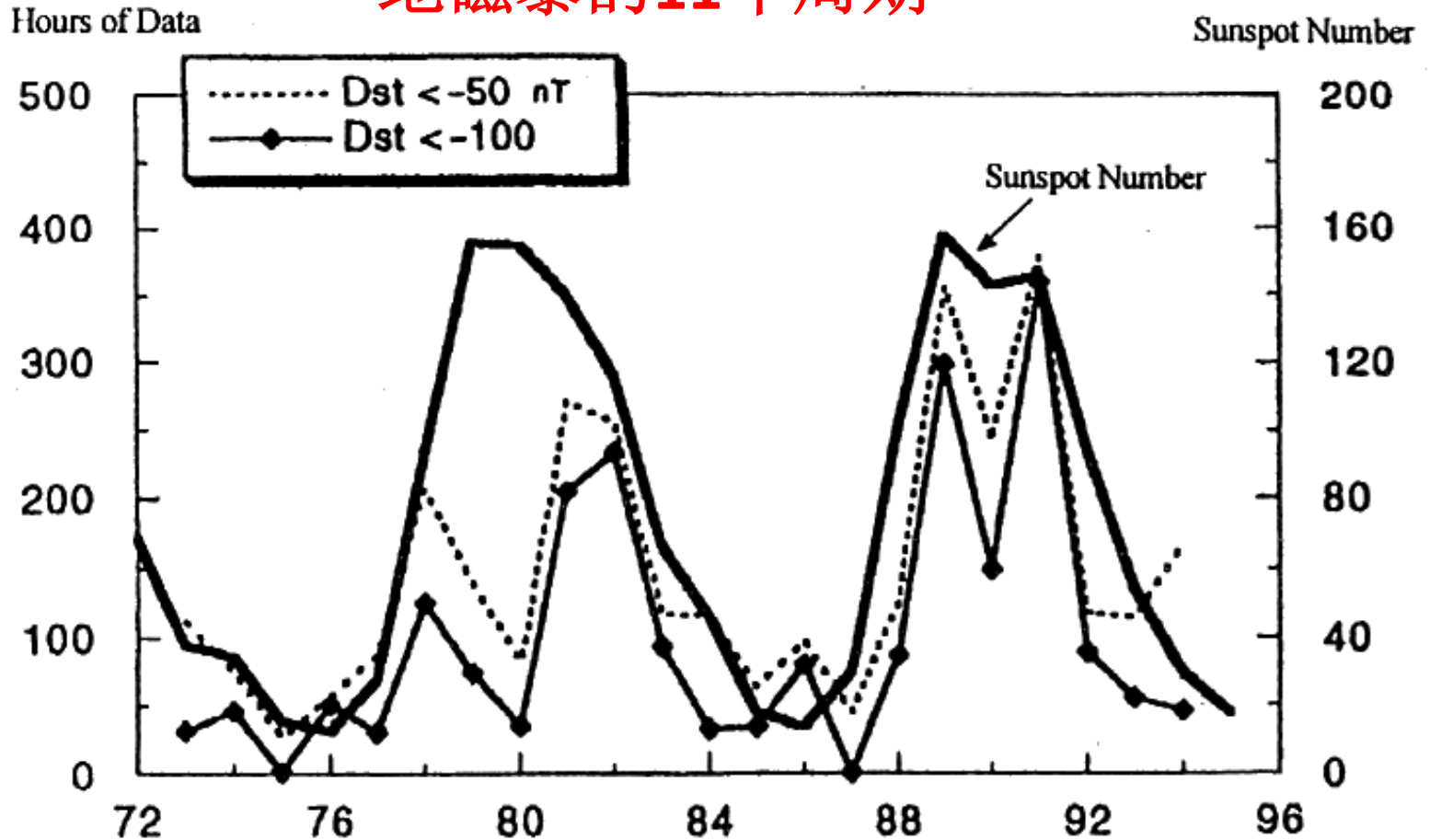
The Recovery Phase

- As the southward component of the IMF weakens or disappears, the ring current starts to decay. This is the *recovery phase* of the storm.
- The recovery phase has several steps.
 - The reduction of the southward IMF causes the reconnection rate to decrease.
 - The reduction of the southward IMF results in a decreasing electric field which leads to a reduction in the injection of new particles into the ring current.

