

第八章：大结局

程鑫

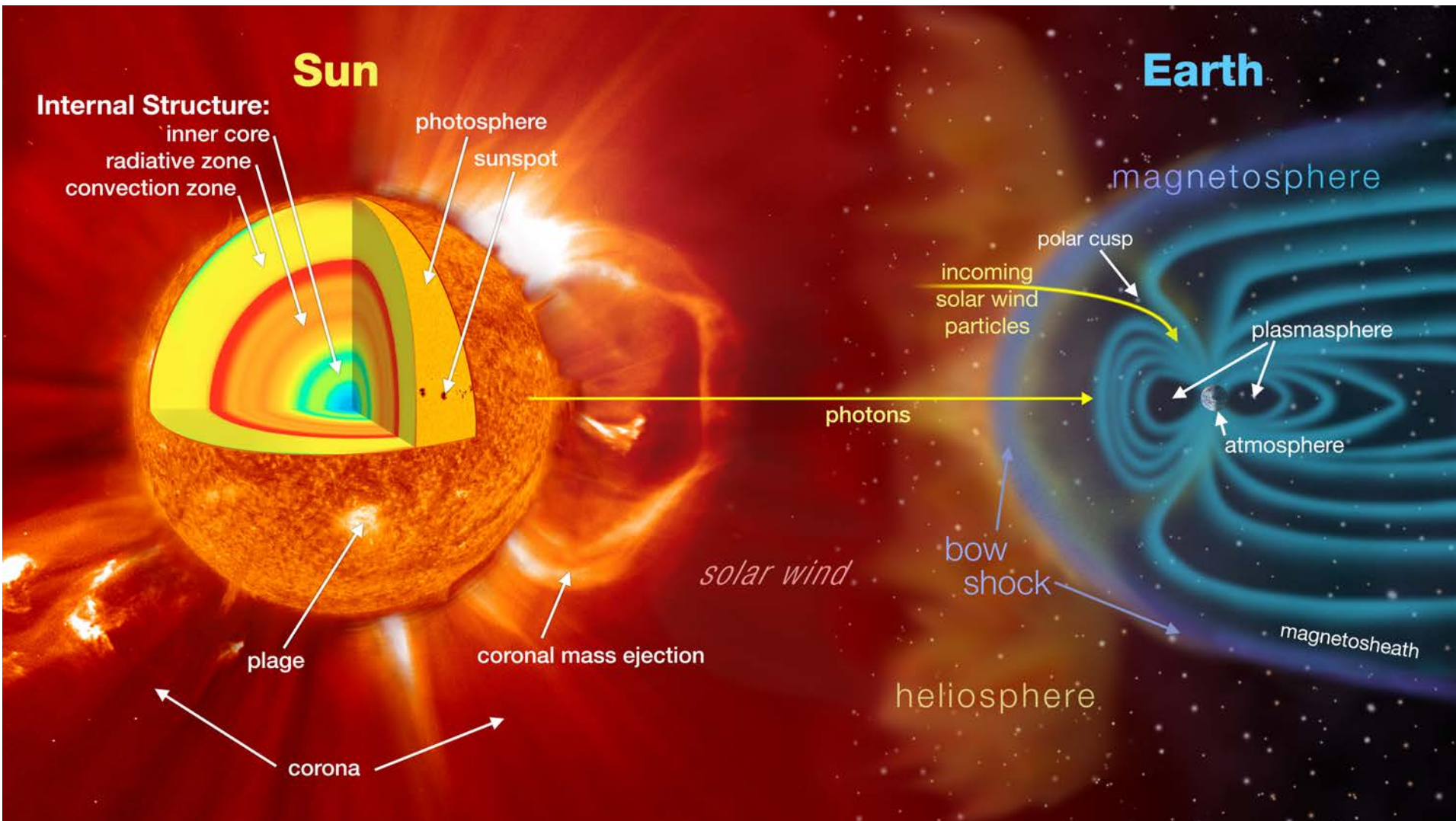
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课程大纲

