

2014年度後期

素粒子宇宙物理学専攻・宇宙地球物理系

B類講義(単位数:2)

## 磁気圏物理学

平原 聖文 (STE研・第2(電磁気圏環境)部門)

毎週木曜日13:00~14:30

研究所共同館(STE研)講義室(301室)

### 講義内容

1. 講義概要と研究活動
2. プラズマの基本的な概念
3. 一つの粒子の運動
4. 地球磁気圏の構造とダイナミクス
5. 磁気圏観測技術
6. 観測データに見る地球磁気圏現象

## 講義内容・成績評価方法

- 多圏構造である宇宙空間の領域とそこでの物理現象、探査方法等を概説する。特にジオスペース磁気圏と総称される地球周辺の宇宙空間を題材に宇宙科学の理解を深める。ジオスペース磁気圏は、太陽風プラズマと地球磁場との電磁場・粒子的相互作用により、反太陽方向に引き延ばされた構造を持ち、その勢力範囲は月軌道の数倍~数十倍の距離まで及んでいる。最近の40年間における人工衛星・ロケットを用いた飛翔体による直接観測技術の急速な進歩により、ジオスペースの主要素である電磁場・プラズマ分布を詳細に調べることが可能になってきた。ここでは太陽近傍や惑星間の宇宙空間、地球・惑星磁気圏の諸現象を紹介しながら宇宙空間物理学・宇宙プラズマ物理学の基本概念、地球・惑星磁気圏の構造・ダイナミクスを学ぶ。特に、観測データ・観測技術を基軸として、具体的な描像と実地的な知見の獲得を目指す。
- キーワード: Space Plasma, In-situ Observation, Spacecraft Exploration, Plasma Process, Region/Energy Coupling
- 成績評価方法: 小レポート(毎週、兼: 出欠確認)+最終レポート?
- 関数電卓持参

# 要点・予定

- 領域・現象、多圏構造・結合と相互作用の概説が基軸
- 初等物理数学・電磁気学・流体力学の基礎知識による特徴量の導出
- 実際の観測・探査の原理・手法も紹介
- 素過程は他講義を参考
  
- 重要な語句・式は板書が基本でスライド集は補助的
- 出来るだけ入門的・実践的な内容の取り入れ
  - 「業界」用語・略語説明、基本式、授業内計算・質疑応答・議論、等

## 分野「名」紹介

- 超高層大気物理学(Upper Atmospheric Physics)
- 宇宙空間物理学(Space Physics)
- 宇宙プラズマ物理学(Space Plasma Physics)
- 磁気圏・電離圏物理学(Magnetospheric/Ionospheric Physics)
- 太陽地球系物理学(Solar-Terrestrial Physics: **STP**)
- 宇宙天気予報・科学(Space Weather Prediction/Science)
- ジオスペース(環境)科学(Geospace (Environment) Science)

学会名、国際会議名

SGEPSS: Society of Geomagnetism and Earth, Planetary and Space Sciences  
(地球電磁気・地球惑星圏学会)

JpGU: Japan Geoscience Union (日本地球惑星科学連合)

AGU: American Geophysical Union

EGU: European Geosciences Union

AOGS: Asia Oceania Geosciences Society

COSPAR、IAGA、IUGG、URSI、WPGM、VarSITI(SCOSTEP)

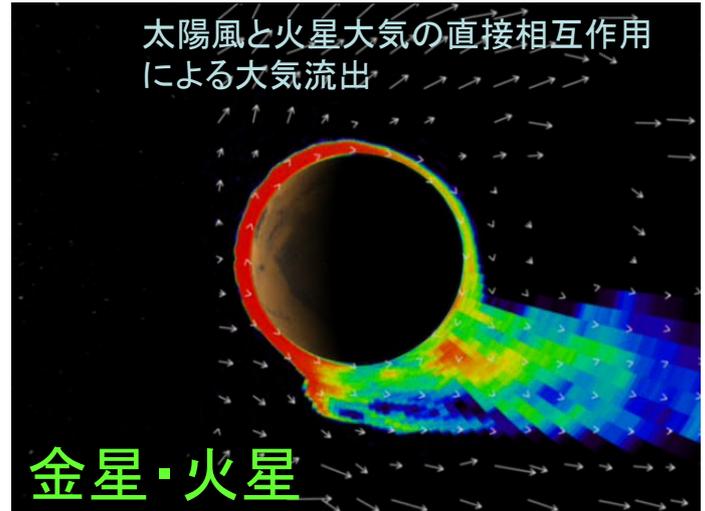
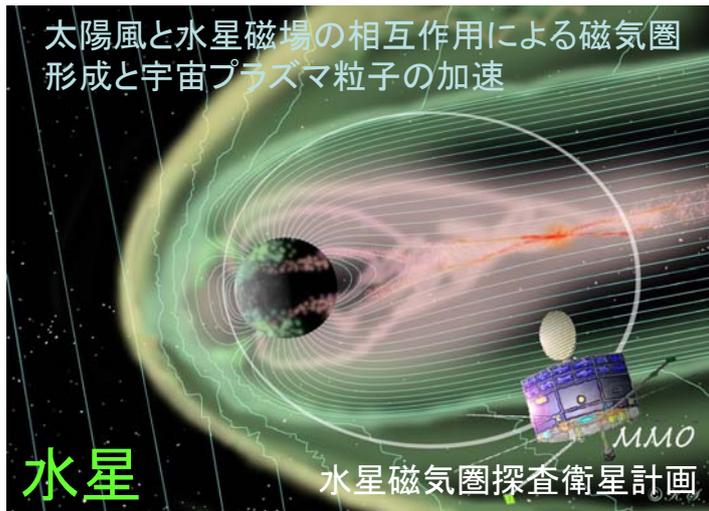
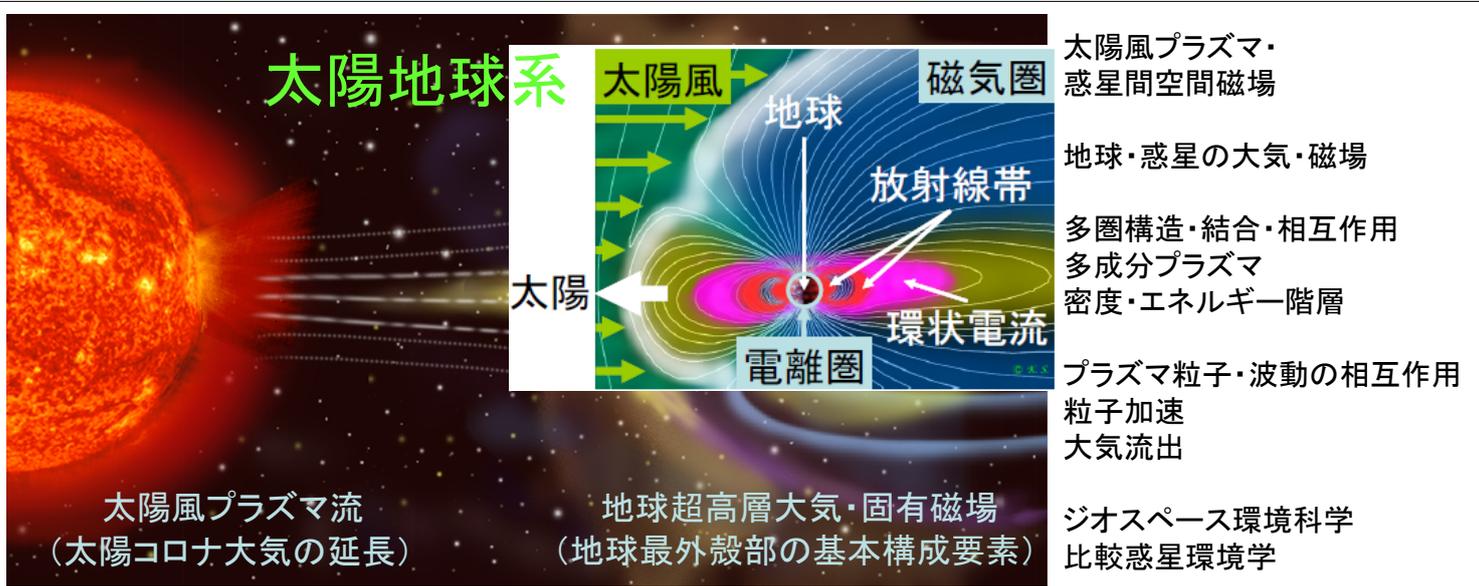
Chapman Conference、Alfven Conference、、、

# 基本物理量

- 単位系
  - 方程式上はMKS系が主で、その他の表記は「STP」系
  - 磁束密度: T, Gauss,  $\gamma$
  - エネルギーの表現:  $mv^2/2$ , kT, qV
- 陽子質量:  $m_p = 1.67 \times 10^{-27}$  [kg]
- 電子質量:  $m_e = 9.11 \times 10^{-31}$  [kg]
- 素電荷:  $e = 1.60 \times 10^{-19}$  [C]
- ボルツマン定数:  $k_B = 1.38 \times 10^{-23}$  [J/K]
- 真空の誘電率:  $\epsilon_0 = 8.85 \times 10^{-12}$  [F/m]
- 真空の透磁率:  $\mu_0 = 4\pi \times 10^{-7}$  [H/m]
- 光速:  $3.00 \times 10^8$  [m/s]
- 地球(赤道)半径・質量: 6378 [km]・ $M_E = 5.97 \times 10^{24}$  [kg]
- 太陽半径・質量: 696000 [km]・ $M = 1.99 \times 10^{30}$  [kg]
- 太陽地球間距離:  $1.496 \times 10^{11}$  [m] (1 AU)
- 万有引力定数:  $G = 6.67 \times 10^{-11}$  [ $N \cdot m^2/kg^2$ ]

## 参考図書

- 太陽惑星環境の物理学、前田坦著、共立出版
- 宇宙空間物理学、大林辰蔵著、裳華房
- 宇宙環境科学、恩藤忠典・丸橋克英編著、オーム社出版局
- 太陽地球圏、小野高幸・三好由純著、共立出版
- 総説宇宙天気、柴田一成・上出洋介編著、京都大学学術出版社
  
- 宇宙流体力学、坂下志郎・池内了共著、培風館
- プラズマ物理入門、F. F. Chen著、内田岱二郎訳、丸善
- 流体力学、神部勉著、裳華房
  
- The Solar-Terrestrial Environment, J. K. Hargreaves, Cambridge University Press
- Introduction to Space Physics, Edited by M. G. Kivelson and C. T. Russell, Cambridge University Press
  
- Physics of Space Plasmas: An Introduction, Second Edition, G. K. Parks, Advanced Book Program, Westview Press
- Basic Space Plasma Physics, W. Baumjohann and R. A. Treumann, Imperial College Press



# GEOSPACE

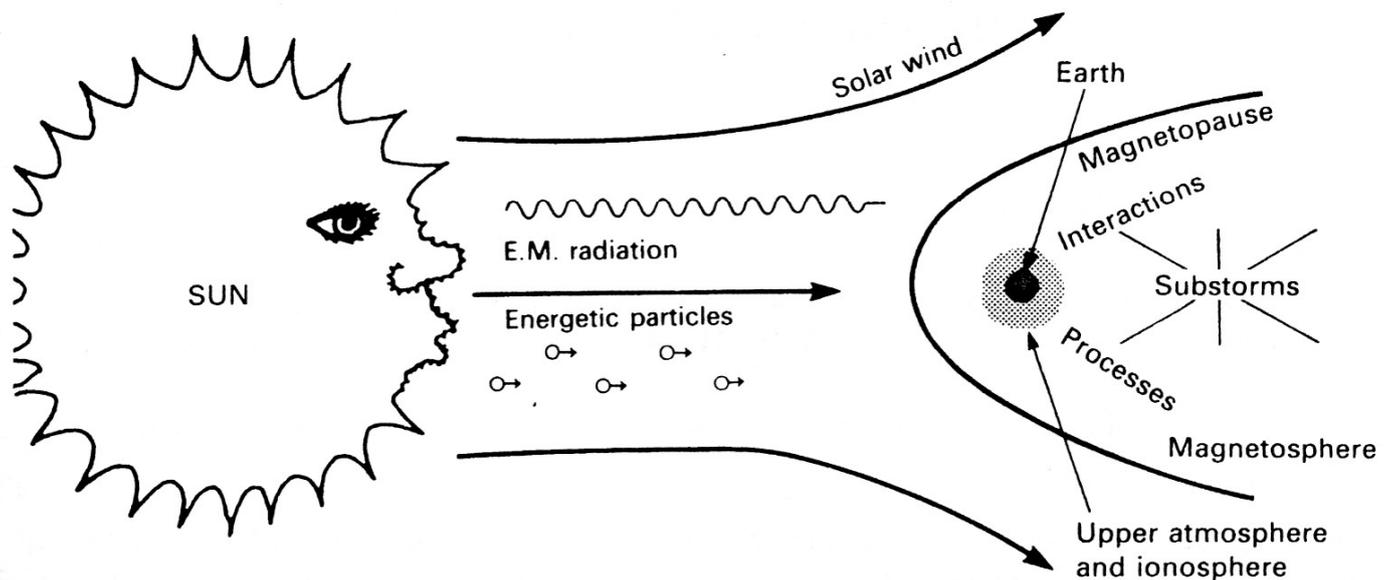
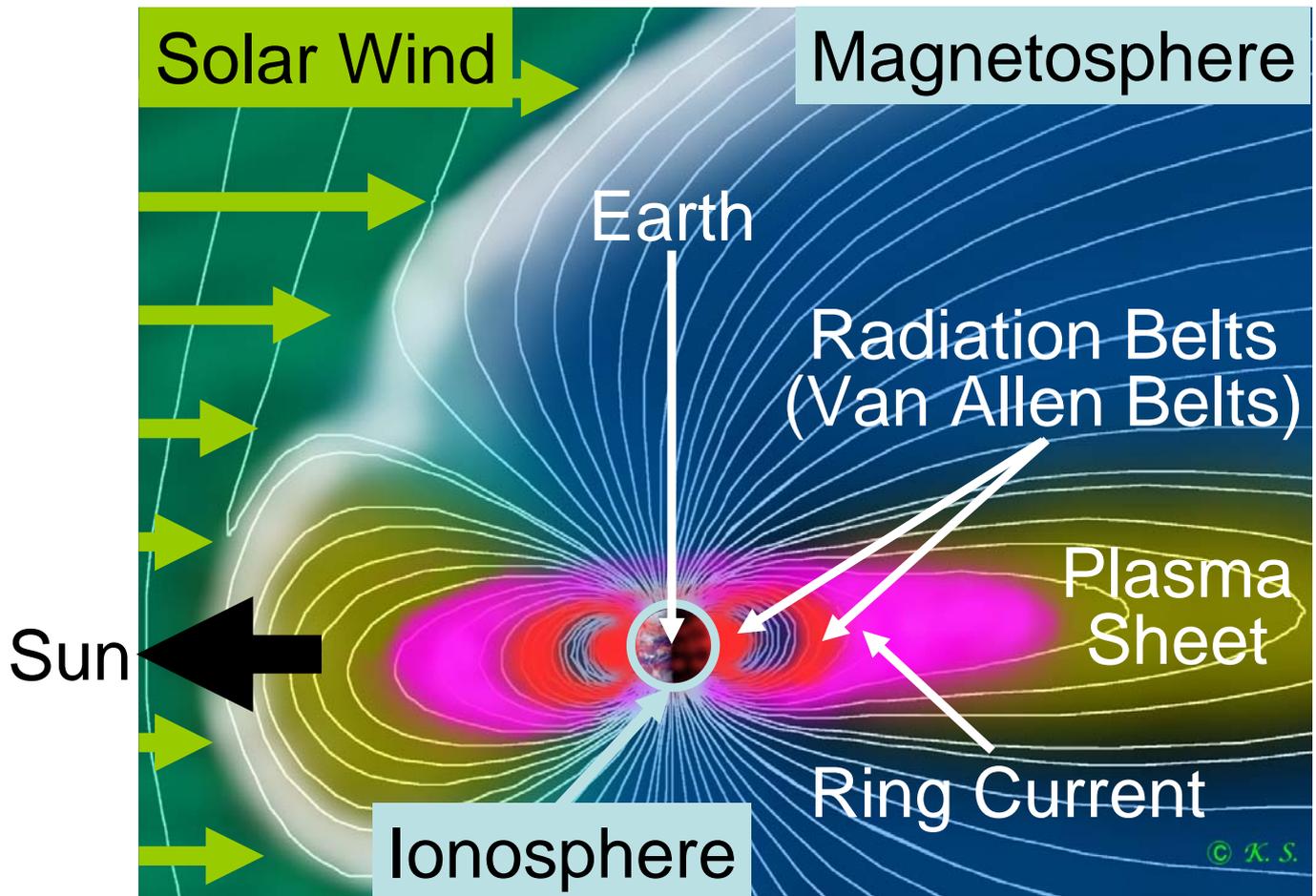
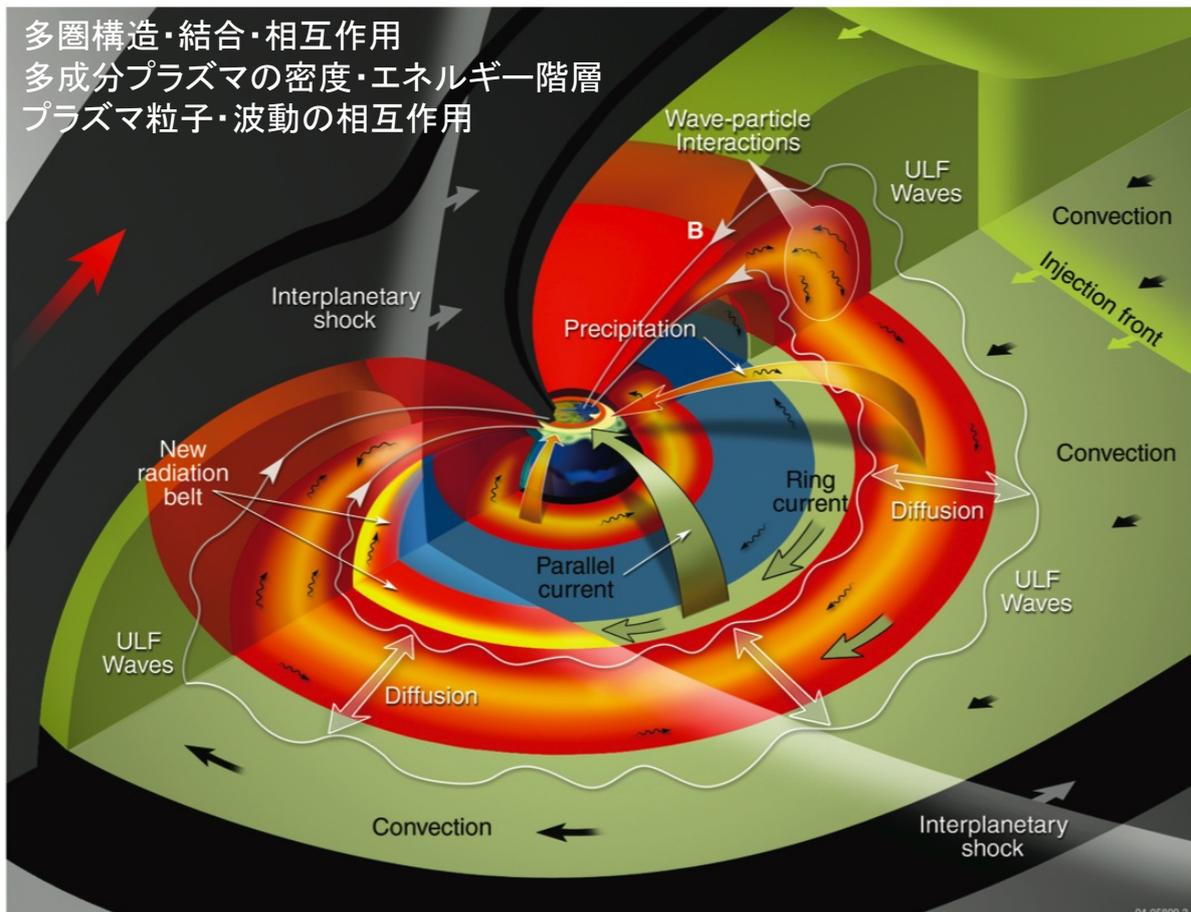


Fig. 1.1 Summary of the solar-terrestrial environment. (After a sketch by J. C. Hargreaves).