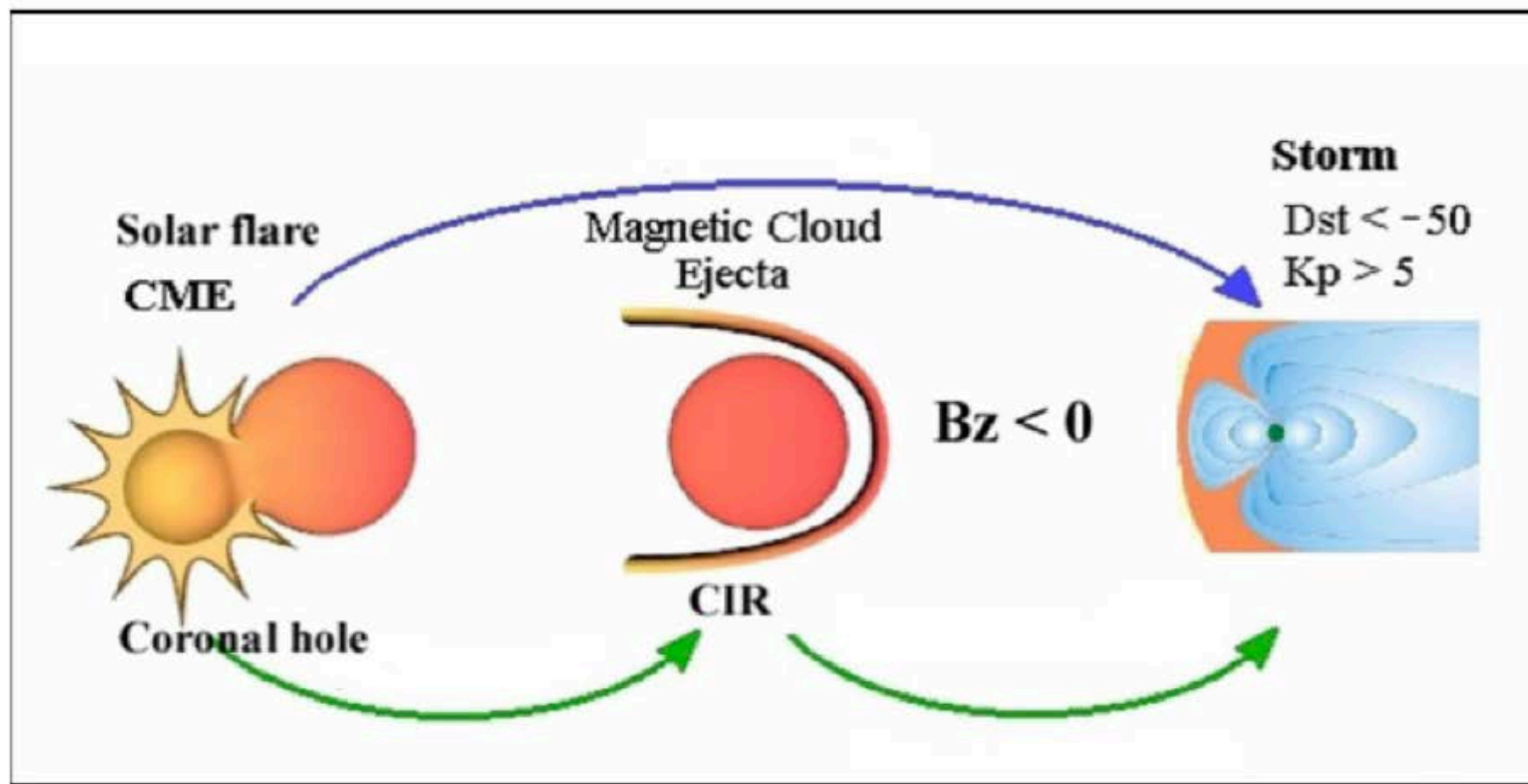
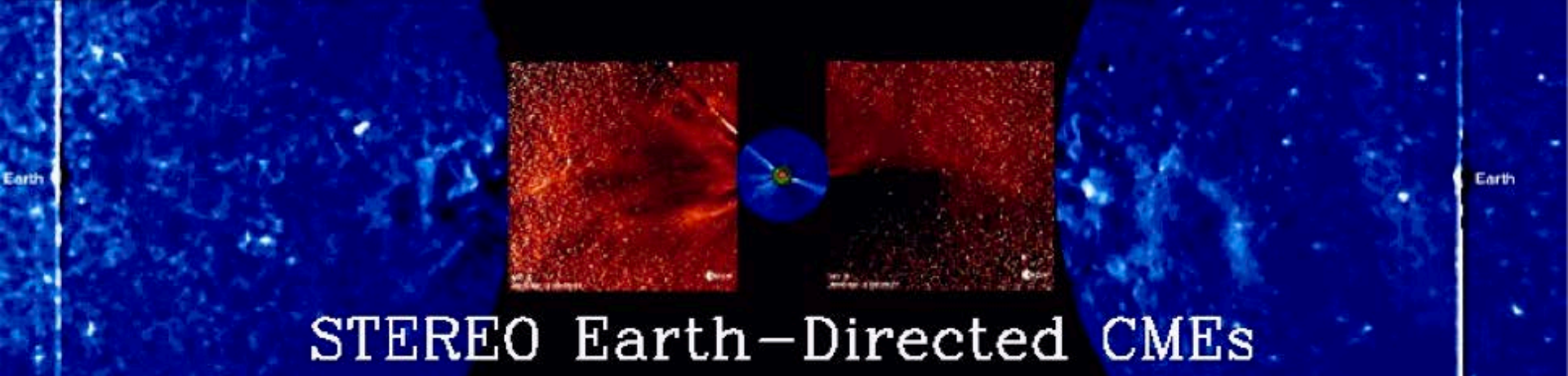