- 绪论
- 等离子体的概念和基本性质
- 单粒子轨道理论
- 磁流体力学（MHD）
- 等离子体波和不稳定性
- 太阳大气和太阳活动
- 太阳风
- 磁层物理

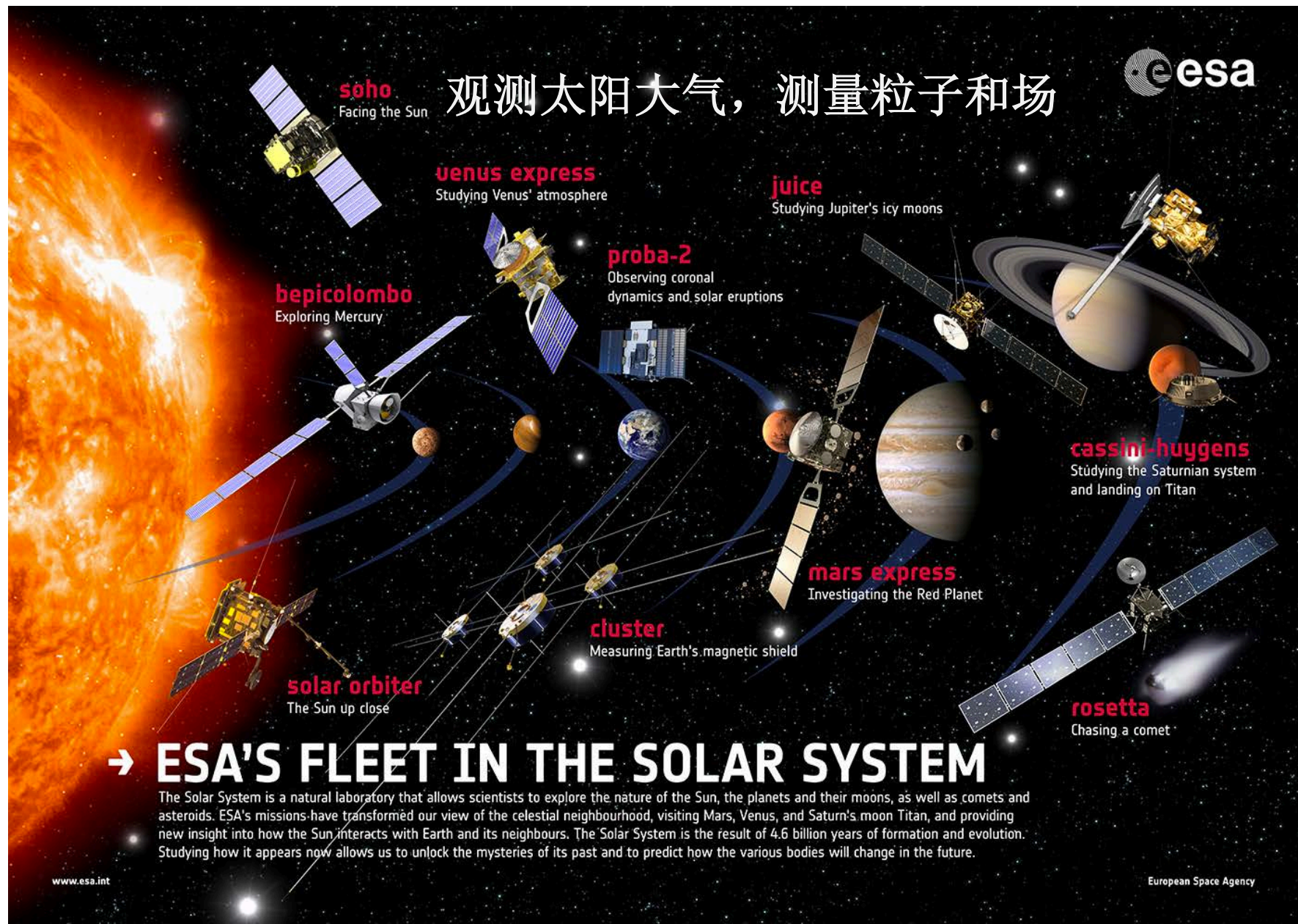
空间物理导论—总结



空间等离子体特性

等离子体区域	密度 (cm^{-3})	温度 (eV)	德拜长度 (cm)	等离子体参量 (N_D)
太阳日冕	10^6	10^2	10^4	10^9
太阳风	10	10	10^6	10^{10}
磁层	10	10^3	10^7	10^{13}
电离层	10^6	10^{-1}	10^2	10^4

太阳系观测



等离子体概述:

1. 等离子体的“电性”和集体行为

1). 等离子体频率

电子频率: $\omega_e^2 = \frac{n_e e^2}{m_e \epsilon_0}$ $f = 9000 \sqrt{n}$

2). Debye (德拜) 屏蔽

Debye半径: $\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e e^2}}$

3). 等离子体的准中性和响应时间

电子热速度: $V_{the} = \sqrt{\frac{k T_e}{m_e}}$, 响应时间: $\tau = \frac{\lambda_D}{V_{the}} = \sqrt{\frac{m_e \epsilon_0}{n_e e^2}}$