# Geospace



## 地球周辺宇宙空間(ジオスペース)



Geospace focus for "International Living With a Star" (ILWS) program

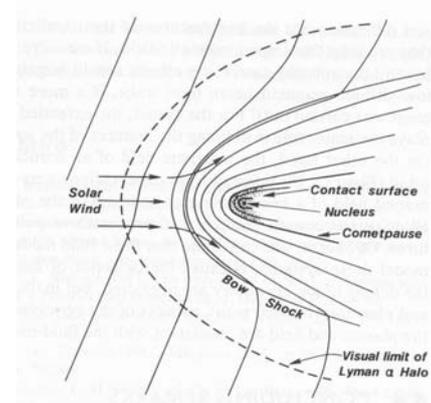
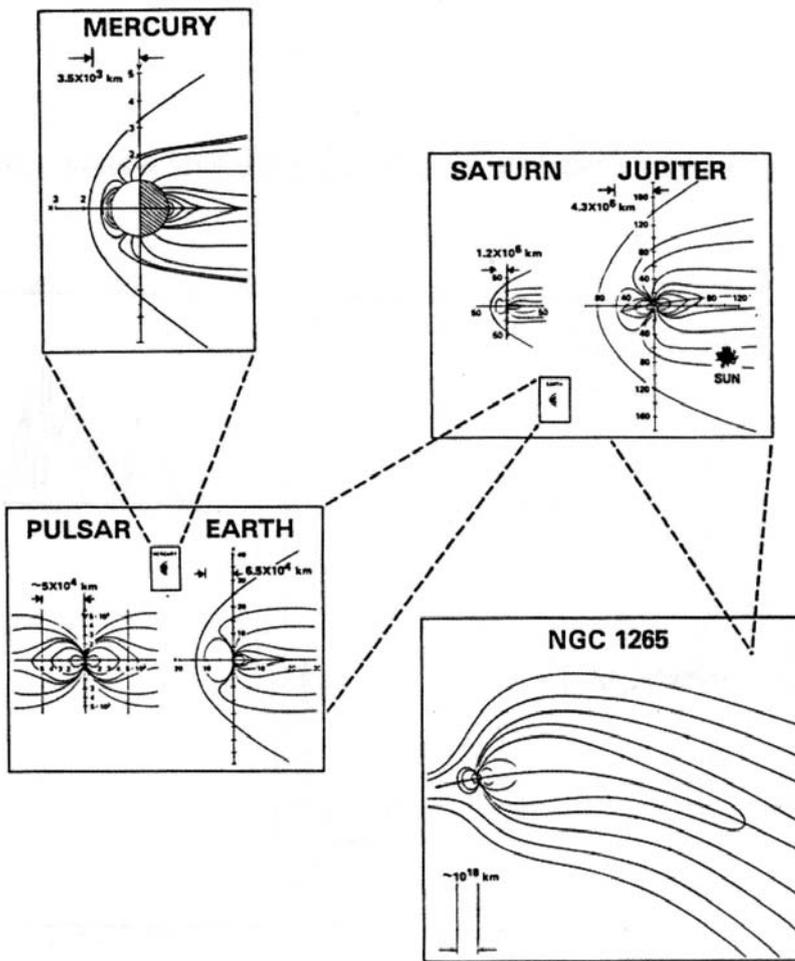
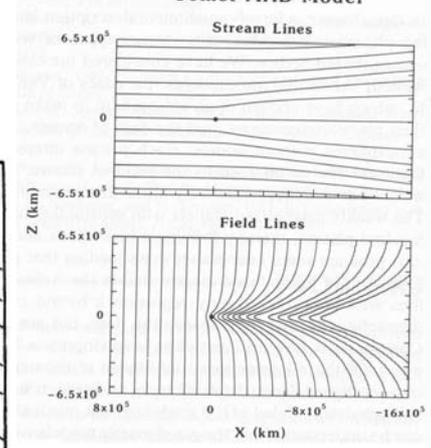


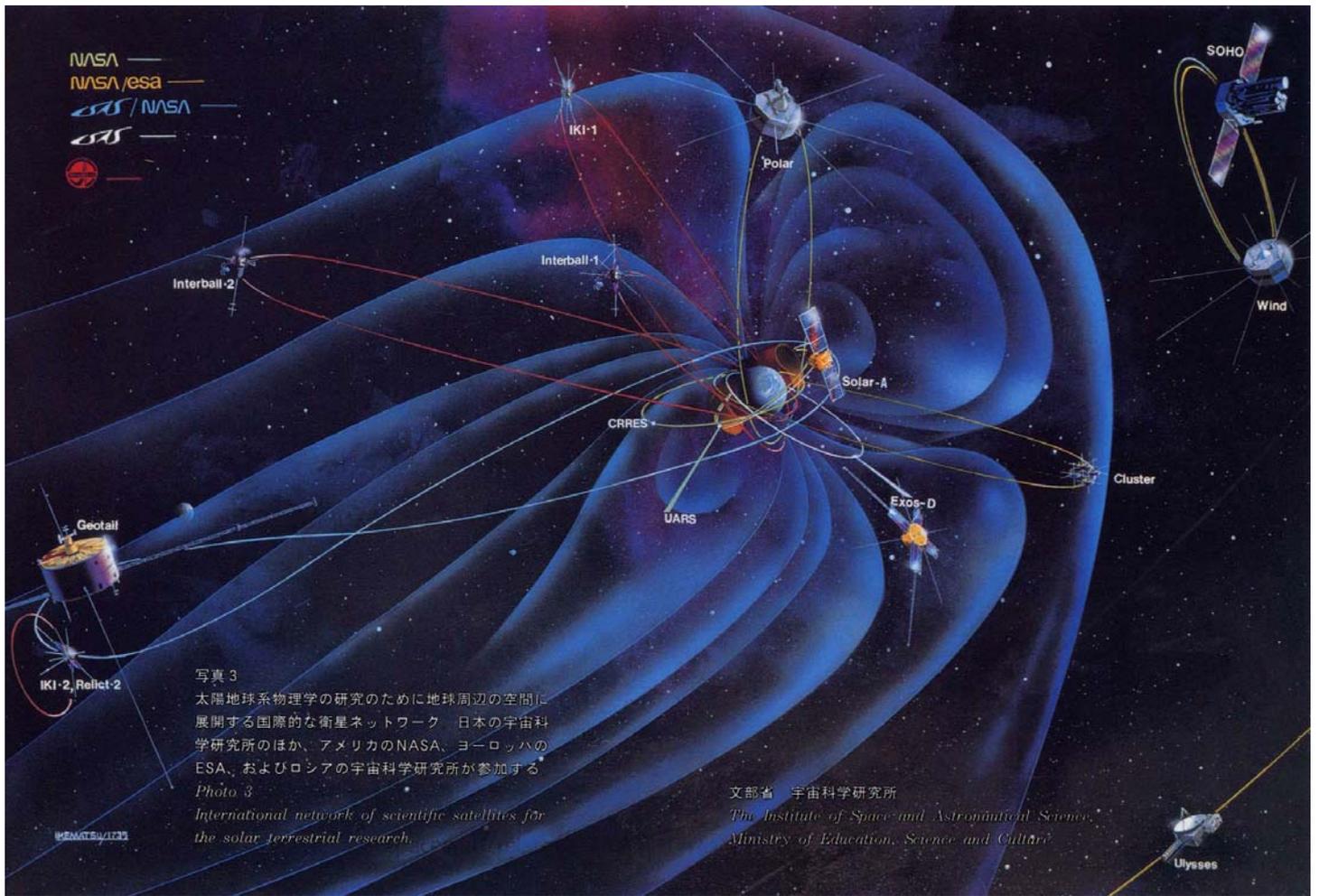
Illustration of the features that make up the comet-solar-wind interaction.

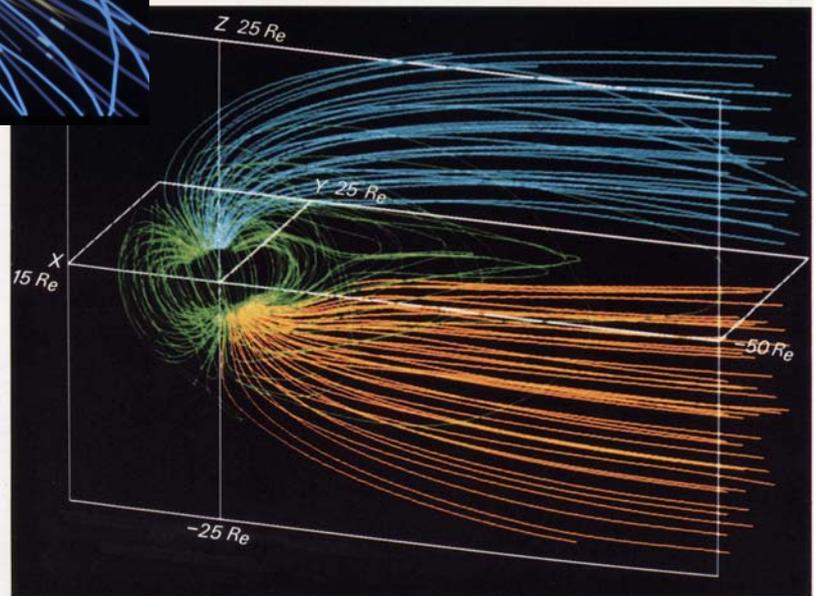
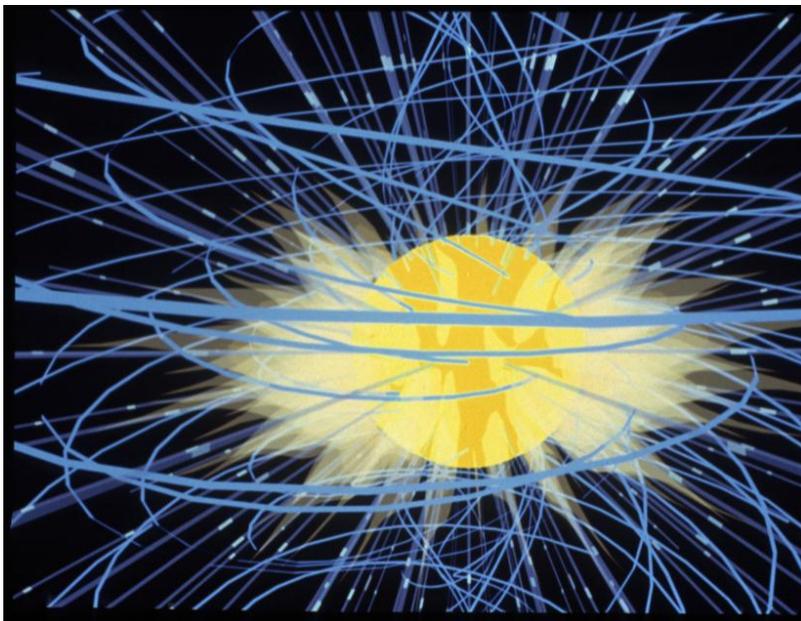
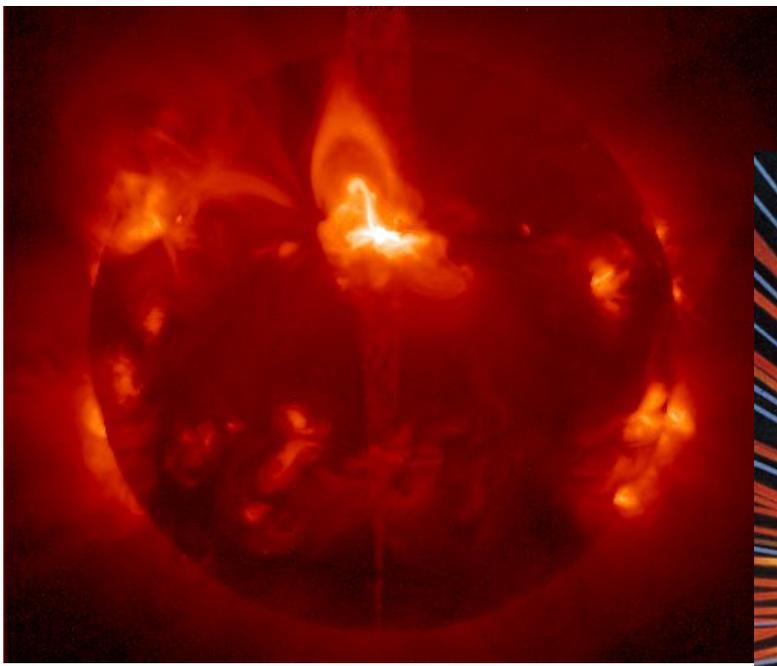


Streamlines and magnetic-field lines derived from the MHD comet-model results for Giacobini-Zinner obtained by Fedder et al. (1986).

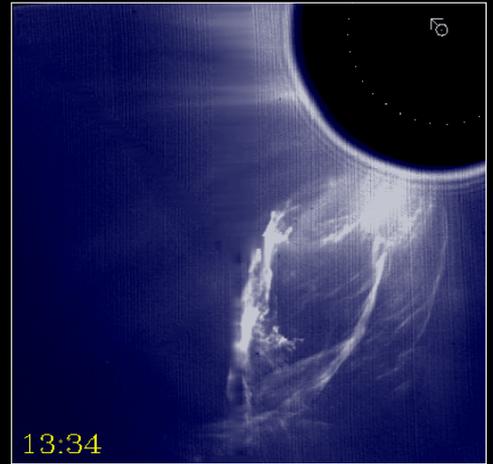
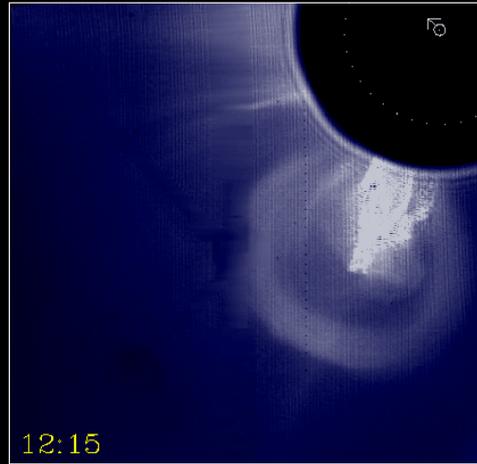
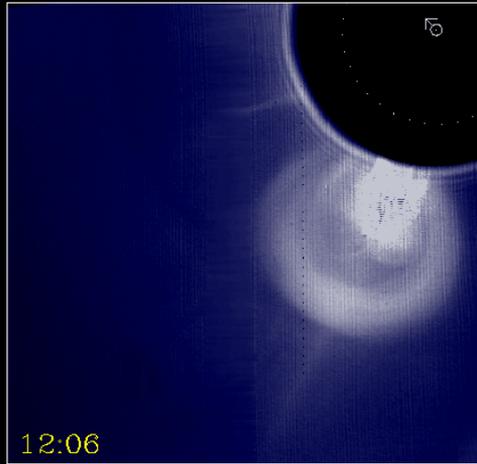
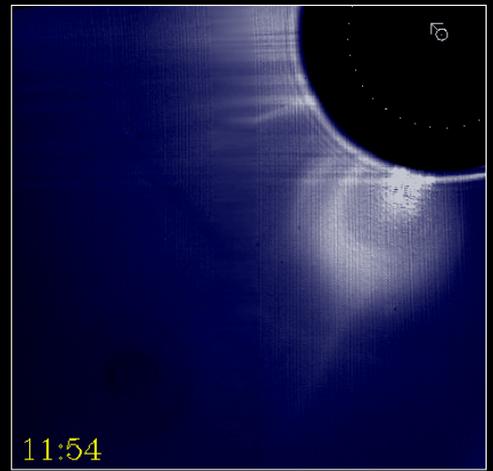
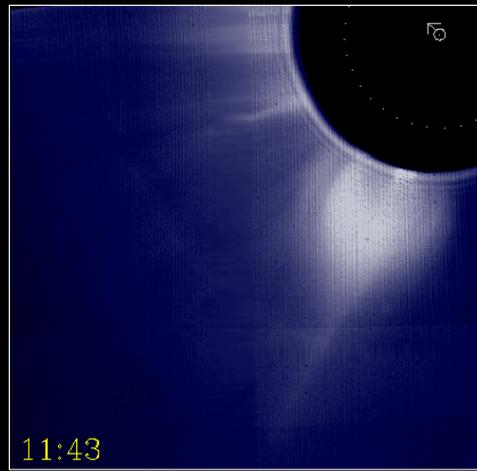
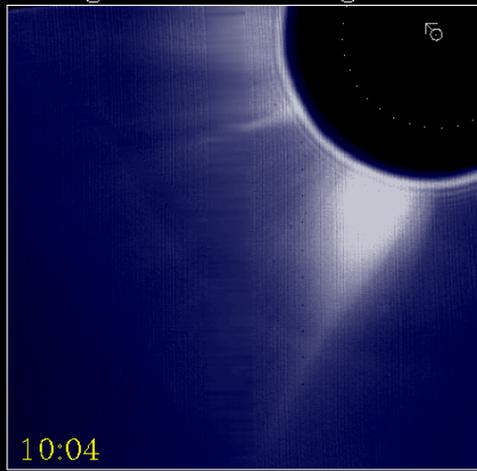


Hale-Bopp彗星のイオン・ダストテール



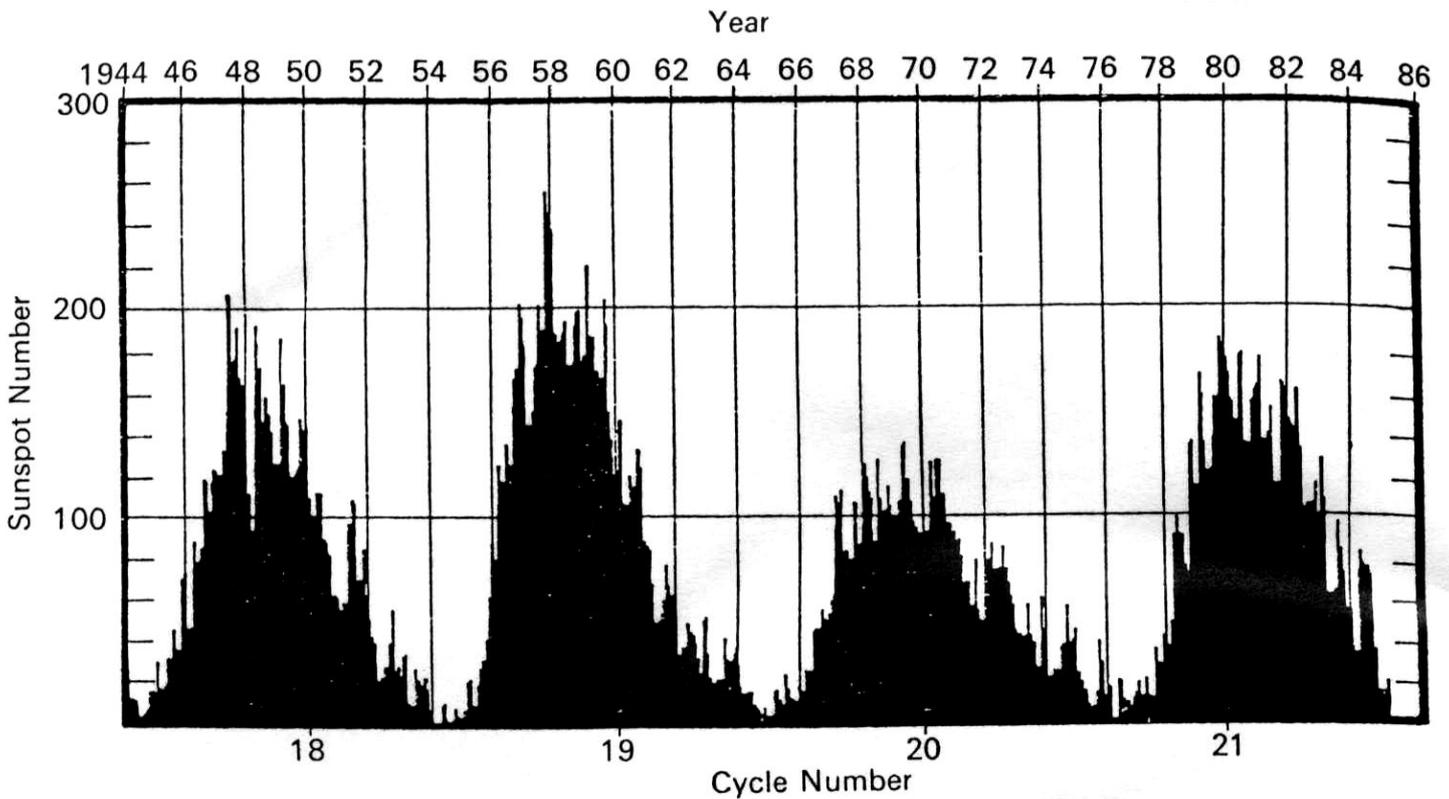


18 Aug 1980: White Light



Source: High Altitude Observatory/Solar Maximum Mission Archives

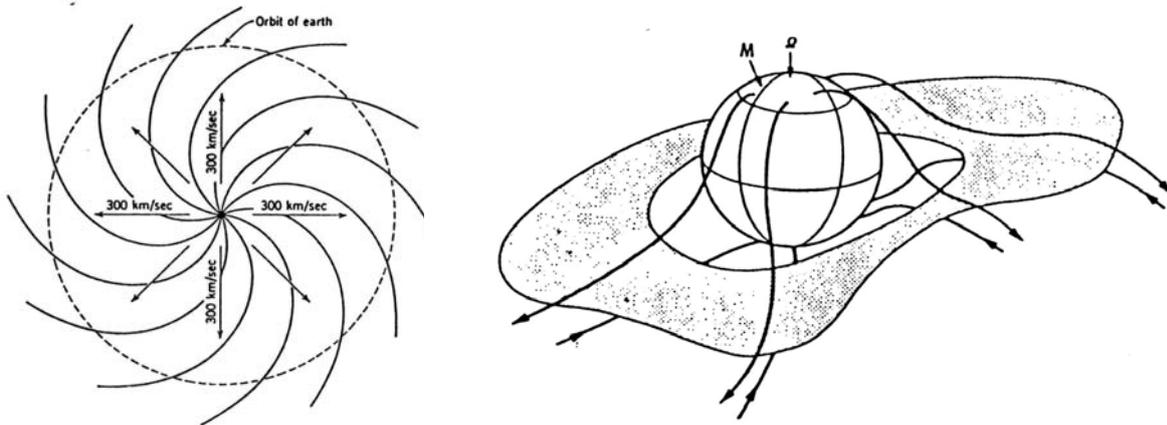
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Monthly-Mean Sunspot Numbers over four solar cycles

