超音速太陽風 與 激震波
Supersonic Solar Wind and Shock Waves

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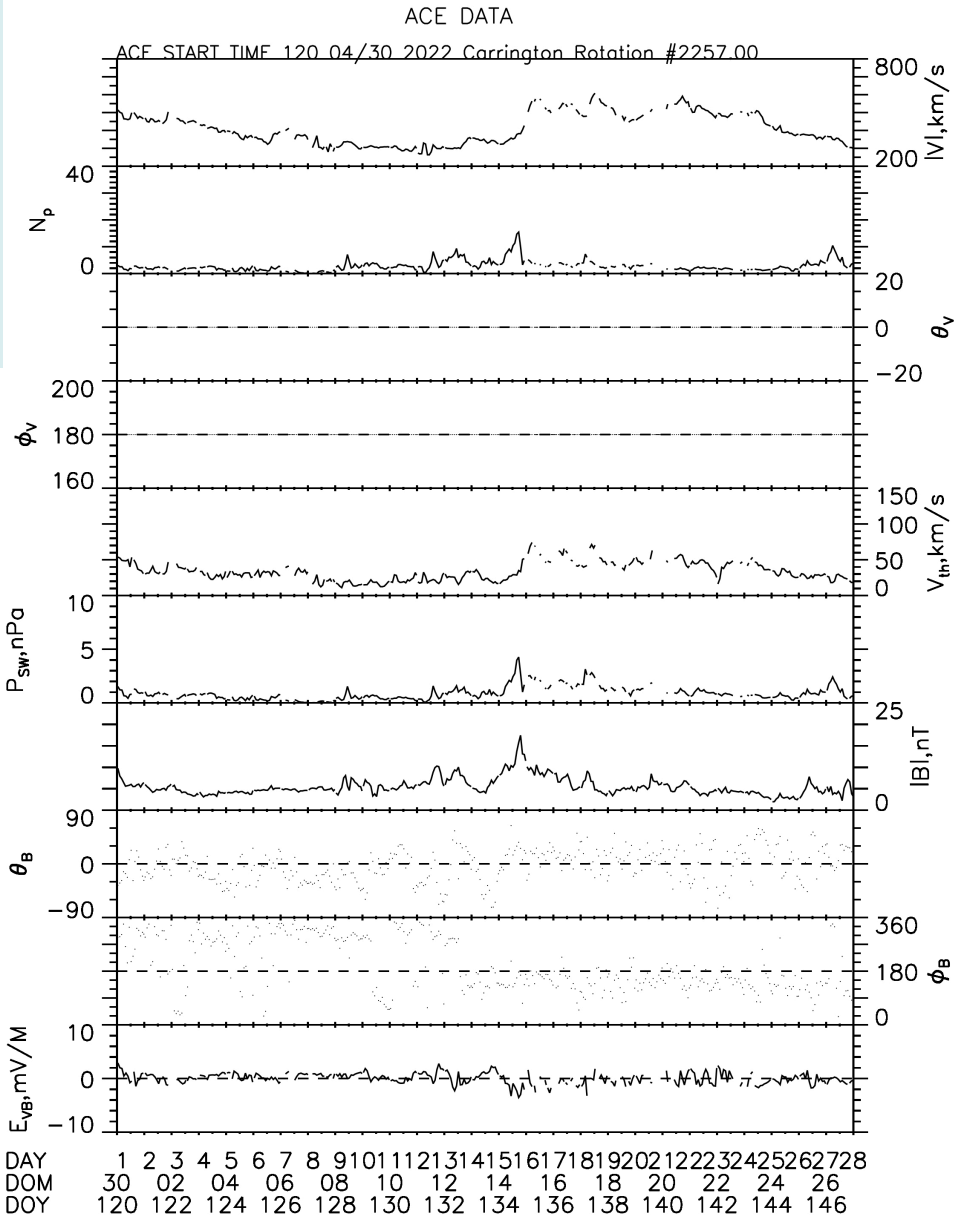
Observations of Solar Wind: High-Speed & Low-Speed Solar Wind
高速 與 低速 太陽風 之觀測

Observations of Solar Wind

- ACE spacecraft Observations (ACE 太空船 的觀測結果)



