

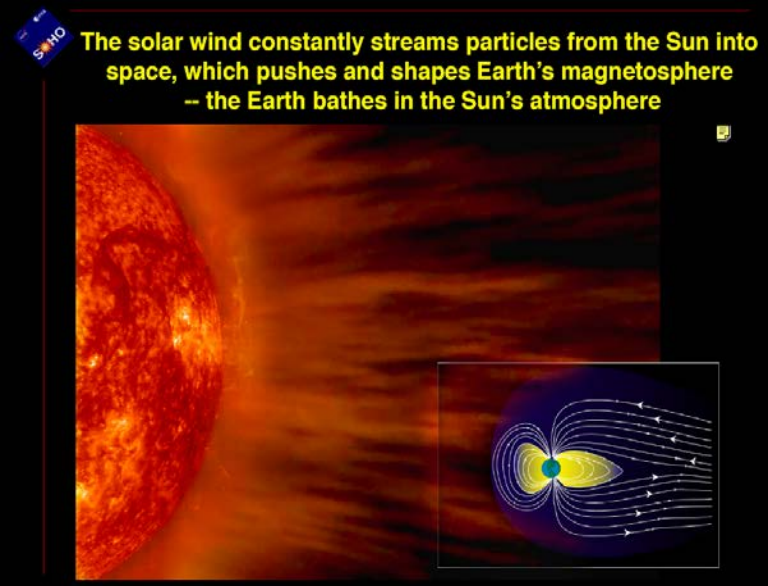
第七章

Solar Wind

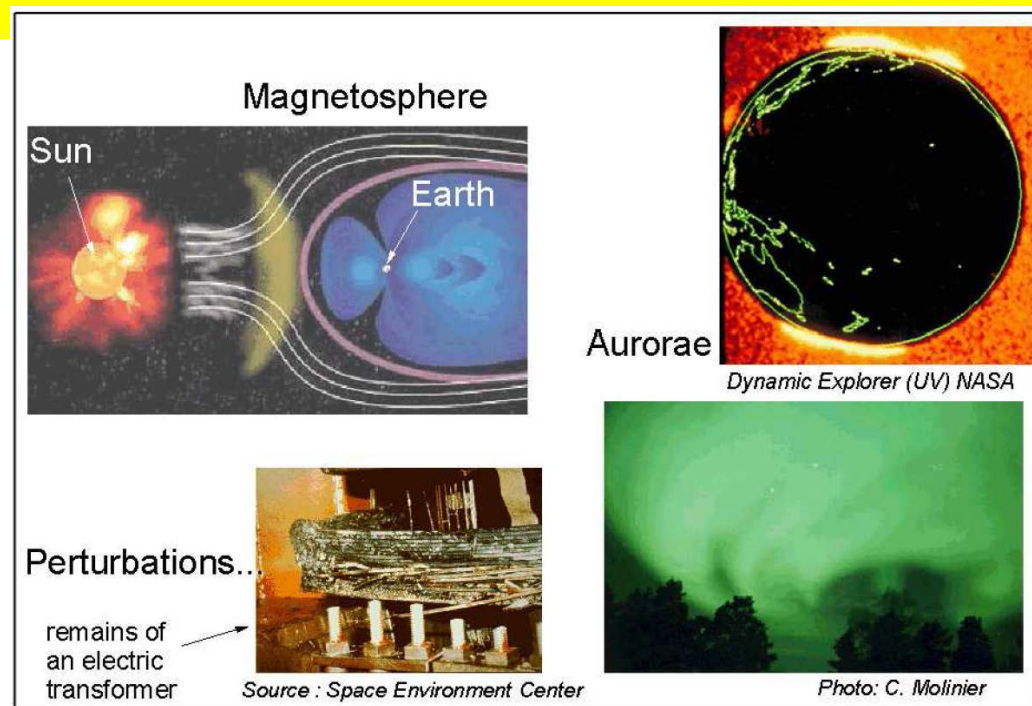
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太阳风是由日冕不断向行星际空间发出的持续超声速带电粒子流。



- 太阳风及其与地球磁层的相互作用： 空间天气
- 太阳风：天然的等离子体物理实验室

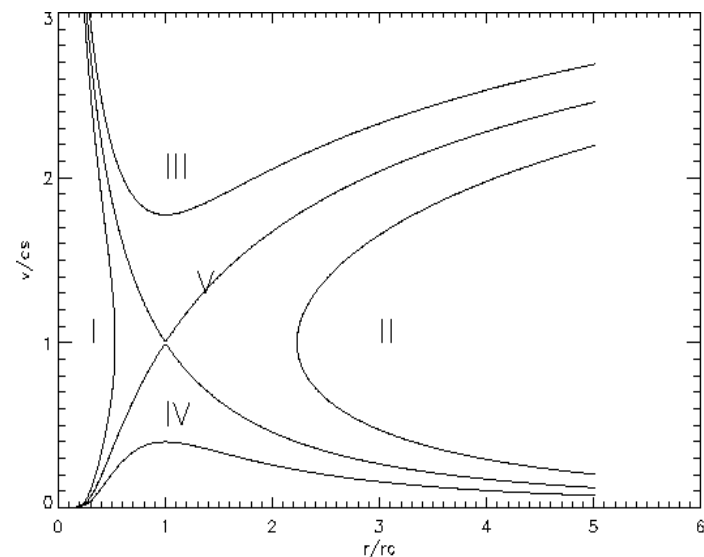


An analog simulation was created by Prof. K. C. Hsieh of the University of Arizona physics department.



主要内容

- 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



Parker, E.N.

超声速太阳风的预言者、
(磁)流体太阳风模型的奠基者。
主要物理思想(1958):

日冕高温膨胀 ➔ 超声速太阳风

高温日冕:

Establishment of the high-temperature corona (Million degrees)

1940: Edlen analyzed spectral lines from the corona and established that corona emission arises from highly ionized elements, at temperatures of ≥ 1 MK

(The issue of the corona heating is still an open question after more than 70 years of study!)

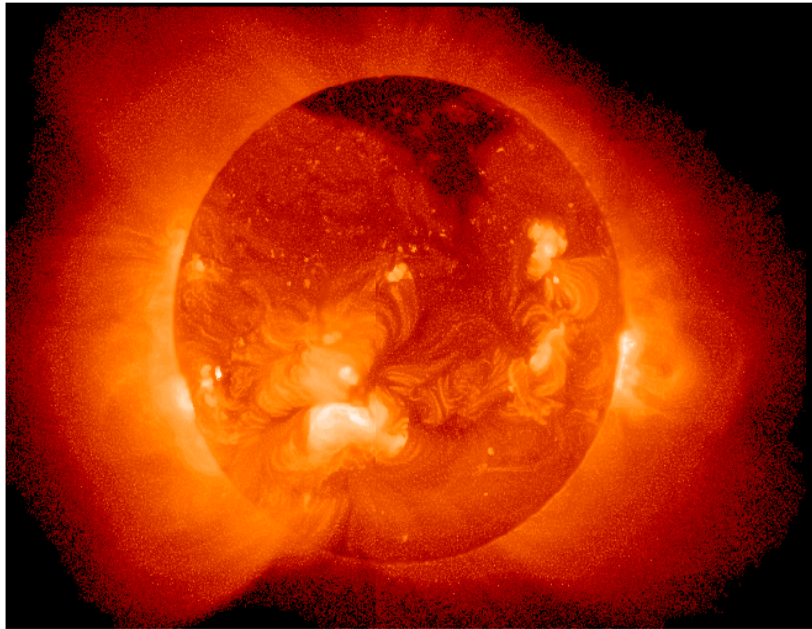
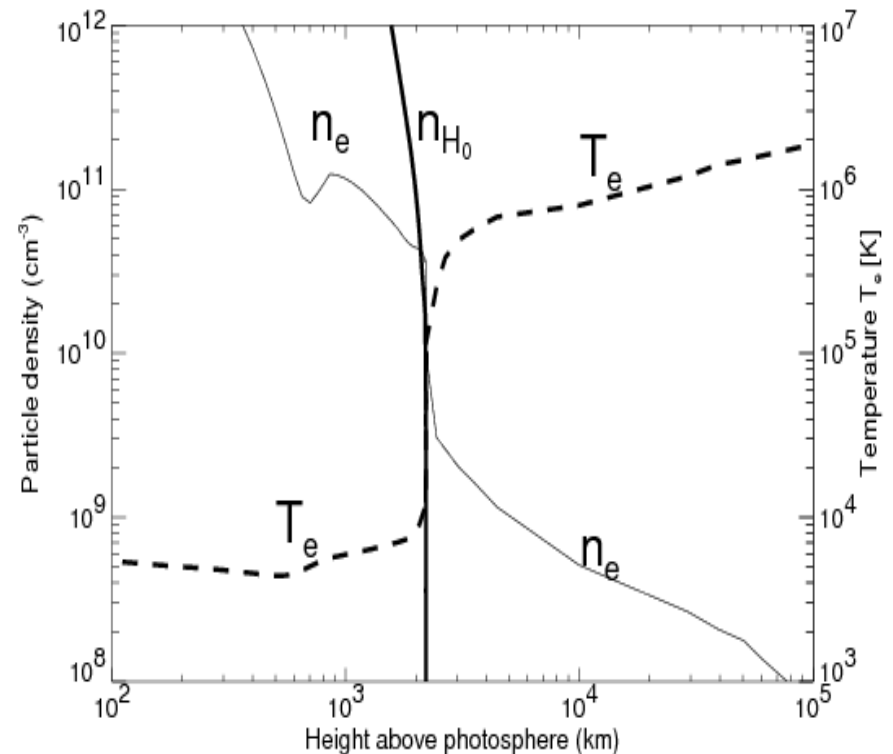


Figure 1.8: Soft X-ray image of the extended solar corona recorded on 1992 August 26 by the *Yohkoh* Soft X-ray Telescope (SXT). The image was made up from two pointings of the spacecraft, one to the east and one to the west, to capture the distant corona far above the Sun's limb (courtesy of *Yohkoh* Team).



太阳风理论

- 日冕平衡状态下的流体模式
- 冻结在太阳风中并被带到行星际的磁场的结构
- 太阳风与行星际介质的耦合

太阳风形成的流体理论

$$\left\{ \begin{array}{l} \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \text{ (质量守恒)} \\ \rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P + \mathbf{j} \times \mathbf{B} + \rho \mathbf{F}_g \text{ (动量守恒)} \end{array} \right.$$

$$\left\{ \begin{array}{l} \nabla \cdot \rho \mathbf{u} = 0 \\ \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P + \mathbf{j} \times \mathbf{B} + \rho \mathbf{F}_g \end{array} \right.$$

进一步简化：球对称，速度沿径向，因此

$$\begin{aligned} \mathbf{u} &= u(r) \\ \mathbf{F}_g &= -\frac{GM}{r^2} \end{aligned}$$

$$\left\{ \begin{array}{l} \nabla \cdot \rho \mathbf{u} = \frac{1}{r^2} \frac{d}{dr} \rho u r^2 \\ \rho \mathbf{u} \cdot \nabla \mathbf{u} = \rho u \frac{du}{dr} \end{array} \right.$$

太阳风形成的流体理论

不考虑磁场，洛伦兹力消逝，因此

$$\left\{ \begin{array}{l} \frac{1}{r^2} \frac{d}{dr} \rho u r^2 = 0 \\ \rho u \frac{du}{dr} = - \frac{dp}{dr} - \rho \frac{GM}{r^2} \end{array} \right.$$

50年代以前，一直认为该方程的解为 $u(r)=0$

动量方程变为 $\frac{dp}{dr} = -\rho \frac{GM}{r^2}$

又 $\rho = nm$, $p = 2nkT$ 得 $\rho = m \frac{p}{2kT}$

上式成为 $\frac{1}{p} \frac{dp}{dr} = - \frac{GMm}{2kT} \frac{1}{r^2}$

求解得： $p = p_0 \exp\left[\frac{GMm}{2kT} \left(\frac{1}{r} - \frac{1}{R}\right)\right]$ 该解在日冕底部较低高度的表达式？

太阳风形成的流体理论

考虑 $r \rightarrow \infty$

$$p = p_0 \exp\left[-\frac{GMm}{2kT} \frac{1}{R}\right]$$

根据 $T=1 \text{ MK}$, 可得 $p = 3 \times 10^{-4} p_0$, 其远大于实际测量值。

Parker's ingenious idea:

Even though the sun's corona is strongly attracted to the sun by solar gravity, it is such a good conductor of heat that it is still very hot at large distances from the sun. Since gravity weakens as distance from the sun increases, the outer coronal atmosphere escapes into interstellar space.

太阳风形成的流体理论

1950年代，Parker首次提出非零流速解：

对于连续性方程，有 $\rho u r^2 = c$
或者 $4\pi r^2 \rho u = c \rightarrow n = \frac{c}{4\pi m} \frac{1}{u r^2}$

对于动量方程 $\rho u \frac{du}{dr} = -\frac{dp}{dr} - \rho \frac{GM}{r^2}$
 $\rightarrow \rho u \frac{du}{dr} = -2kT \frac{dn}{dr} - \rho \frac{GM}{r^2}$

两边除 $\rho = nm \rightarrow u \frac{du}{dr} = -\frac{2kT}{m} \frac{1}{n} \frac{dn}{dr} - \frac{GM}{r^2}$

代入 $n = \frac{c}{4\pi m} \frac{1}{u r^2} \rightarrow \frac{dn}{dr} = \frac{c}{4\pi m} \left(-\frac{2}{u r^3} - \frac{1}{r^2} \frac{1}{u^2} \frac{du}{dr} \right)$ 可得



太阳风形成的流体理论

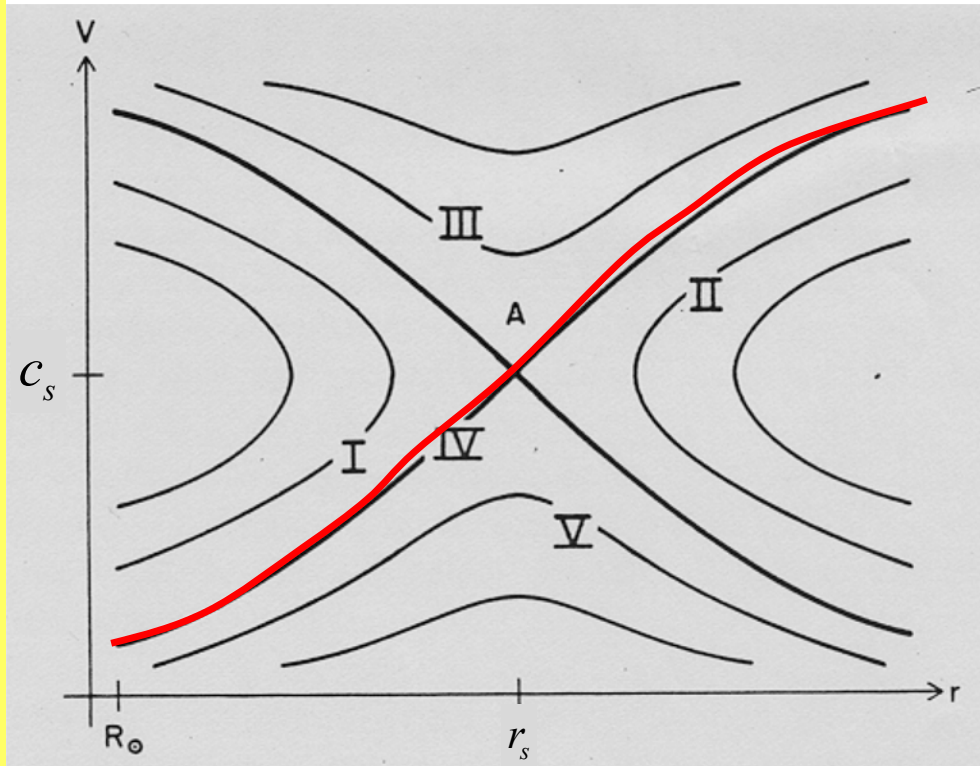
$$\left(u^2 - \frac{2kT}{m}\right) \frac{1}{u} \frac{du}{dr} = \frac{4kT}{mr} - \frac{GM}{r^2}$$

讨论：

1. 在高温日冕底部， r 较小，导致 $\frac{4kT}{mr} - \frac{GM}{r^2} < 0$ ，等离子体被引力束缚。
2. 随着 r 增加，右边第二项减小的更快，通过零值的位置为

$$r_c = \frac{GMm}{4kT}$$

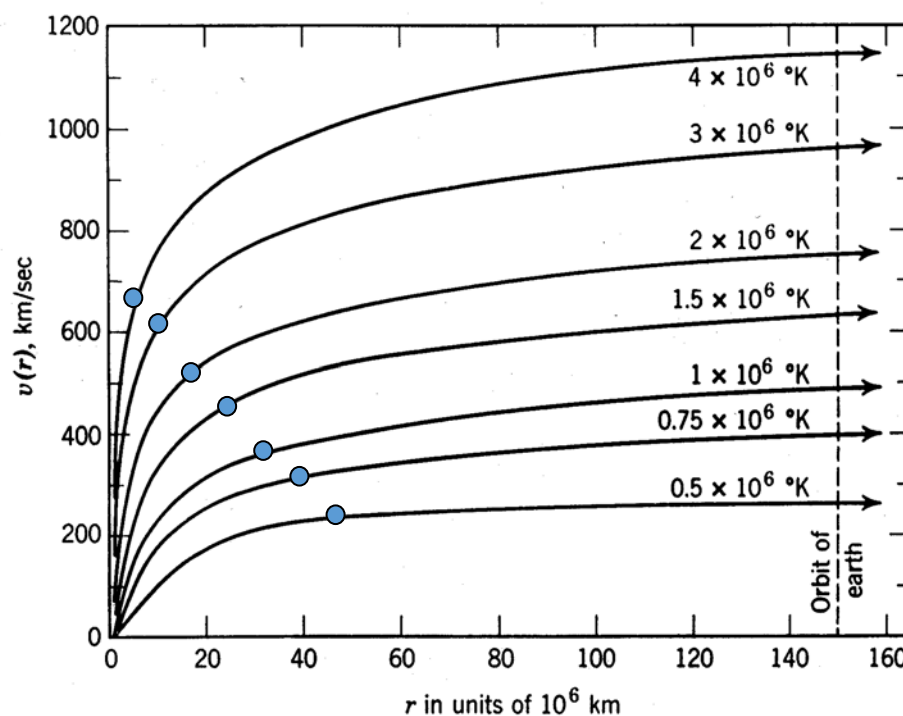
- **I, II区**: 有两个值, 非物理解.
- **III区**: 解永远超声速, 不合理.
- **V 区**: 解永远低于声速, 与观测不符.
- **IV**: 仅有通过临界点(声速点)**A**的太阳风解, 才有物理意义, 并有: $r \rightarrow \infty$ 时, $n \rightarrow 0$, $p \rightarrow 0$ 。这就是著名的**Parker**太阳风解。



Parker's article on the discovery of the solar wind (1958, ApJ) was rejected by two reviewers. It was saved by then editor Subrahmanyan Chandrasekhar, who received the 1983 Nobel Prize in physics.