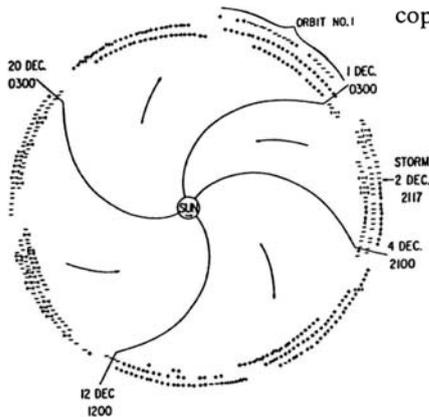
Monthly-mean sunspot numbers over four solar cycles. (*Annual Report for FY 1984*, National Geophysical Data Center, Boulder, Colorado)

(a)

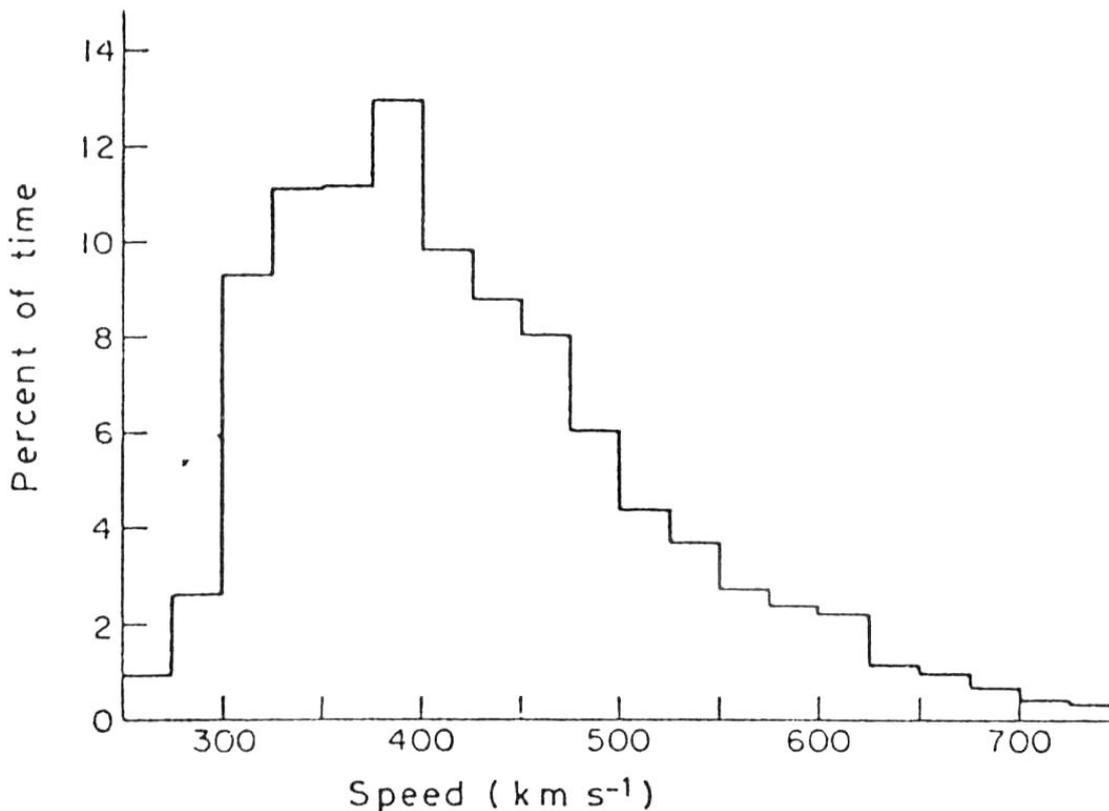


Ballerina model of current sheet in the solar wind. M is the axis of the current sheet and  $\Omega$  is the Sun's rotation axis. (E. J. Smith, *Rev. Geophys. Space. Phys.* 17, 610, 1979, copyright by the American Geophysical Union)

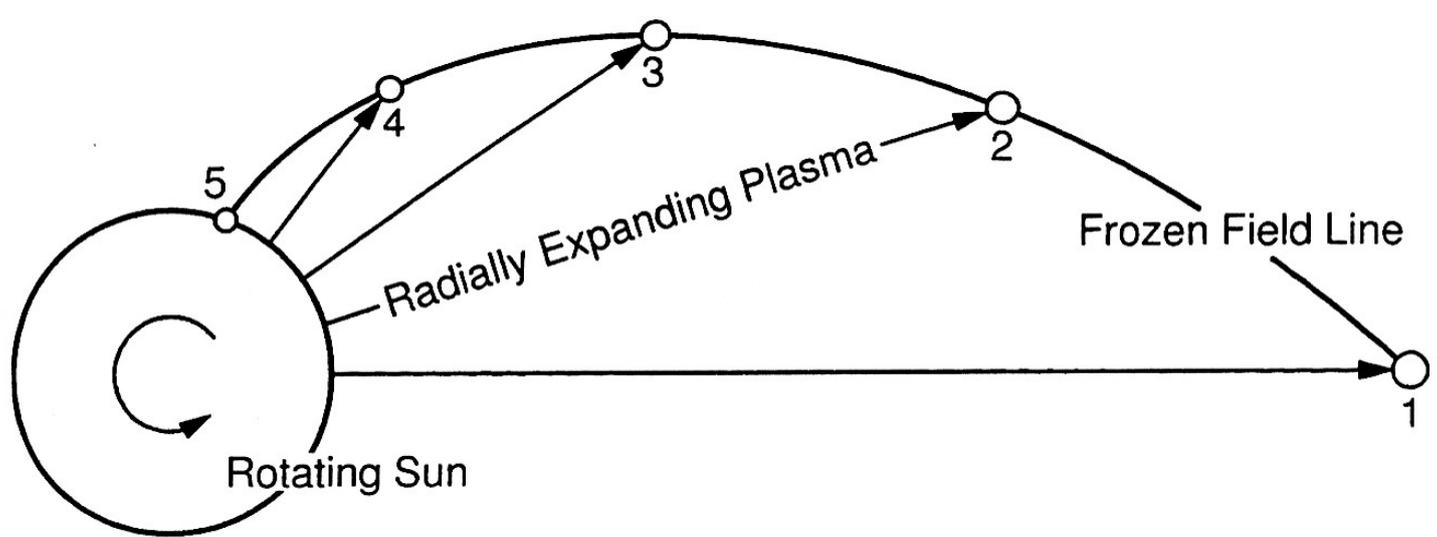
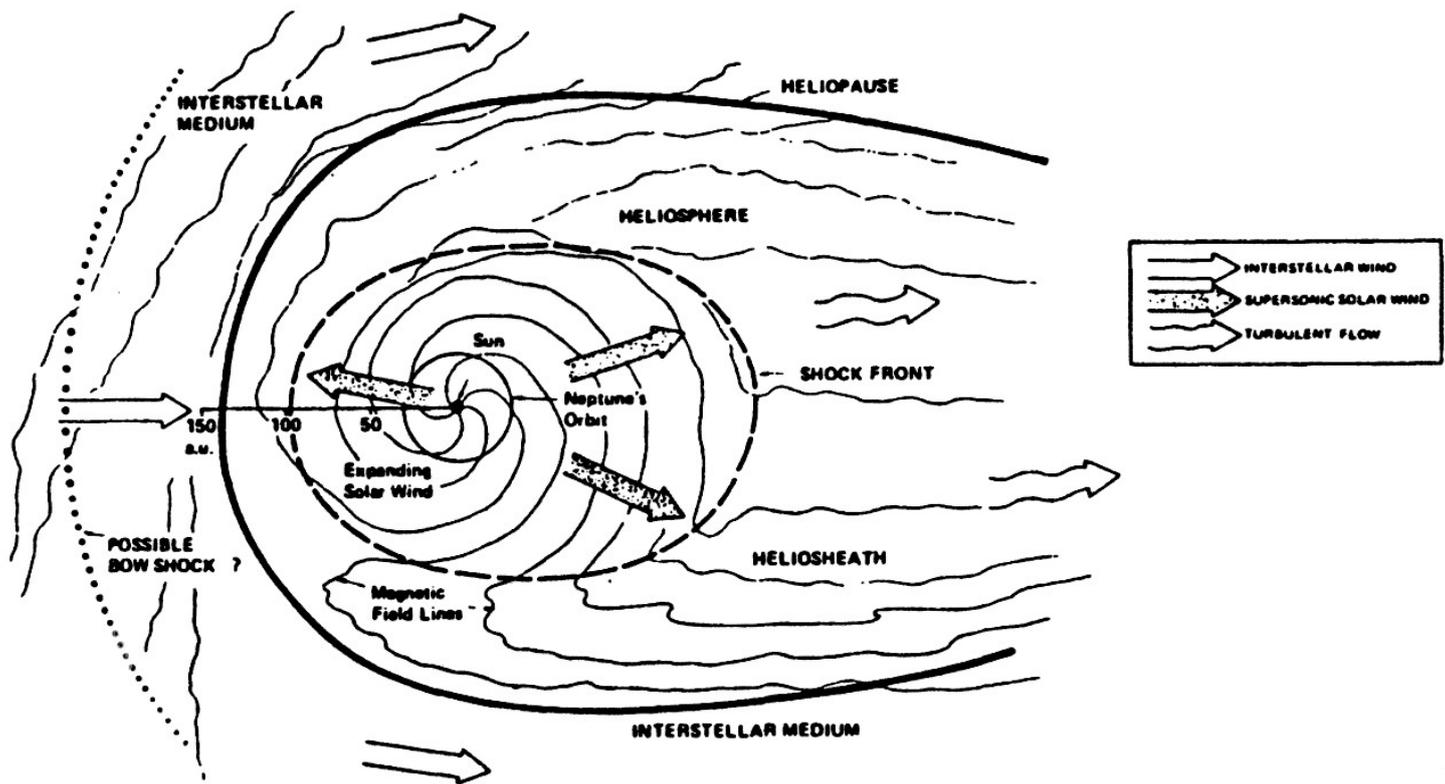
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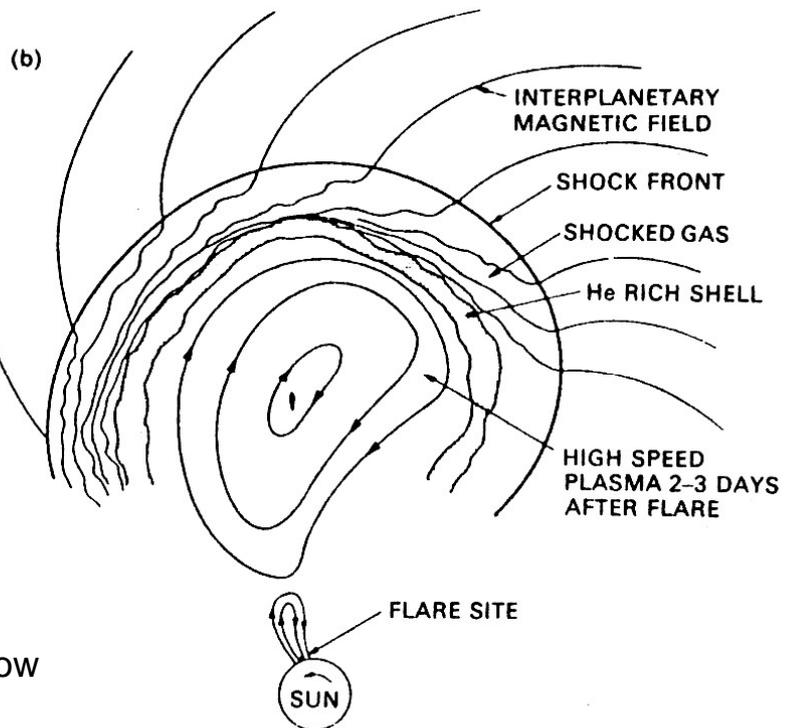
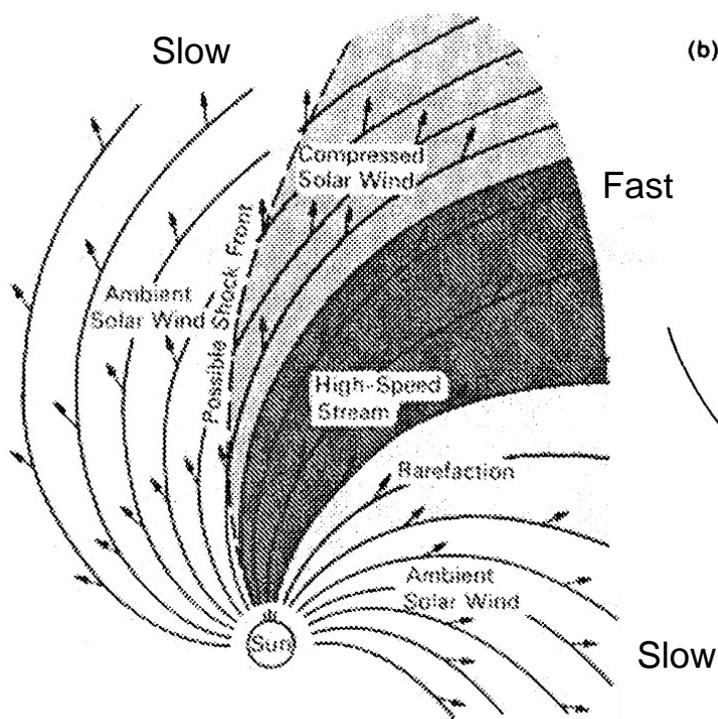
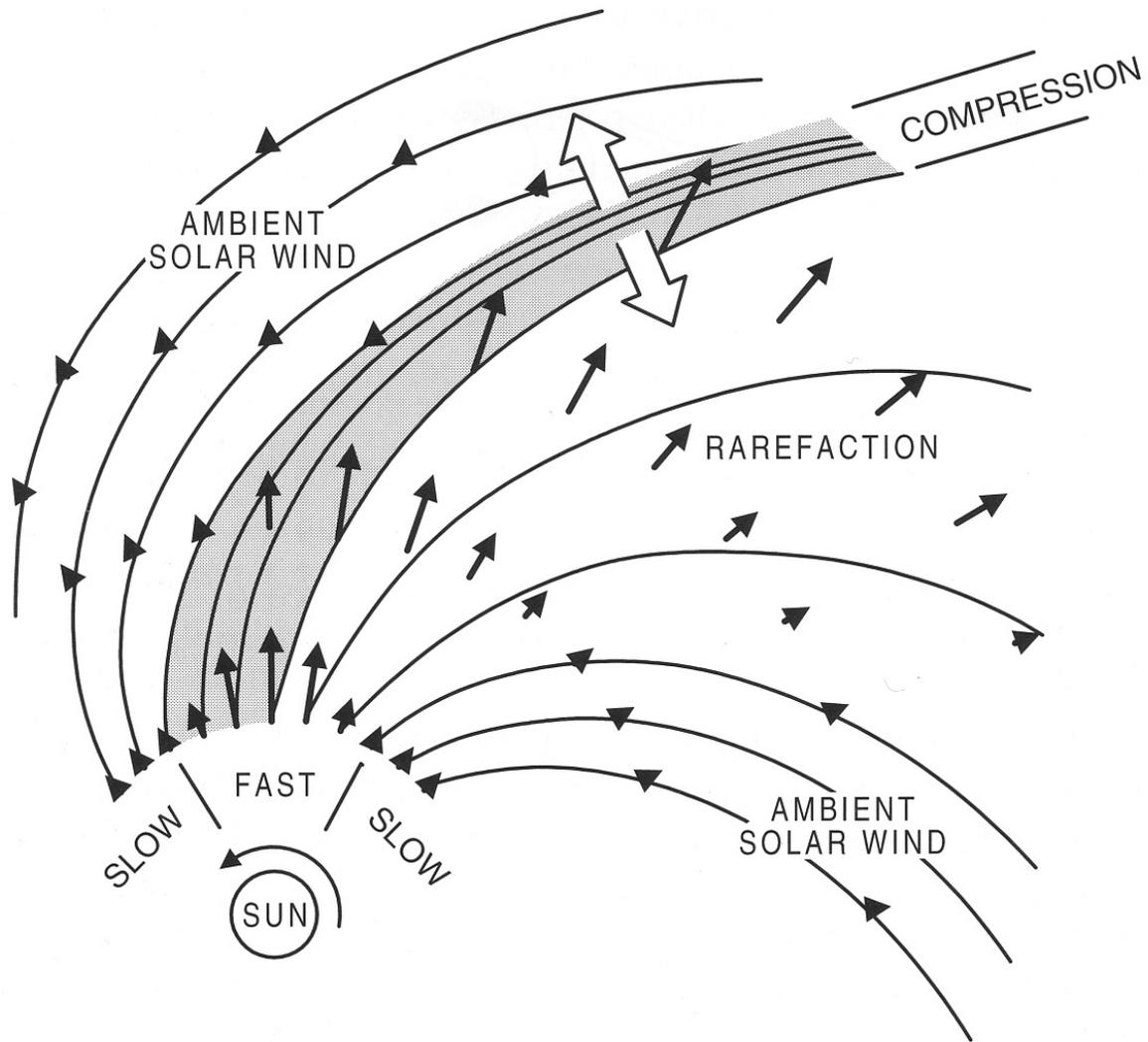