地磁暴与太阳活动的关系

地磁暴的11年周期

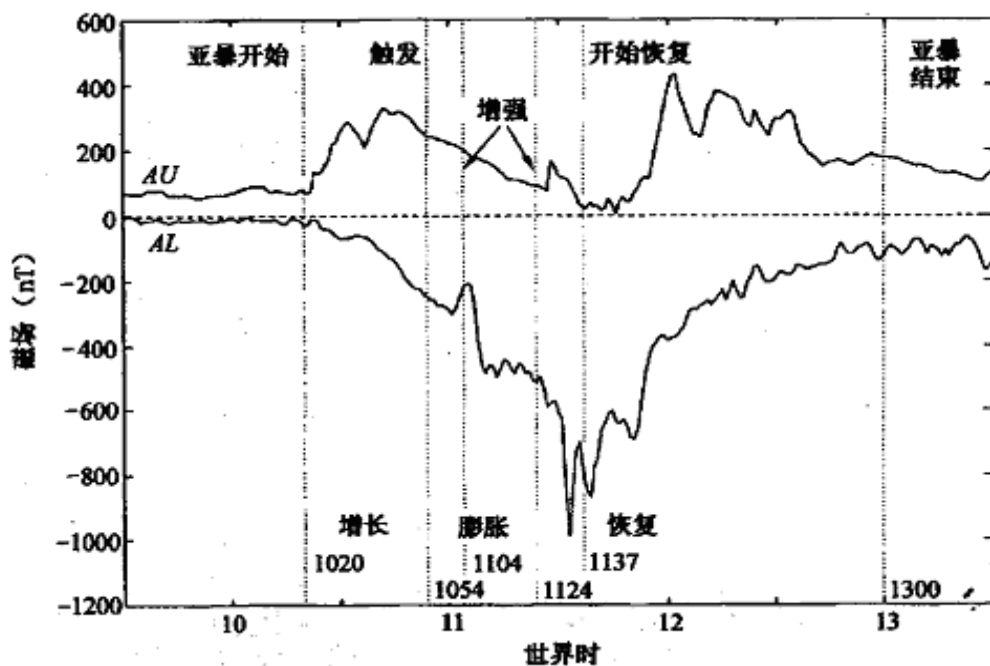


地磁暴其他周期？



磁层亚暴

磁层亚暴是从地球夜侧开始的一种爆炸式的释能过程，是一种重要的磁层活动现象，是地球磁层动力学性质最生动的表现。一次亚暴过程的持续时间约为1-3小时，释放能量约 10^{14} 次方-- 10^{15} 次方焦耳。



Geomagnetic perturbation lasting a few hours, which tends to occur during local post-midnight nighttime.

A substorm corresponds to an injections of charged particles from the magnetotail into the auroral oval.