Parker 的太阳风解有哪些特点？

- 温度增加，临界点向日面移动。
- 温度增加， $r \rightarrow 0$ 的渐进速度及太阳风速度也增加。
- 太阳风的加速大部分发生在临界点内。



不同温度下的Parker太阳风解

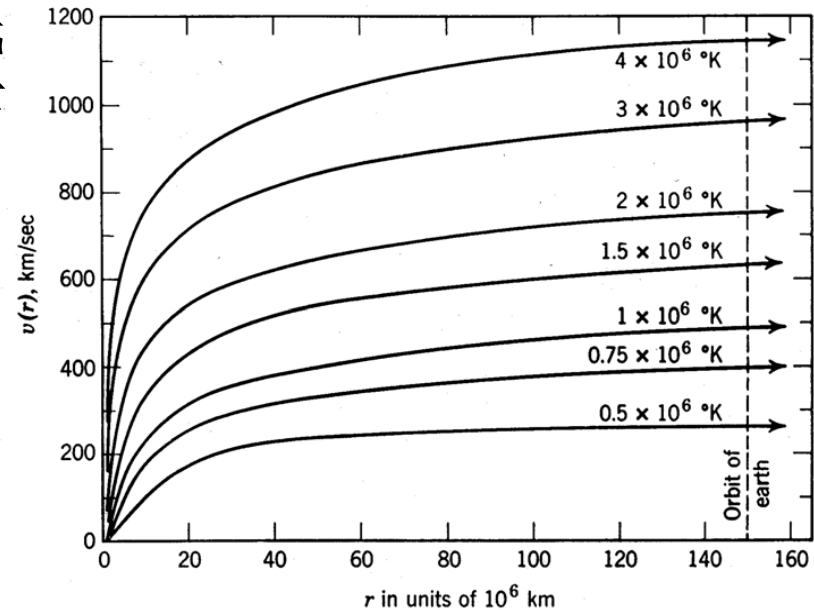
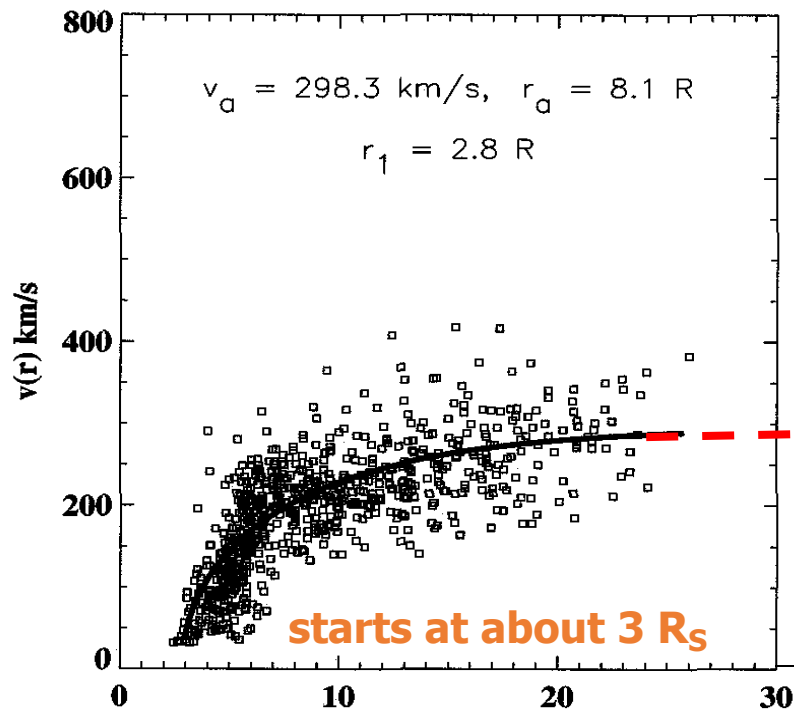
Parker, 1963

More realistic case

- Polytropic Solar Wind
- Energy Equation
- Effect of Rotation and a Magnetic Field
- Temporal and Spatial structures

低速太阳风的速度分布

观测表明，太阳风含有高速太阳风和低速太阳风两种成份。**Parker**解和低速太阳风的观测速度基本一致，但高速太阳风需要其它的加速机制。



如何测量快慢太阳风的速度？

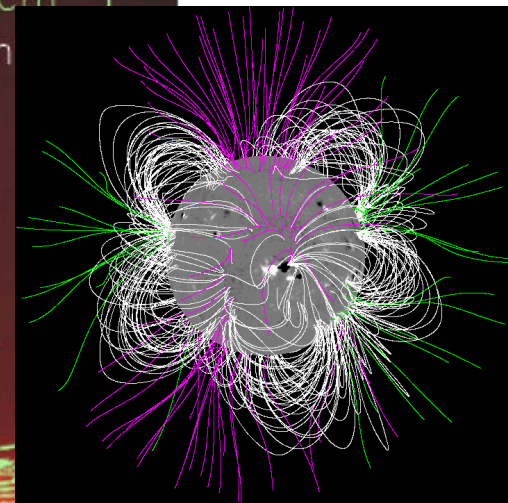
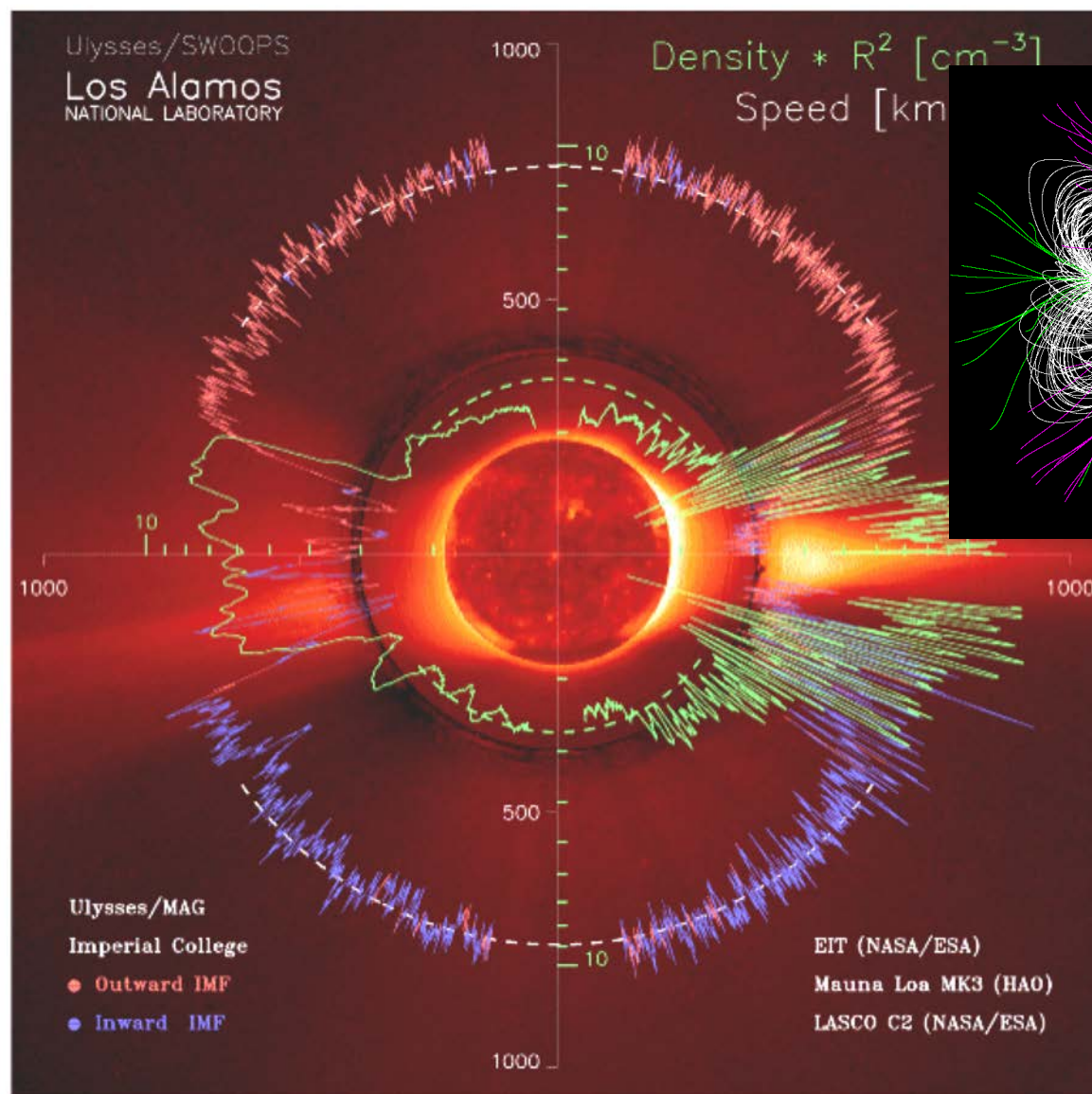
高速太阳风和低速太阳风的速度和密度

B 向外

黄道面

B 向内

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



$n R^2$

观测表明太阳风的主体是高速太阳风

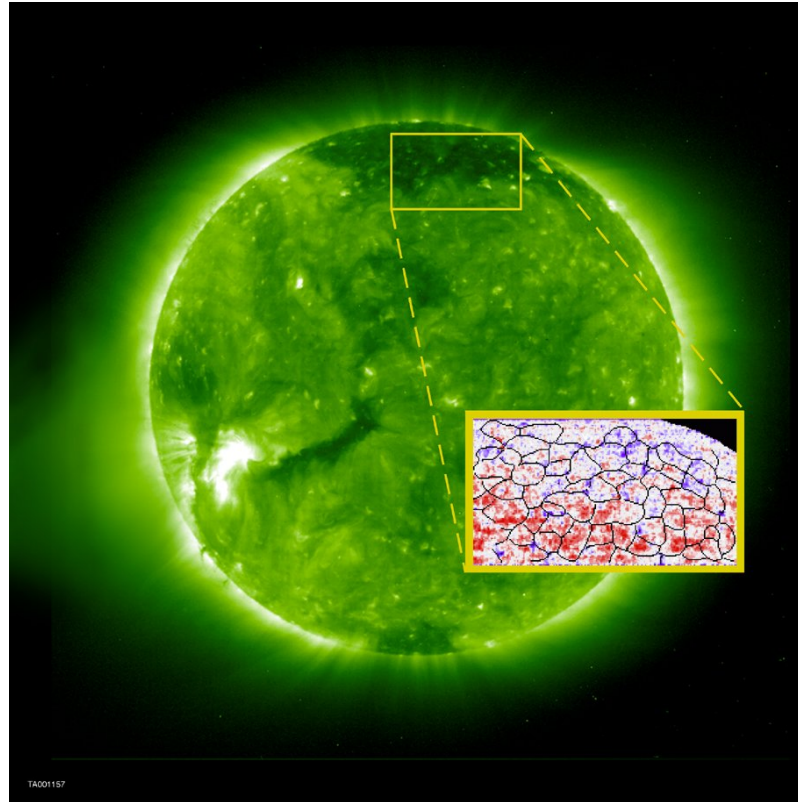
高速太阳风的基本参数

- **1 R_S 的能通量:** $F_E = 5 \cdot 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$
- **10 R_S 以外的速度:** $V_p = (700 - 800) \text{ km s}^{-1}$
- **1 AU 处的质子通量:** $n_p V_p = 2 \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1}$
- **1 AU 处的密度:** $n_p = 3 \text{ cm}^{-3}$; $n_\alpha / n_p = 0.04$
- **1 AU 的温度:**
 $T_p = 3 \cdot 10^5 \text{ K}$; $T_\alpha = 10^6 \text{ K}$; $T_e = 1.5 \cdot 10^5 \text{ K}$
太阳风对太阳质量的影响?
- **重离子:** $T_i \cong m_i / m_p T_p$; $V_i - V_p \leq V_A$

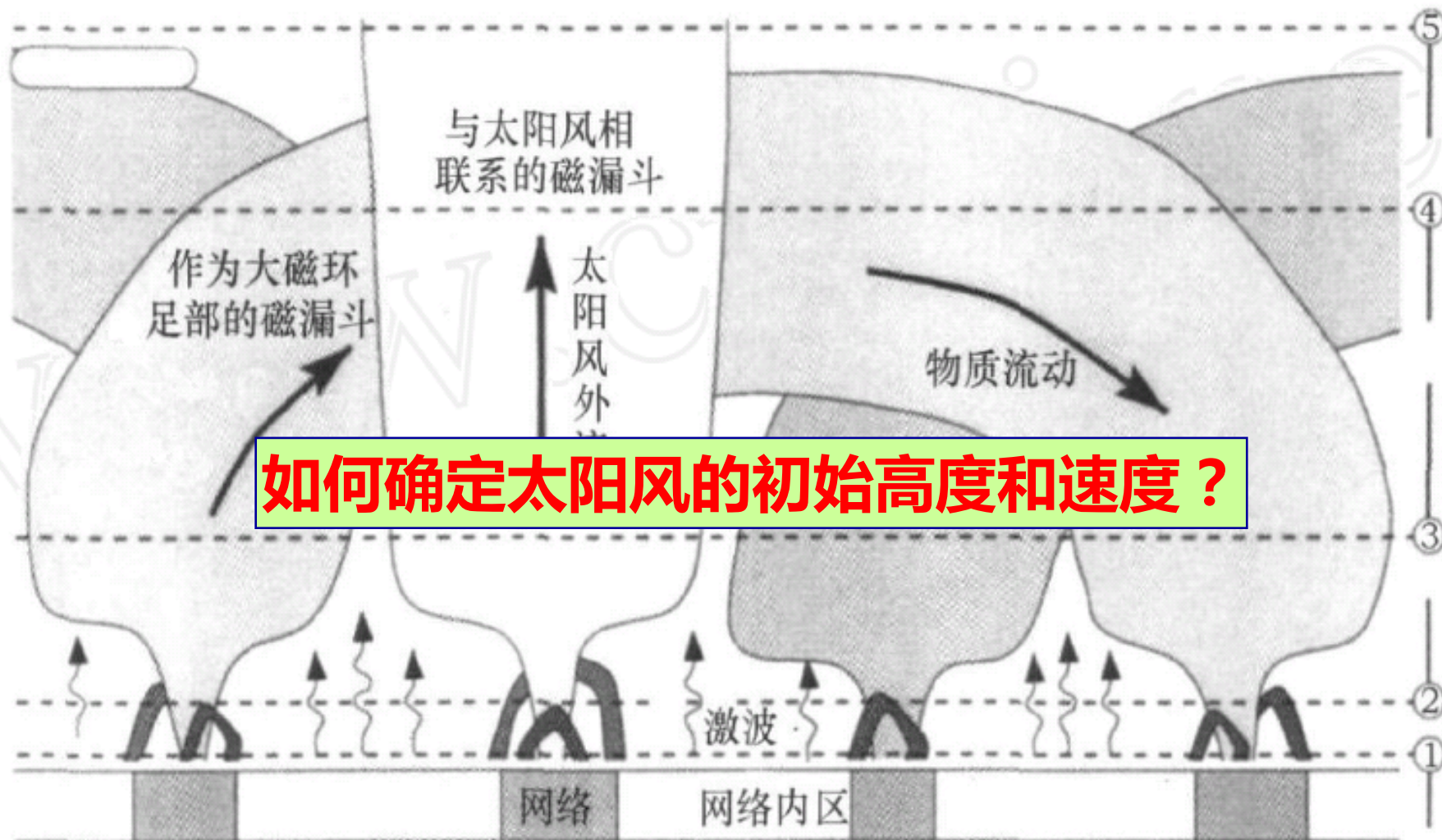
如何加速?

高速太阳风的起源和加速机制是太阳物理的重大基础问题之一!

冕洞：高速太阳风的来源



The SOHO instruments have shown, that the fast solar wind from coronal holes emerges from the network boundaries, in particular from their intersections

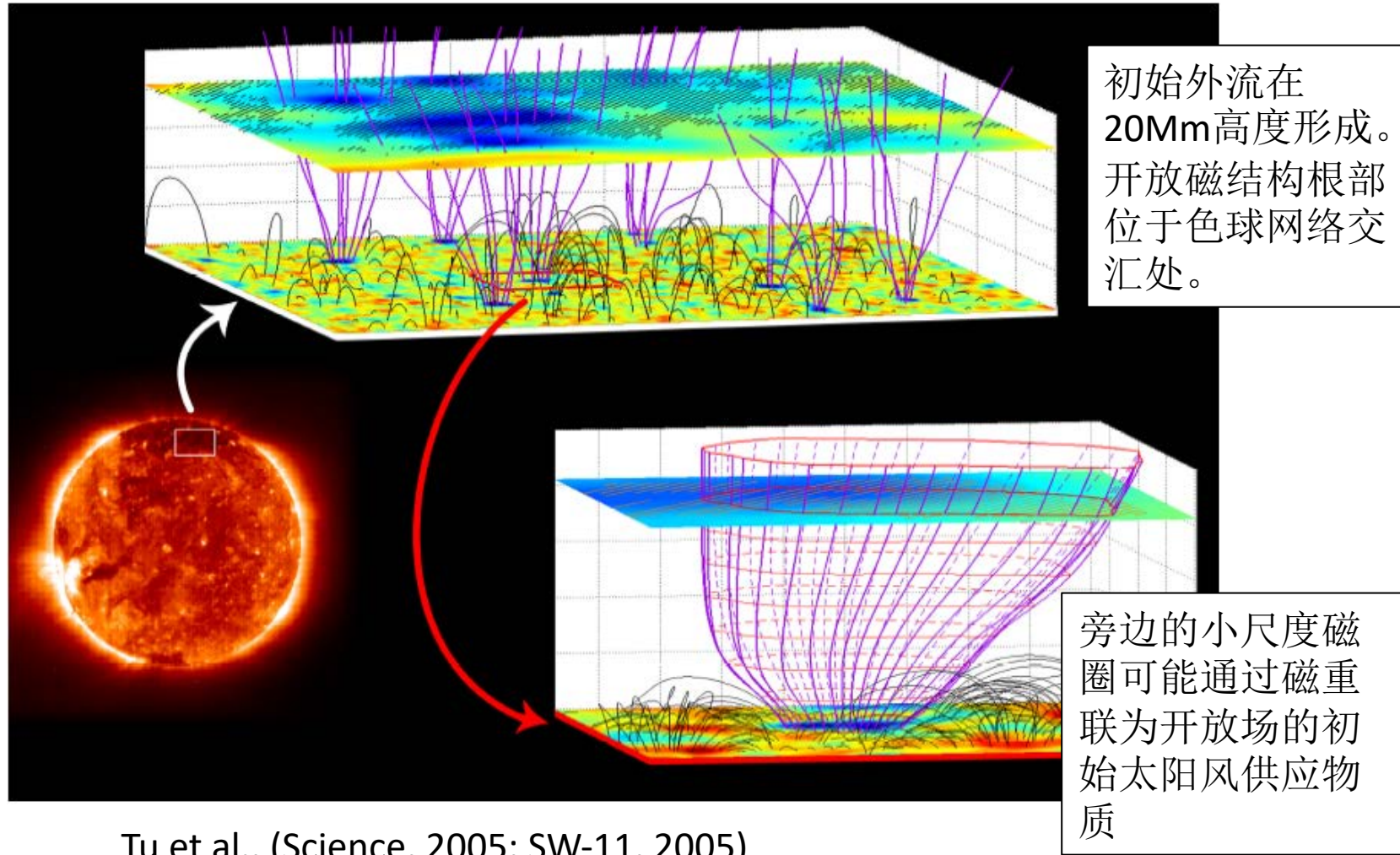


如何确定太阳风的初始高度和速度？

图 3 过渡区结构 [29]

高速太阳风起源于冕洞中网络边界的漏斗状开放磁通量管。

Origin of Solar Wind from the Coronal Funnel



彗尾的指向分析：

1950 Biermann pointed out that the anti-solar pointing of gaseous Comet tails is a consequence of the outward pressure of solar corpuscular radiation (SCR).