4). 等离子体判据

空间尺度 $L \gg \lambda_D$, 维持时间 $T \gg \tau$, Debye球内粒子数 $\Lambda \gg 1$

2. 等离子体中的辐射

3. 描述等离子体的方法

单粒子轨道理论

●在均匀恒定磁场中的运动

$$v_x = v_{\perp} \cos(\Omega t + \alpha)$$

$$v_y = -v_{\perp} \sin(\Omega t + \alpha)$$

●均匀恒定电磁场中的电漂移

$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

●重力漂移

$$\mathbf{v}_E = \frac{m\mathbf{g} \times \mathbf{B}}{qB^2}$$

●梯度漂移

$$\mathbf{v}_{\nabla B} = \frac{W_{\perp}}{qB^3} \mathbf{B} \times \nabla B = \frac{W_{\perp}}{qB^2 R^2} \mathbf{R} \times \mathbf{B}$$

●曲率漂移

$$\mathbf{v}_{DBC} = \frac{2W_{\parallel}}{qB^2 R^2} \mathbf{R} \times \mathbf{B} = \frac{2W_{\parallel}}{qB^2} \mathbf{B} \times \left(\frac{\mathbf{B}}{B} \cdot \nabla \right) \frac{\mathbf{B}}{B}$$

$$\mathbf{v}_{DB} = \mathbf{v}_{\nabla B} + \mathbf{v}_{DBC} = \frac{(2W_{\parallel} + W_{\perp})}{q} \frac{\mathbf{R} \times \mathbf{B}}{B^2 R^2}$$

●带点粒子在随时间缓变磁场中的漂移

$$v_{DB} = \frac{r}{2B} \frac{dB}{dt}$$

Ideal MHD at a glance (cgs units)

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0$$

Momentum Equation

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla \right) \mathbf{V} = \frac{\mathbf{J} \times \mathbf{B}}{c} - \nabla p$$

Ampere's law

$$\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$$

Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} = -c \nabla \times \mathbf{E}$$

Ideal Ohm's law

$$\mathbf{E} + \frac{\mathbf{V} \times \mathbf{B}}{c} = 0$$

Divergence constraint

$$\nabla \cdot \mathbf{B} = 0$$

Adiabatic Energy Equation

$$\frac{d}{dt} \left(\frac{p}{\rho^\gamma} \right) = 0$$

Definitions: $\mathbf{B}$, magnetic field; $\mathbf{V}$, plasma velocity; $\mathbf{J}$, current density; $\mathbf{E}$, electric field; ρ , mass density; p , plasma pressure; γ , ratio of specific heats (usually 5/3); t , time.

磁感应方程

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

运动方程

Moving plasma will experience the Lorentz force ($\mathbf{j} \times \mathbf{B}$) $\Rightarrow$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g}$$

How do we interpret the Lorentz Force? Using Ampere's Law:

$$\mathbf{j} \times \mathbf{B} = -\frac{1}{\mu_0} \mathbf{B} \times (\nabla \times \mathbf{B})$$

but using the vector identity $\nabla \left(\frac{1}{2} \mathbf{B} \cdot \mathbf{B} \right) = \mathbf{B} \times (\nabla \times \mathbf{B}) + (\mathbf{B} \cdot \nabla) \mathbf{B}$

$$\Rightarrow \mathbf{j} \times \mathbf{B} = \frac{1}{\mu_0} (\mathbf{B} \cdot \nabla) \mathbf{B} - \nabla \left(\frac{B^2}{2\mu_0} \right)$$

1st term is magnetic tension parallel to $\mathbf{B}$ - important for curved fields. 2nd term is magnetic pressure - important when $|\mathbf{B}|$ changes along field.