太陽風速度

太陽風熱速度

Origin of the high-speed solar wind
高速太陽風 來自何處？

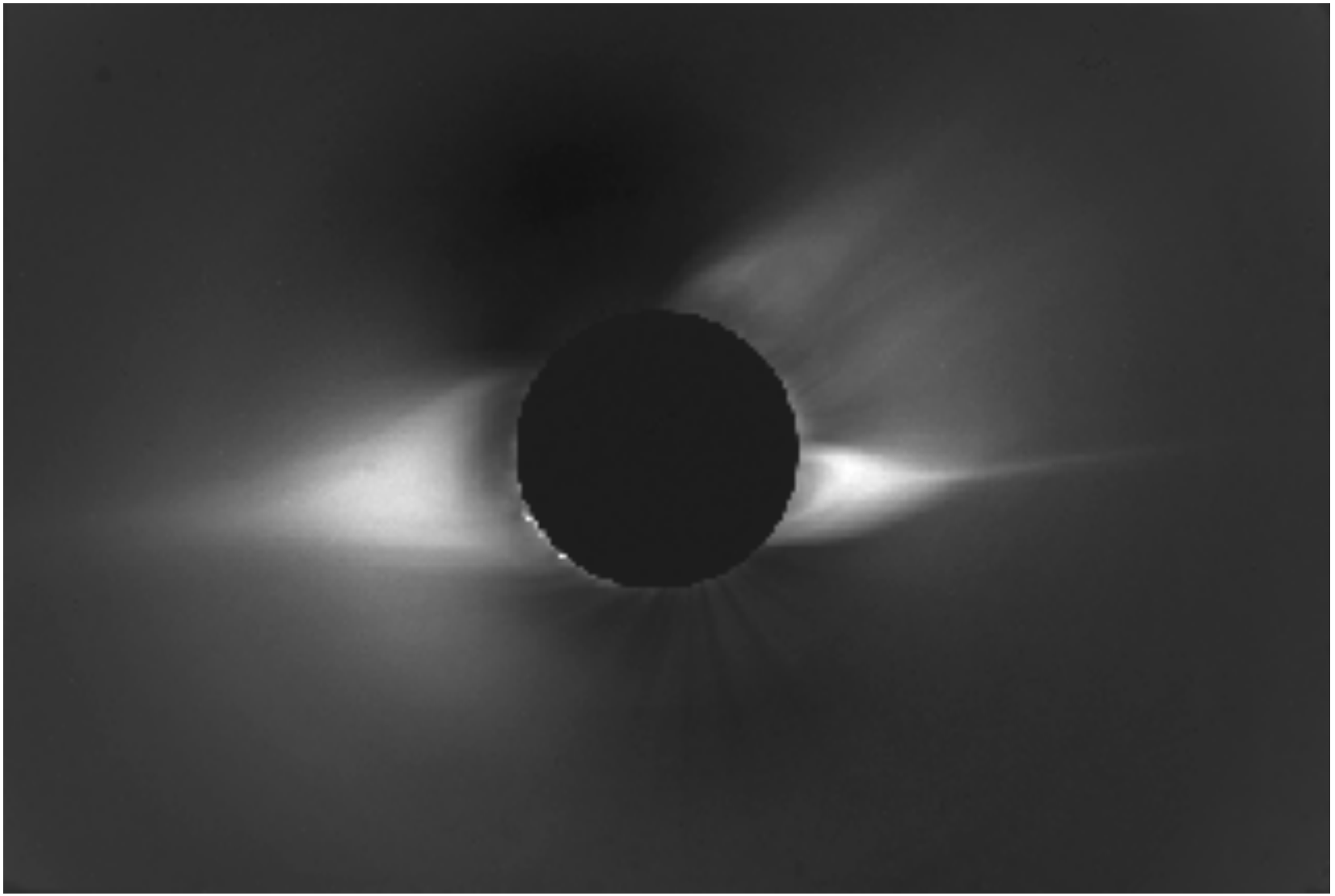
- Origin of the quasi-steady high-speed low-density solar wind
- 高速、低密度的 穩定太陽風 是源自何處？