离子尾：彗星的物质被电离，在太阳风的作用下完全指向朝向太阳相反的方向

尘埃尾：是相对较大的颗粒在太阳光压的作用下形成的。



COMET TAILS:

(强风中的一缕炊烟或飘带)

always in anti-solar direction

No Matter when and where:

low or high solar activity

low or high heliocentric latitude

**→(1) SCR is an ordinary
everyday phenomenon**

**(2) Interplanetary space is filled
with SCR all the time.**

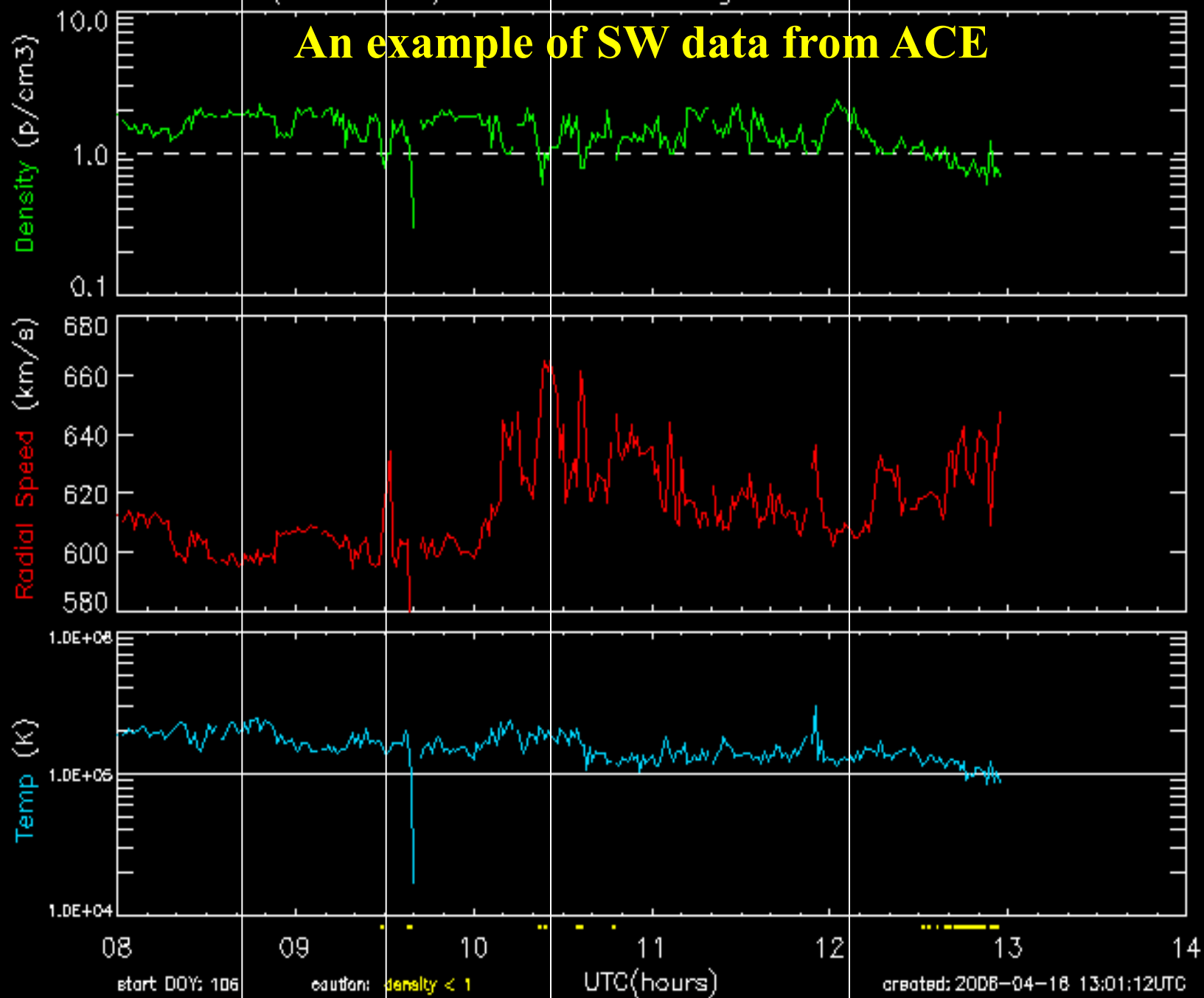
Confirmation of the supersonic solar wind

1. First detection of high speed ions ($>100\text{km/s}$) from the direction of sun: Luna 2, Luna 3, Venus 3 (Gringauz, 1960)
2. Found intermittent wind of about 300 km/s , 5 ions/cm^3 : Pioneer 10 (Rossi, Bonetti, et al., 1961)
3. About six months of uninterrupted data showed the solar wind with velocities ranging from 320 km/s – 770 km/s : Mariner II (Snyder and Neugebauer, 1962)
4. Parker's spiral interplanetary magnetic field detected by the Magnetometer carried on IMP 1 (Ness et al., 1964)

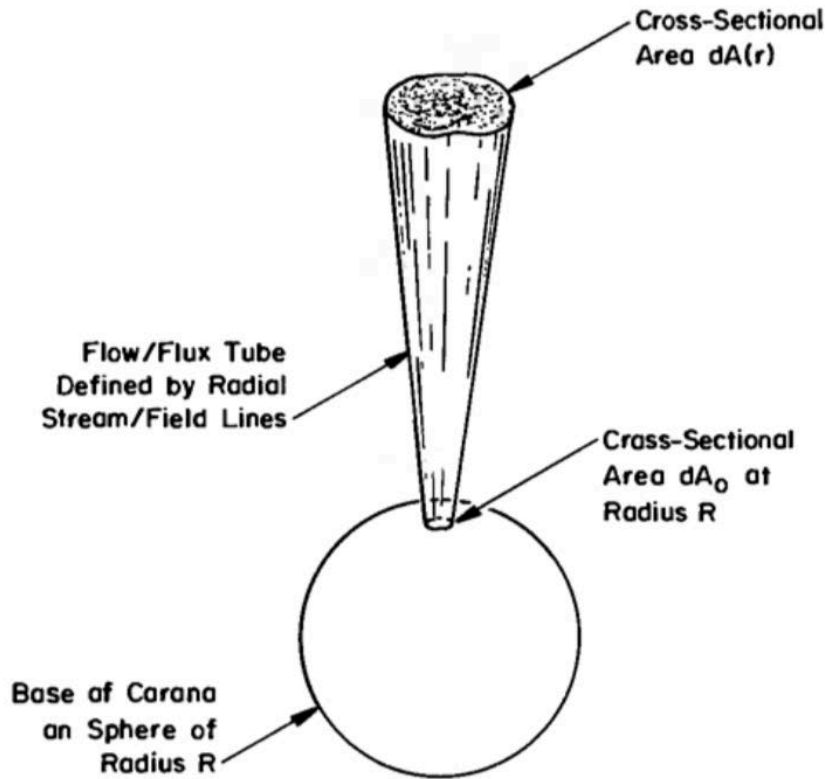
ACE RTSW (Estimated) SWEPM

Begin: 2006-04-16 08:00:00UTC

An example of SW data from ACE



太阳风的磁场结构

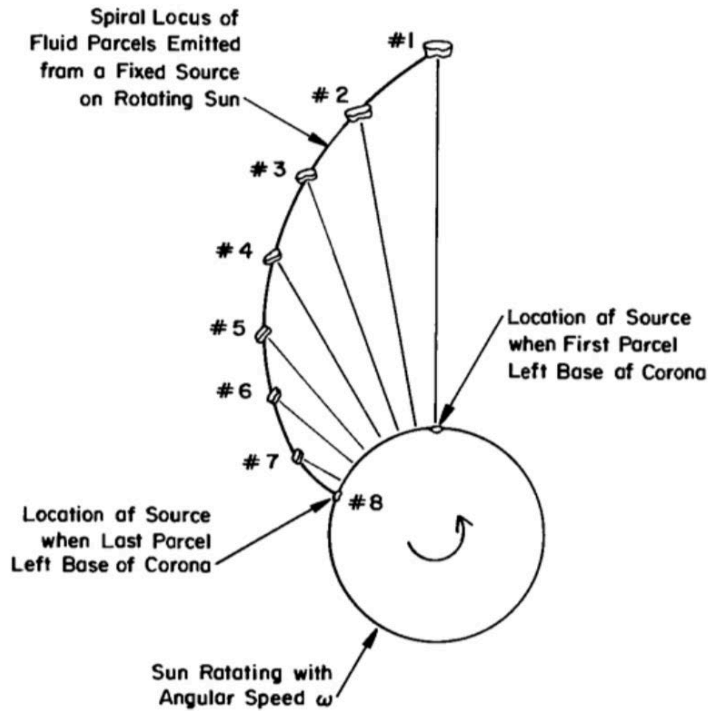


通量守恒

$$B(r)\left(\frac{r}{R}\right)^2 dA_0 = B(R) dA_0$$

$$\text{即, } B(r) = \left(\frac{R}{r}\right)^2 B(R)$$

太阳风的磁场结构



在旋转坐标系下，只有径向速度：

$$U_r = u(r)$$

太阳的角向速度：

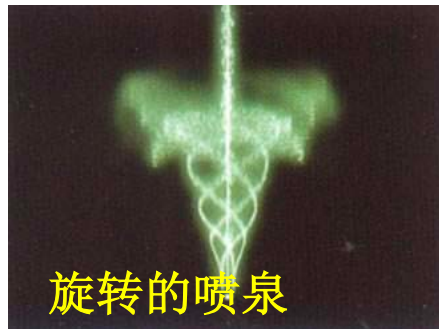
$$U_\varphi = -\omega r$$

由于磁冻结

$$\frac{B_\varphi}{B_r} = \frac{U_\varphi}{U_r} = -\frac{\omega r}{u(r)}$$

即，赤道附近的微分方程

$$\frac{r d\varphi}{dr} = -\frac{\omega r}{u(r)}$$



太阳风的磁场结构

赤道附近的微分方程

$$\frac{rd\varphi}{dr} = -\frac{\omega r}{u(r)}$$

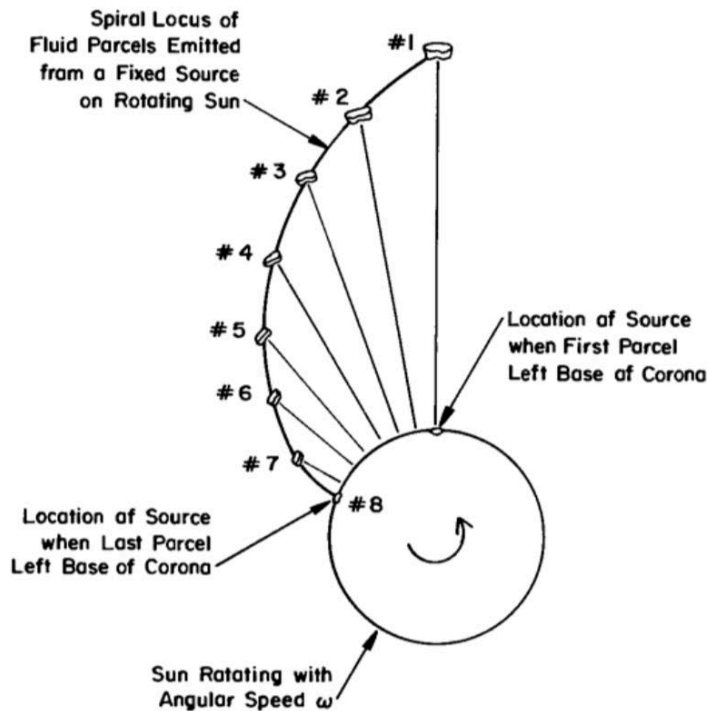
如果径向速度不变

$$\frac{dr}{d\varphi} = -\frac{u}{\omega}$$

解得

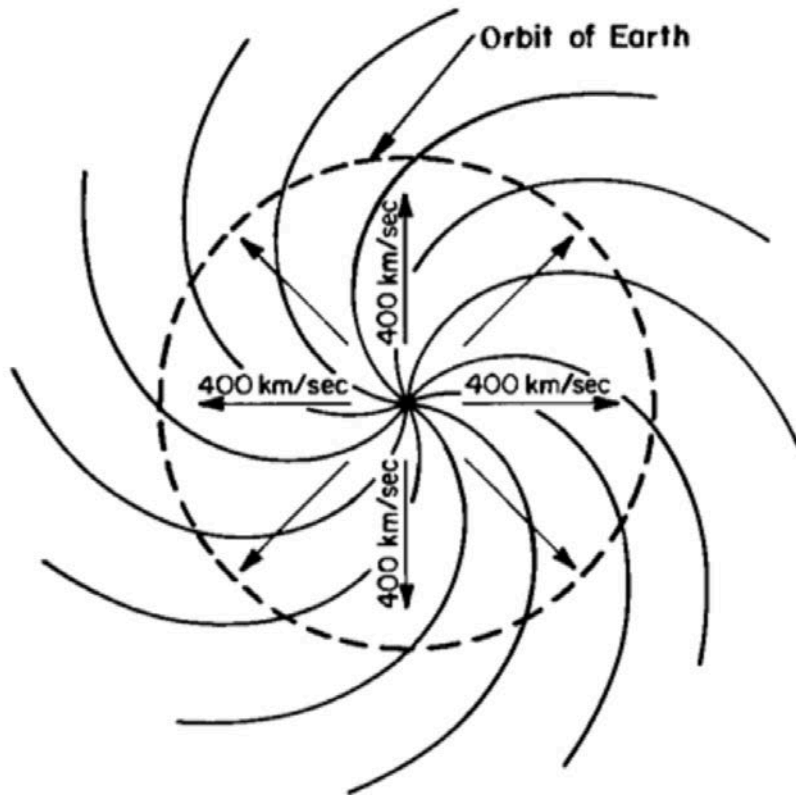
$$r = -\frac{u}{\omega}\varphi + c$$

或
$$r - R = -\frac{u}{\omega}(\varphi - \varphi_0)$$



写出磁场表达式?

太阳风的磁场结构



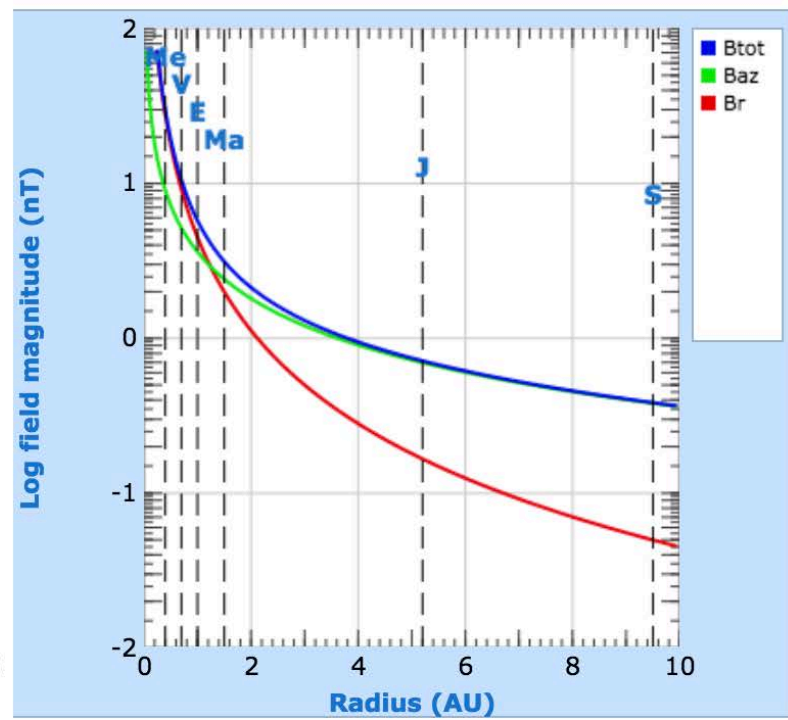
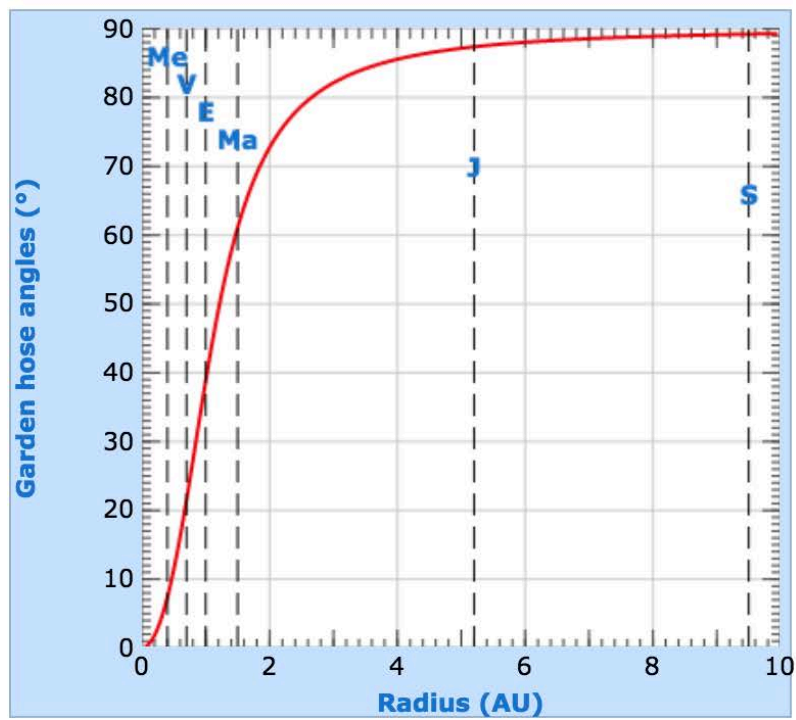
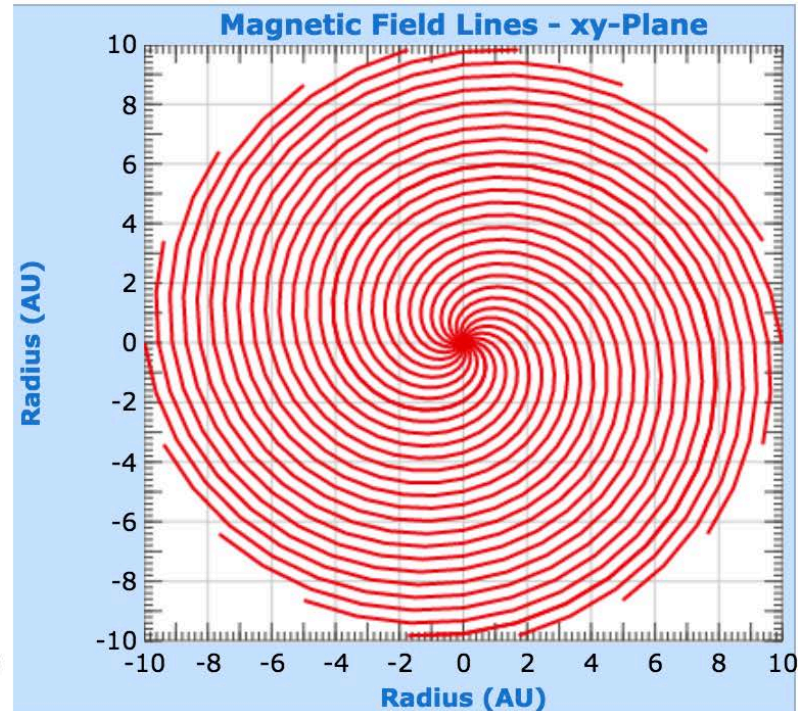
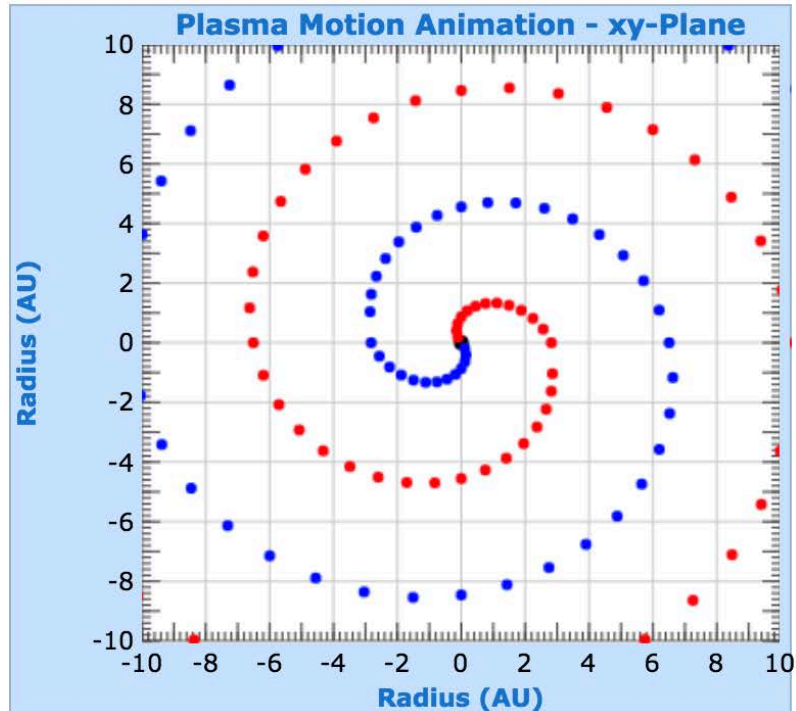
$$B(r) = \left(\frac{R}{r}\right)^2 B(R)$$

$$B_{\phi}(r) = -\frac{\omega r}{u} B(r) = -B(R) \frac{\omega R^2}{ur}$$

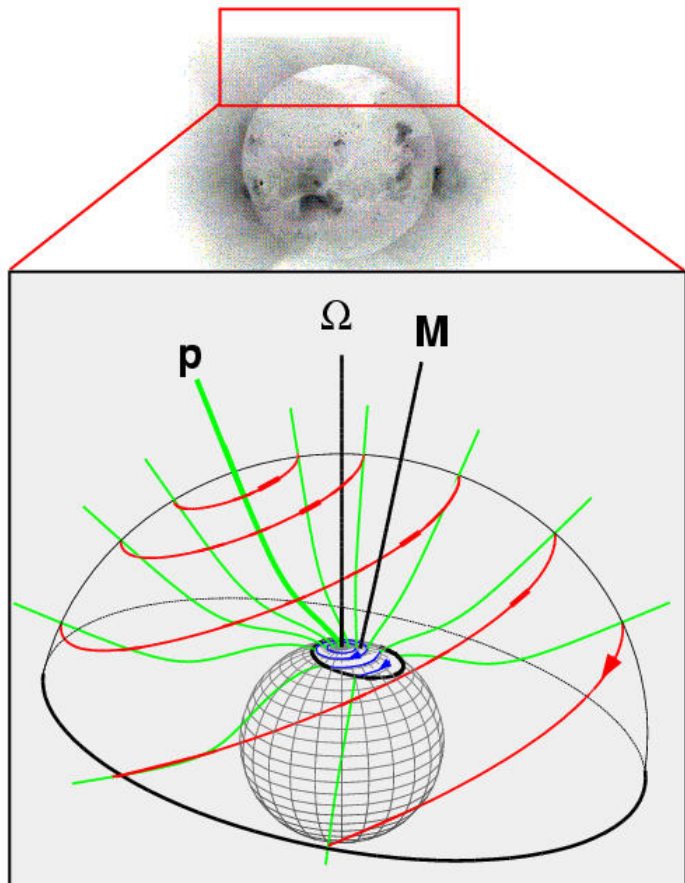
太阳自转周期25.4天

$$\omega = \frac{2\pi}{25.4 \text{ 天}} = 2.7 \times 10^{-6} \frac{\text{rad}}{\text{s}}$$