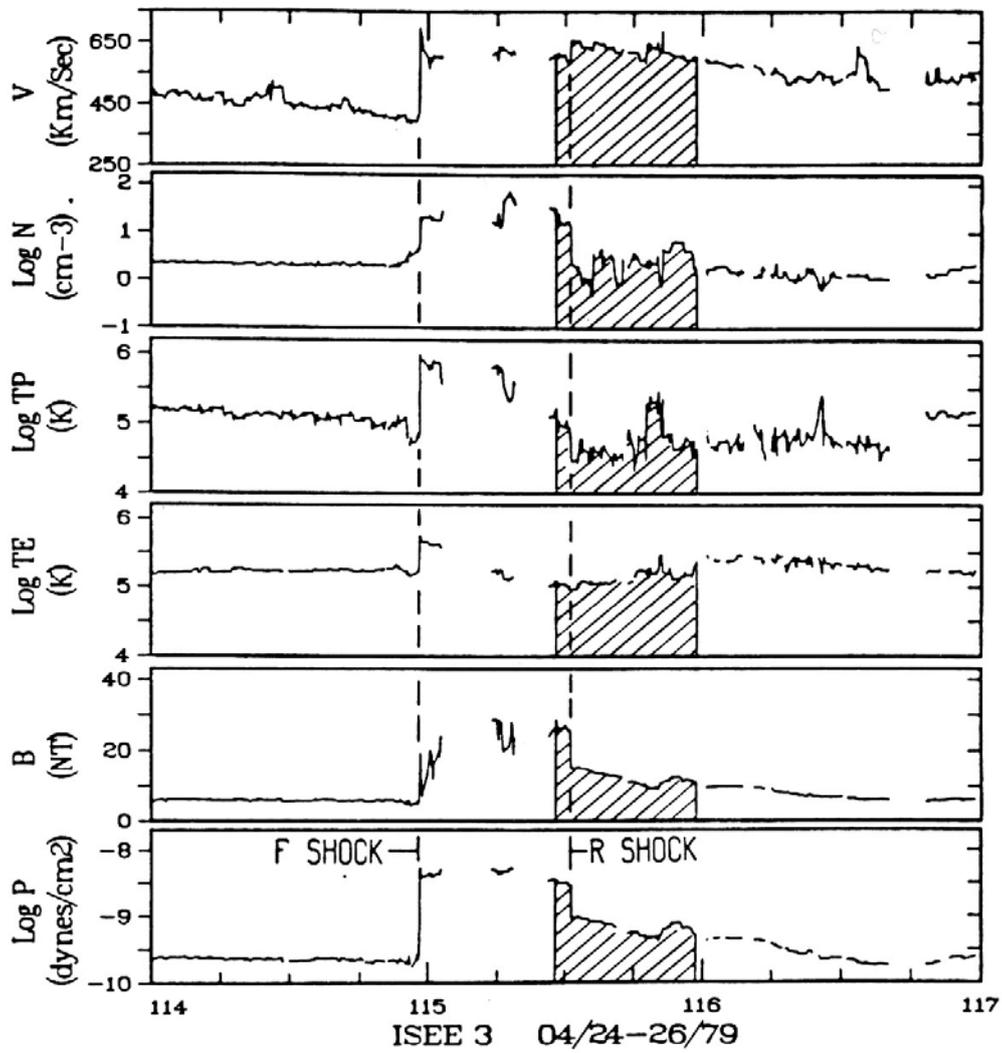
Form of the interplanetary magnetic field in the solar equatorial plane, corresponding to a solar wind speed of 300 km/s. (T. E. Holzer, *Solar System Plasma Physics, Vol I.* North-Holland, 1979, p. 103. Elsevier Science Publishers) (b) Sector structure of the solar wind in late 1963, showing inward (-) and outward (+) IMF. (J. M. Wilcox and N. F. Ness, *J. Geophys. Res.* 70, 5793, 1965, copyright by the American Geophysical Union)



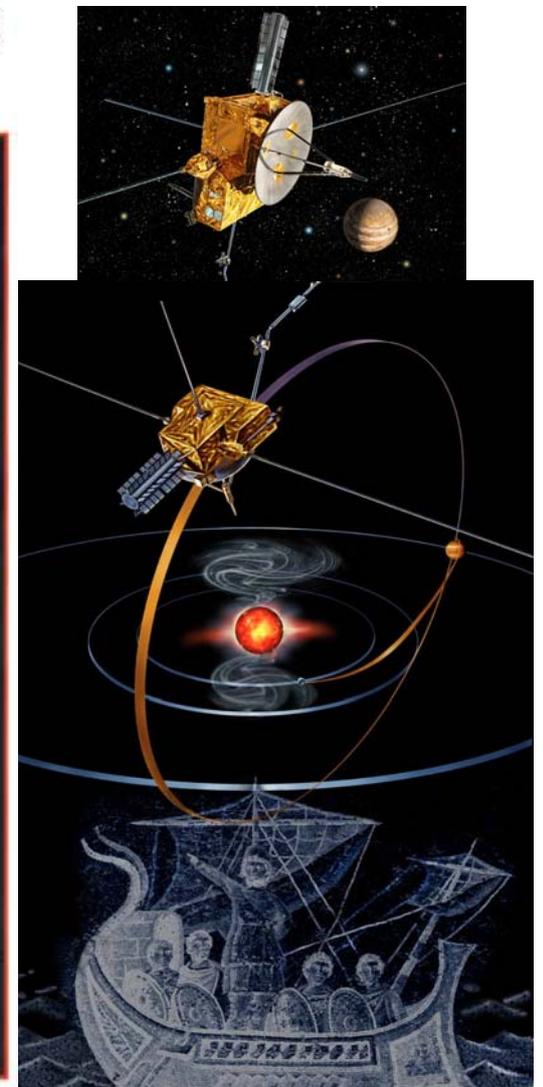
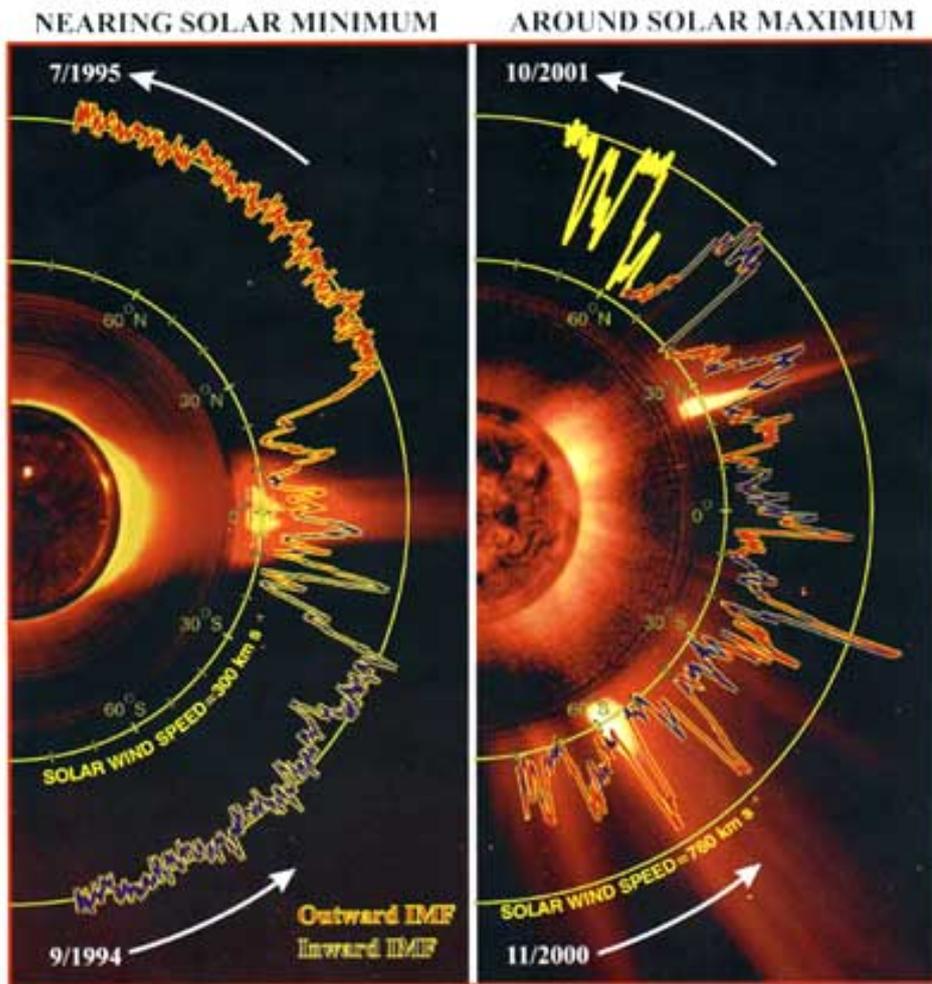
Speed of the solar wind: a histogram of measurements between 1962 and 1970. (J. T. Gosling, in *Solar Activity Observations and Predictions* (eds. McIntosh and Dryer). MIT Press, 1972)

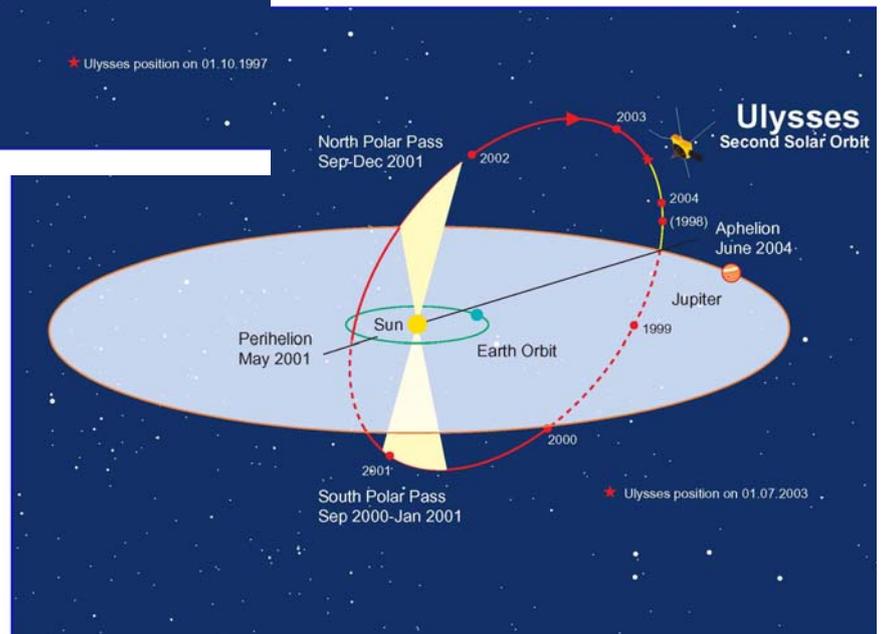
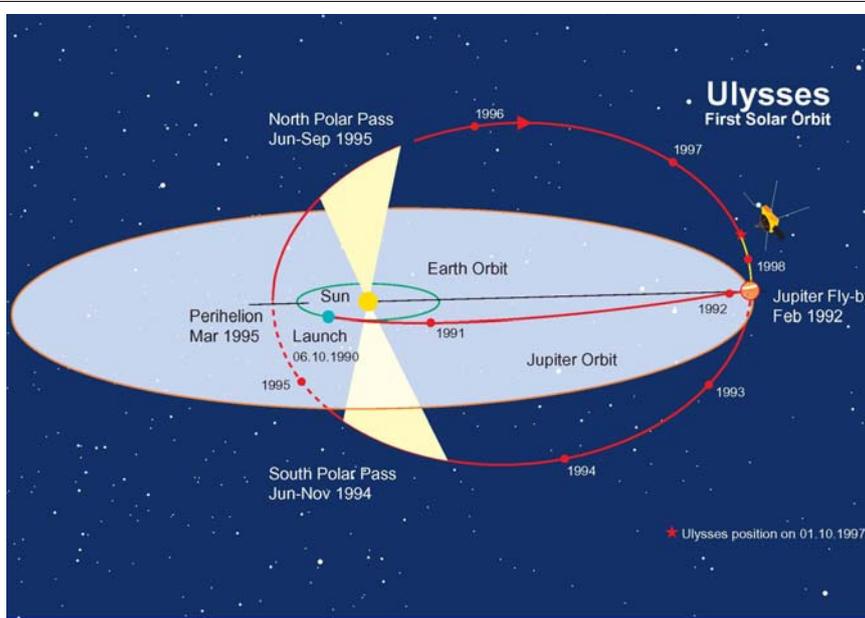