磁层亚暴

- 增长相 (growth phase), 能量由太阳风转移到磁尾储存起来;
- 膨胀相 (expansion phase), 在这一过程中能量爆炸式地释放;
- 恢复相 (recovery phase), 这一阶段磁层弛豫到平静时的状态。

• Growth phase

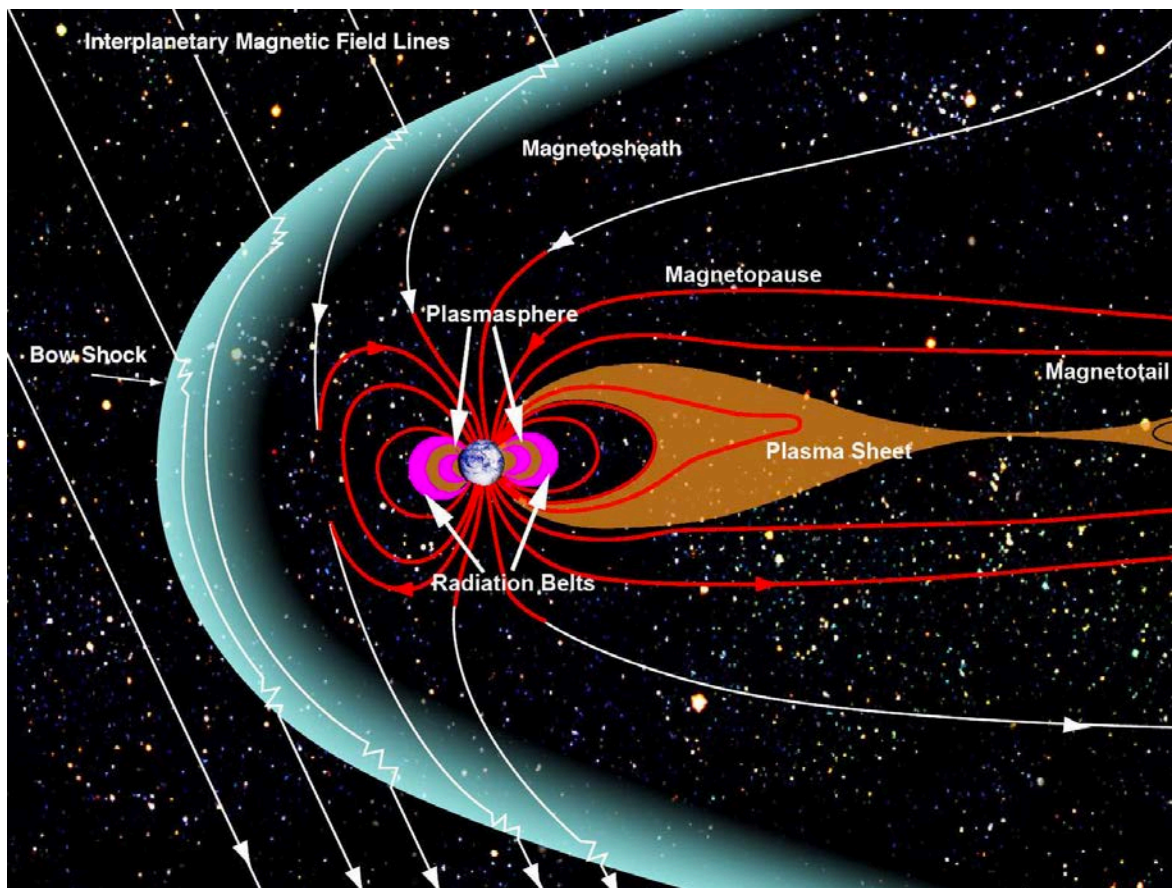
- ✓ About 1 hour
- ✓ Energy accumulation
- ✓ Magnetic reconnection on the dayside
- ✓ Enhanced magnetic field in the magneto-tail lobes
- ✓ Narrowing of the plasma sheet thickness