Ans.: Coronal Hole 日冕洞

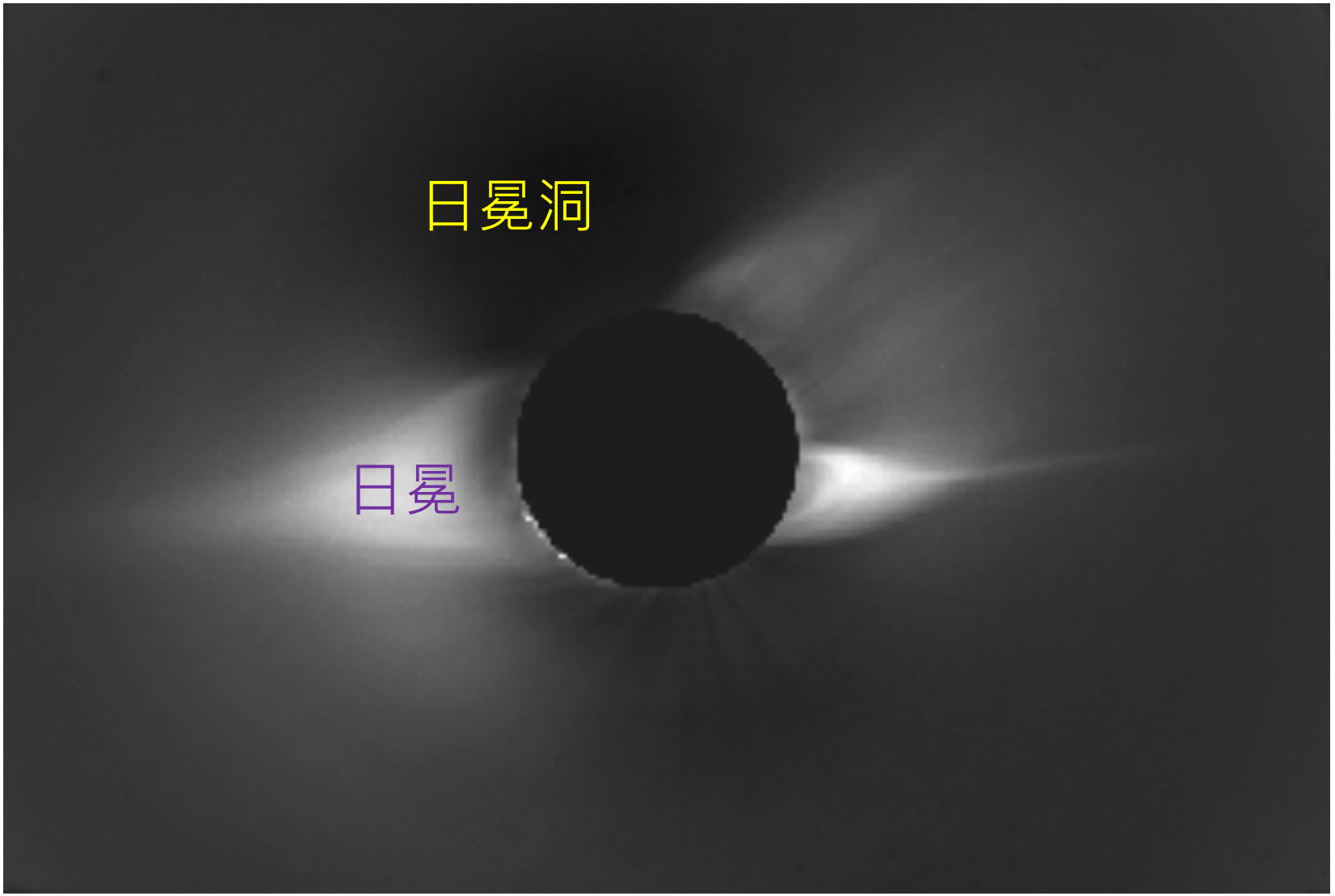
- Origin of the transient high-speed high-density solar wind
- 高速、高密度的 暫態太陽風 是源自何處？