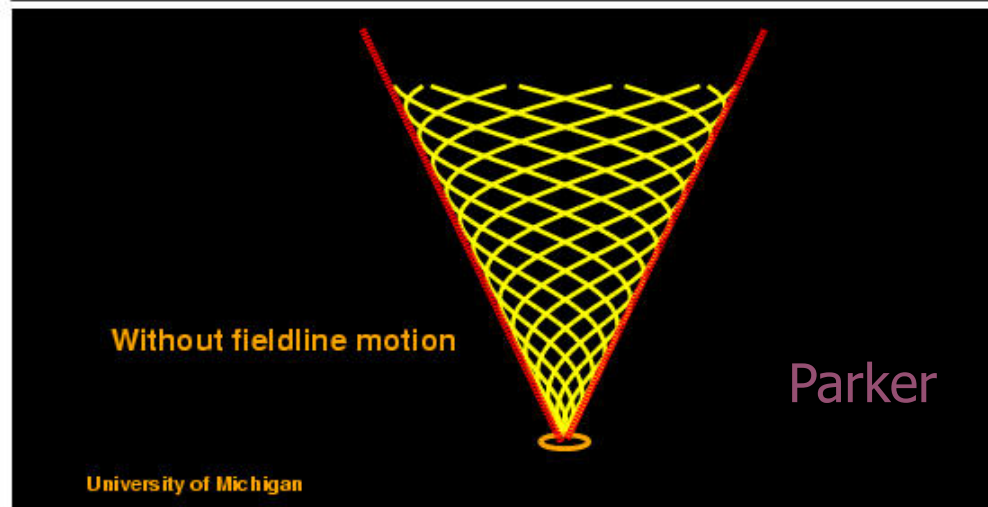
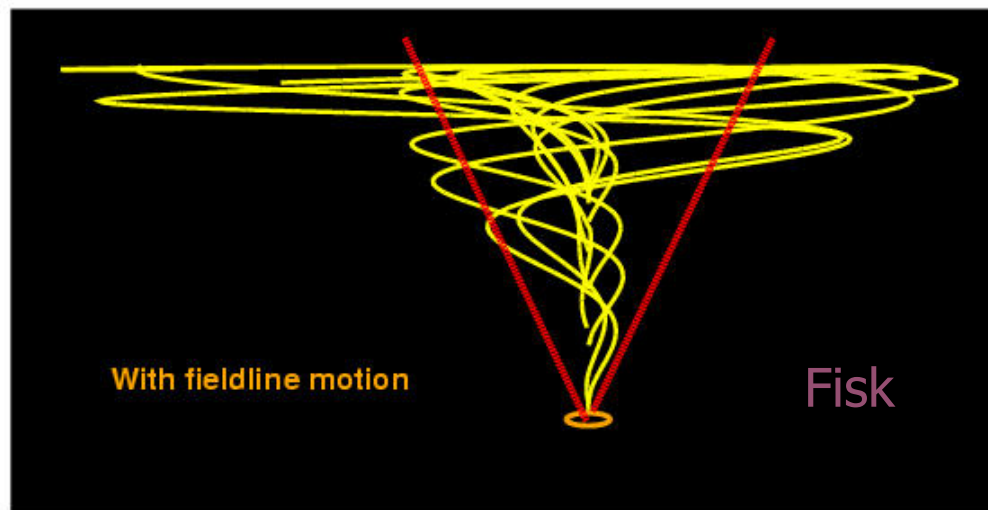
求地球附近磁场与日地连线的角度？



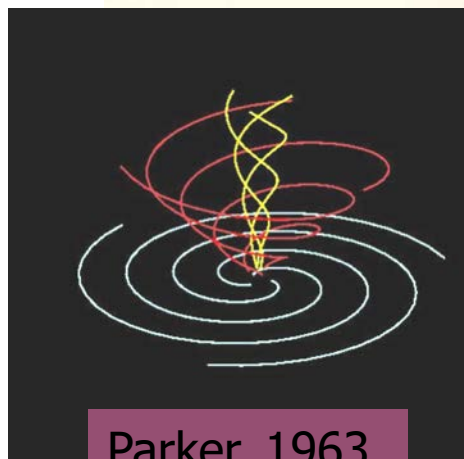
日冕-日球层磁场模型



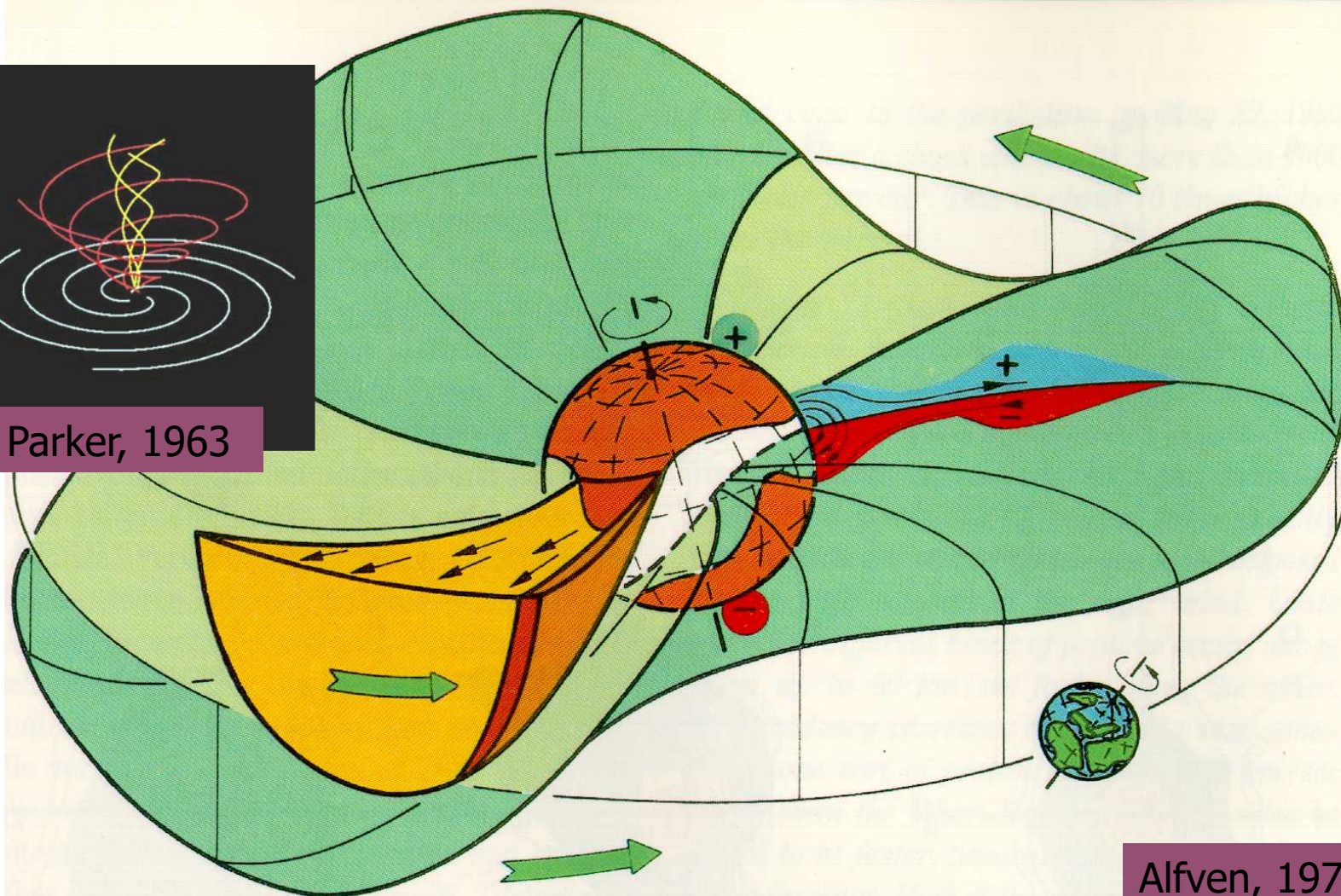
Fisk, JGR, 1996



太阳风流和电流片结构

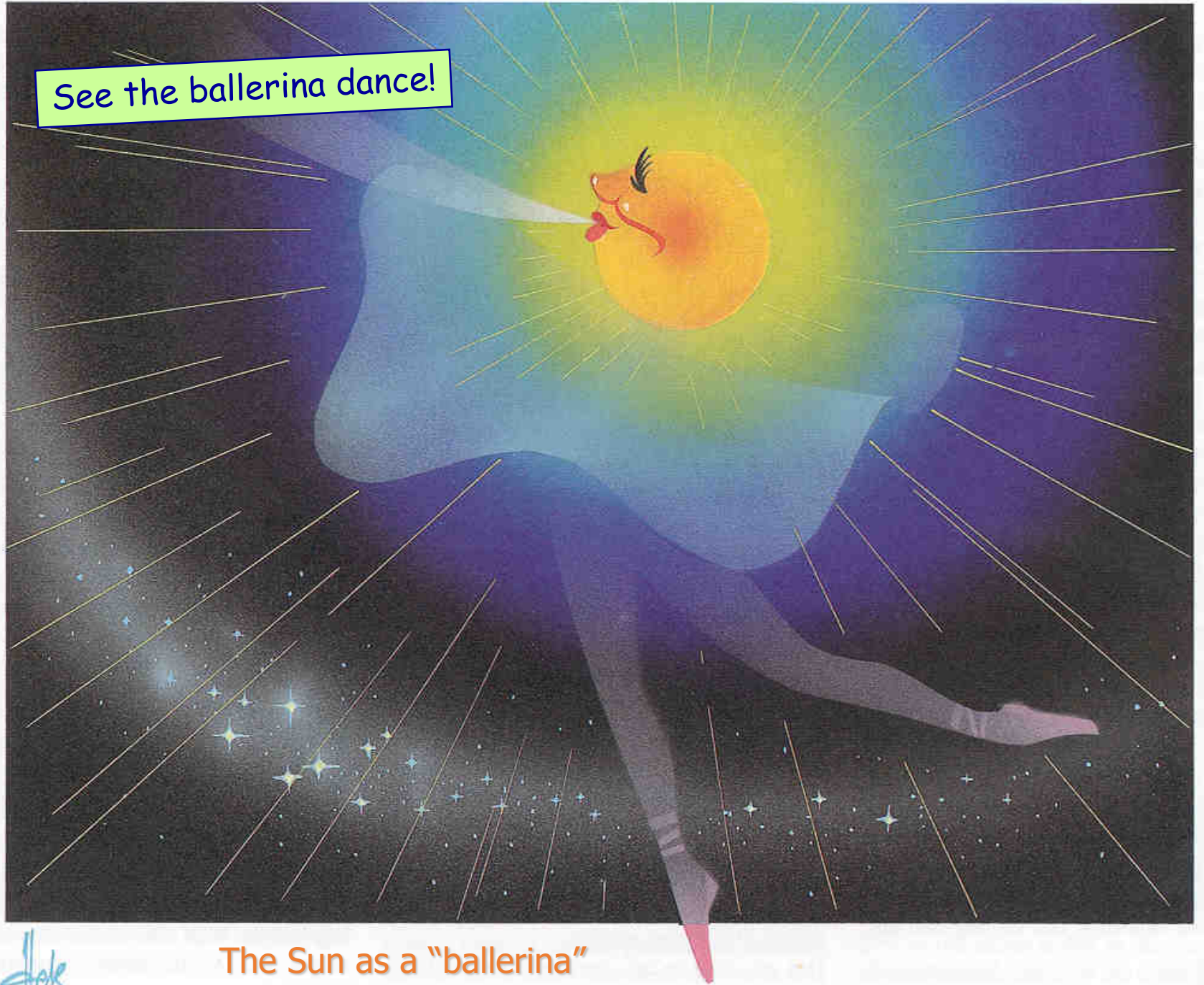


Parker, 1963



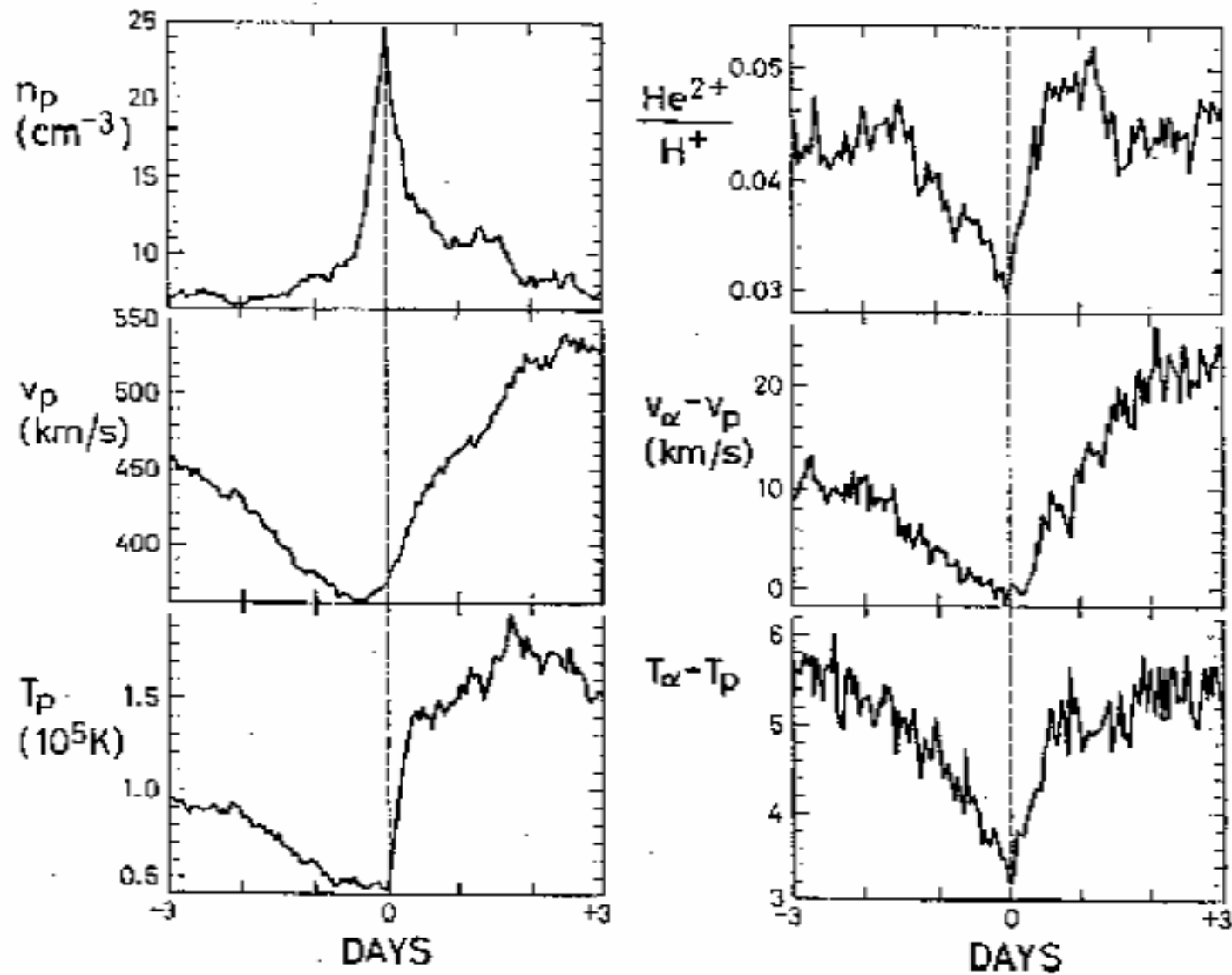
Alfven, 1977

See the ballerina dance!

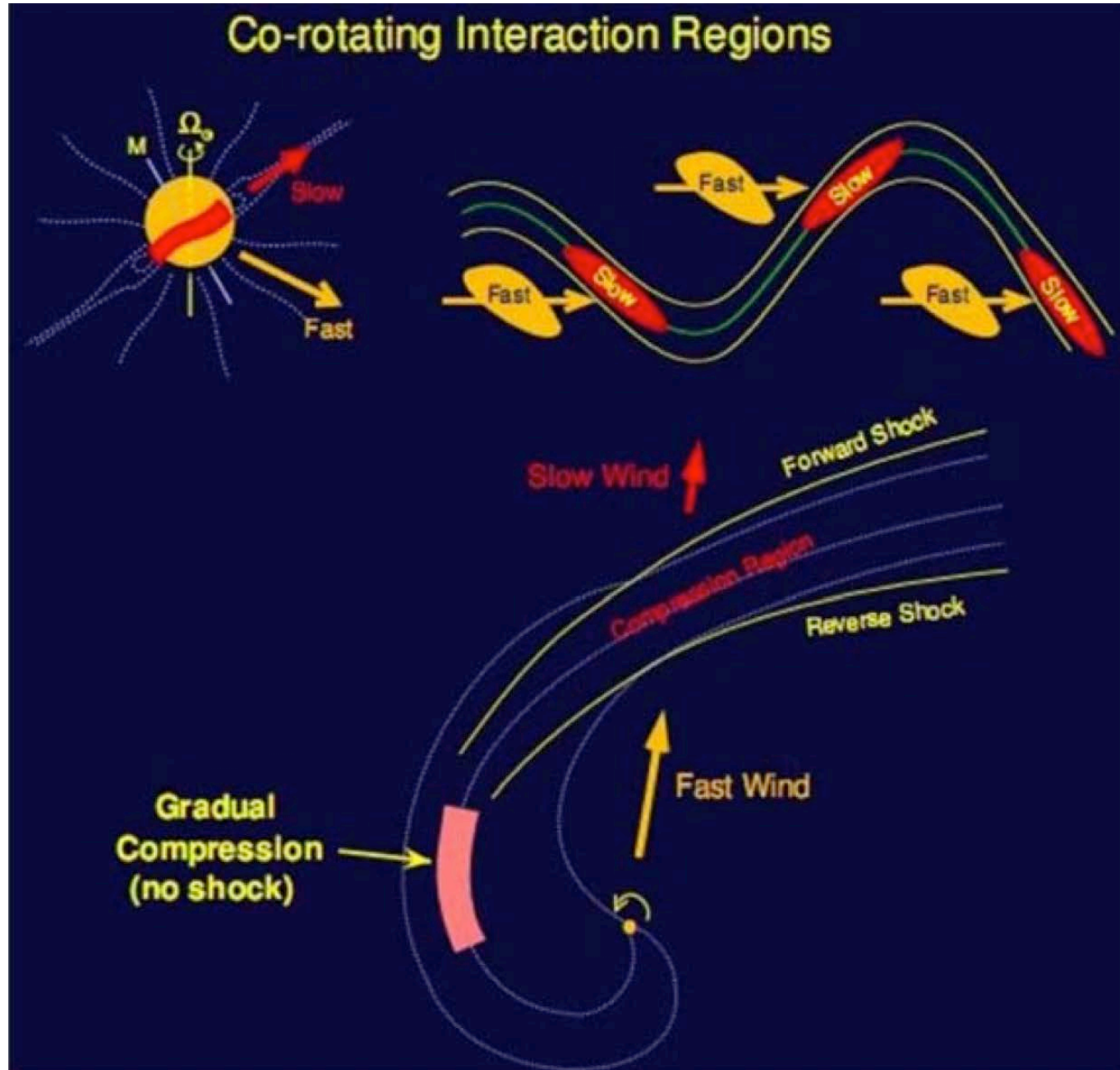


The Sun as a "ballerina"