磁静力学平衡

$$0 = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g},$$

$$0 = -\nabla p + \mathbf{j} \times \mathbf{B}$$

$$0 = \mathbf{j} \times \mathbf{B}$$

MHD方程线性化

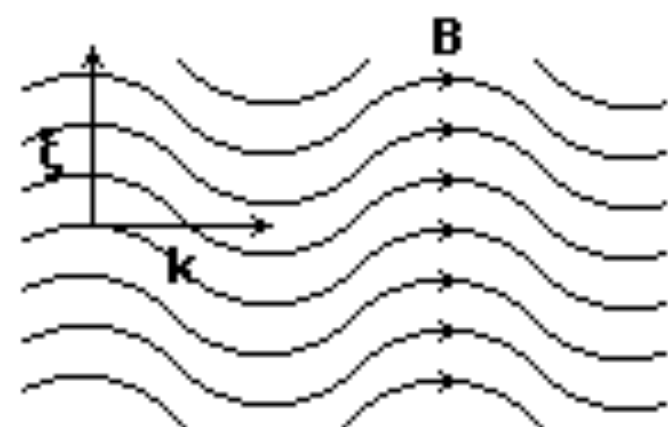
- ▶ The continuity, momentum, induction, and adiabatic energy equations are
- ▶ The continuity, momentum, induction, and adiabatic energy equations are linearized to become

$$\frac{\partial \rho_1}{\partial t} = -\mathbf{V}_1 \cdot \nabla \rho_0 - \rho_0 \nabla \cdot \mathbf{V}_1 \quad (43)$$

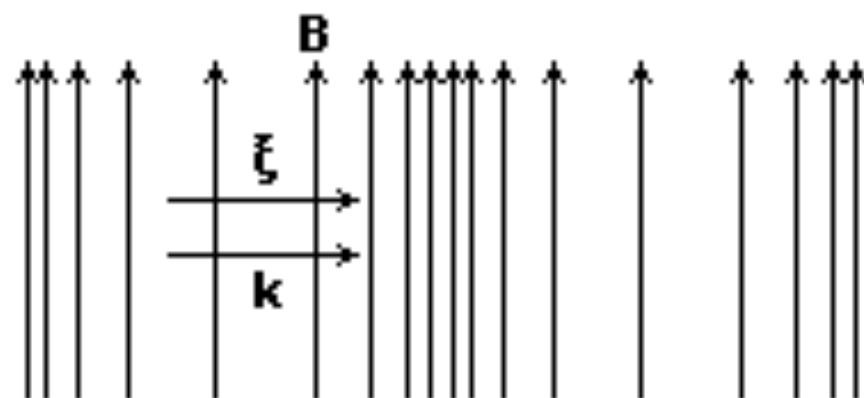
$$\rho_0 \frac{\partial \mathbf{V}_1}{\partial t} = \frac{(\nabla \times \mathbf{B}_1) \times \mathbf{B}_0}{4\pi} - \nabla p_1 \quad (44)$$

$$\frac{\partial \mathbf{B}_1}{\partial t} = \nabla \times (\mathbf{V}_1 \times \mathbf{B}_0) \quad (45)$$

$$\frac{\partial p_1}{\partial t} = -\mathbf{V}_1 \cdot \nabla p_0 - \gamma p_0 \nabla \cdot \mathbf{V}_1 \quad (46)$$