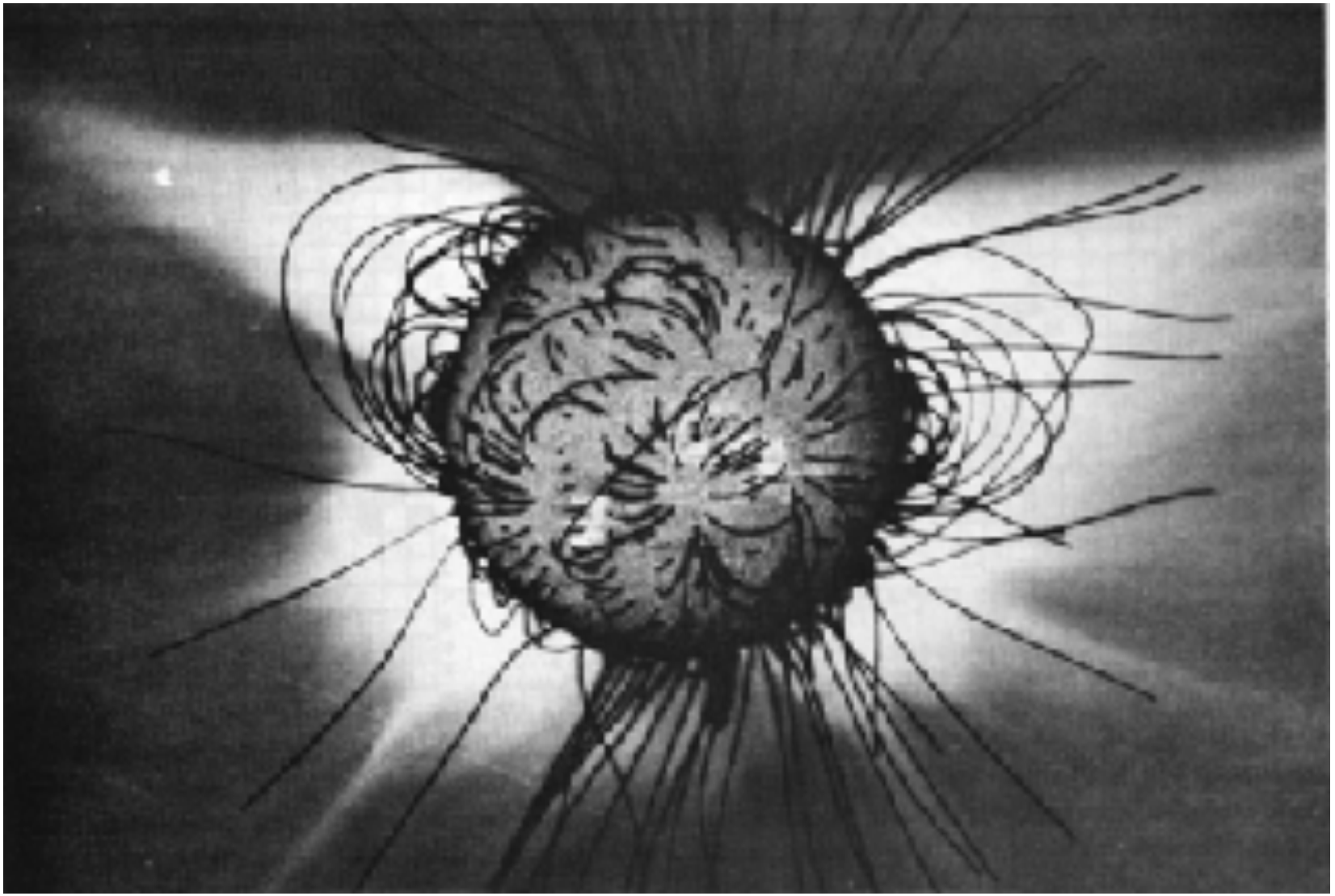
Ans.: Coronal Mass Ejection (CME) 日冕物質拋射