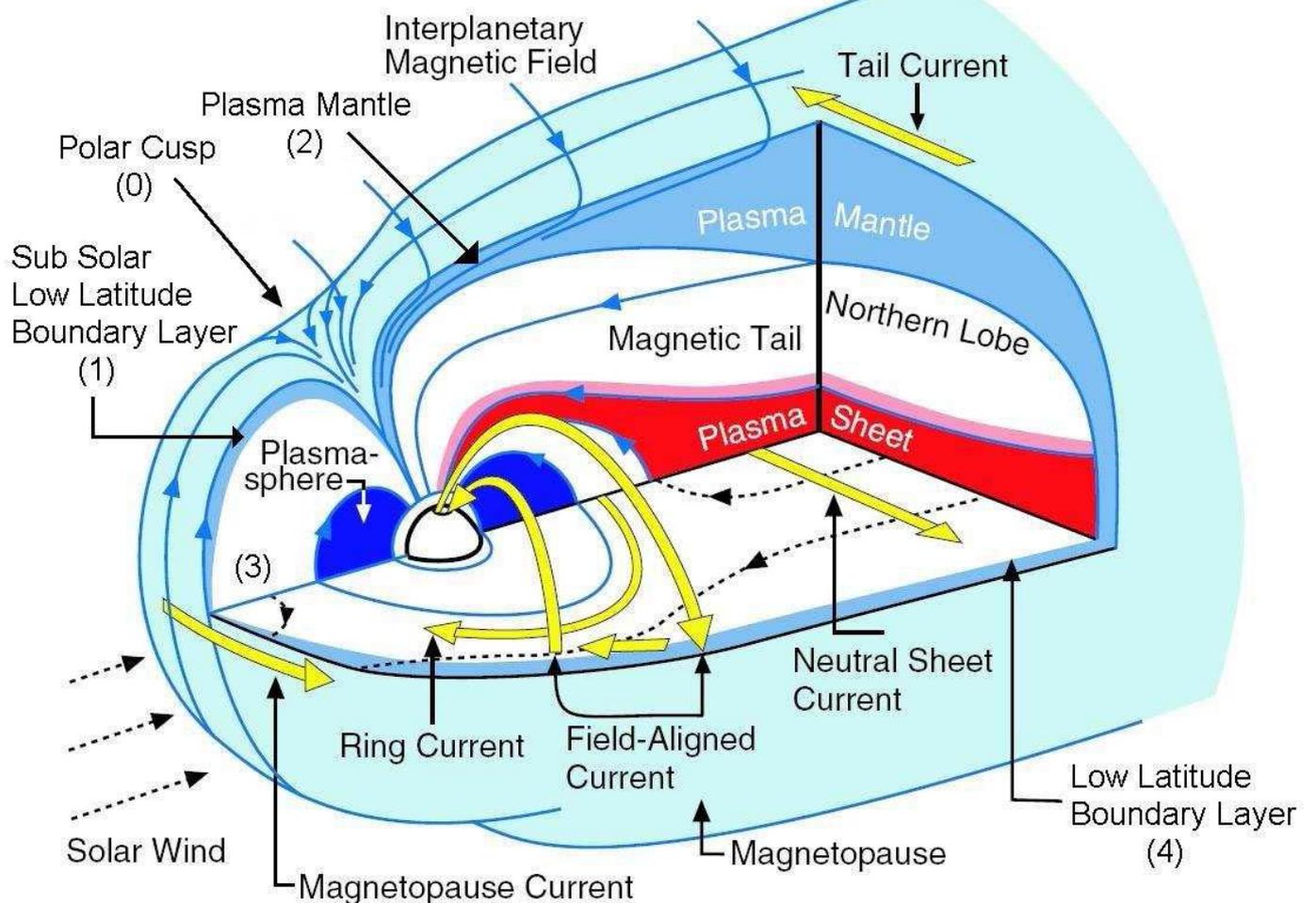


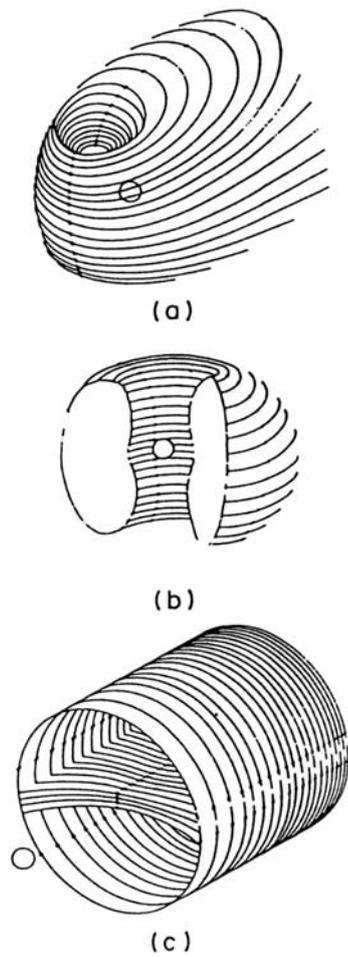
## ULYSSES FAST-LATITUDE SCANS



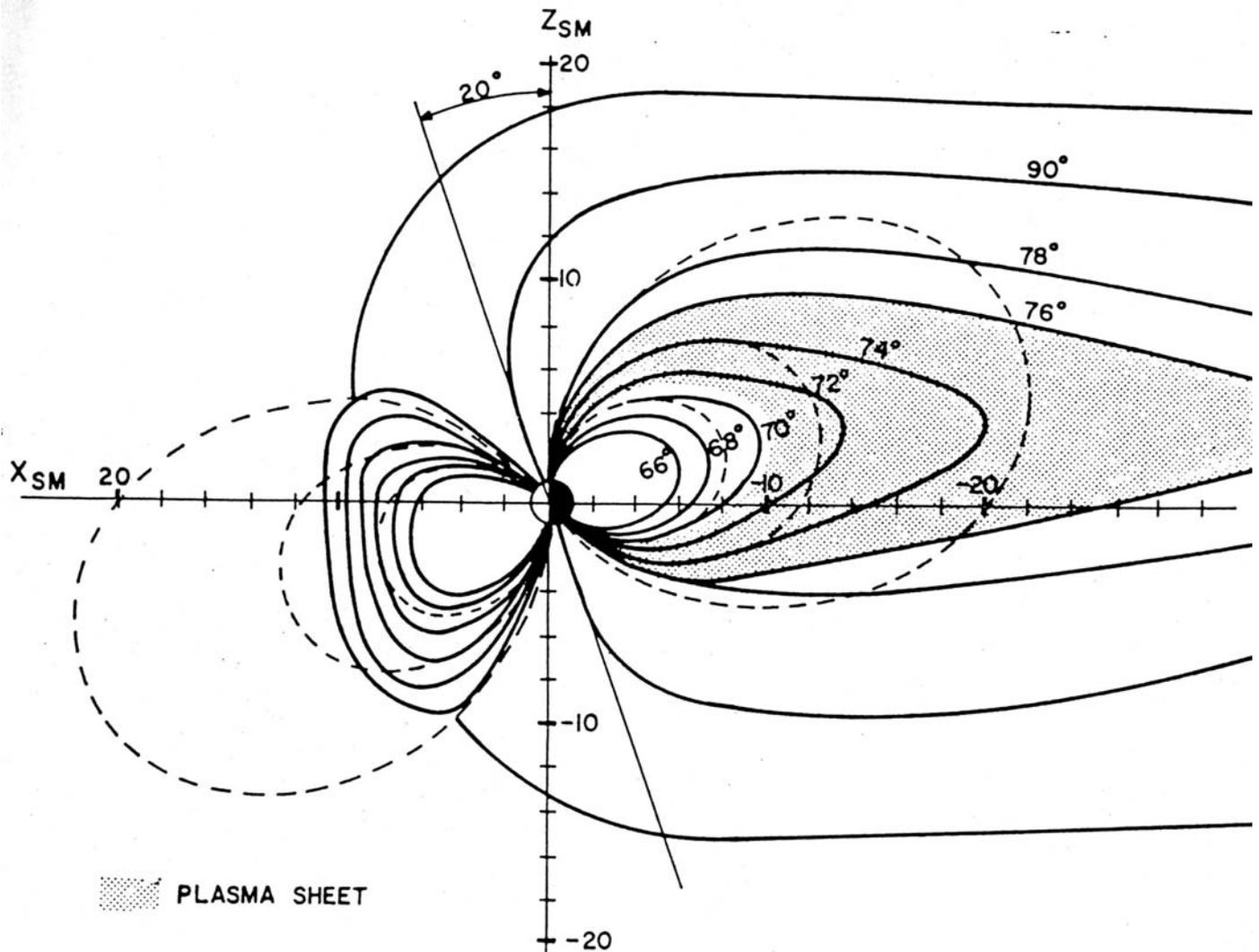


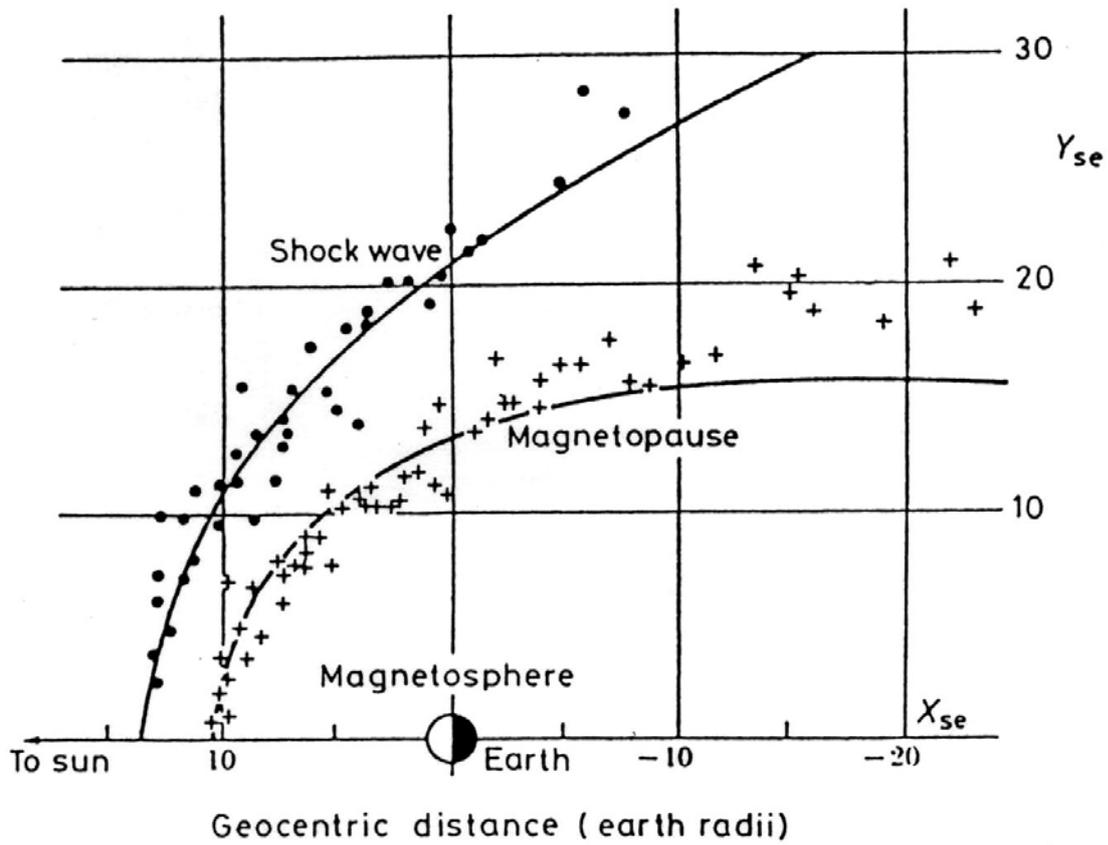
# 地球の磁気圏構造



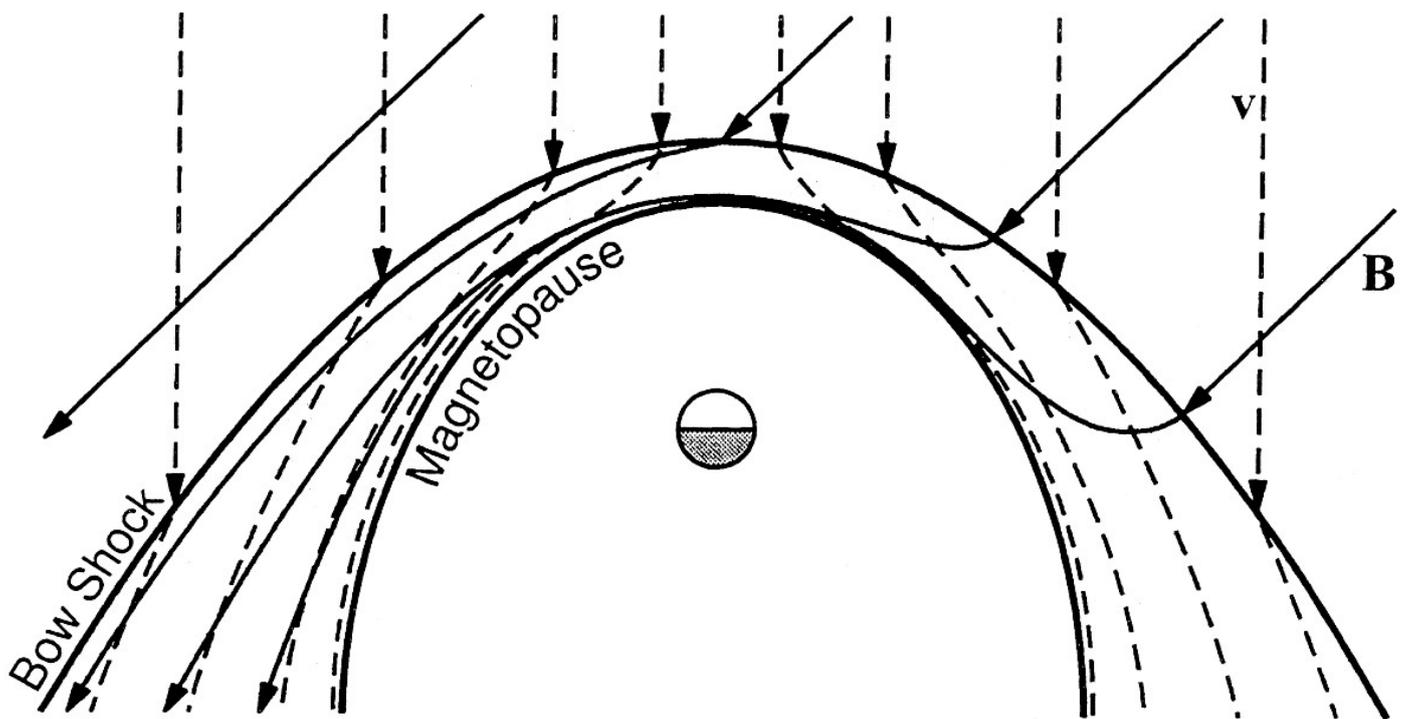


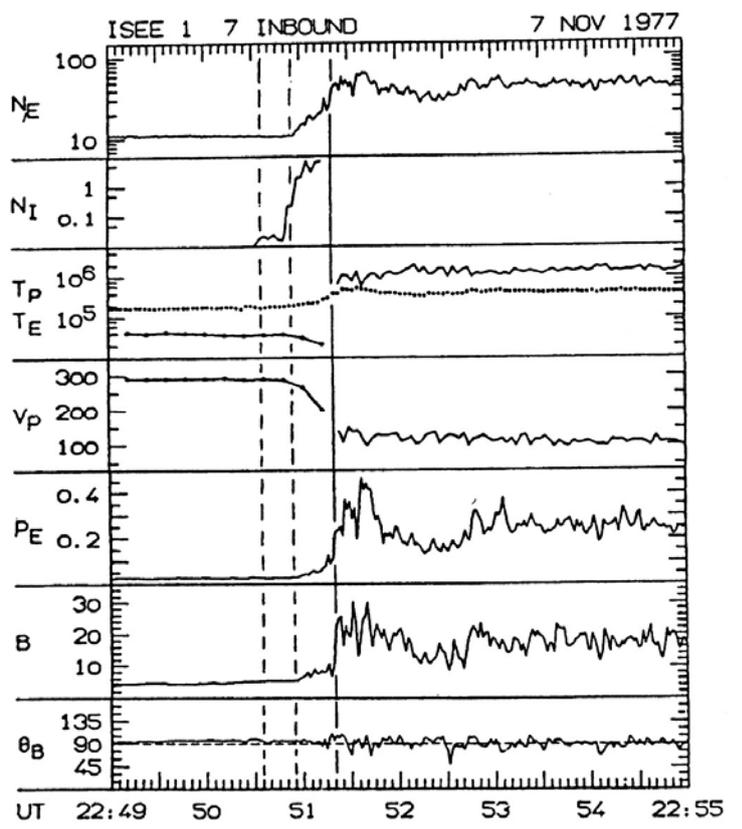
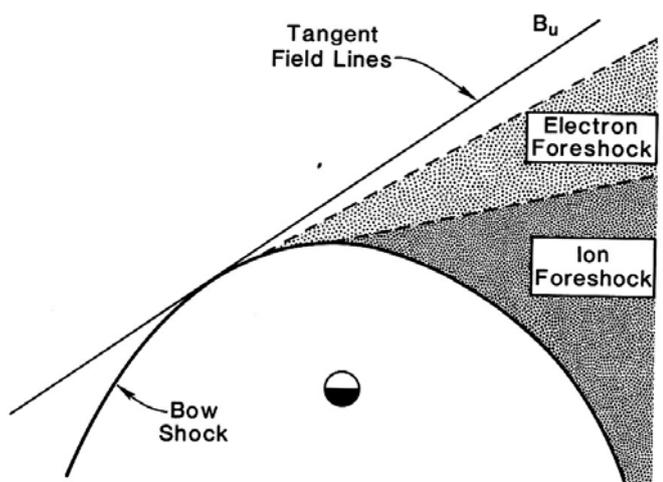
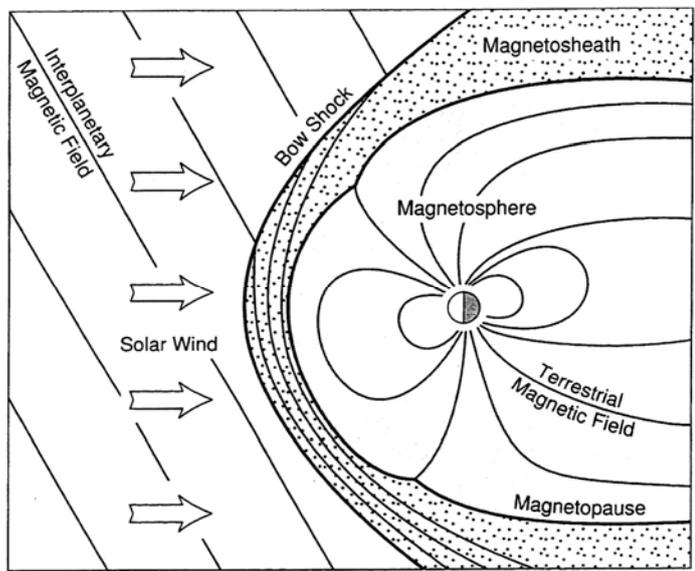
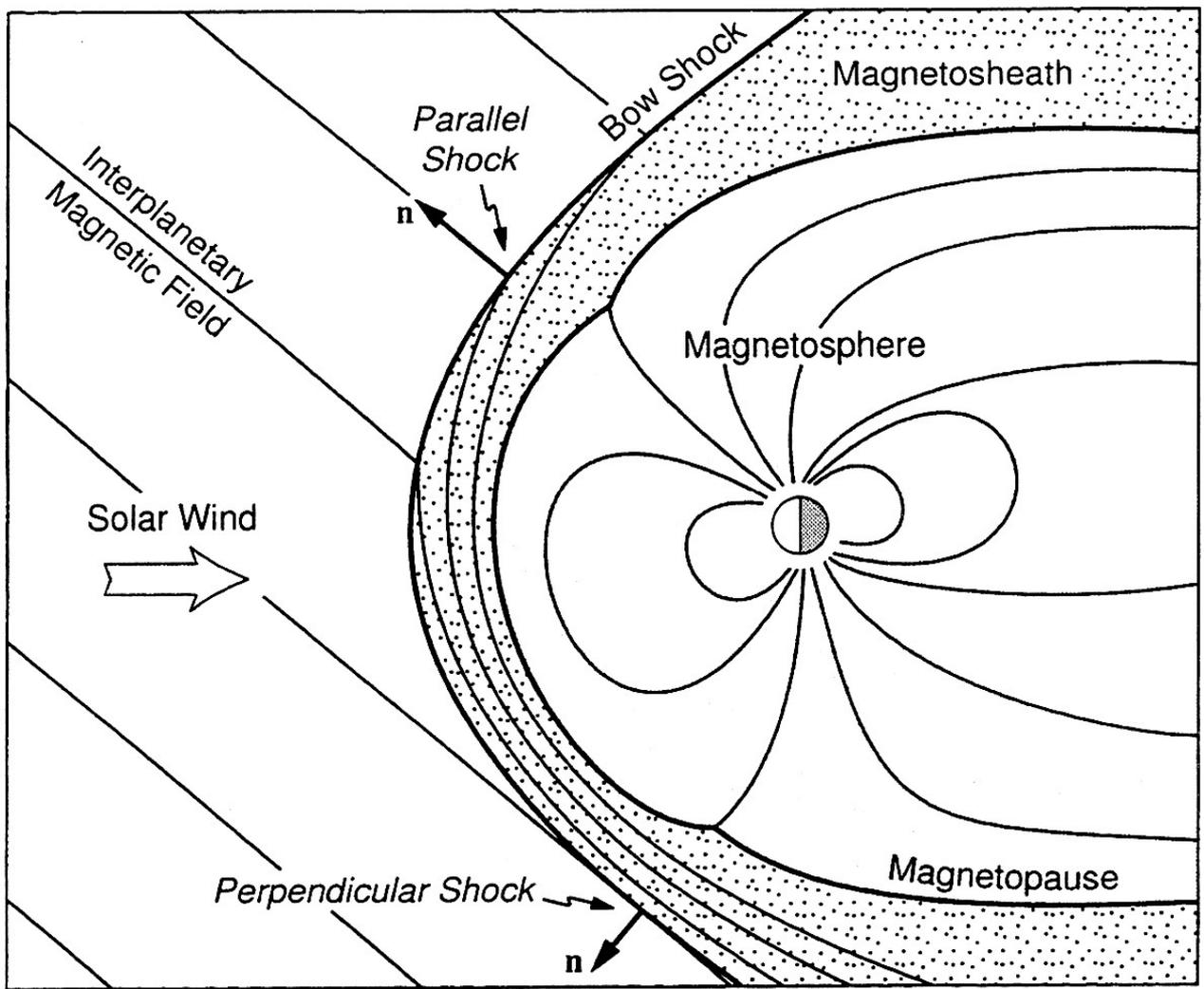
Magnetospheric current systems: (a) magnetopause (Chapman-Ferraro); (b) ring; (c) tail. (Reprinted with permission from W. P. Olsen, *Adv. Space Res.* 2, 13, copyright (1982) Pergamon Press PLC)

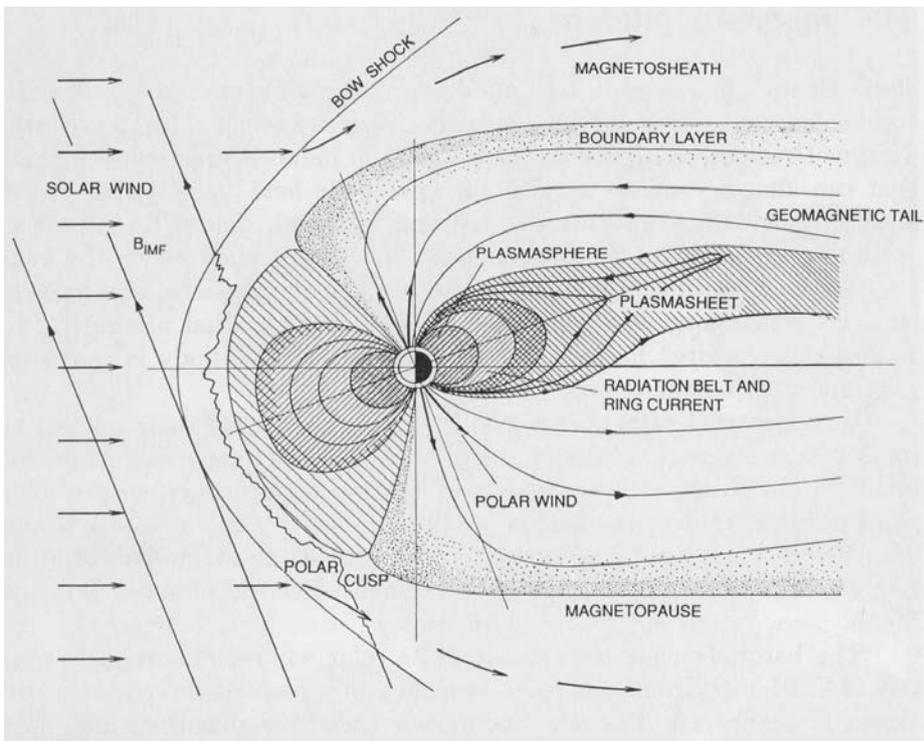
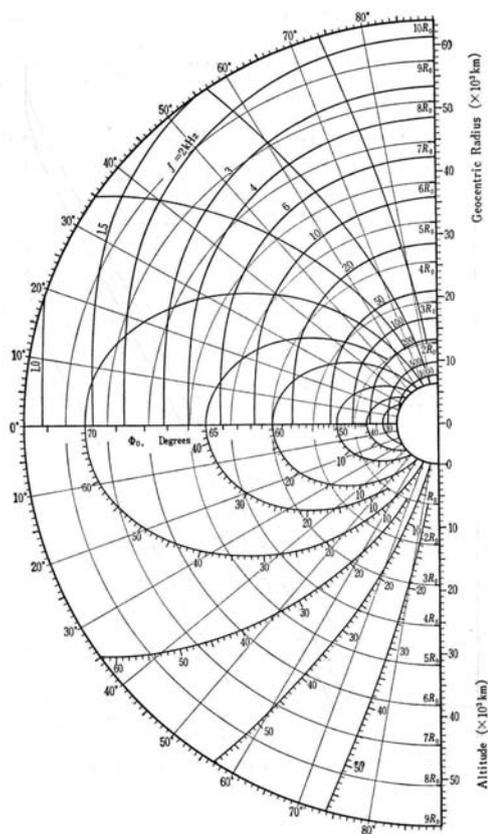




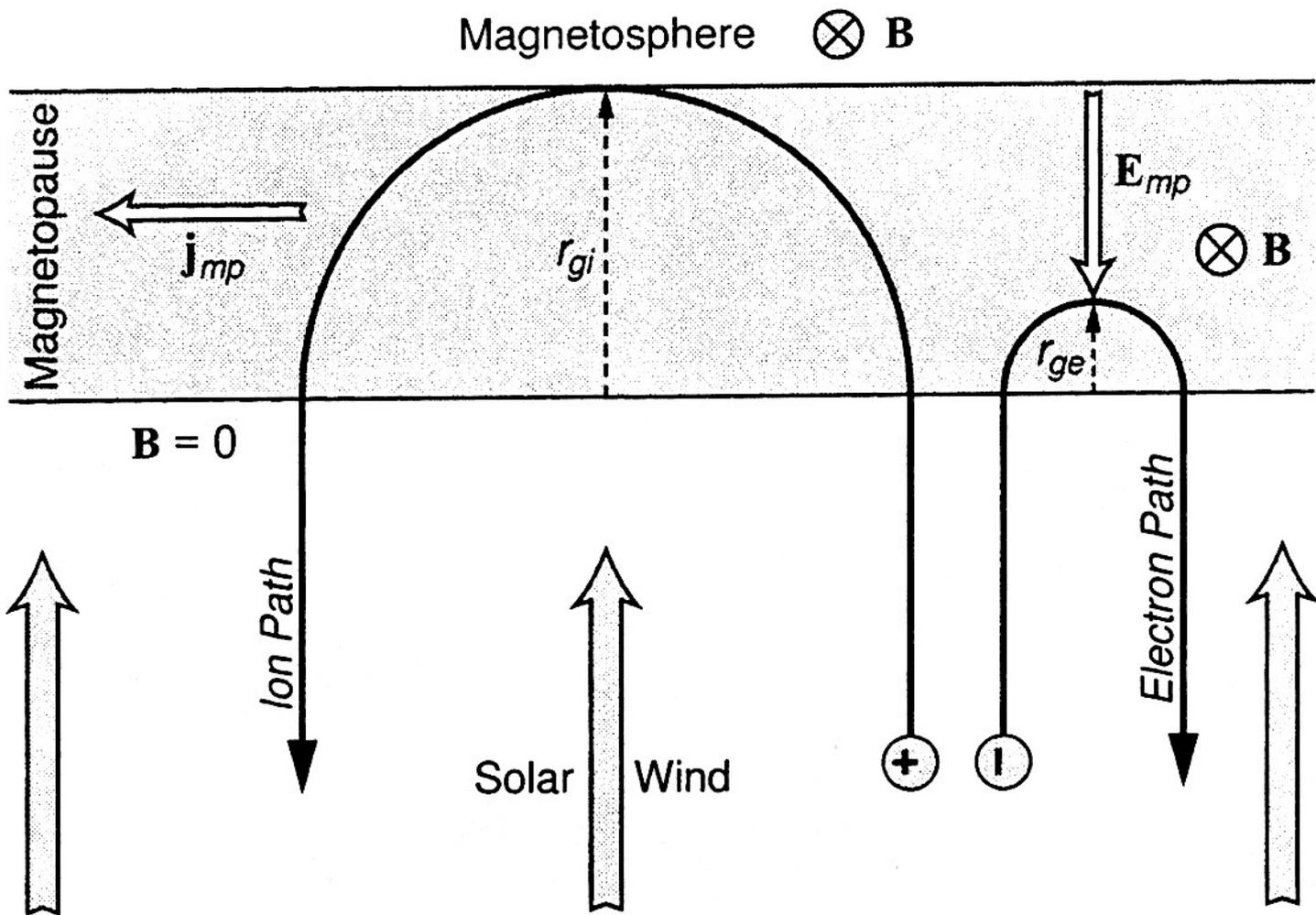
Observed and calculated positions of the magnetopause and the shock in the solar-equatorial plane. (After N. F. Ness *et al.*, *J. Geophys. Res.* 69, 3531, 1964, copyright by the American Geophysical Union)