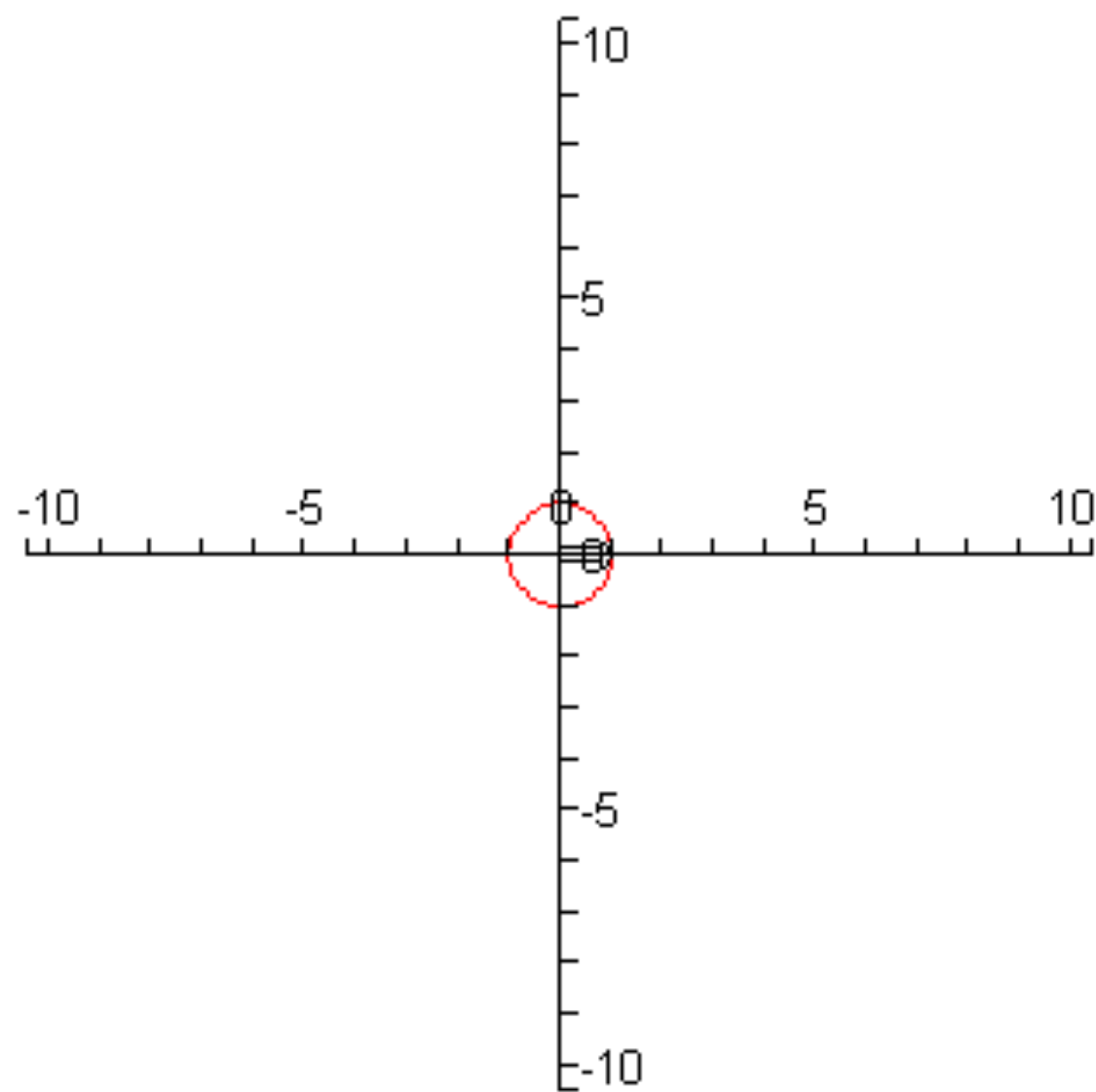
Alfvén



Magnetosonic

Magnetohydrodynamic Waves

$$v_a = 0.$$



MHD Shock

- 平行激波

$$\frac{v_1}{v_2} = \frac{\rho_2}{\rho_1} = X = \frac{(\gamma + 1)M_1^2}{2 + (\gamma - 1)M_1^2},$$

$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1},$$

$$\frac{B_2}{B_1} = 1$$

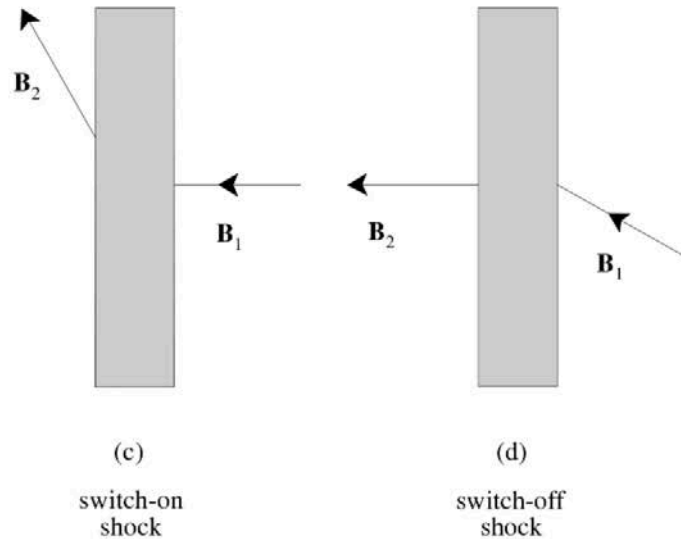
- 垂直激波

$$\frac{B_2}{B_1} = \frac{v_1}{v_2} = \frac{\rho_2}{\rho_1} = X,$$

$$\frac{p_2}{p_1} = \gamma M_1^2 (1 - 1/X) - \frac{1 - X^2}{\beta_1},$$

$$2(2 - X)X^2 + [2\beta_1 + (\gamma - 1)\beta_1 M_1^2 + 2]\gamma X - \gamma(\gamma + 1)\beta_1 M_1^2 = 0$$

Switch-on shocks and switch-off shocks



- ▶ Switch-on shocks
 - ▶ Tangential $\mathbf{B}$ develops as a result of the shock
 - ▶ Example of a fast mode shock
- ▶ Switch-off shocks
 - ▶ Tangential $\mathbf{B}$ disappears as a result of the shock
 - ▶ Example of a slow mode shock
- ▶ Remember: $[[\mathbf{B} \cdot \hat{\mathbf{n}}]] = 0$! Only the tangential component of $\mathbf{B}$ may change.