日球层电流片内外的低高速流的状态差异



俯视和侧视激波对的几何位形



太阳风与行星际介质的耦合

太阳风速度在 $r \gg r_c = \frac{GMm}{4kT}$ 时为

$$u^2 \approx 8 \frac{kT}{m} \ln \frac{r}{r_c}$$

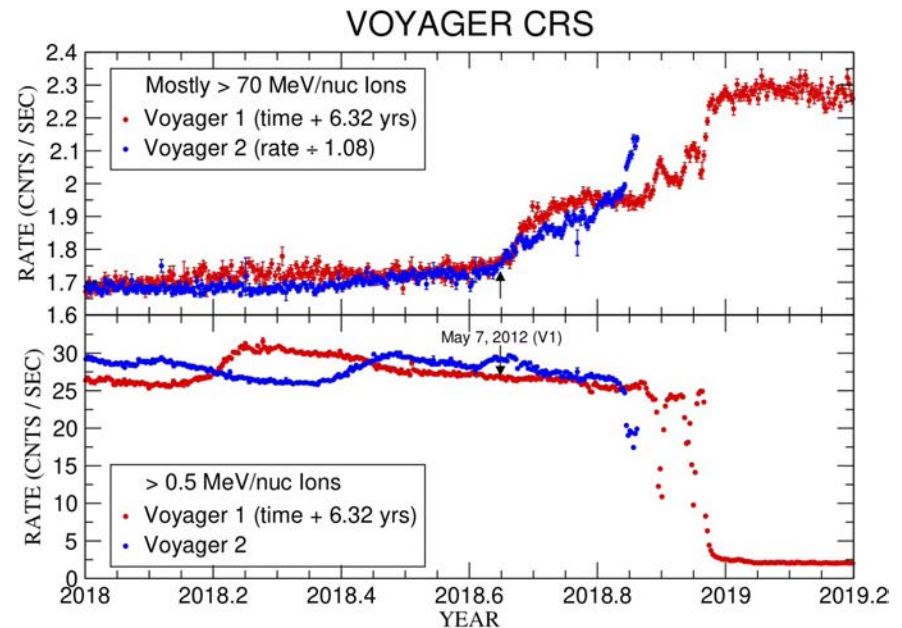
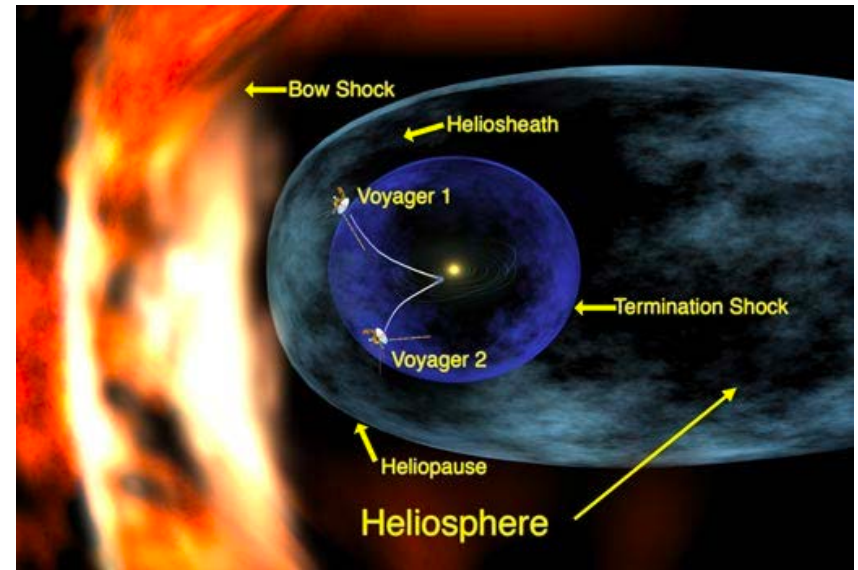
$$c_s^2 \approx \frac{2kT}{m}$$

$$\frac{u}{c_s} = 2 \left(\ln \frac{r}{r_c} \right)^{\frac{1}{2}}$$

另需考虑非常小的行星际压强

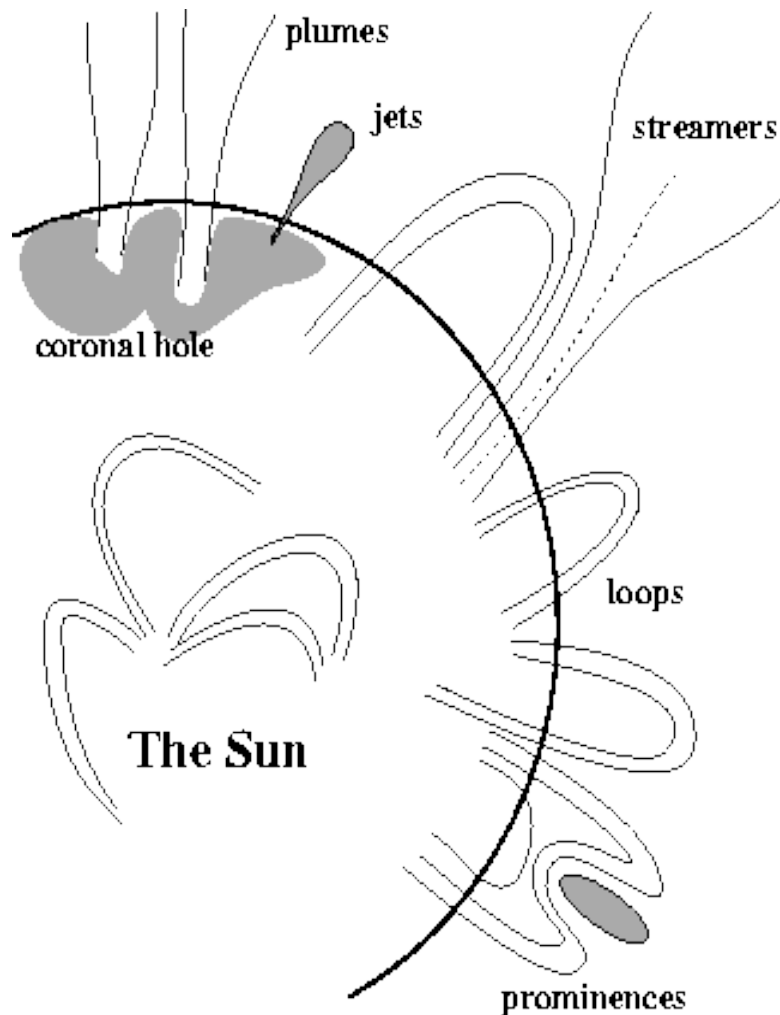
$$\sim 10^{-13} \text{ Pa}$$

如何耦合？？



- 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研究简介

Fundamental structures in the inner corona



Open & closed fields
Coronal Hole
(solar wind)
Plumes-interplumes
Jets
Streamers
Loops
Prominences
(filaments)

Image credit: Valery Nakariakov
<http://tbird5.astro.warwick.ac.uk/~valery/>

**extended corona
feature**

solar wind type

coronal holes

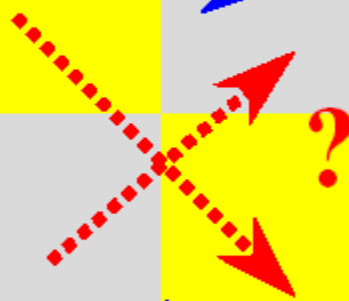


fast ($v > 500$ km/s)

streamers



slow ($v < 500$ km/s)



低速流：冕流、冕洞边缘、小冕洞、活动区边缘

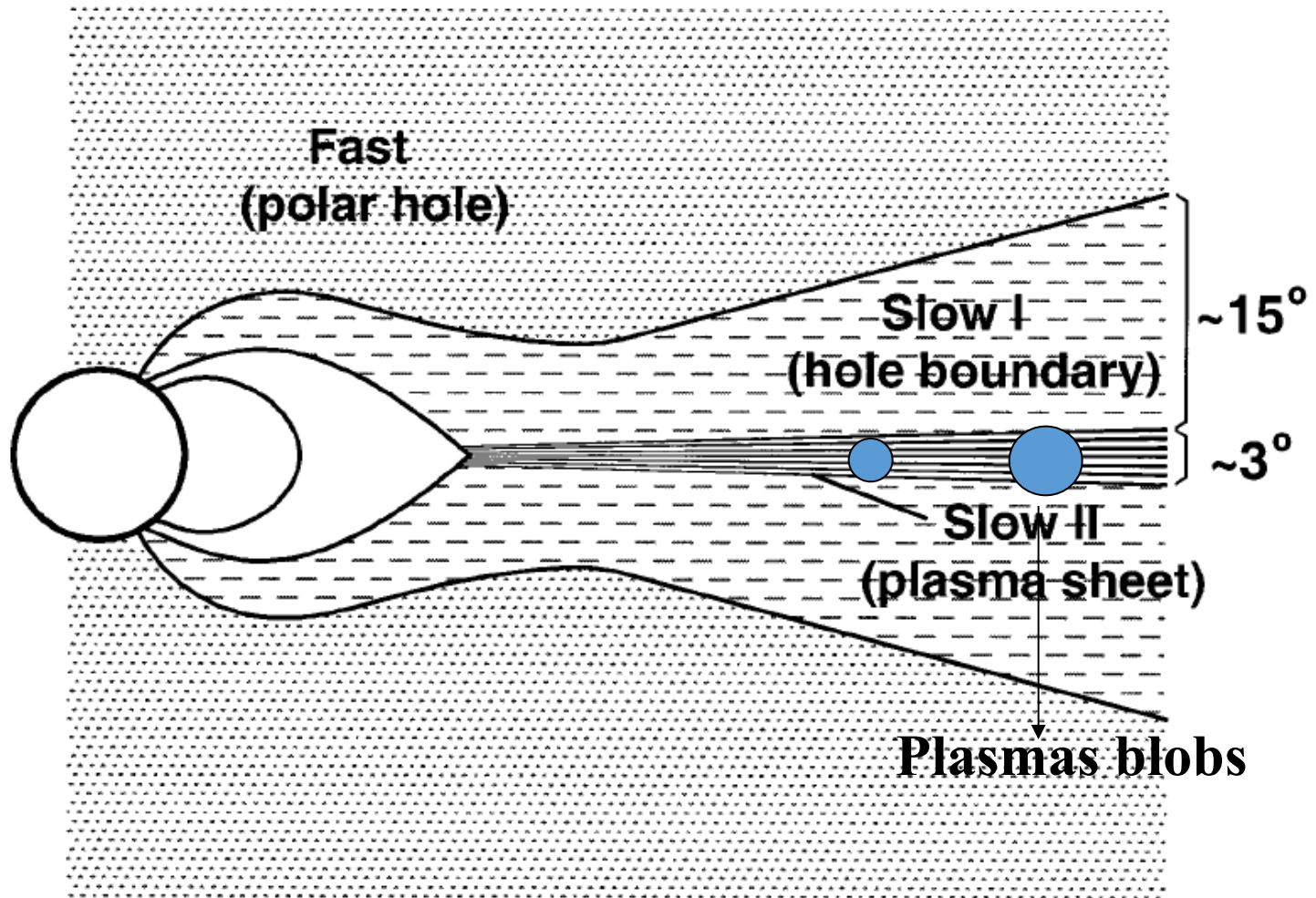
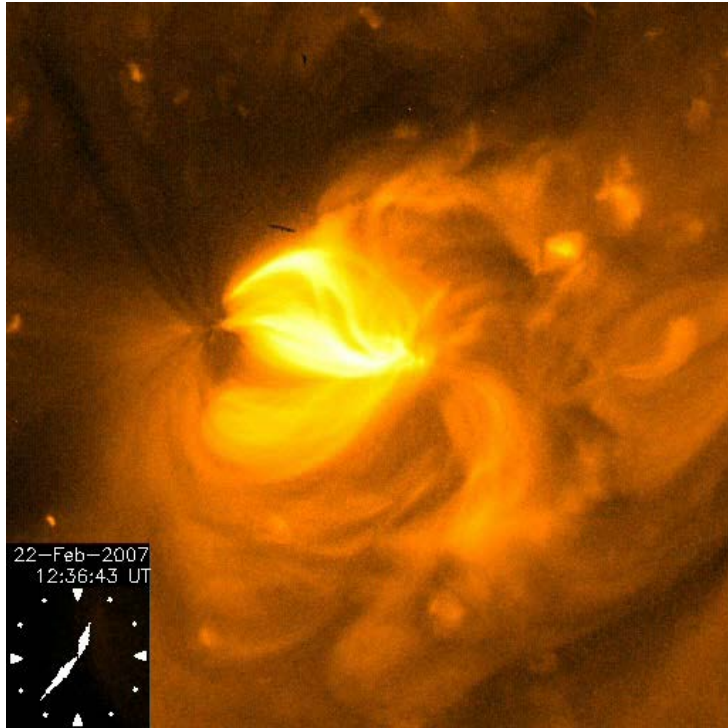
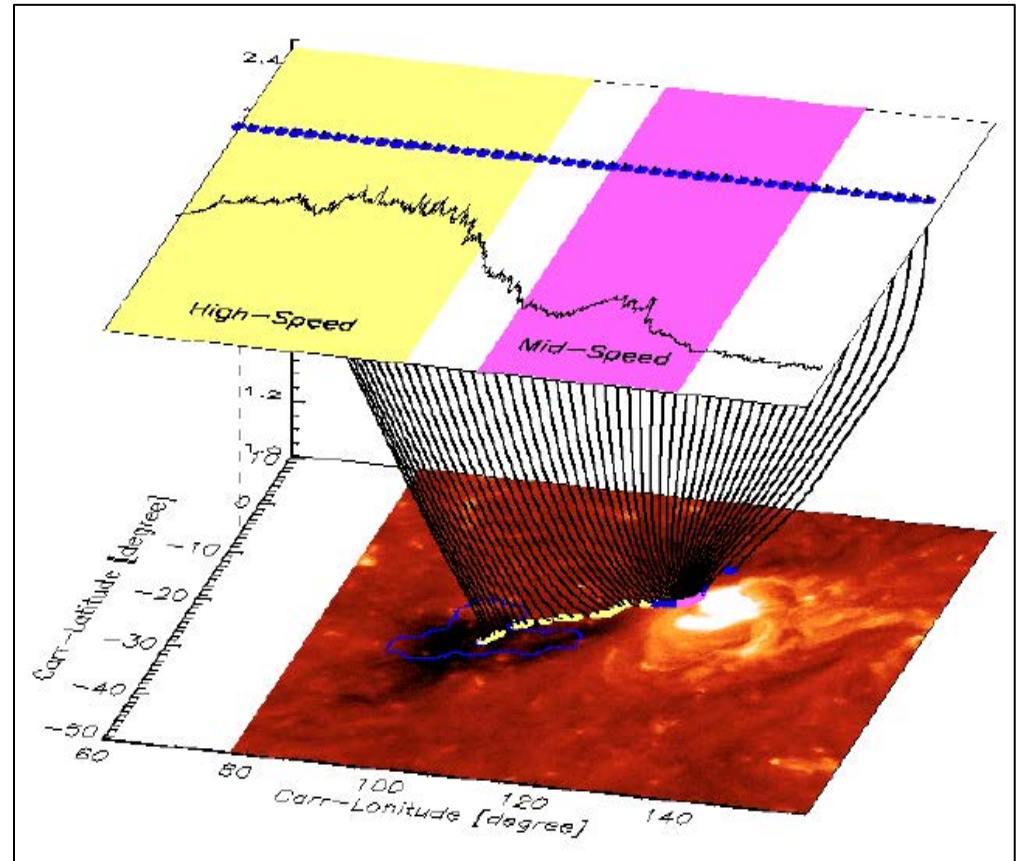


Figure 12. Schematic showing the three components of the solar wind at sunspot minimum. High-speed wind escapes along the slowly diverging, open field lines in the polar hole interiors. Component I of the slow wind flows out along the rapidly diverging, open field lines rooted just inside the polar hole boundaries, which are located near latitude 60° in each solar hemisphere. Component II of the slow wind, which originates from the closed field zone equatorward of the polar hole boundaries, is confined to the dense equatorial plasma sheet that extends beyond $r \sim 3 R_S$.