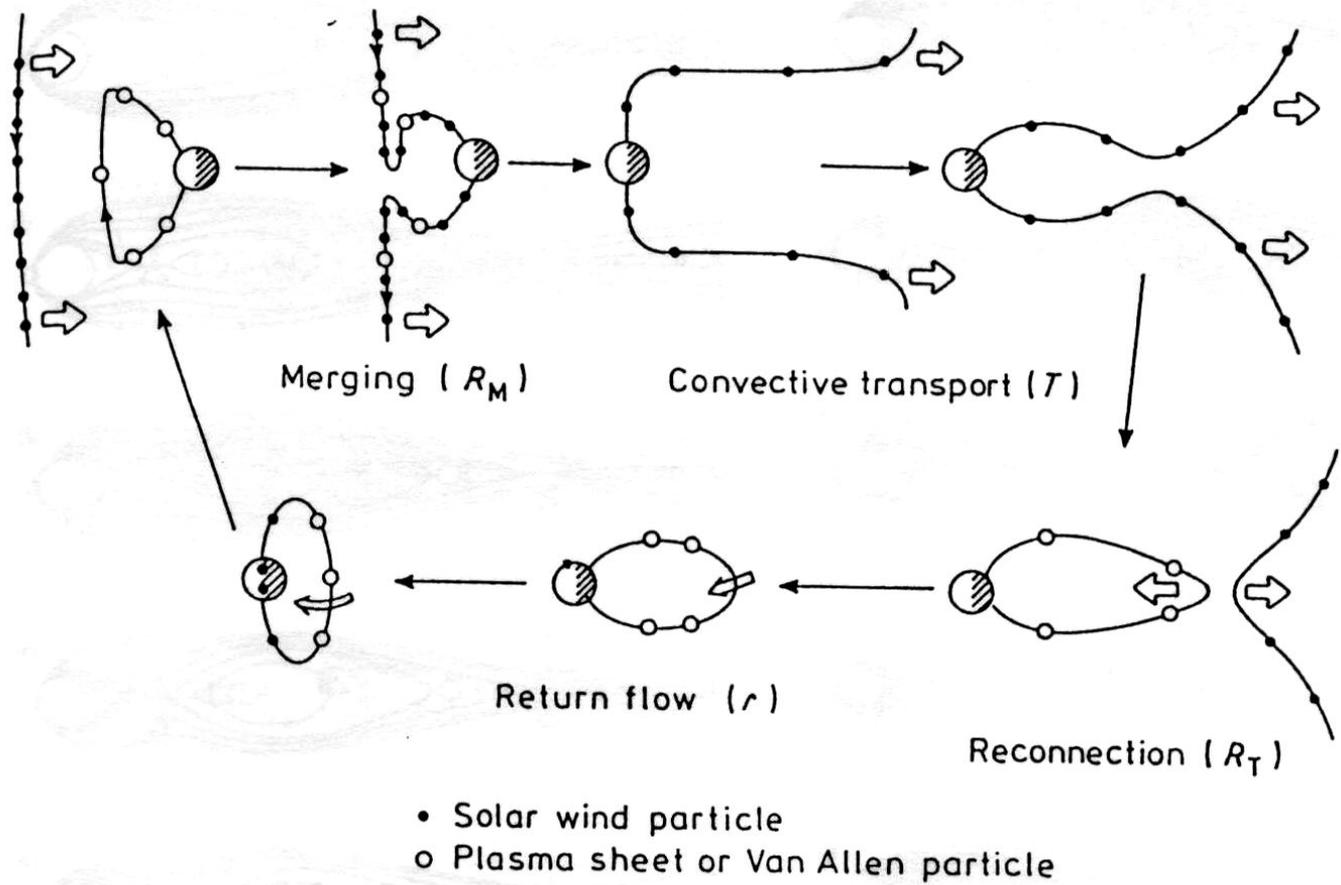




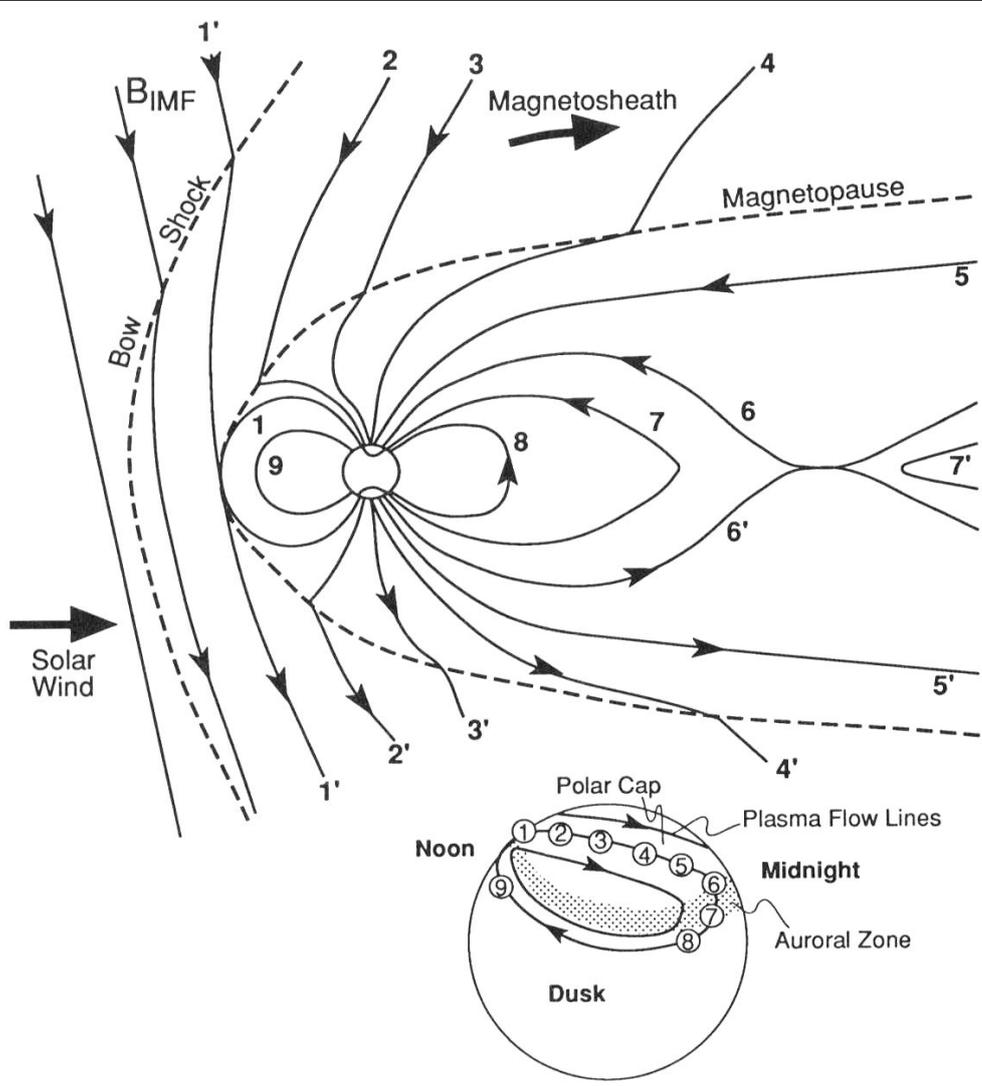


A schematic diagram of Earth's magnetosphere in the noon-midnight plane. The basic particle and magnetic field features are representative of other planetary magnetospheres although the details can be different.





History of a selected field-line.



Flow of plasma within the magnetosphere (convection) driven by magnetic reconnection. The numbered field lines show the succession of configurations a geomagnetic field line assumes after reconnection with an IMF field line (1') at the front of the magnetosphere. Field lines 6 and 6' reconnect at a second x-line in the tail, after which the field line returns to the dayside at lower latitudes. The inset shows the positions of the feet of the numbered field lines in the northern high-latitude ionosphere and the corresponding high-latitude plasma flows, an antisunward flow in the polar cap, and a return flow at lower latitudes.

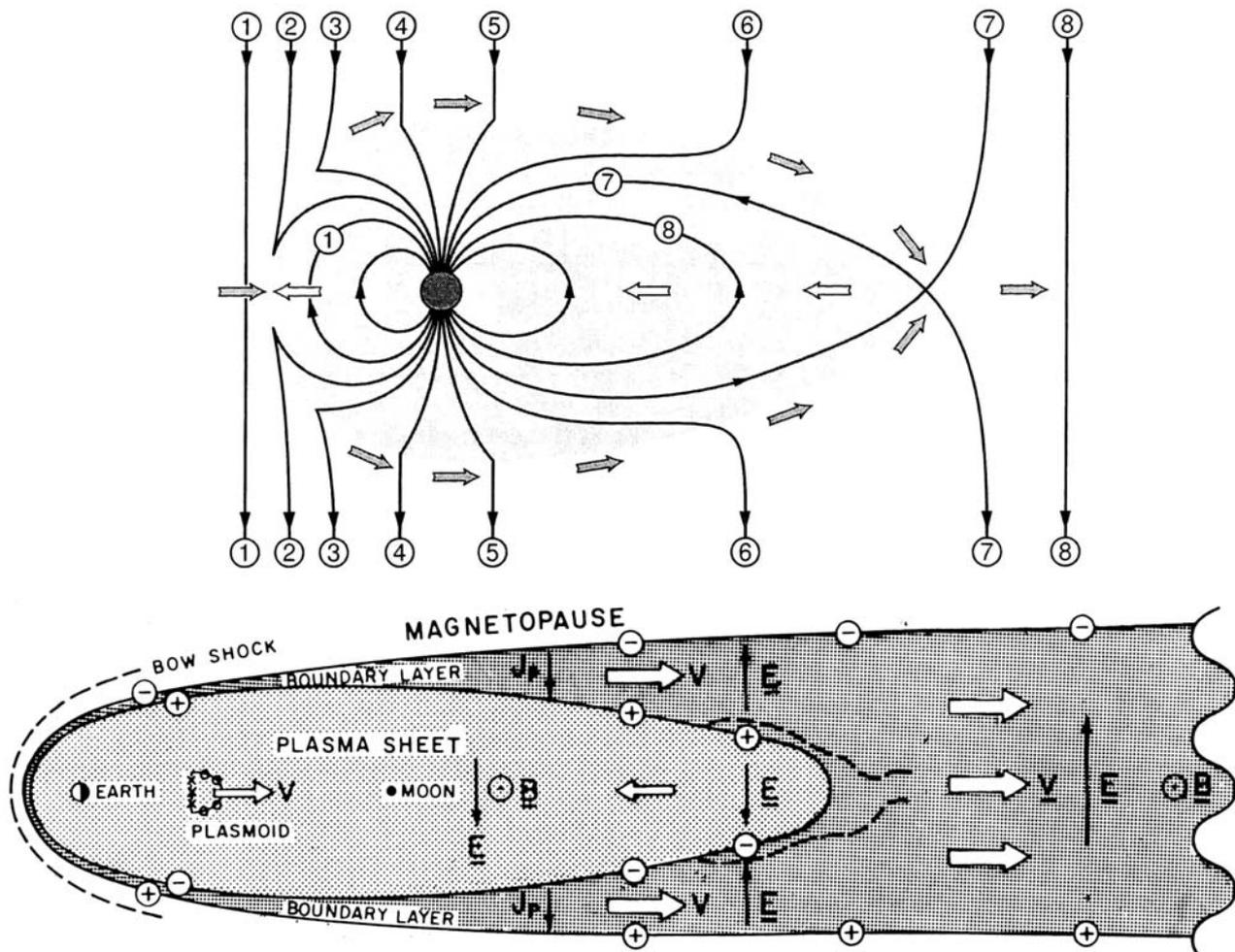
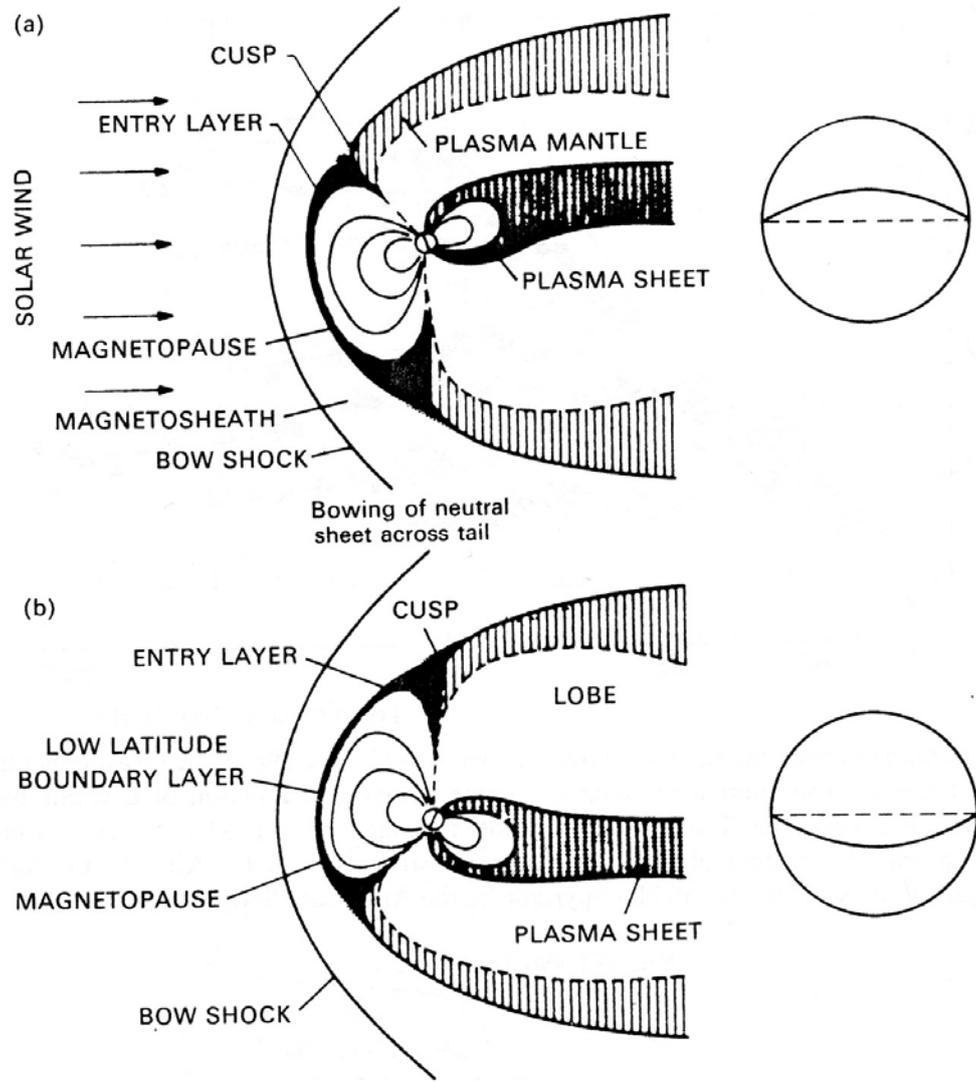
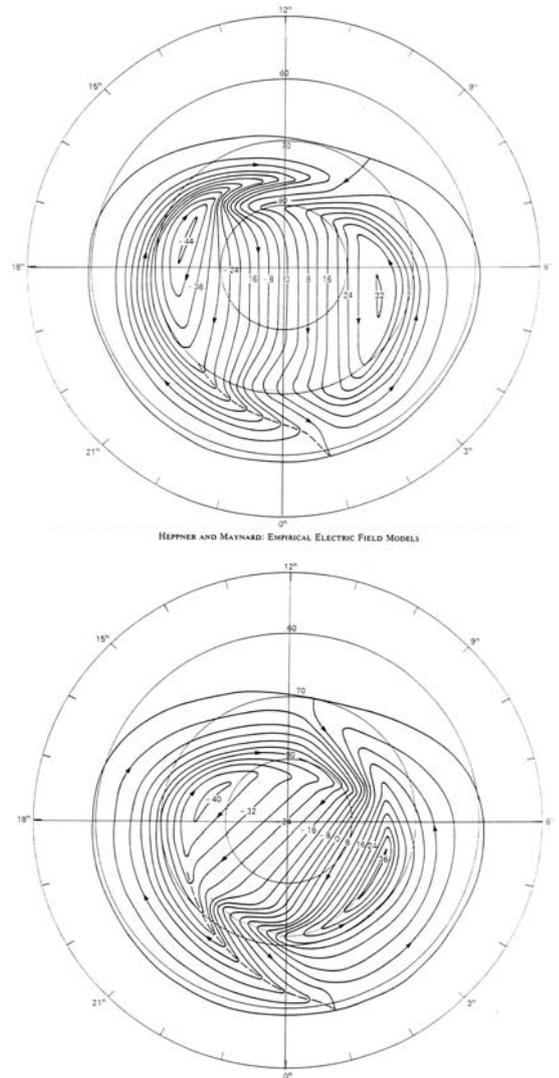
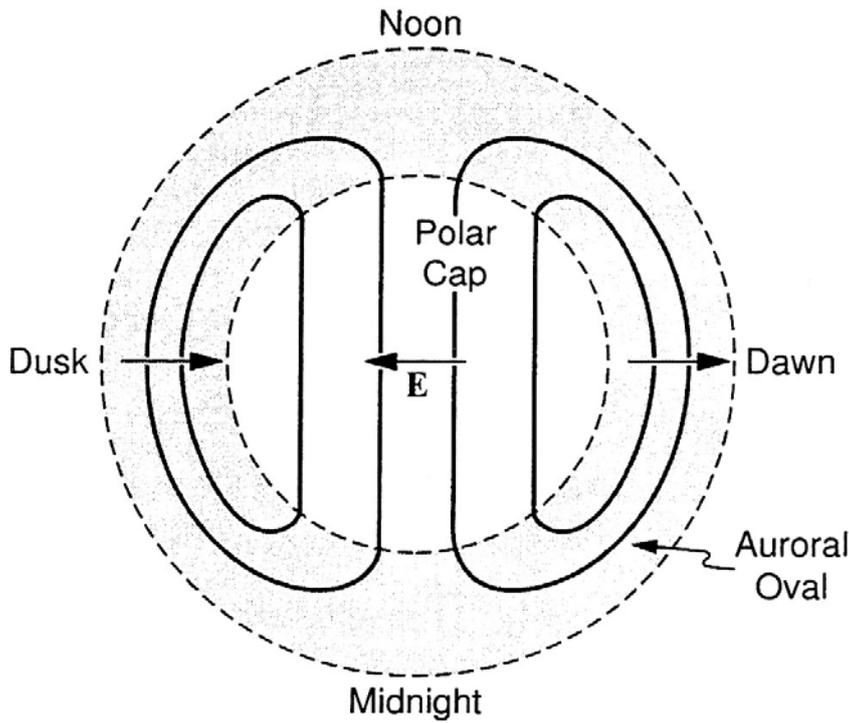


Fig. 5. The low latitude boundary layer has been added to the model of Axford and Hines, based on ISEE-3 data. The plasmasheet is a small cavity of energized low density plasma surrounded by high density solar wind plasma, with some plasmasheet plasma due to the sunward circulation.



HEPPNER AND MAYNARD: EMPIRICAL ELECTRIC FIELD MODELS

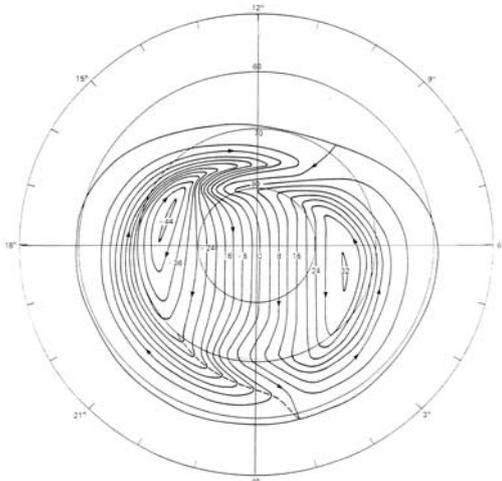


Fig. 1. Convection electric field model A, one of two models representing pattern distributions encountered in the northern hemisphere under  $-Y$  IMF conditions and in the southern hemisphere under  $+Y$  IMF conditions ( $1 \text{ mV}$  contour intervals) ( $3^{\circ} \leq K_p \leq 4^{\circ}$ ).