日食時 所觀測到的 日冕分佈



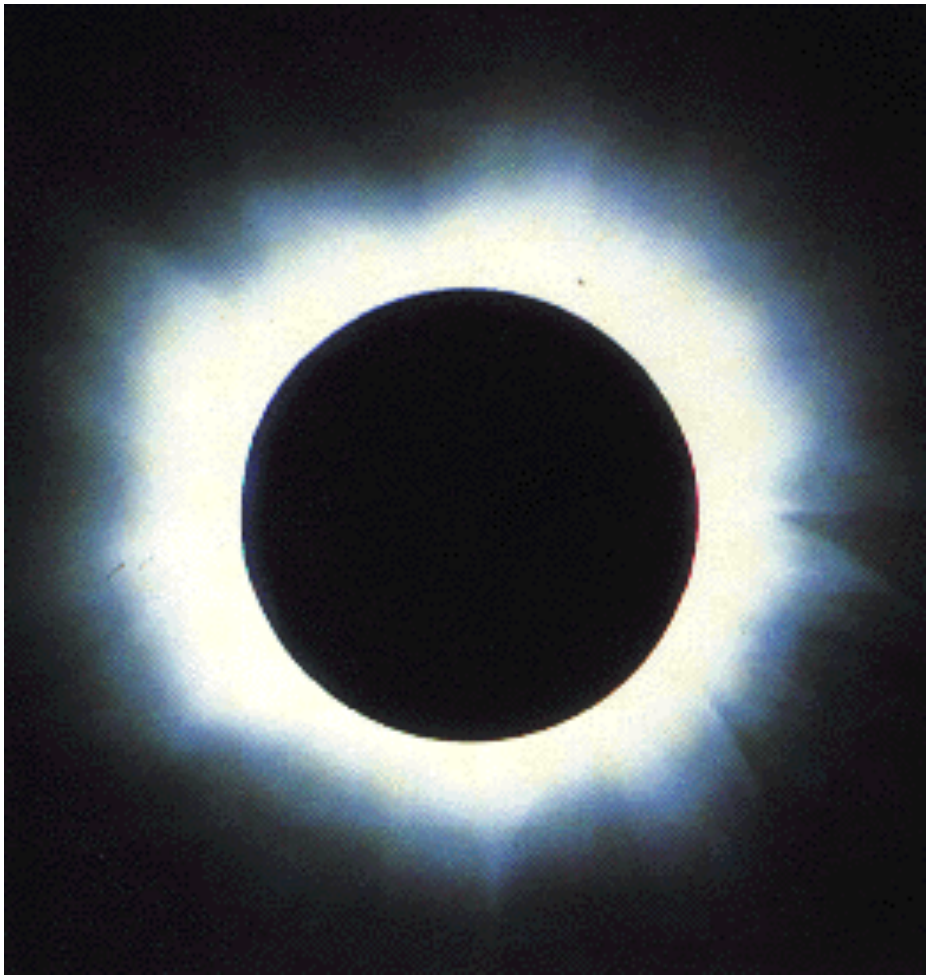
日食時 所觀測到的 日冕分佈





Distributions of Solar Corona During Solar Maximum

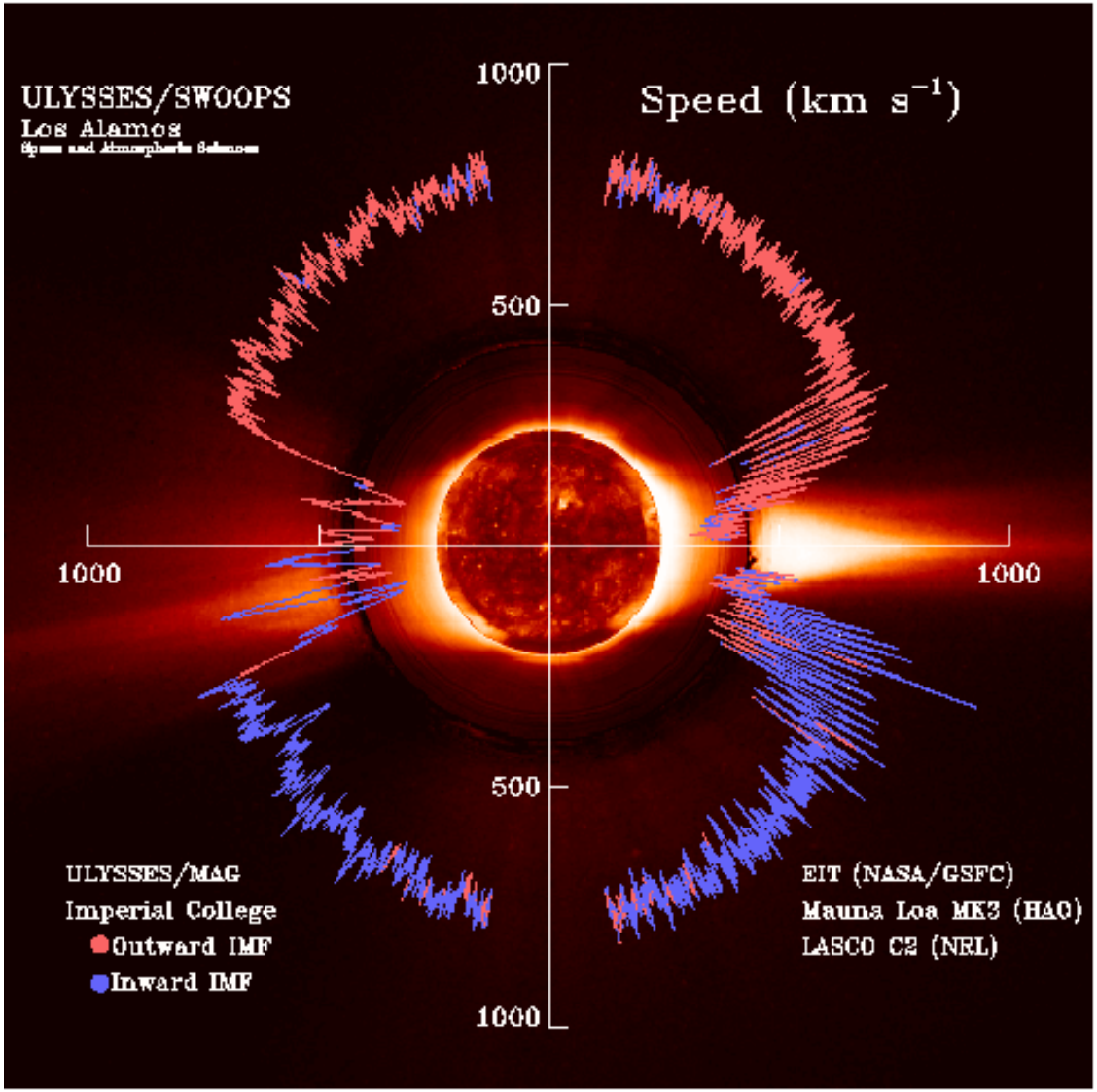
太陽黑子極大期時的日食 所觀測到的 日冕分佈



Distributions of Solar Corona and Coronal Hole During Solar Minimum

太陽黑子極小期時的日食 所觀測到的 日冕＆日冕洞分佈

Ulysses Observation of Solar-Wind Speed(1991-1998)



Acceleration of Solar Wind
太陽風加速原理

Acceleration of Solar Wind
太陽風加速原理

- How to generate a supersonic flow in a wind tunnel ?
  科學家 如何在 風洞中產生 超音速的氣流？
- 如何加速 次音速流？如何加速 超音速流？
- 提示：次音速流 可視為不可壓縮的流體（如：水流）
  超音速流 為可壓縮的流體（如：車流）
- de Laval nozzle (一種 超音速氣流 產生器)
  - https://en.wikipedia.org/wiki/De_Laval_nozzle
- How to accelerate the subsonic coronal breeze
  to the supersonic solar wind ?
  如何將 次音速的日冕微風 加速到 超音速的太陽風
  - https://adsabs.harvard.edu/full/1969CoASP...1...31D