Intermittent Outflows near the Active Region

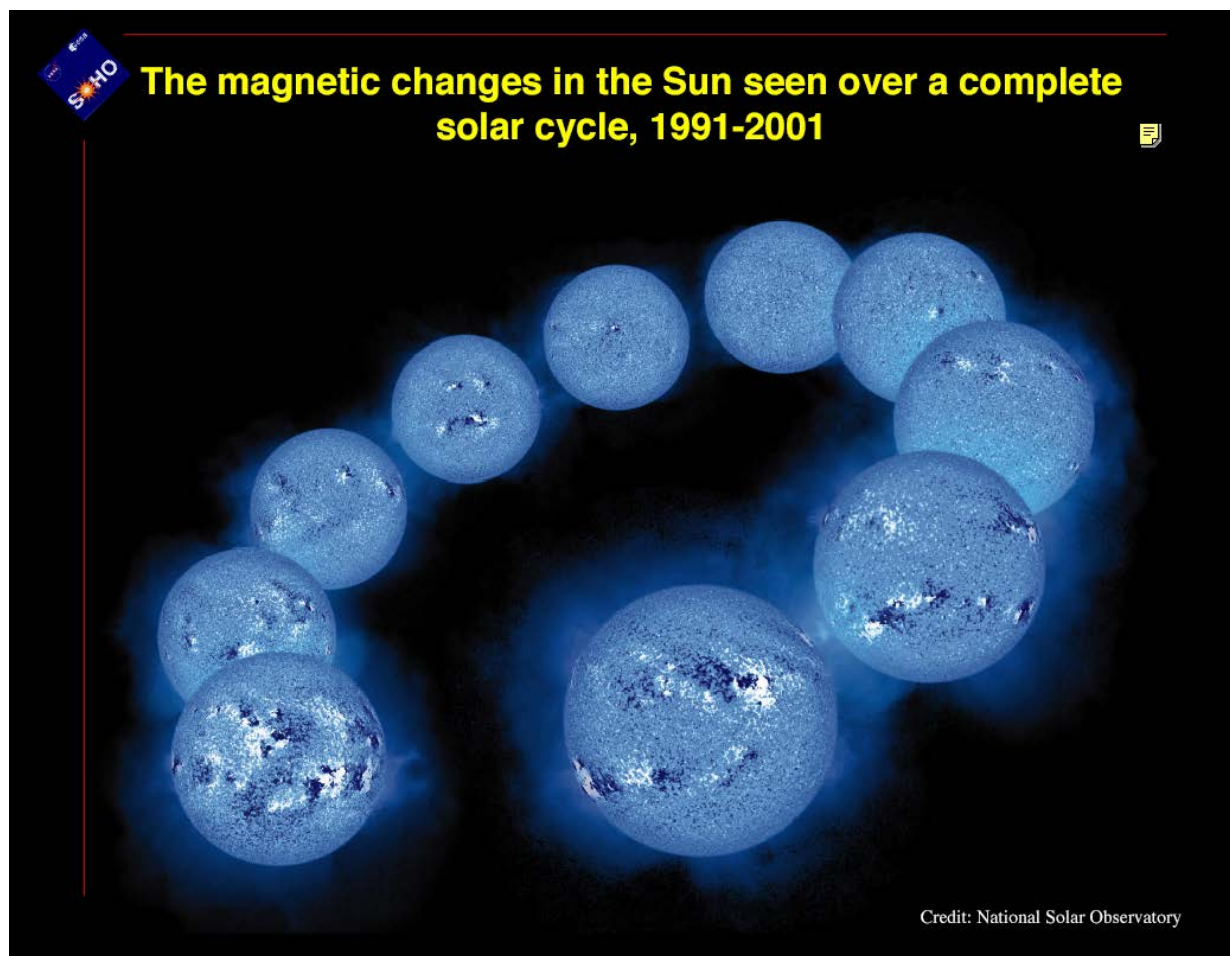


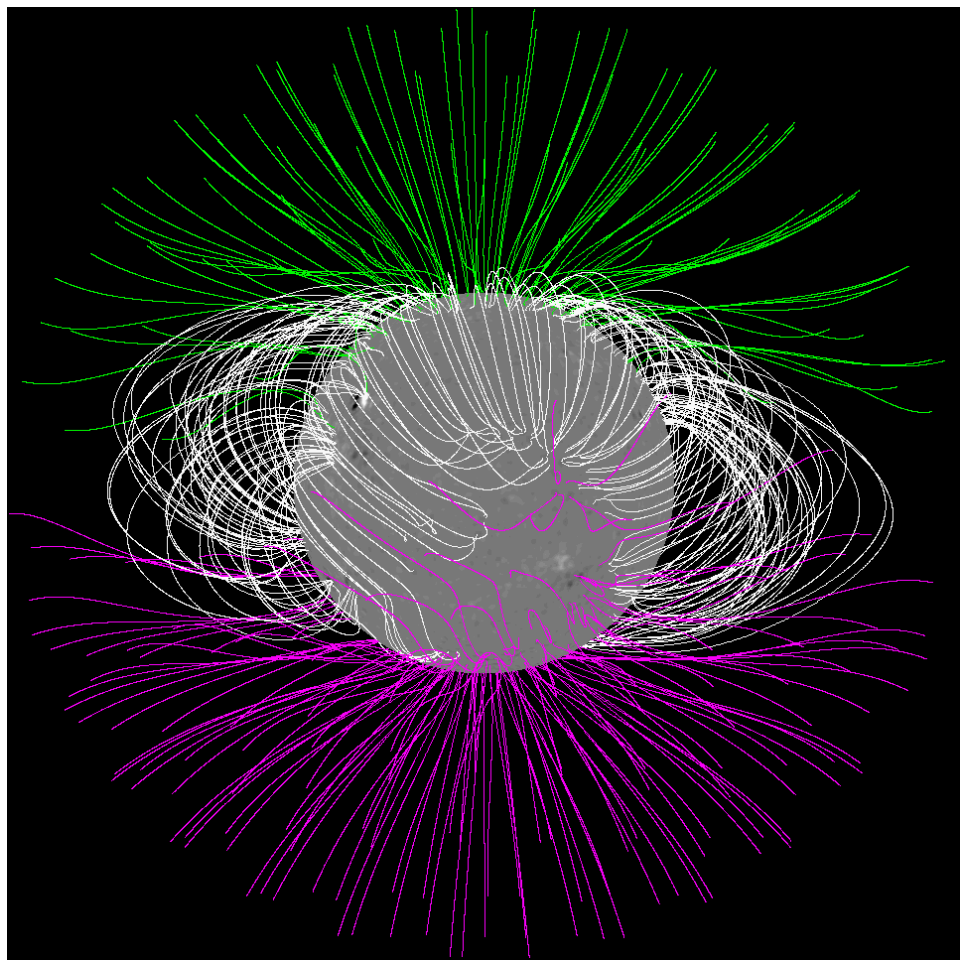
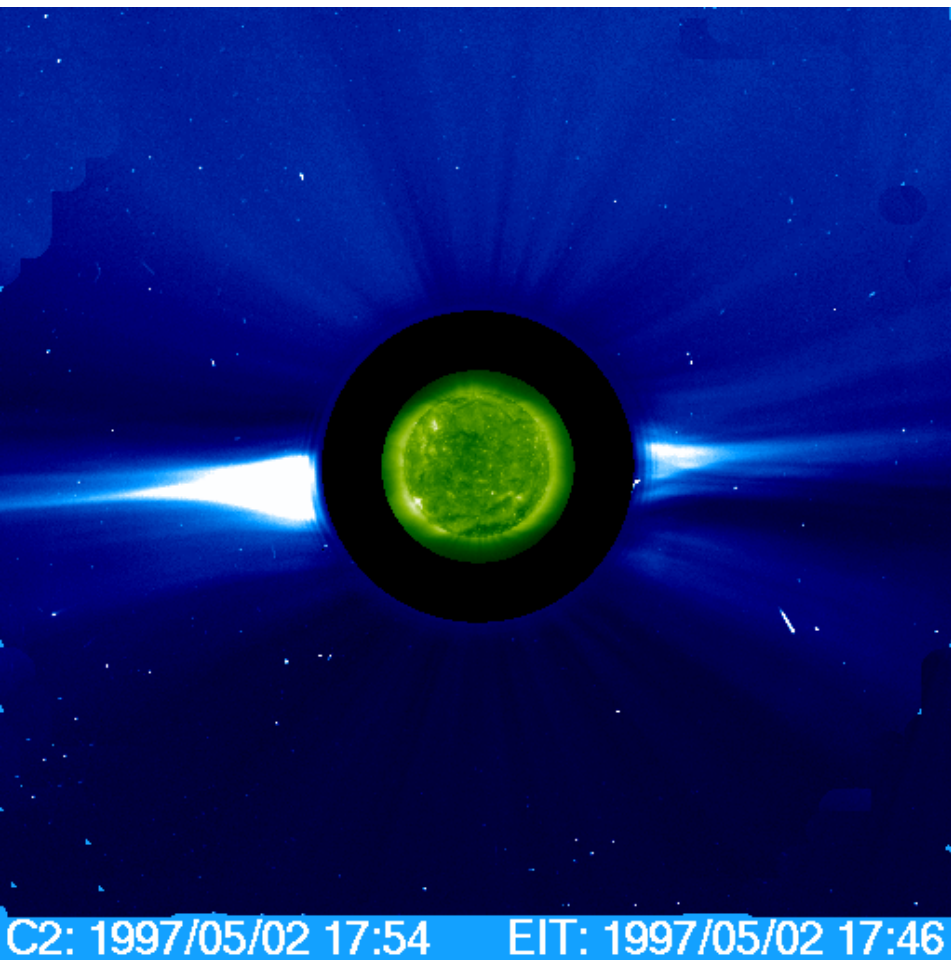
Propagation of Intensity Disturbances [Sakao et al., Science, 2007]

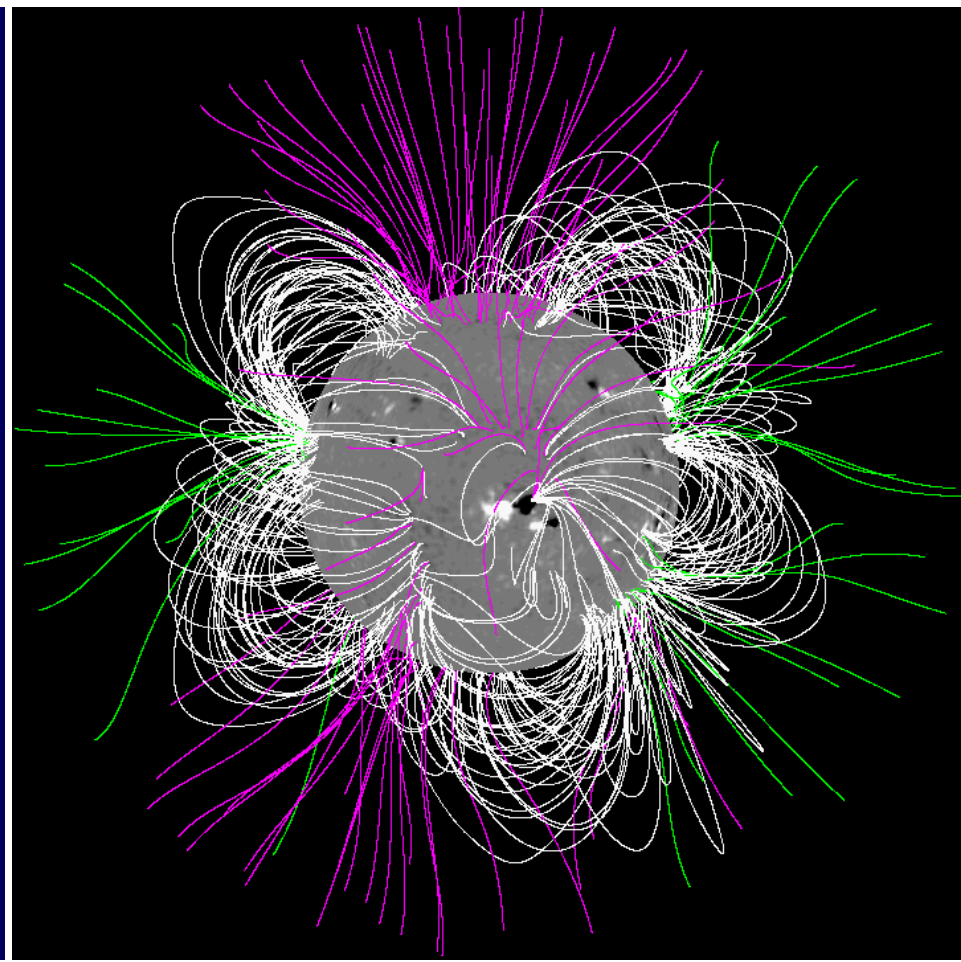
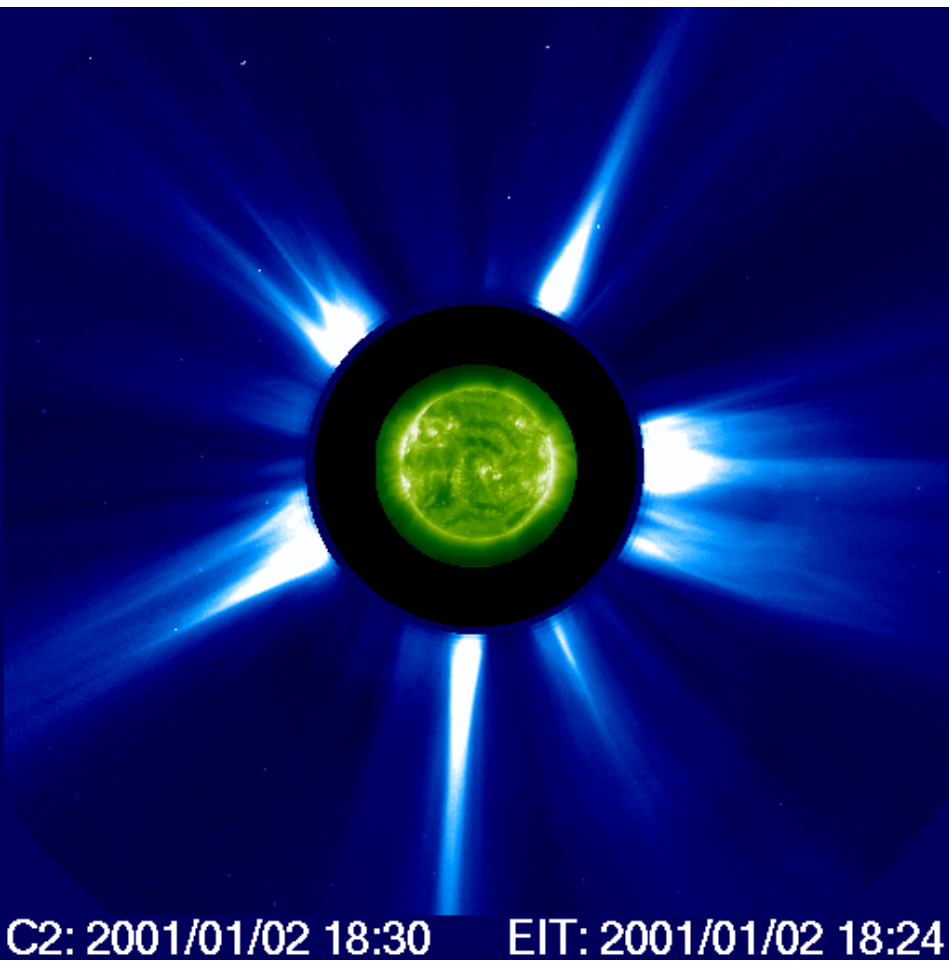


Outflow from AR-edge evolves into intermediate-speed solar wind (400km/s). High speed solar wind comes from equatorial coronal hole (600km/s) [He et al., A&A, 2010]

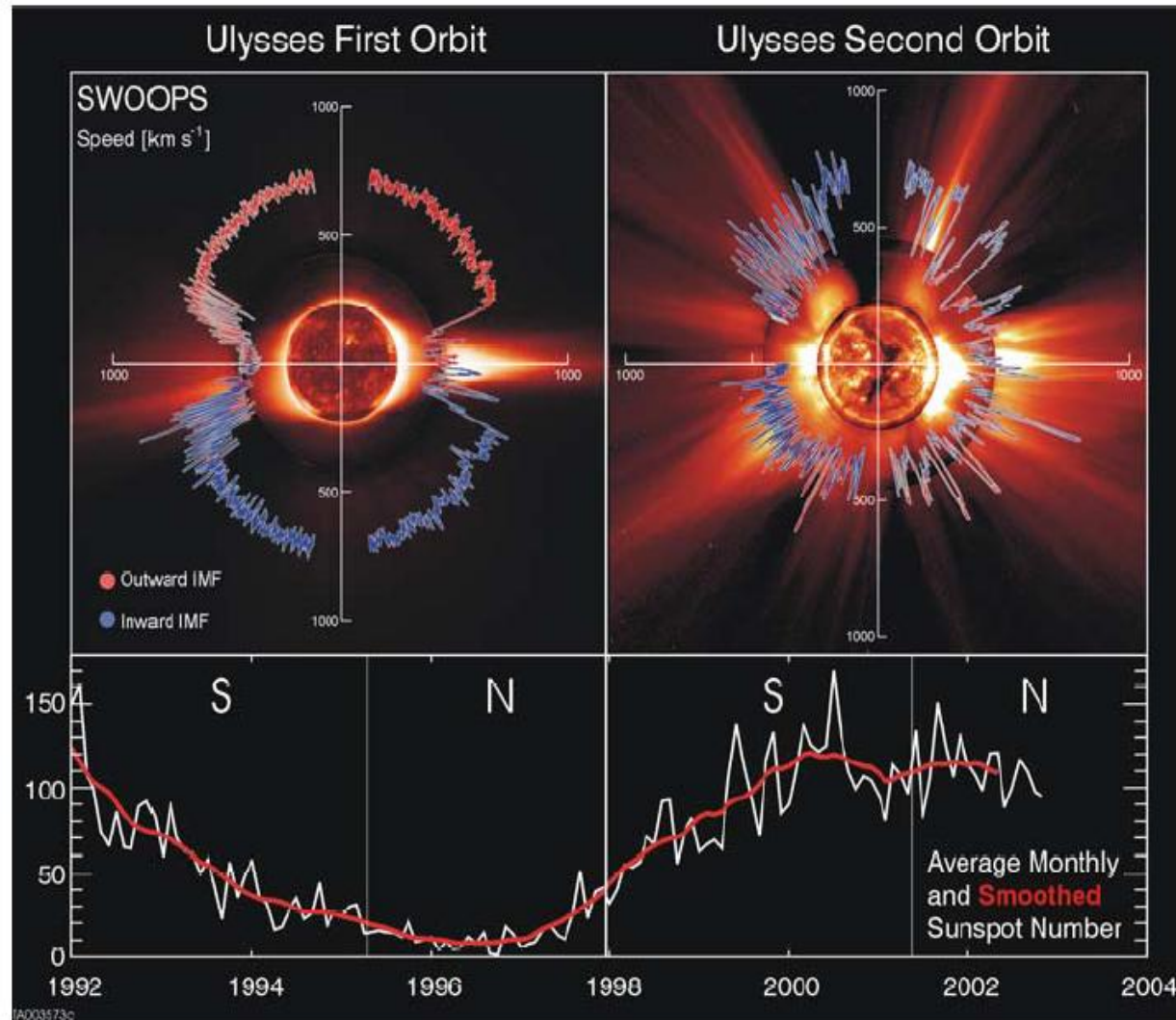
太阳风高速流和低速流的源区



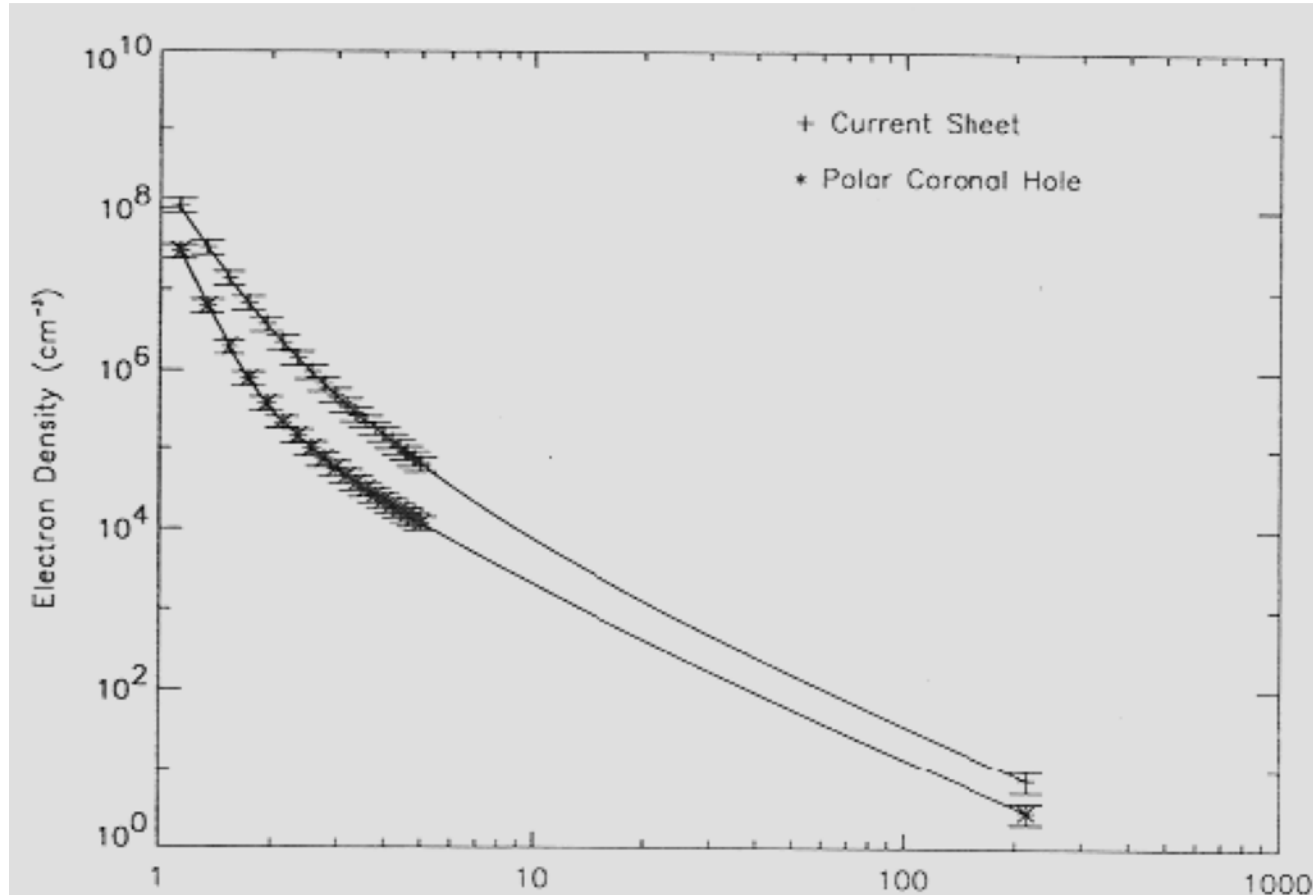




FROM SOLAR MINIMUM TO SOLAR MAX: Solar wind and large-scale coronal morphology



冕洞和冕流的密度和温度



+ **Current sheet and streamer belt, closed**

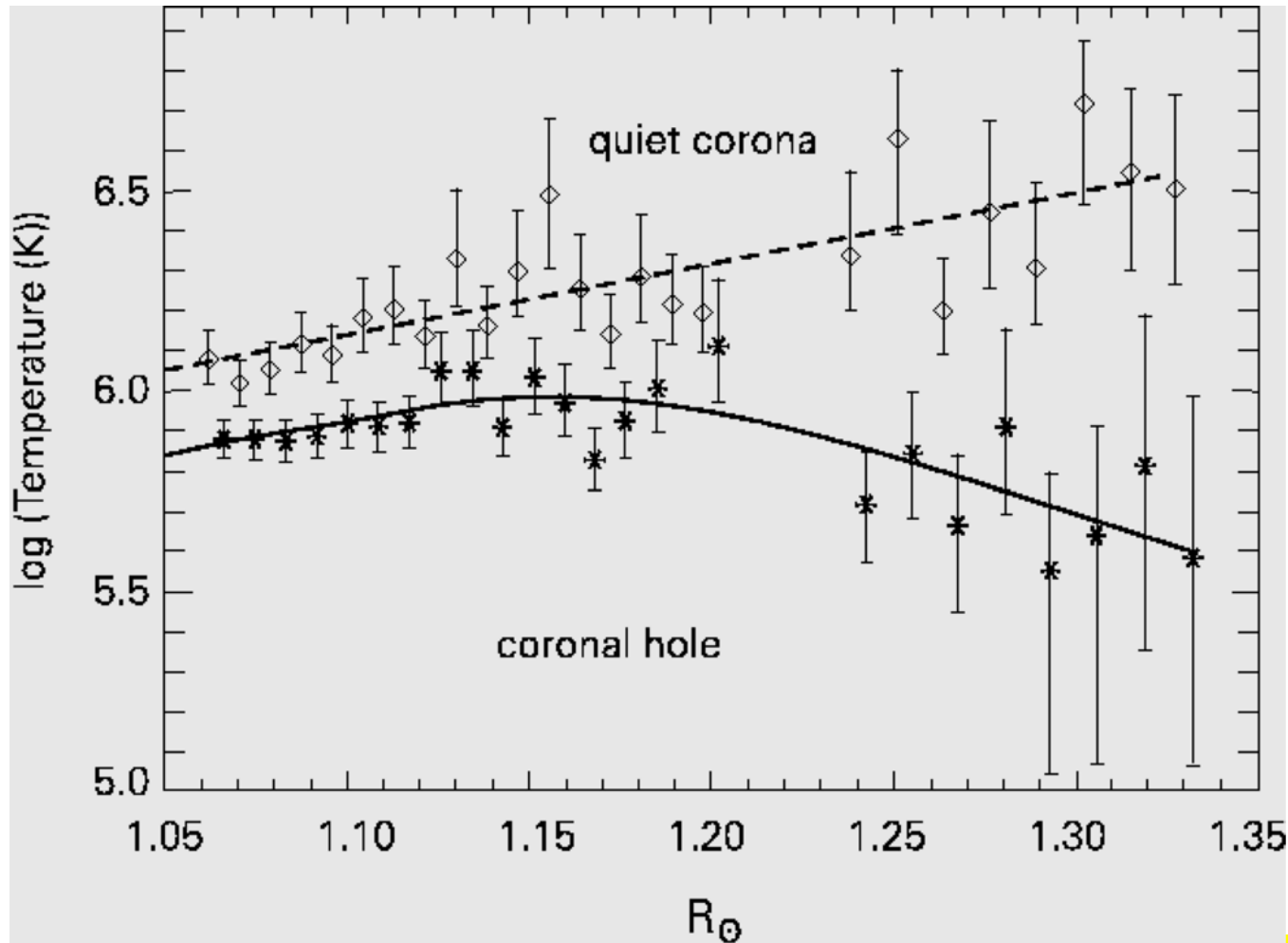
• **Polar coronal hole, open magnetically**