MHD instabilities

尺度:

- ✓ 宏观不稳定性: 大尺度, MHD不稳定性
- ✓ 微观不稳定性: 速度分布函数偏离平衡分布

形态:

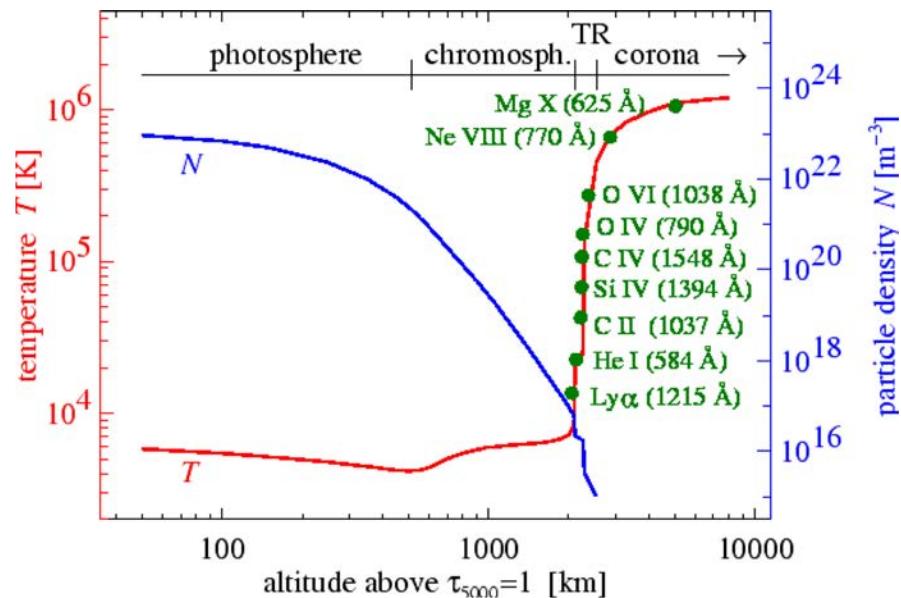
- ✓ 腊肠、扭曲不稳定性
- ✓ 气球模不稳定性

驱动因素:

- ✓ Rayleigh-Taylor (RT)
- ✓ Kelvin-Helmholz (KH)
- ✓ 束流不稳定性

太阳大气

- 太阳的分层结构.
- 太阳活动与宁静太阳.
- 太阳辐射.
- 太阳的磁场.