• Expansion phase

- ✓ also called “**dipolarization**”
- ✓ About 1- 2 hour
- ✓ Aurora brightening
- ✓ Depression of geomagnetic field
- ✓ Energy release through night side reconnection
- ✓ Injection energetic particles into the inner magnetosphere
- ✓ Plasma sheet heating
- ✓ Bursty bulk flow
- ✓ Tailward plasmoid release

磁层顶 → 磁尾

→ 磁层亚暴的起源



1. 地球自转的作用？

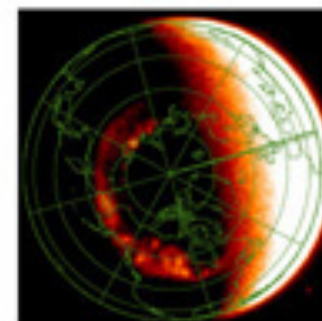
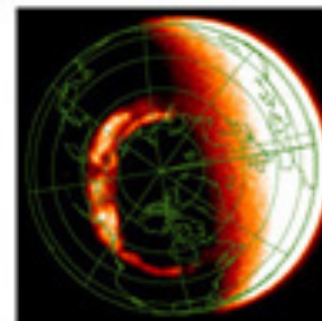
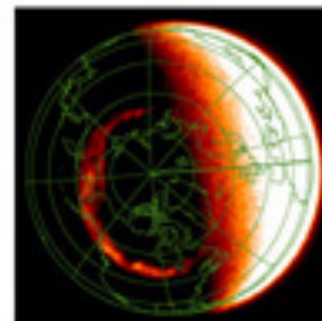
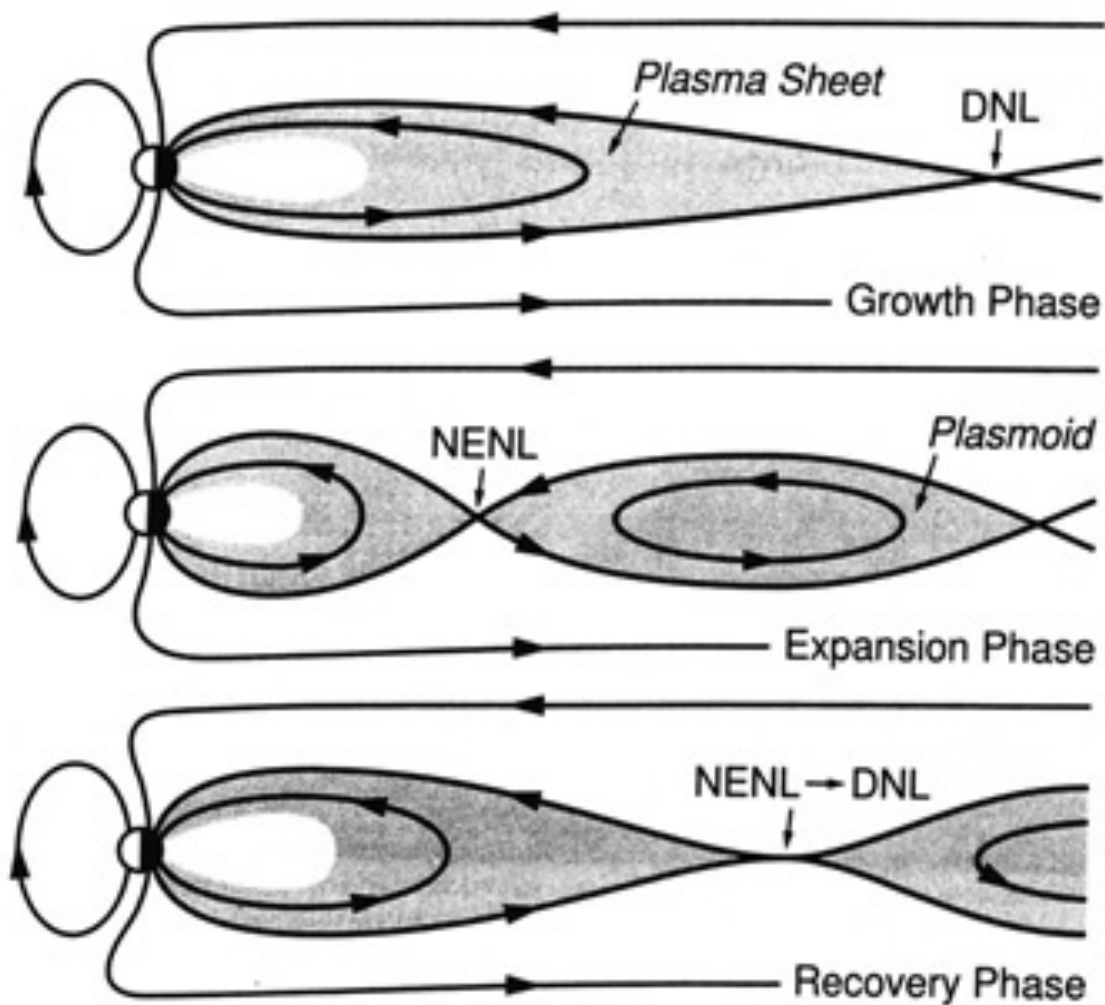
2. 向阳面重联速度超过背阳面？