Heliocentric distance / R_s

Guhathakurta and Sittler,
1999, Ap.J., **523**, 812

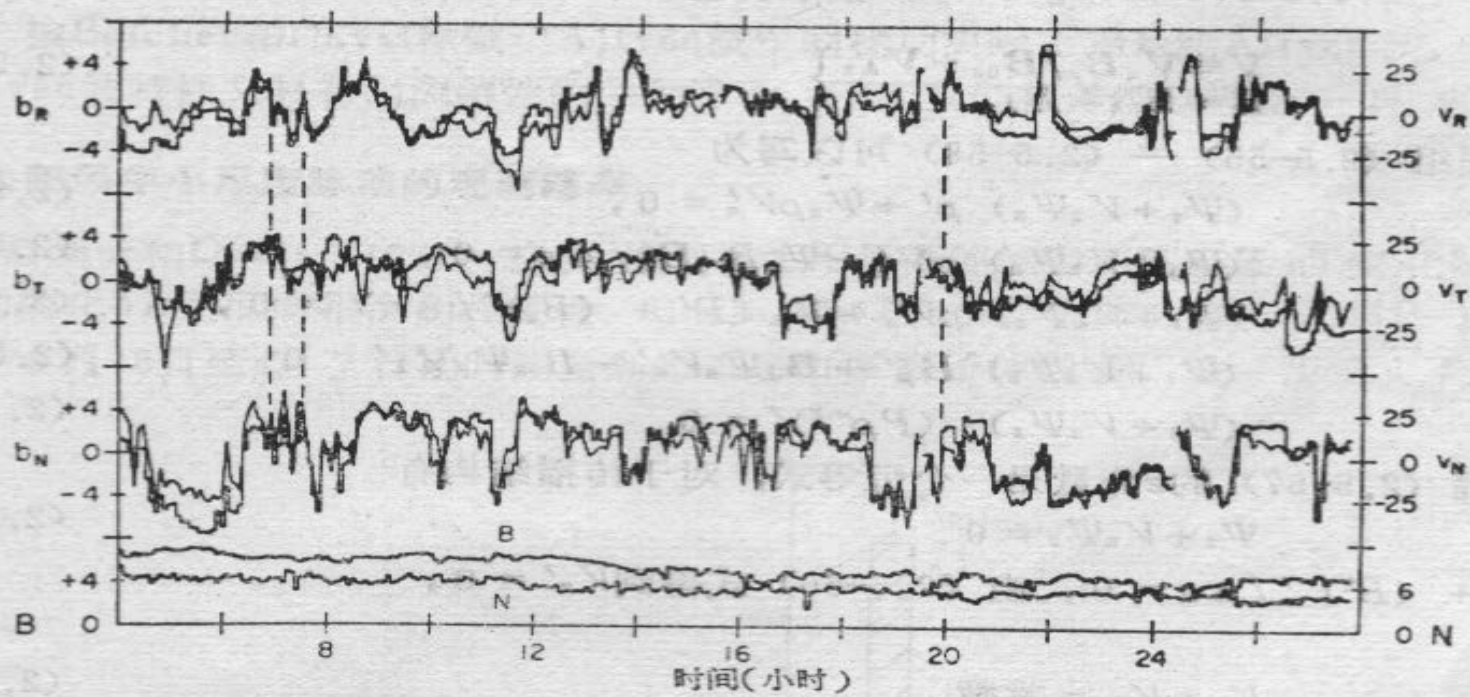
Skylab coronagraph/Ulysses in-situ

Electron temperature in the corona



**Streamer
belt, closed**

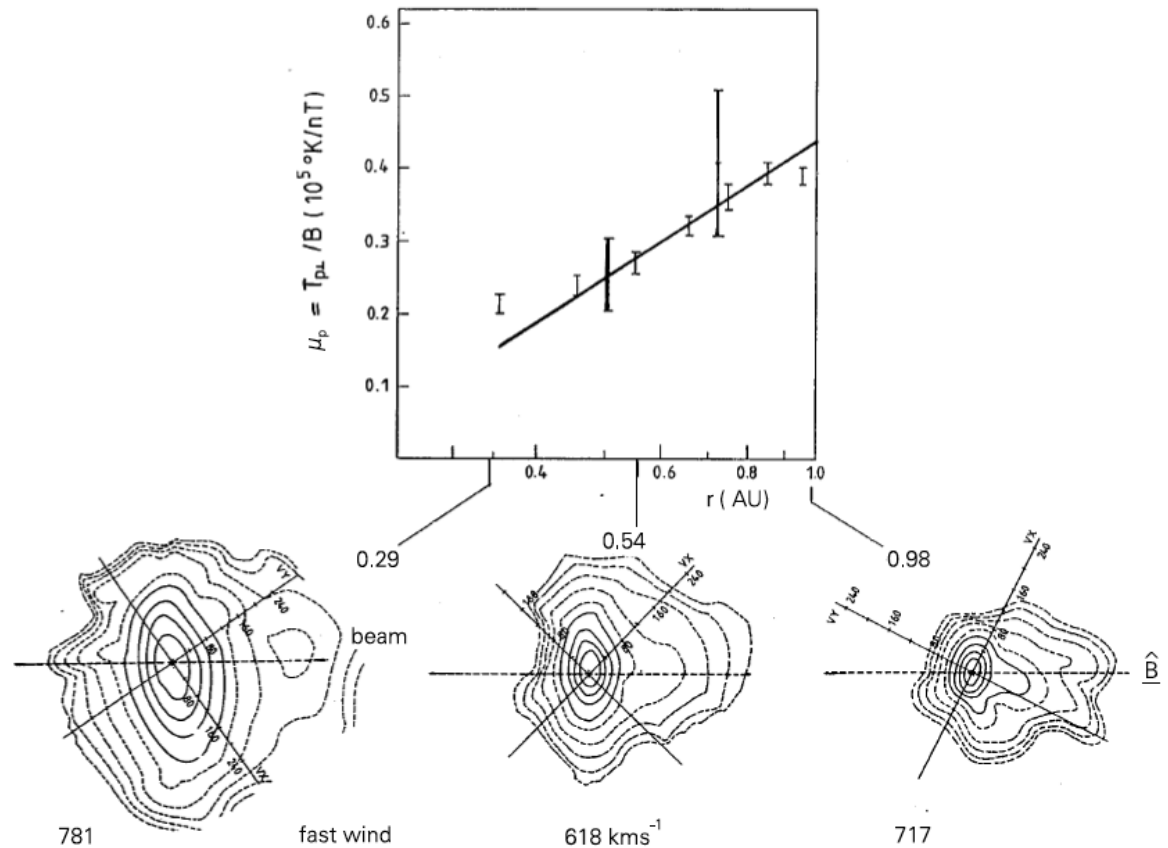
**Coronal hole,
open
magnetically**



太阳风中的波动现象

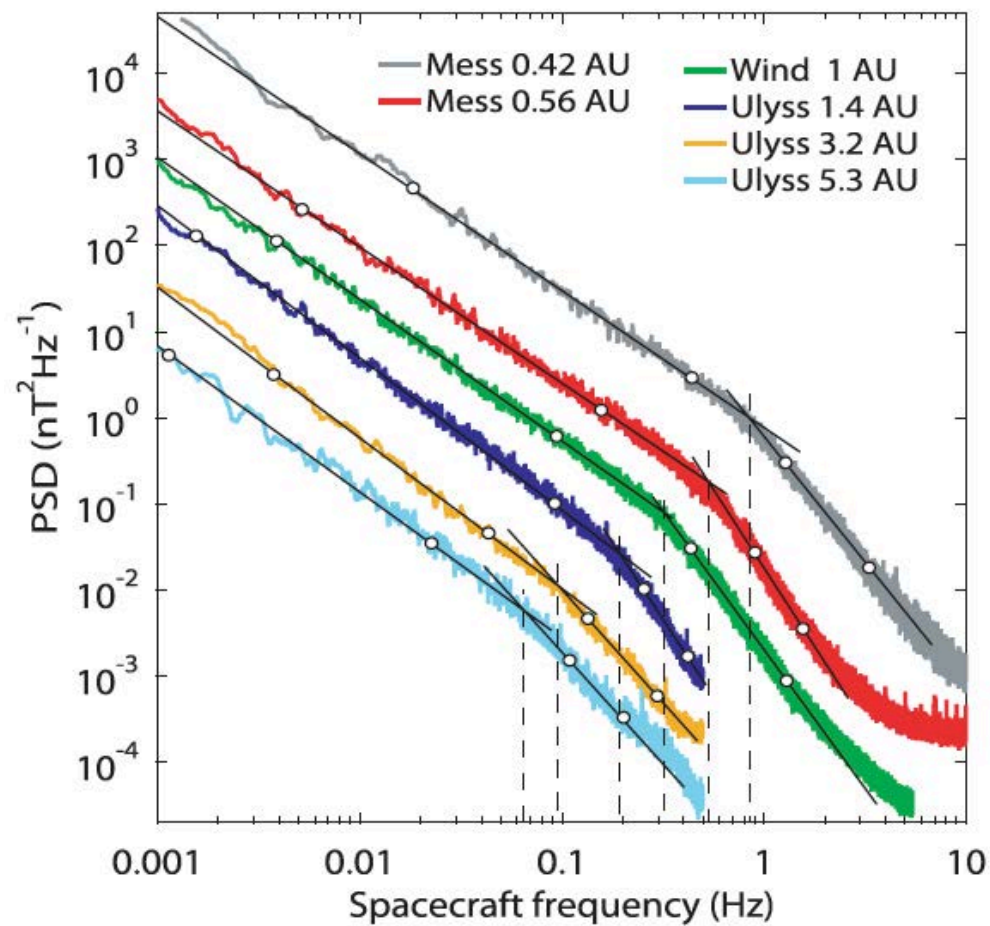
- 太阳风在很宽的频率范围内存在大量的波动现象。**Belcher and Devis**首次指出，太阳风高速流中速度起伏和磁场涨落之间存在很高的相关性，说明太阳风中的起伏具有阿尔芬波动特性。**Helios**及**Ulysses**的观测结果也确认太阳风中普遍存在着大尺度的低频(10^{-4} - 10^{-2} Hz)阿尔芬波。

湍流在膨胀太阳风中的串级耗散加热



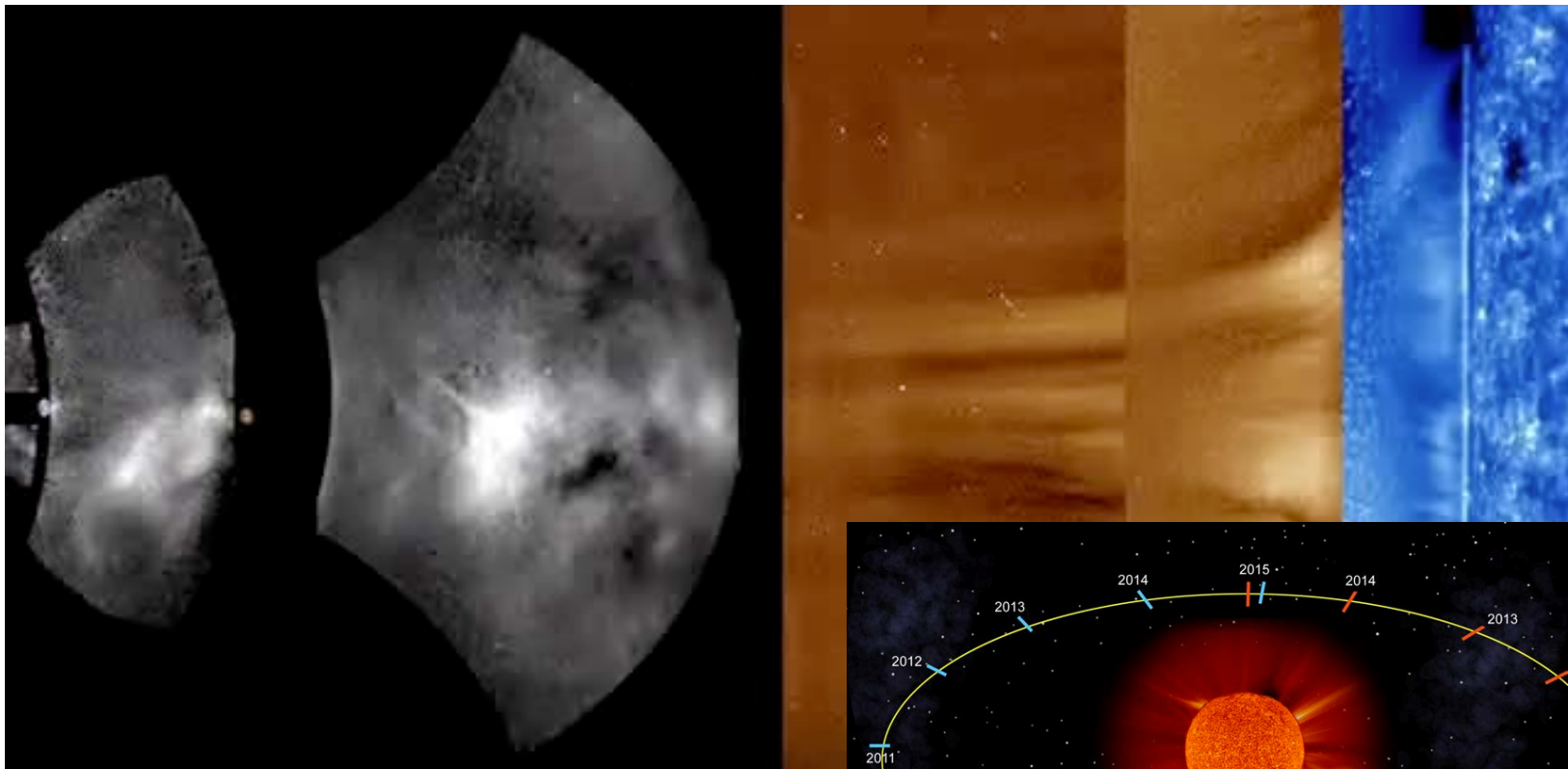
[Marsch et al., JGR, 1982]

太阳风湍流惯性区-耗散区 拐点位置的径向演化特征

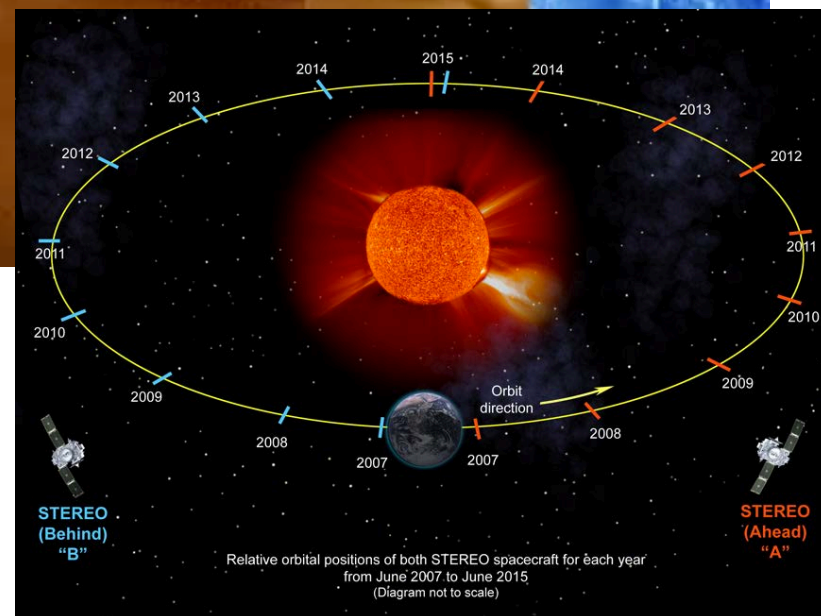


Interval	<i>s/c</i>	<i>R</i> (AU)	<i>B</i> (nT)	<i>n</i> (cm ⁻³)	<i>V</i> _{sw} (km s ⁻¹)	<i>T</i> (K)	IR	DR	<i>f</i> _b (Hz)
2011, 100.87–101.03	MESS	0.42	21.53	(22.58)	(586)	(670581)	−1.58	−2.90	0.848 ± 0.008
2010, 182.04–182.65	MESS	0.56	6.28	(6.25)	(604)	(218382)	−1.58	−3.72	0.534 ± 0.003
2010, 182.83–183.95	WIND	0.99	3.89	1.96	604	140390	−1.65	−3.26	0.331 ± 0.002
2011, 102.65–102.78	WIND	0.99	5.93	3.98	586	327533	−1.64	−3.17	0.387 ± 0.003
2007, 239.12–240.24	WIND	0.99	4.81	2.58	632	242000	−1.69	−3.45	0.409 ± 0.002
2007, 241.77–243.29	ULYSS	1.4	2.14	1.25	560	107162	−1.76	−3.58	0.192 ± 0.001
2000, 192.96–193.34	ULYSS	3.2	0.737	0.216	732	74060	−1.74	−2.59	0.096 ± 0.003
1992, 235.92–236.30	ULYSS	5.3	0.412	0.087	766	48322	−1.68	−2.59	0.065 ± 0.005

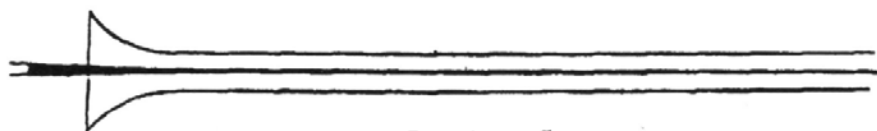
超声速太阳风湍流的全景成像



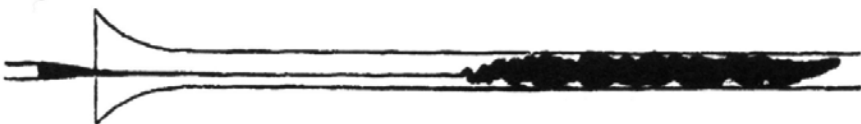
[Credit: C. Deforest et al., 2011]



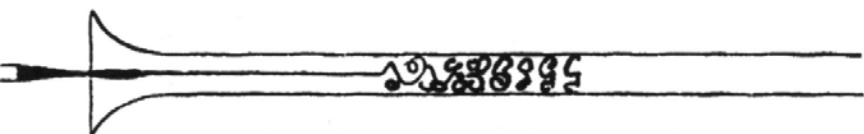
从层流→紊流 →湍流的发展



Laminar flow



Turbulent flow



Turbulent flow (observed with an electric spark)

[O. Reynolds, 1883]