太阳风

- I 超声速太阳风的预言和发现
- II 太阳风的基本观测特征
- III 日冕加热与太阳风加热加速

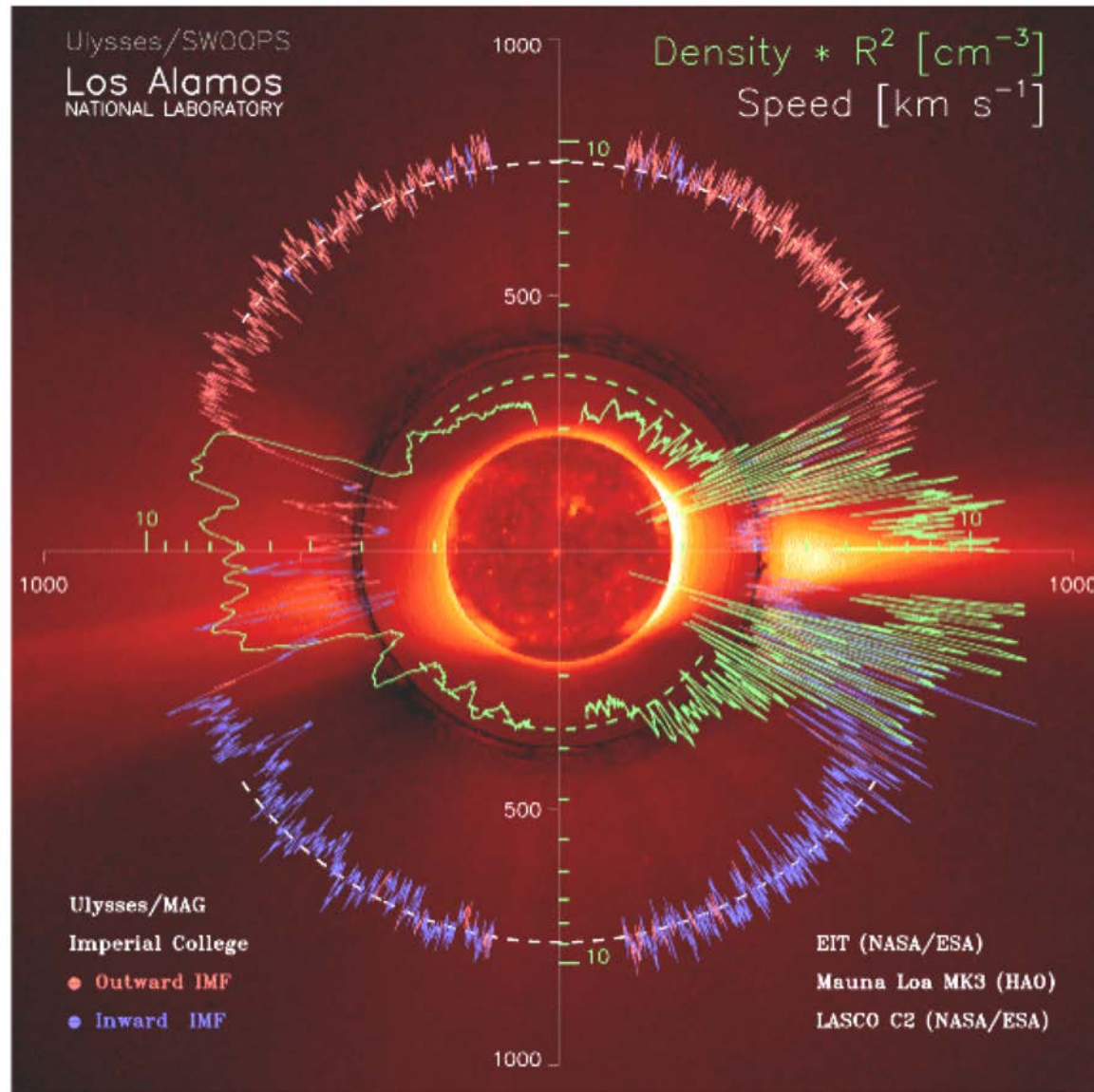
高速太阳风和低速太阳风的速度和密度

B 向外

黄道面

B 向内

McComas et al., GRL, **25**, 1, 1998



速度

V

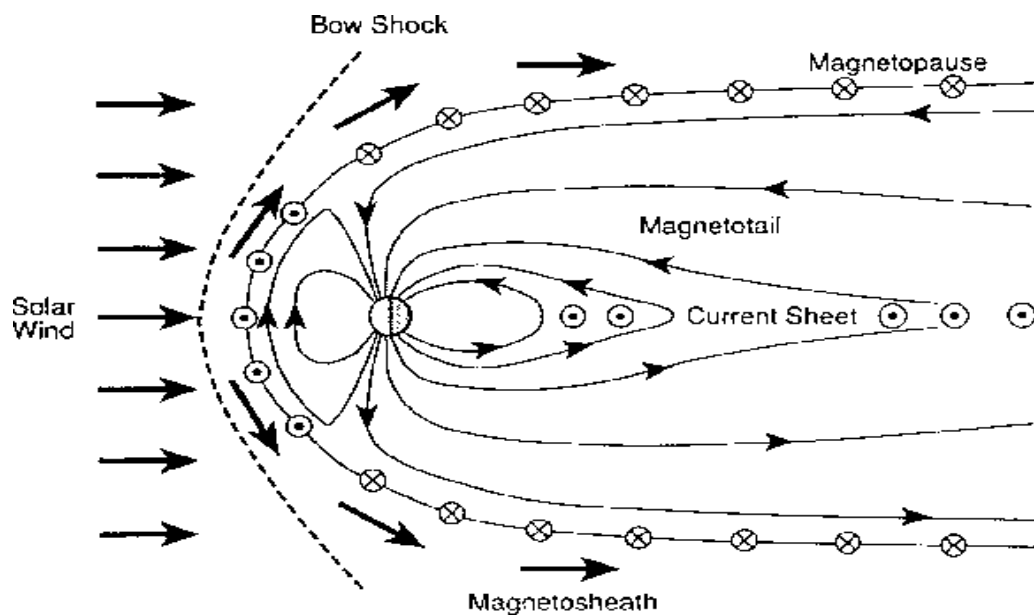
密度

n R²