磁层亚暴几种解释

- 近地中性线模式(NENL) (McPherron, 1973)
- 近地电流中断模式(NECD) (Lui, 1991)
- 磁层电离层耦合模式(MIC) (Kan, 1990)
- 边界层动力学模式(PSBL) (Rostoker & Eastman, 1987)
- 热灾变模式(TC) (Geortz & Smith, 1989)

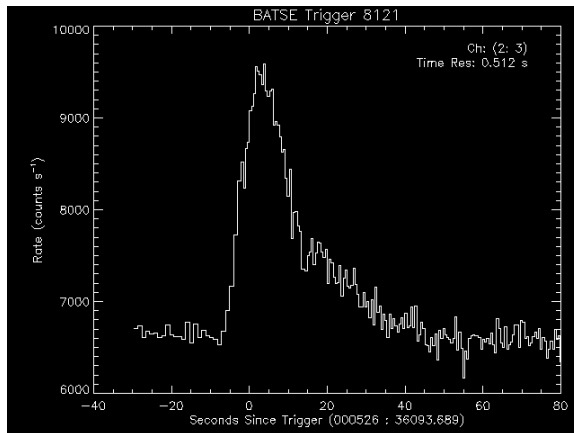
磁层亚暴

近地中性线模式

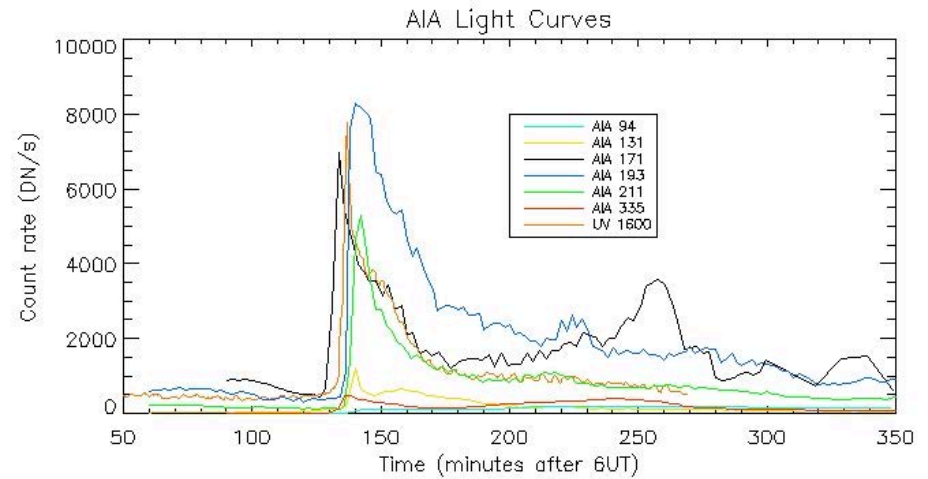


思考：比较不同能量释放过程的异同？

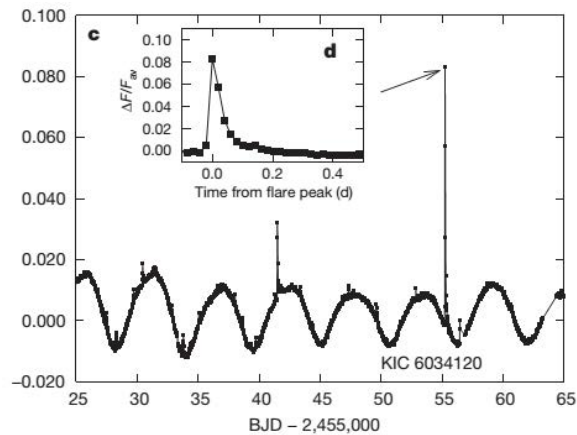
GRB



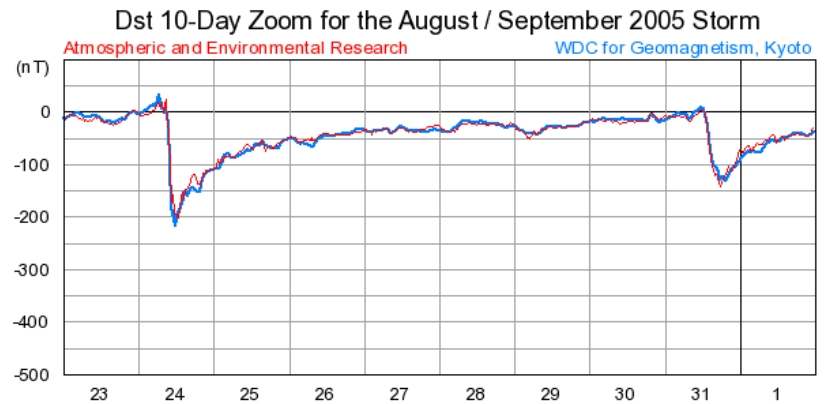
Solar flare



Stellar flare



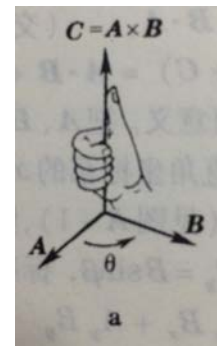
Magnetic storm



Backup

- 直线电流产生的磁场

右手规则：大拇指指向电流方面，四指弯曲方向为磁场方向。



Estimating the standoff distance to the magnetopause

Estimating the standoff distance to the magnetopause [\[edit\]](#)

If the pressure from particles within the magnetosphere is neglected, it is possible to estimate the distance to the part of the magnetosphere that faces the [Sun](#). The condition governing this position is that the dynamic [ram pressure](#) from the [solar wind](#) is equal to the magnetic pressure from the [Earth's magnetic field](#).

$$(\rho v^2)_{sw} \approx \left(\frac{4B(r)^2}{2\mu_0} \right)_m \quad \text{[note 1] where } \rho \text{ and } v \text{ are the density and velocity of the solar wind, and}$$

$B(r)$ is the [Magnetic field strength of the planet](#) in SI units (B in T, μ_0 in H/m)