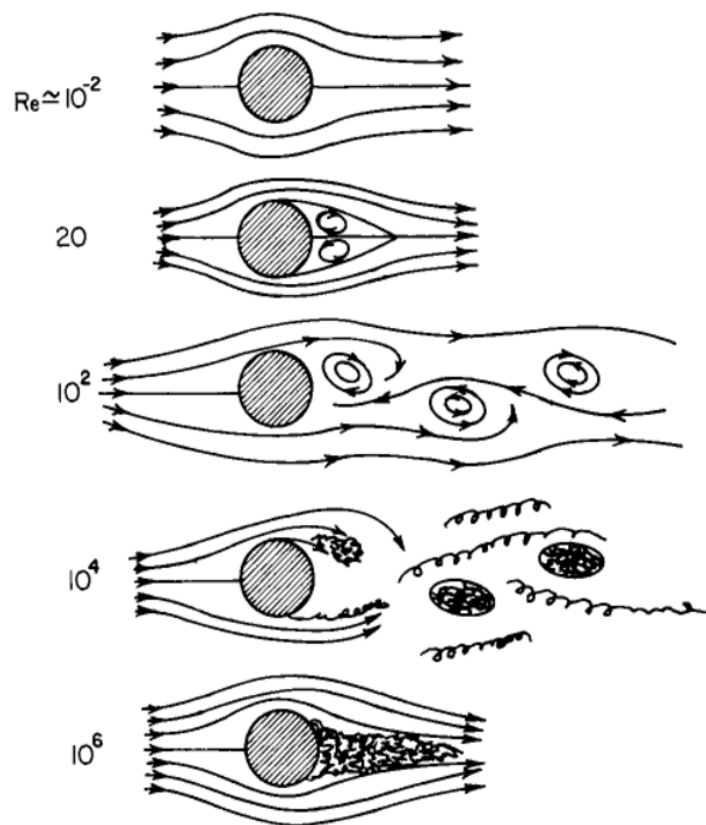
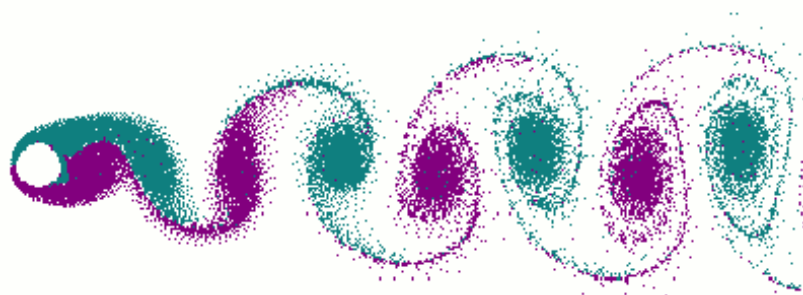
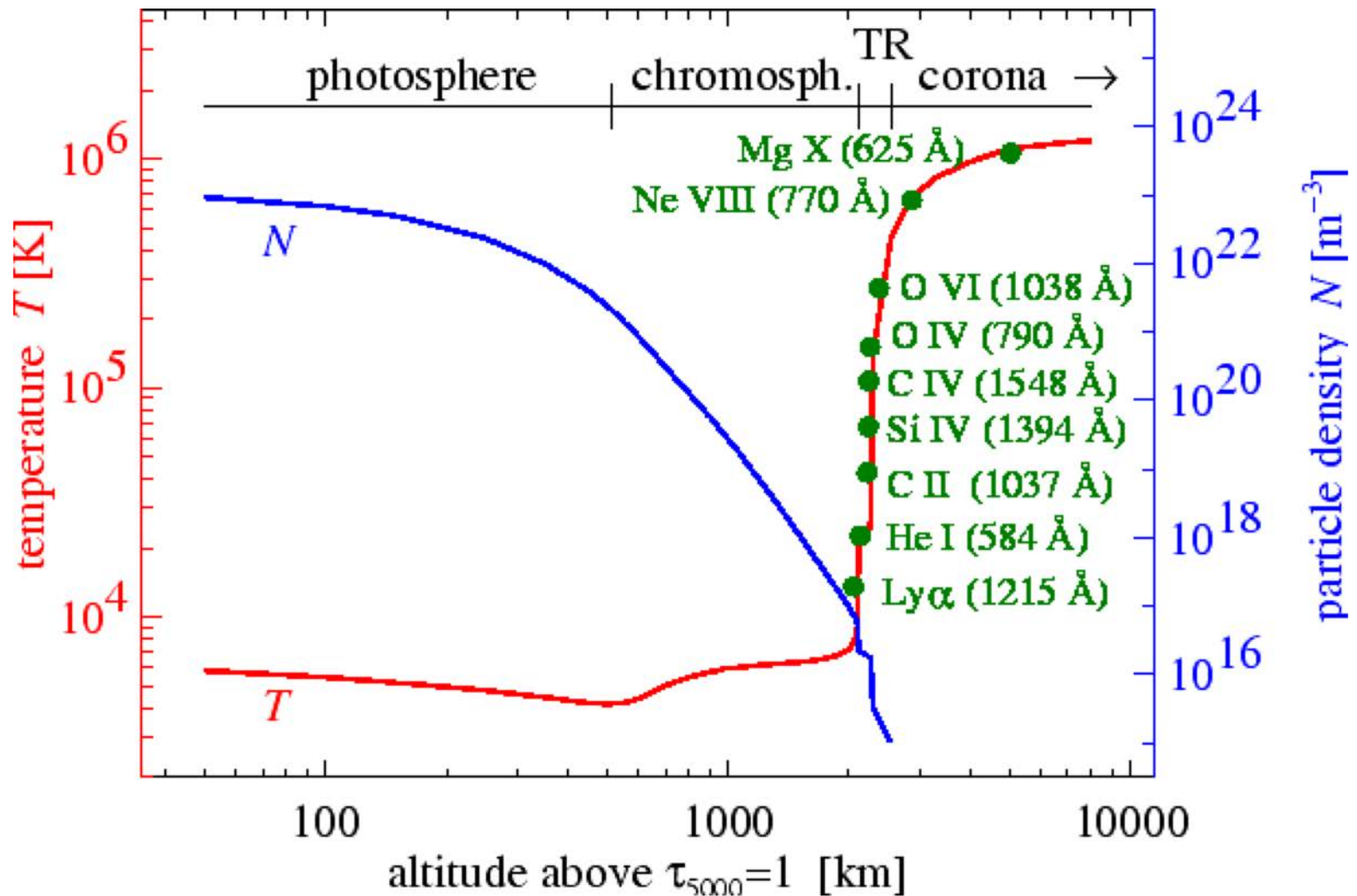


Figure 1.1 Schematic picture of a fluid around a cylinder at different Reynolds numbers.



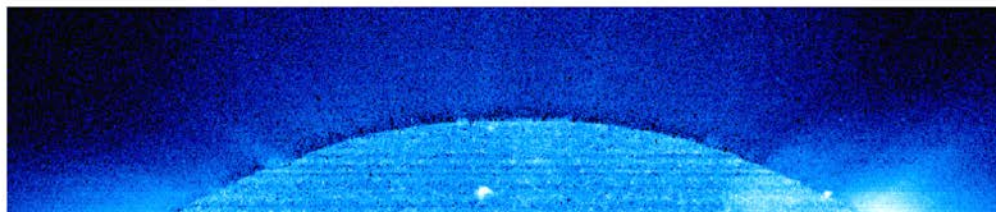
- I 超声速太阳风的预言和发现
- II 太阳风的基本观测特征
- III 日冕加热与太阳风加热加速研究简介

色球和日冕的温度梯度



不同谱线看到的北极冕洞

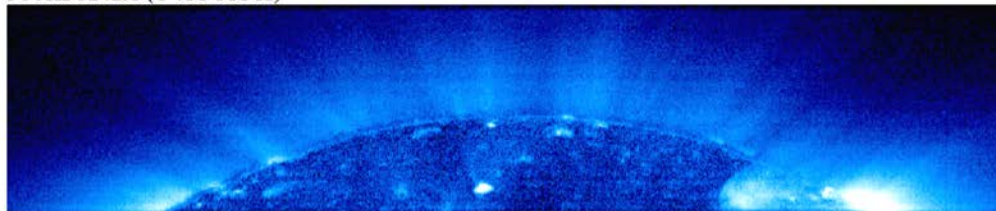
1400000 K



Fe XII 1242.0 (1 400 000 K)

FeXII 1242 Å

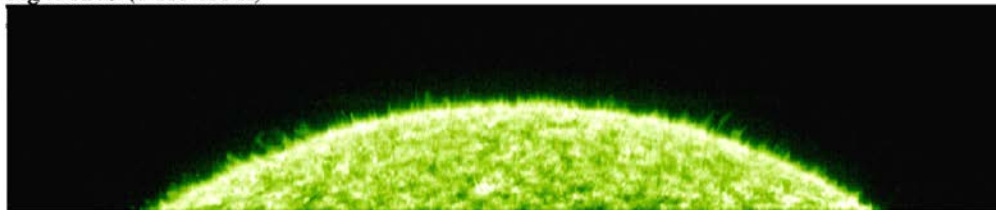
1100000 K



Mg X 624.9 (1 100 000 K)

MgX 624.9 Å

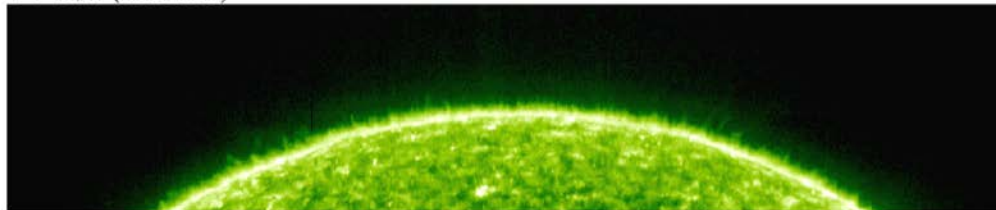
230000 K



O V 629.7 (230 000 K)

OV 629.7 Å

180000 K



N V 1238.8 (180 000 K)

NV 1238.8 Å

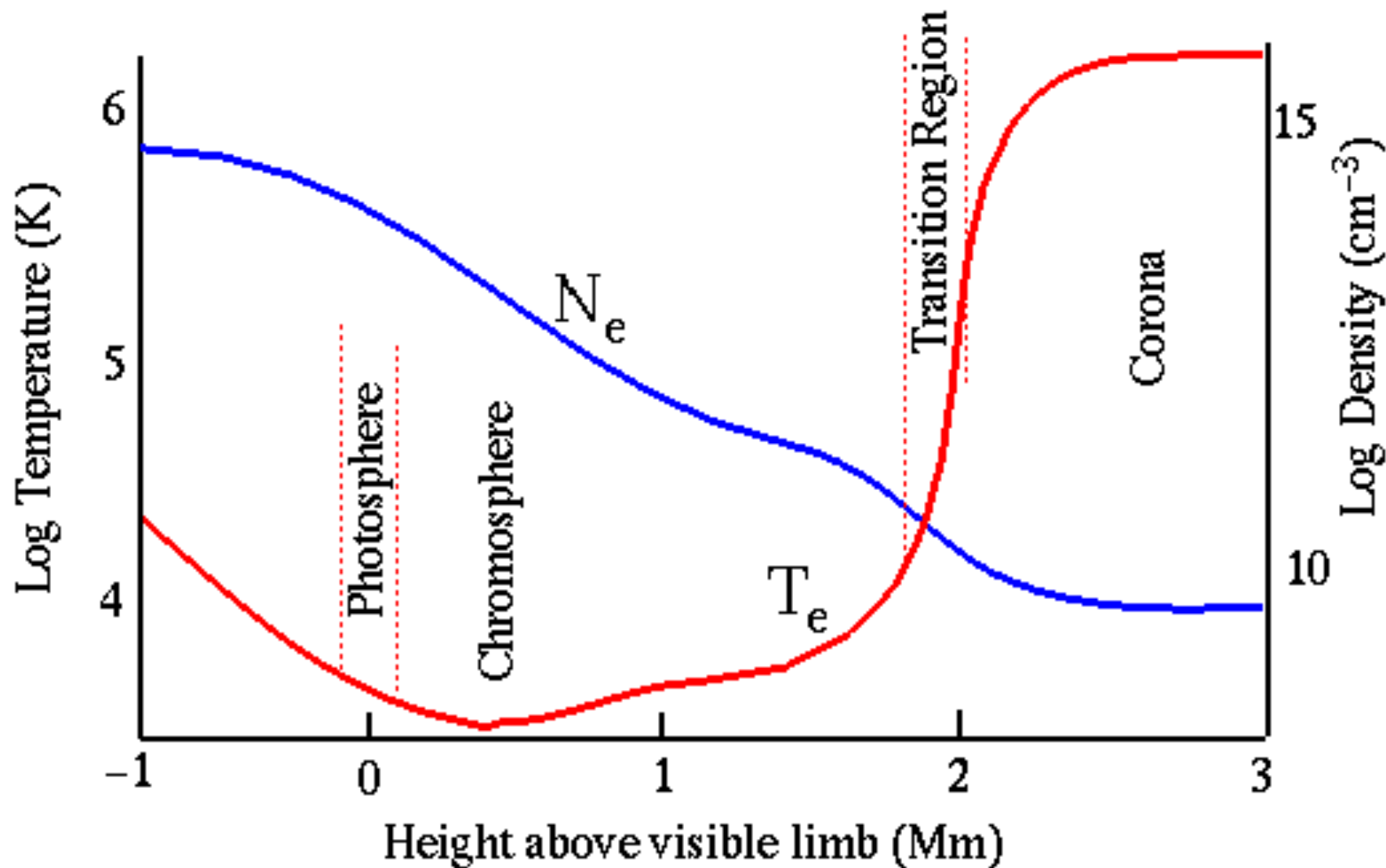
10000 K



Continuum @ 1240 (10 000 K)

cont. 1240 Å

色球和日冕如何被加热?



Coronal heating, what does it mean?

有哪些问题过程？

加热的能量来源：机械能和磁能

要解释的物理过程：

1. 能量的产生/积累

- 磁力线的对流、剪切运动, 磁场的重构

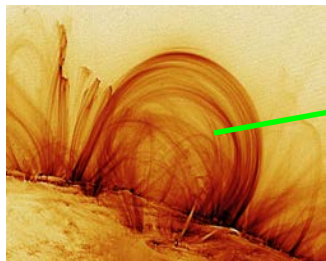
2. 能量的输运/传递

- 磁流体力学过程 + 等离子体波动, 激波

3. 能量的转换/耗散

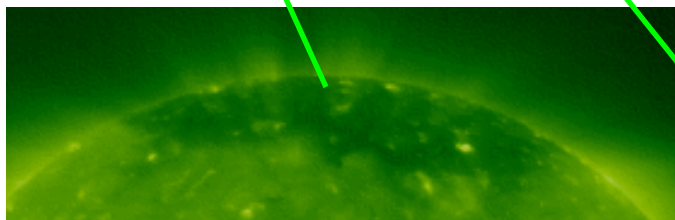
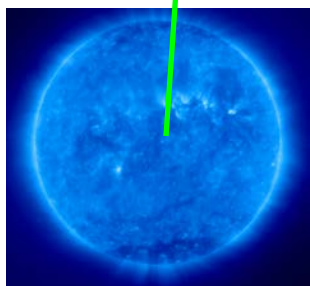
- 欧姆耗散 + 湍动加热, 共振吸收, 磁场重联, 辐射致冷

日冕加热的方方面面

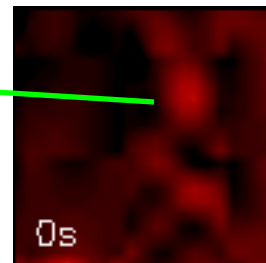


closed magnetic loops are observed at a wide range of temperatures

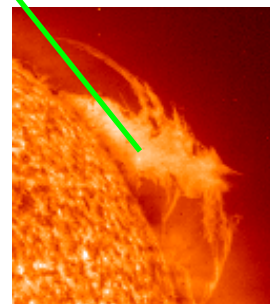
"diffuse" corona radiating at 2 MK is not confined to "bright" loops



polar plumes are observed at "coronal" temperatures in open magnetic structure, the coronal holes



Small brightenings at a range of wavelengths



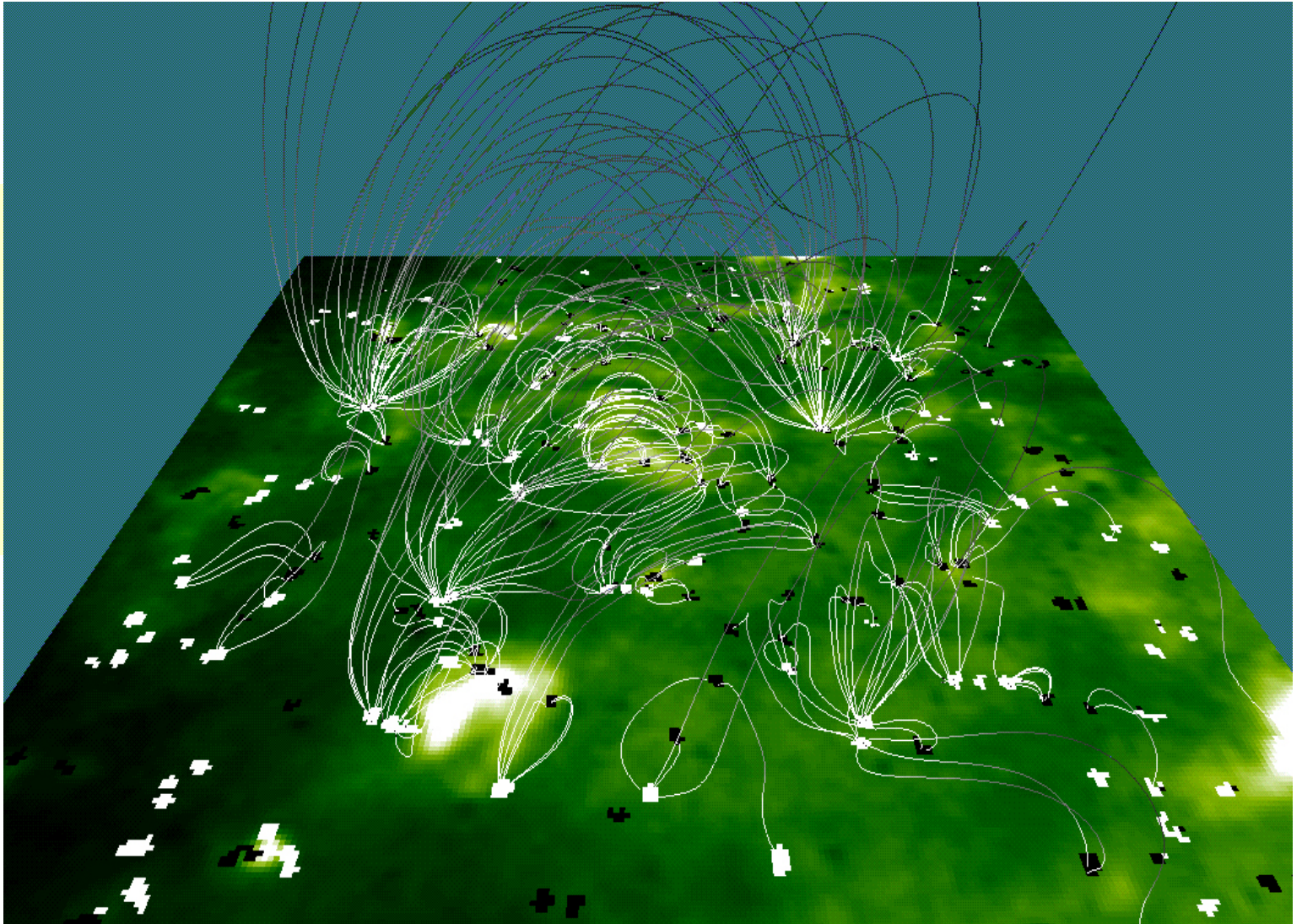
special energy requirements in cool (10^4 K) prominence

不同的时间和空间尺度!

不同的磁场位型和结构!

由光球磁场
外推得到:

- 闭合环
- 开放区
- 网络



光球网络磁场向上的延伸

色球和日冕加热 — 一个未解之谜

Why?

需要面对各种复杂性和不确定性:

- 色球和日冕是高度不均匀和有结构的。
- 是随时间变化的 (**magnetic activity cycle**)。
- 各种时间和空间尺度都有。
- 日冕远离热动平衡（或碰撞平衡）态，无碰撞。
- 各种过程往往是变化的、非线性的。
- 等离子体物理的一些基础问题也未完全解决。

几类色球和日冕加热的可能机制

波加热机制 (AC) (波的产生, 传播, 耗散, 非均匀性)

- 声波, 激波, 湍流
- 磁声波(**body, surface**), **Alfvén** 波(共振吸收)
- 离子回旋波, 动力学**Alfven**波, 动力学效应 (**Landau** 阻尼, 回旋共振)

电流片耗散机制(DC) (磁力线的扭转、剪切或磁通量浮现等产生电流片)

- **Quasistatic current sheet formation in force-free fields**
- **Dynamic formation driven by flux emergence**
- **Field-aligned currents (ohmic and anomalous resistivity)**

微耀斑加热机制 (磁场重联)

- 磁力线的随机行走、磁通量的浮现
- 磁通量管的碰撞相互作用
- 高能粒子的热化 (**Bremsstrahlung: radio to X-rays**)