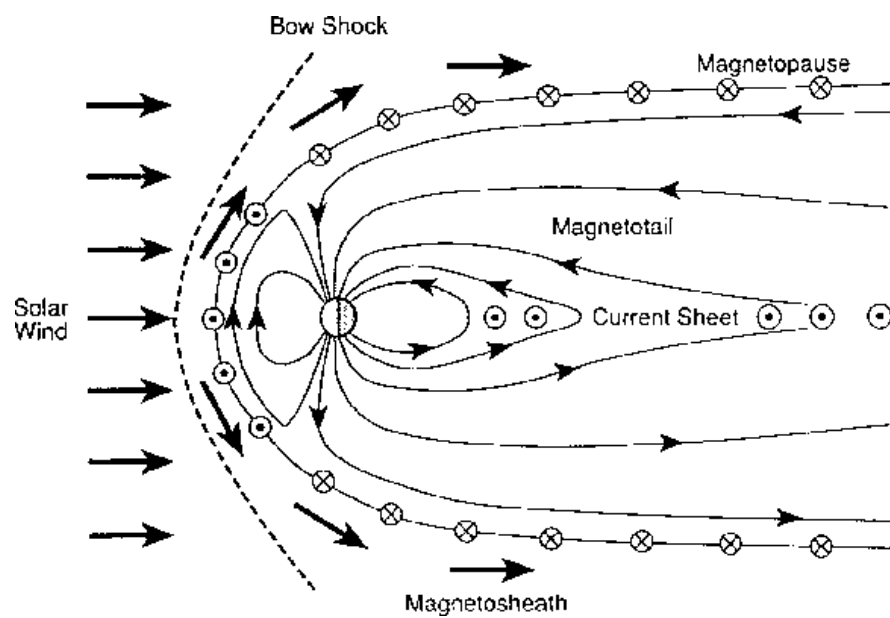
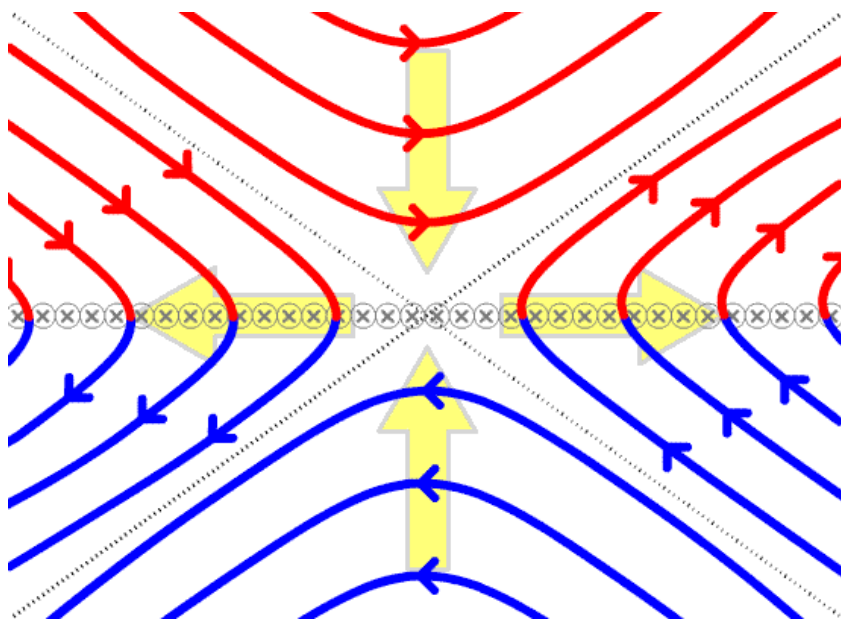
观测表明太阳风的主体是高速太阳风

磁层结构

- 地球磁层（磁层电流）
- 地磁暴、磁层亚暴



磁重联



空间物理和天体物理的关系

空间物理

天体物理

空间物理和等离子体物理的关系

成绩计算公式

考勤	随机签到4次（-5/次）	30%
Test+Project	15+15分	30%
课程汇报	相关文献, 8+2分钟	40%