Since the [dipole](#) magnetic field strength varies with distance as $1/r^3$ the magnetic field strength can be written as $B(r) = B_0/r^3$, where B_0 is the planet's magnetic moment, expressed in $[T \cdot m^3]$.

$$\rho v^2 \approx \frac{2B_0^2}{r^6 \mu_0}.$$

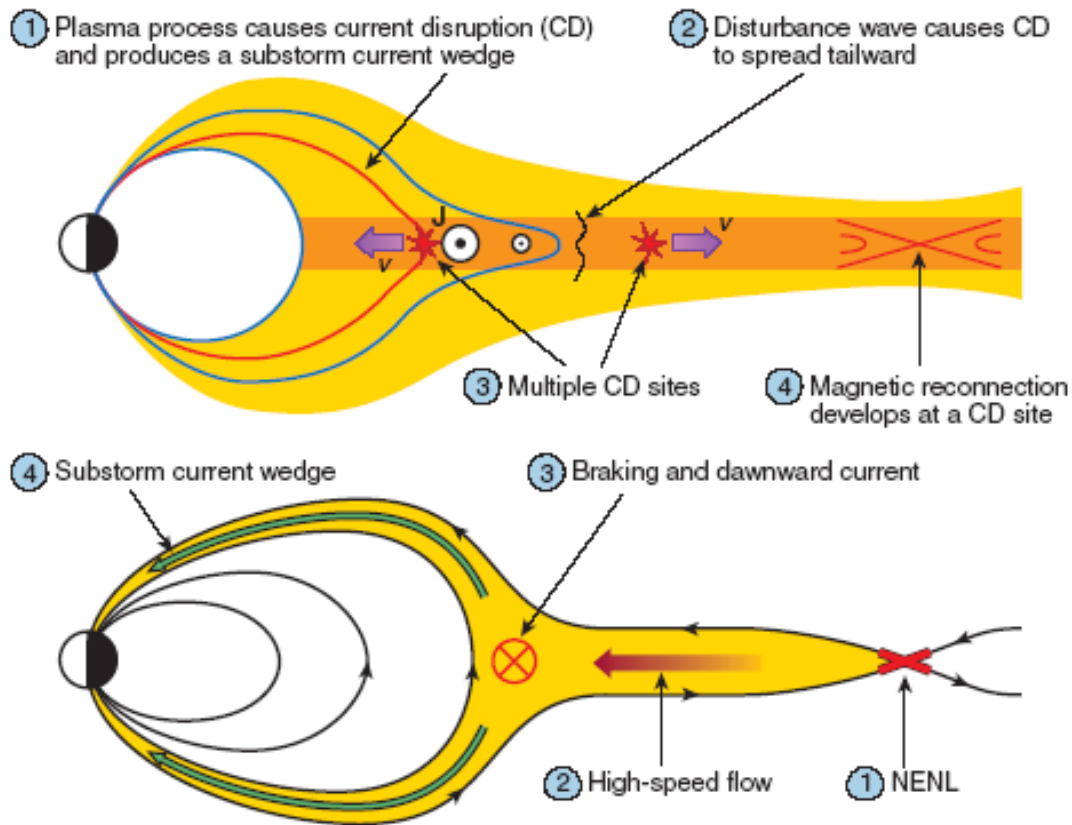
Solving this equation for r leads to an estimate of the distance

$$r \approx \sqrt[6]{\frac{2B_0^2}{\mu_0 \rho v^2}}$$

The distance from Earth to the subsolar magnetopause varies over time due to solar activity, but typical distances range from 6 – 15 $R_{\oplus}$. Empirical models^{[\[8\]](#)[\[9\]](#)} using real-time [solar wind](#) data can provide a real-time estimate of the magnetopause location. A [bow shock](#) stands upstream from the magnetopause. It serves to decelerate and deflect the solar wind flow before it reaches the magnetopause ^{[\[10\]](#)}

磁层亚暴

两种模型的演化



Time History of Events and Macroscale Interactions during Substorms (THEMIS)