HEPPNER AND MAYNARD: EMPIRICAL ELECTRIC FIELD MODELS

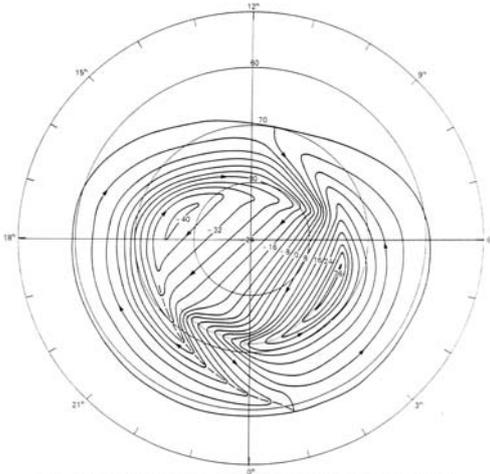


Fig. 3. Convection electric field model BC, representing the most typical pattern distribution encountered in the northern hemisphere under  $+Y$  IMF conditions and in the southern hemisphere under  $-Y$  IMF conditions ( $3^{\circ} \leq K_p \leq 4^{\circ}$ ).

Heelis: IMF Effects of High-Latitude Convection

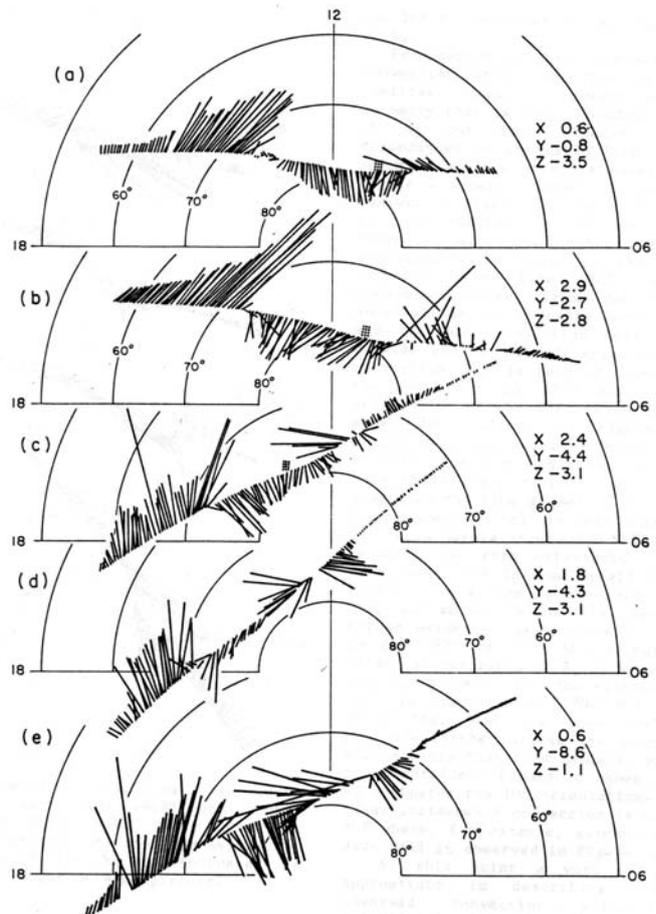
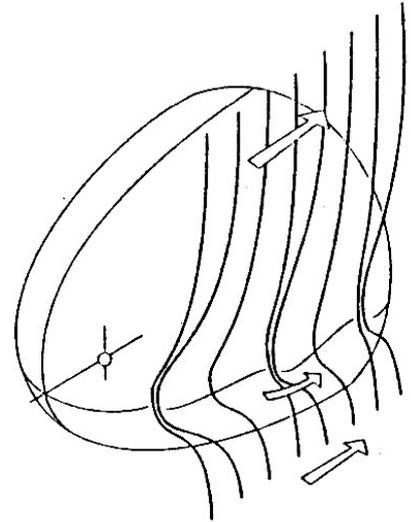
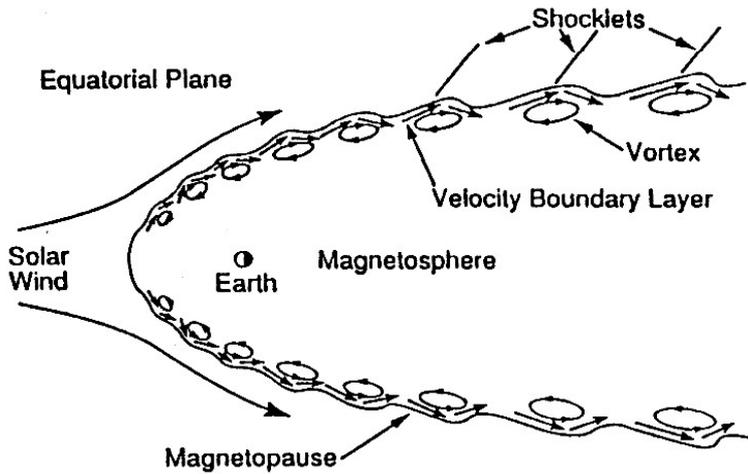
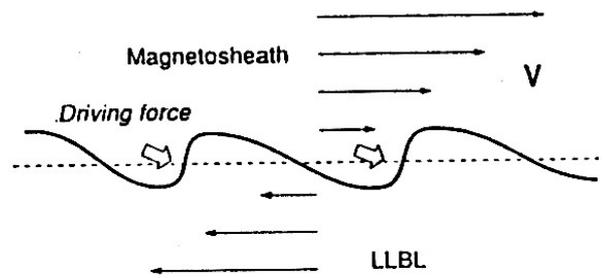
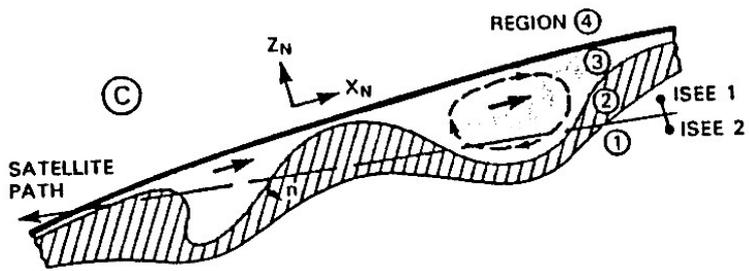
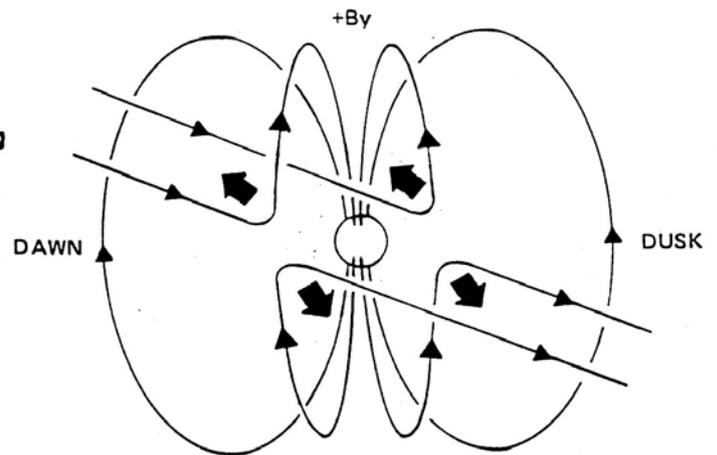
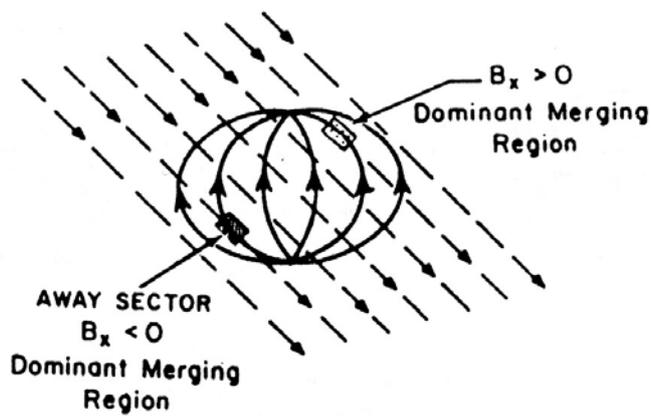


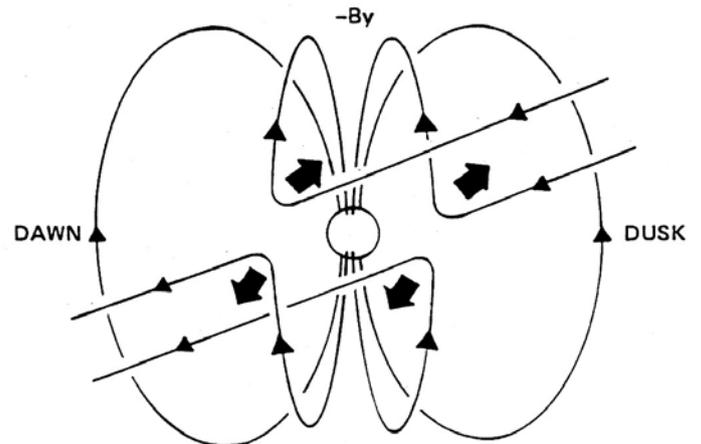
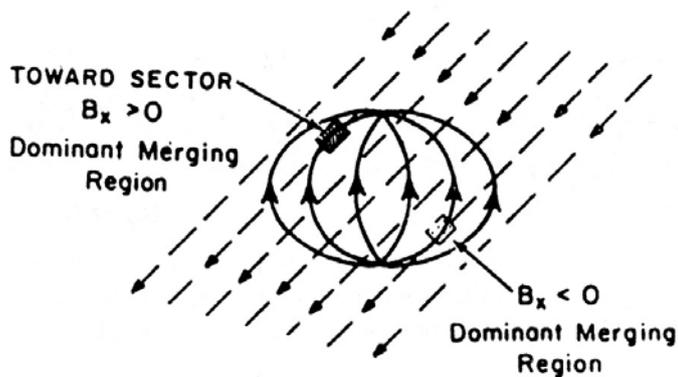
Fig. 1. Ion convection velocities observed by AE-C during toward sector IMF conditions. Different values of  $B_y/B_x$  have been chosen to illustrate their effects on the flow asymmetry. The GSM components of the IMF are indicated by X, Y, and Z to the right of each picture.

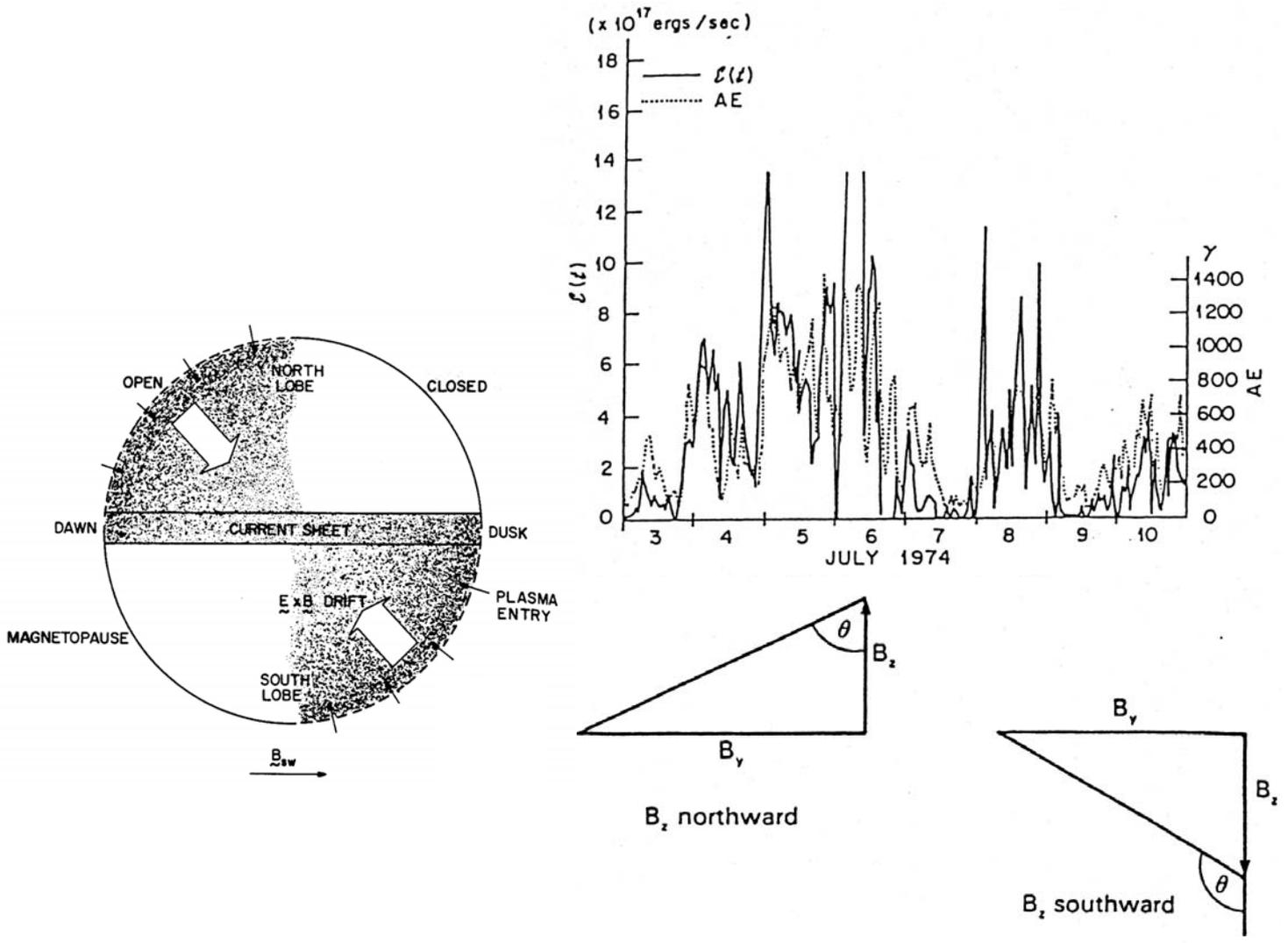
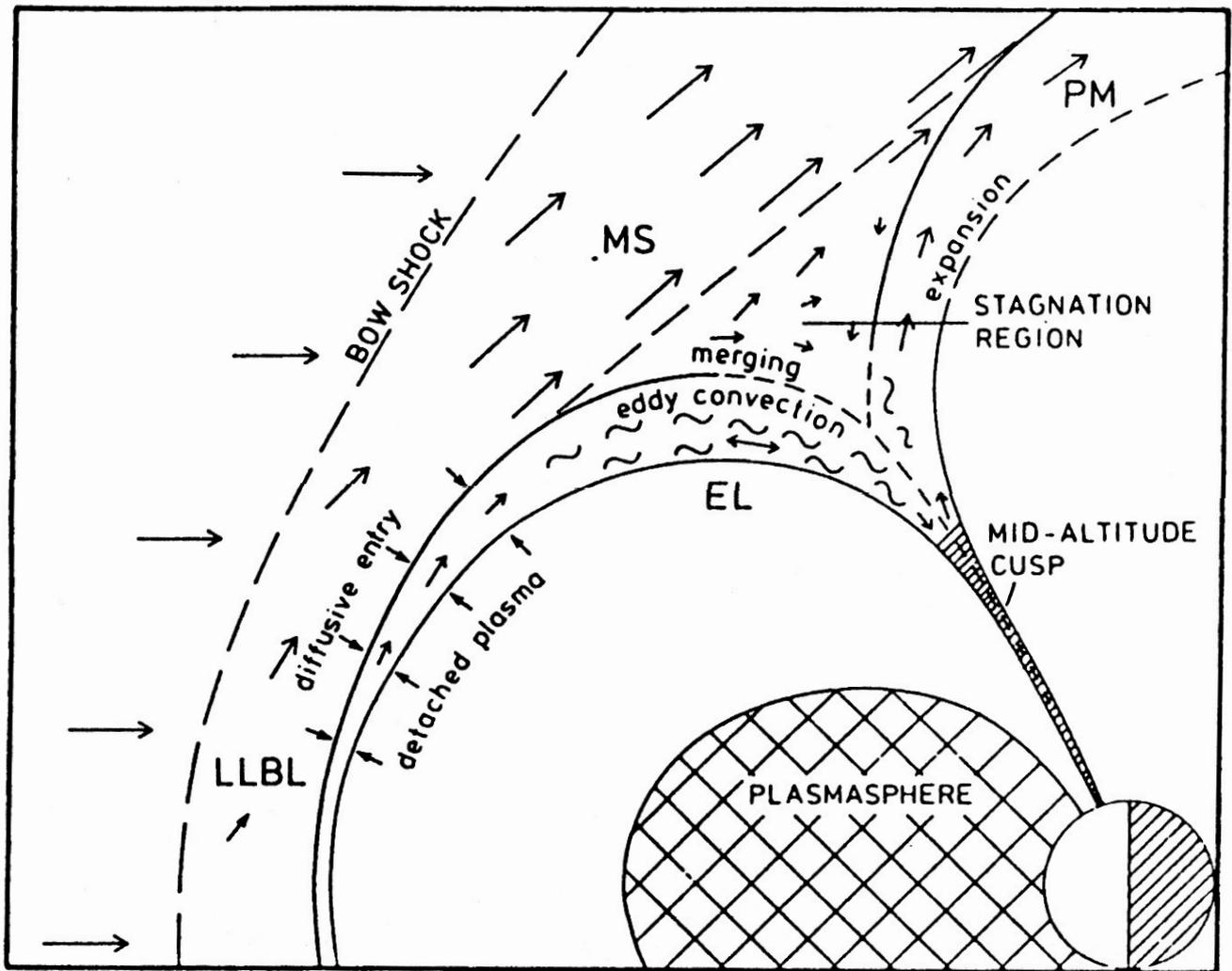


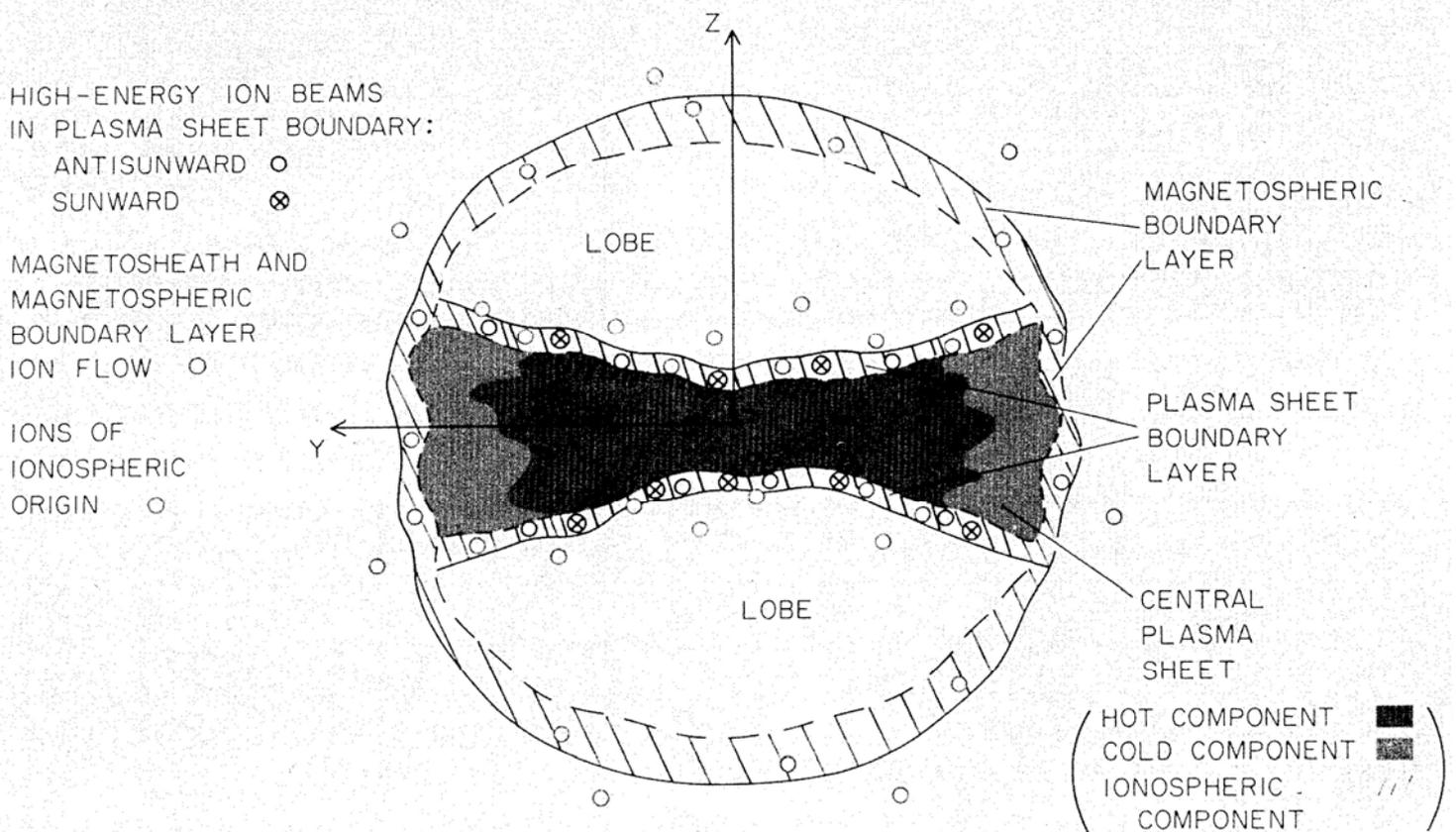
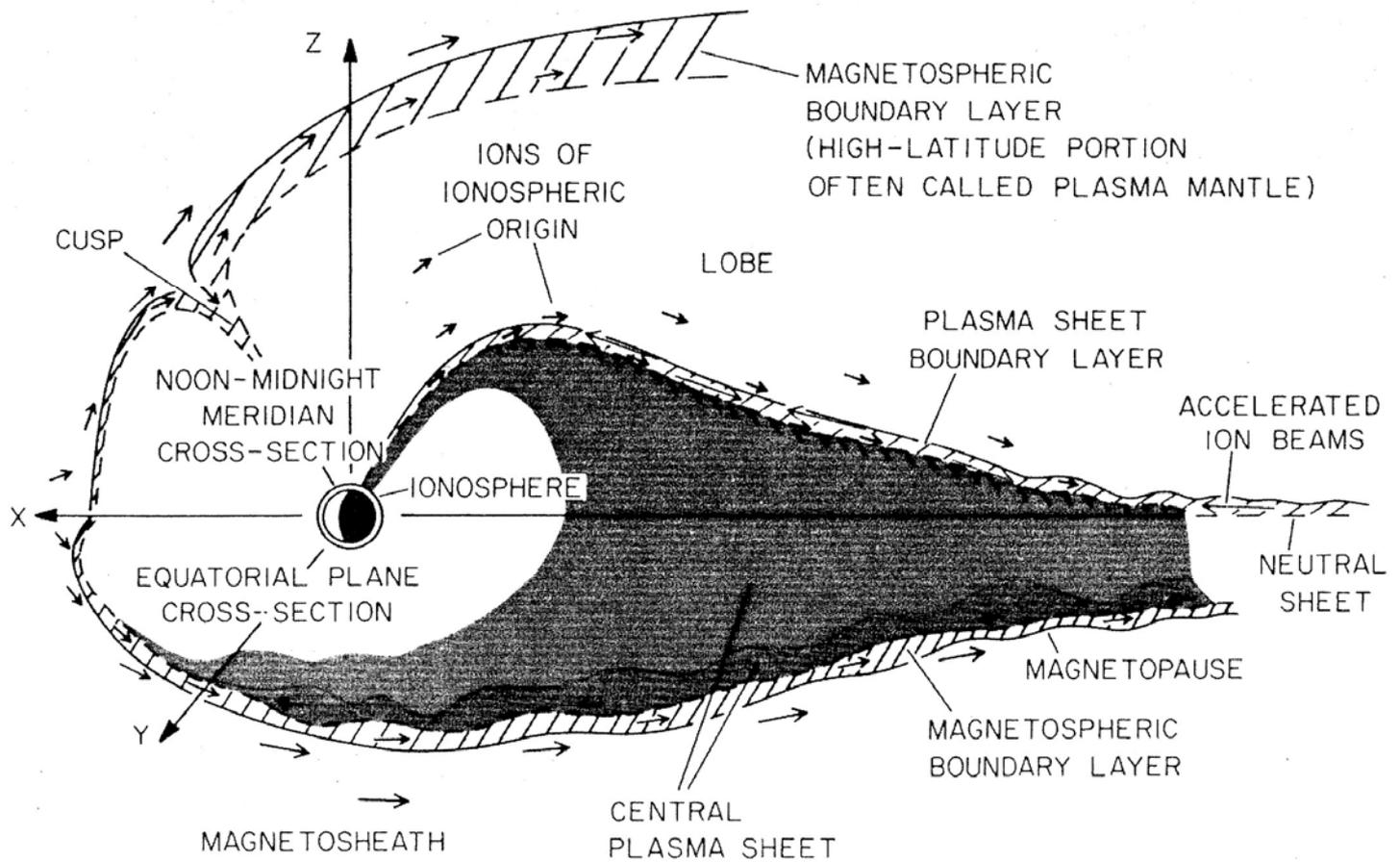
MERGING REGIONS FOR  $B_y > 0$



MERGING REGIONS FOR  $B_y < 0$

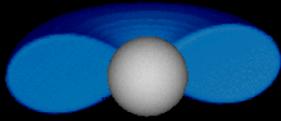




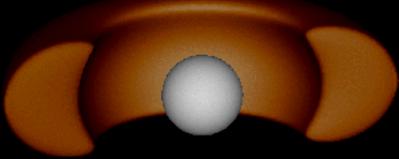


# 内部磁気圏のエネルギー階層構造

プラズマ圏 (~1 eV)



リングカレント (~10<sup>4</sup>-10<sup>5</sup> eV)



電子放射線帯 (>10<sup>5</sup> eV)



## ■ プラズマ圏 (数密度)

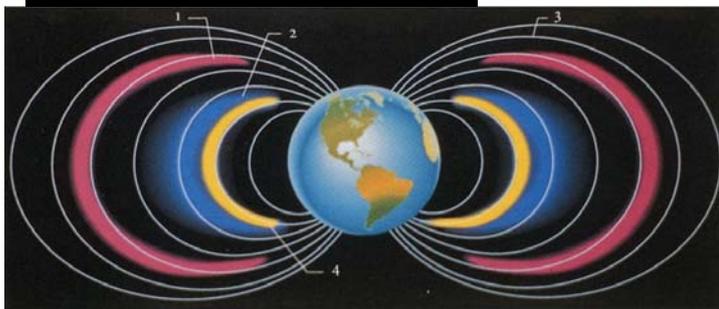
- 電離圏起源の冷たいプラズマ
- クーロンの衝突や波動励起に重要な役割

## ■ リングカレント (エネルギー密度)

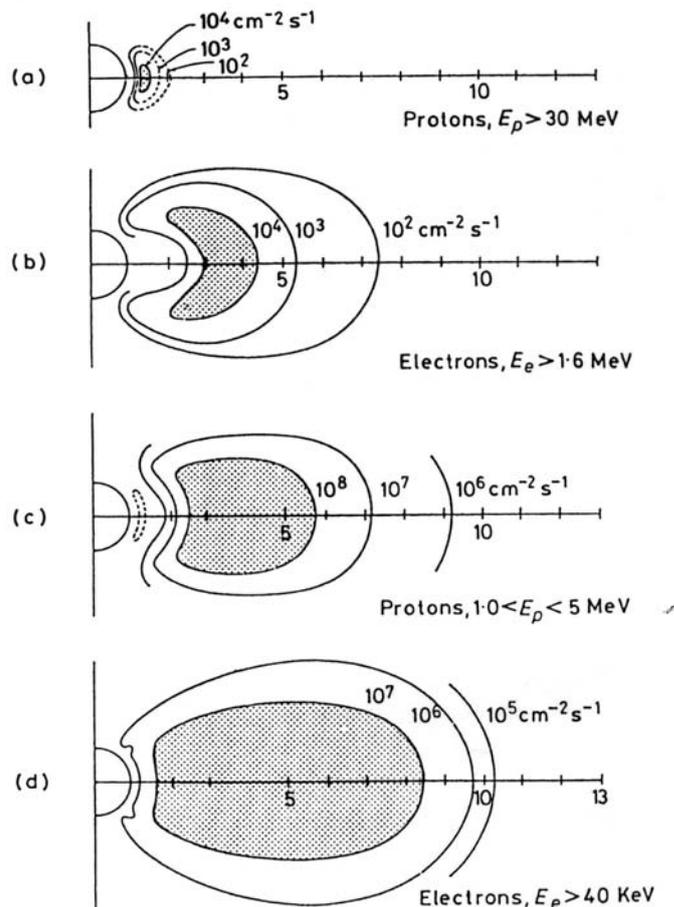
- 太陽風又は電離圏起源の熱いプラズマ
- 電流源 (内部磁気圏の磁場), 二次的な電離圏電場変動 (遮蔽電場)

## ■ 放射線帯

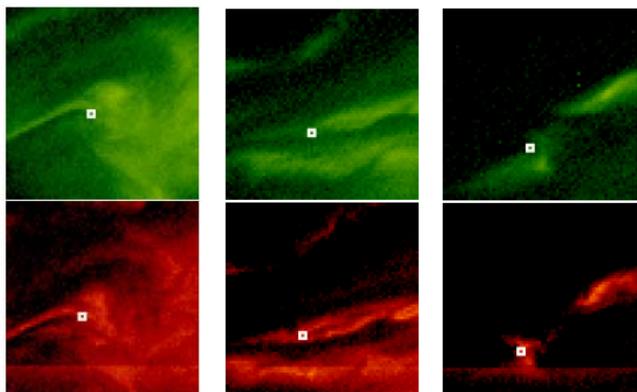
- 数100 keV以上の電子 (外帯・内帯)
- 数MeV以上の陽子



# 地球放射線帯のフラックス・エネルギー分布



Spatial distributions of trapped protons and electrons of higher and lower energy. (After W. N. Hess, *Radiation Belt and Magnetosphere*. Blaisdell, 1968)



UT=15:08:17.07      UT=15:08:23.91      UT=15:08:29.79

Mode-0

Exp. 60 ms

Mode-0

Exp. 60 ms

Mode-0

Exp. 60 ms

intensity in log<sub>10</sub> scale (kR)

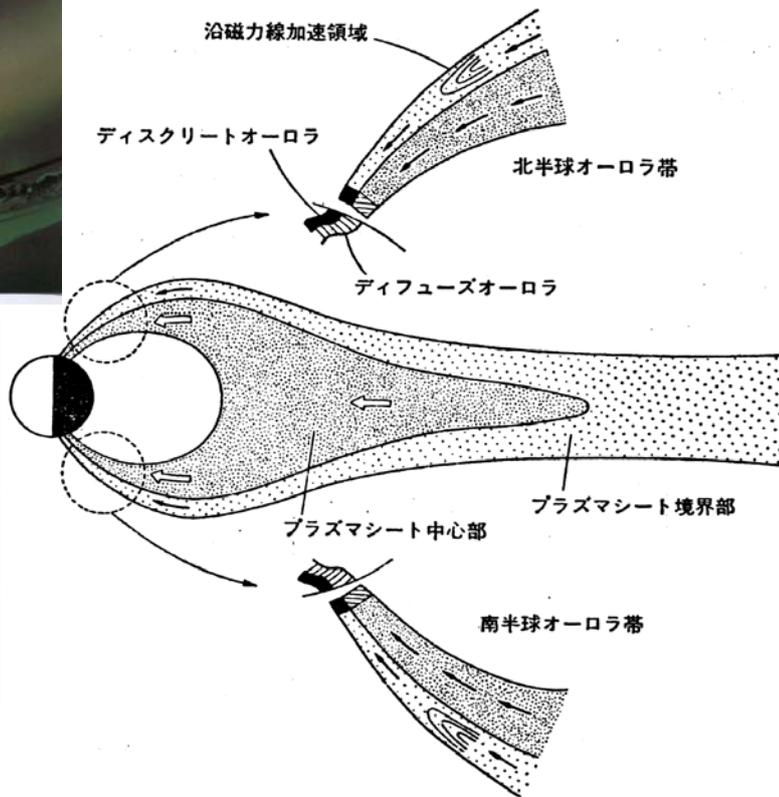
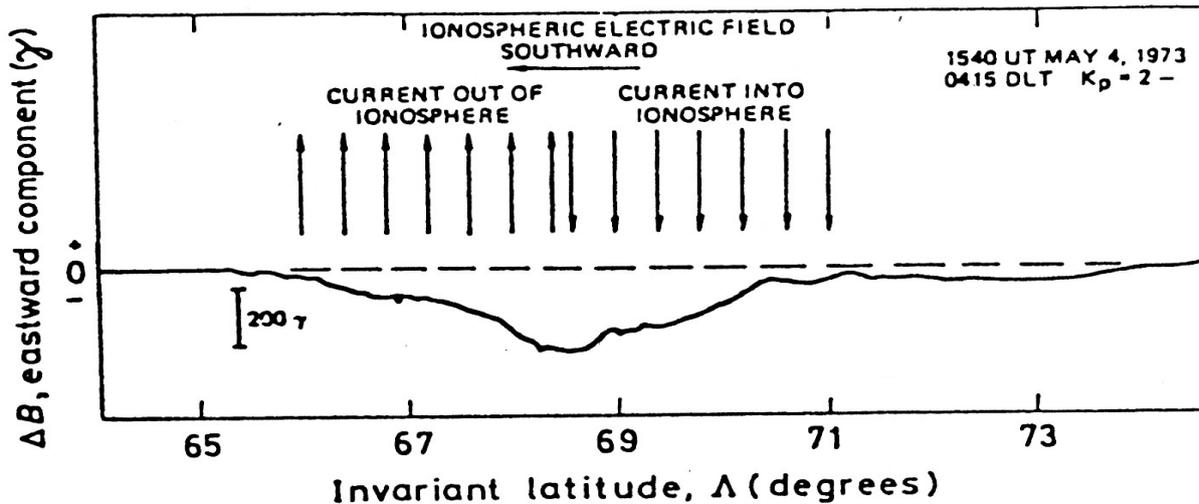
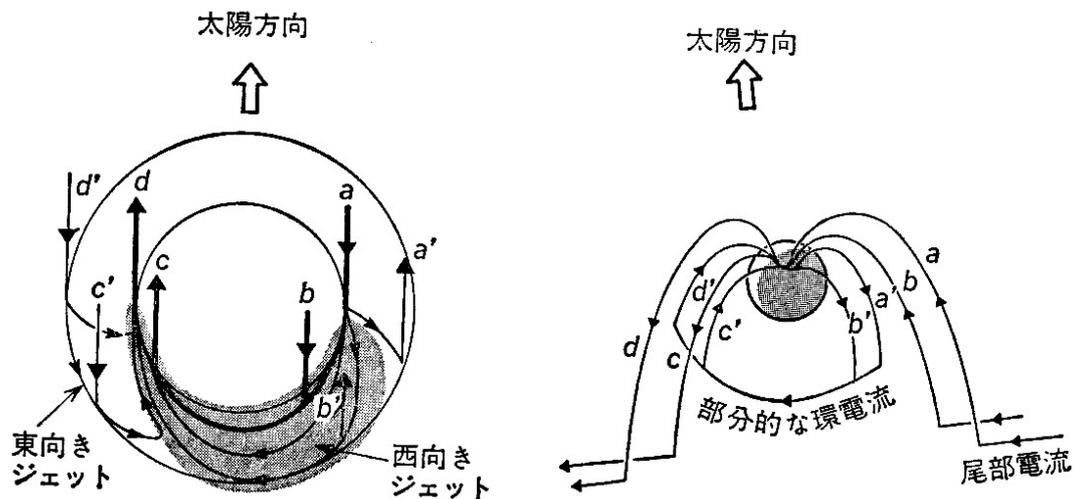


図 2.41 ディスクリートオーロラとディフューズオーロラをおこす粒子 (主として電子) の供給源と沿磁力線加速領域の関係



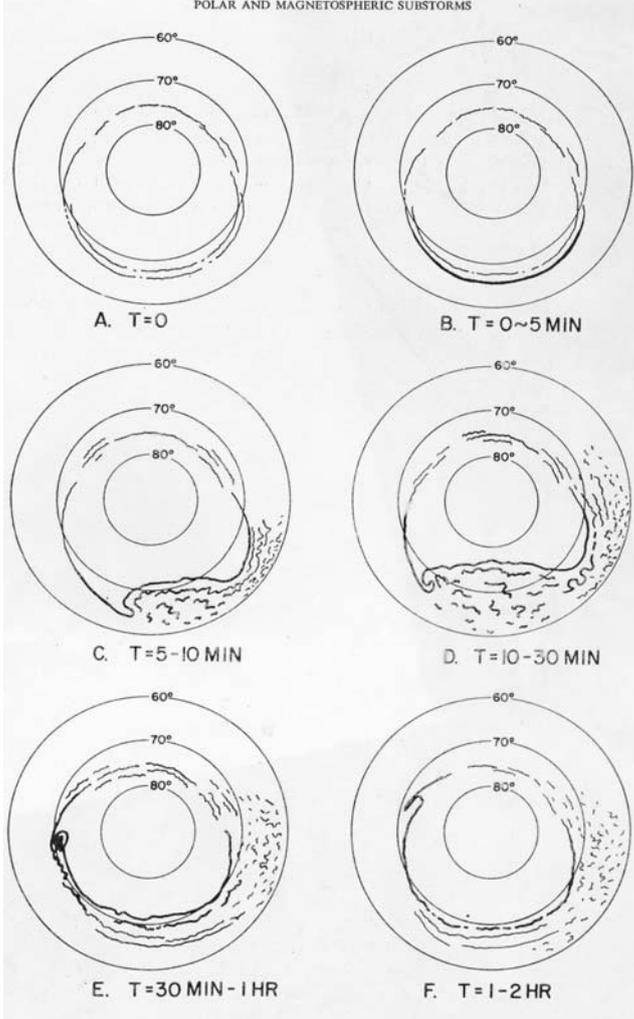


Fig. 17. Schematic diagram to show the development of auroral substorm.

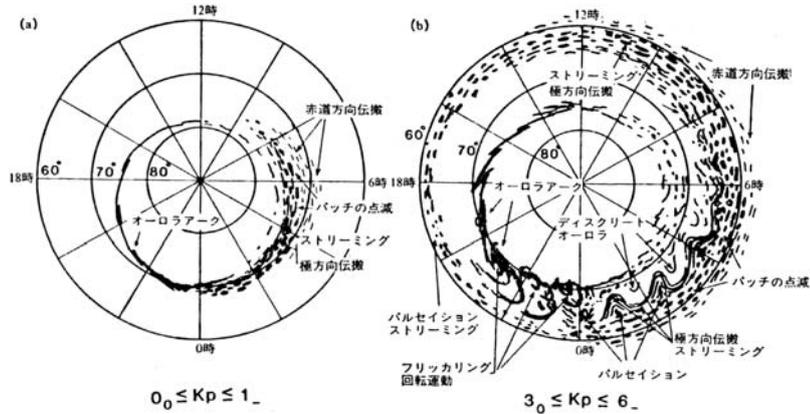


図 2.53 オーロラの運動形態により分類したオーロラのタイプとその出現領域。a) は地磁気活動の静穏時の状態を、b) は擾乱時の状態を表す (Oguti, 1981)。

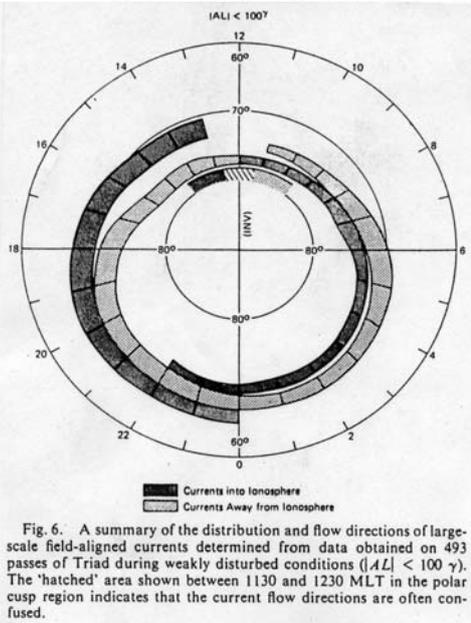


Fig. 6. A summary of the distribution and flow directions of large-scale field-aligned currents determined from data obtained on 493 passes of Triad during weakly disturbed conditions ( $|AL| < 100 \gamma$ ). The "hatched" area shown between 1130 and 1230 MLT in the polar cusp region indicates that the current flow directions are often confused.