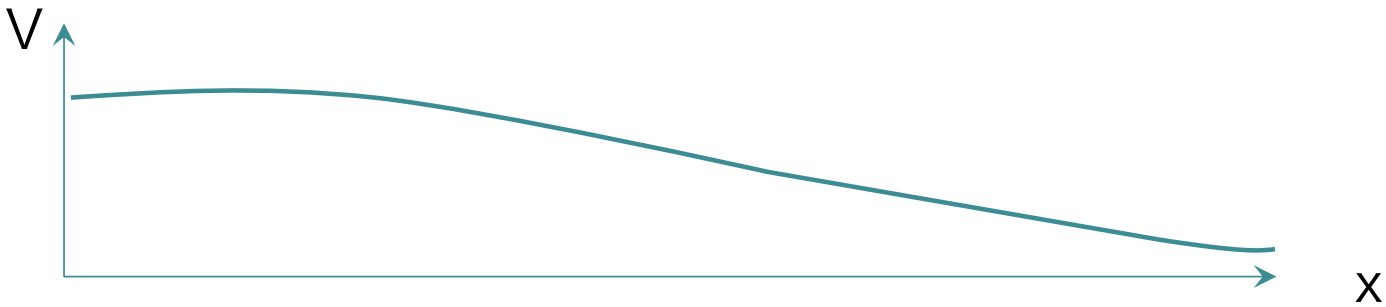
Formation of Shock Waves
激震波的成因

上游流速超音速 → 下游流速次音速 → 阻礙物

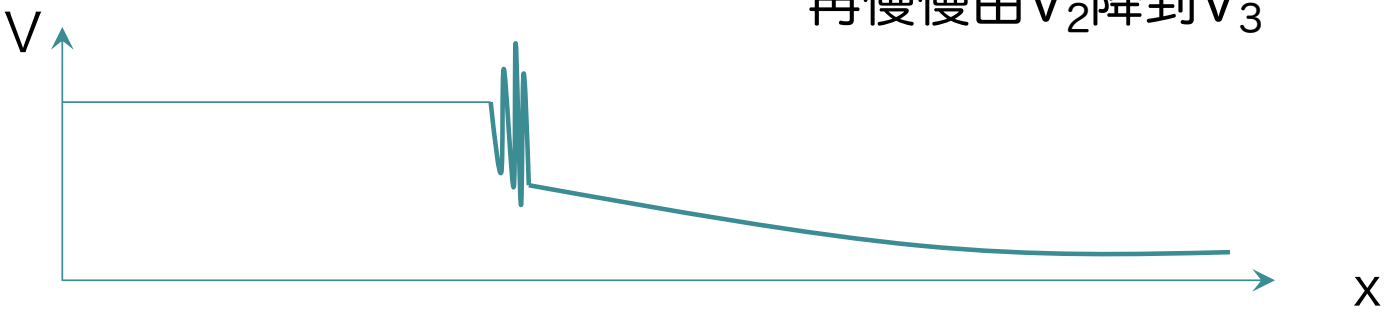
$V_1 > C_{S1}$ $V_2 < C_{S2}$ $V_3 \rightarrow 0$

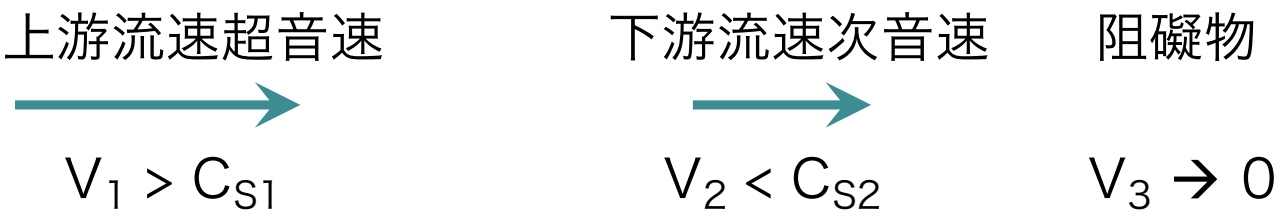
以下敘述何者正確？ and Why?

(1) 流速逐漸由超音速流V_1降到V_3

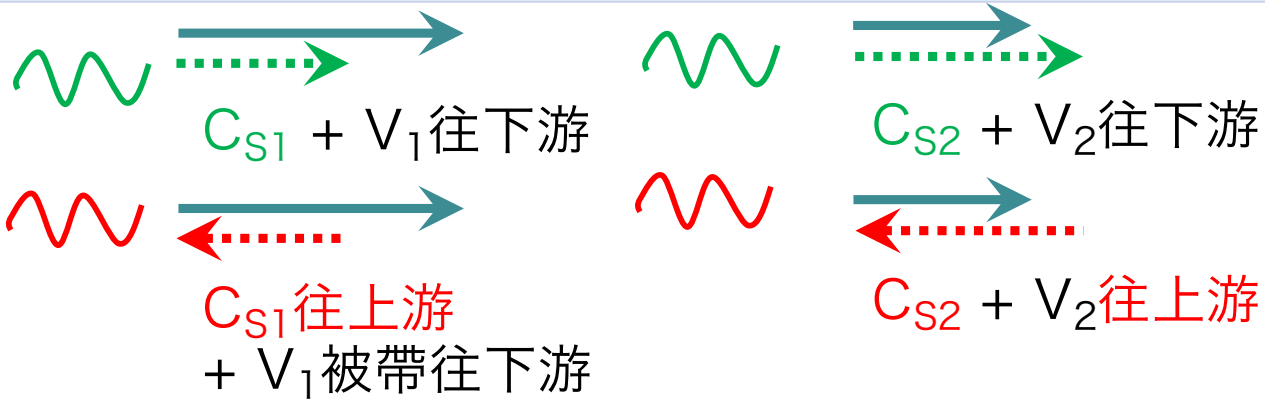


(2) 流速在很窄的區域由超音速流V_1快速降到次音速流V_2,
再慢慢由V_2降到V_3



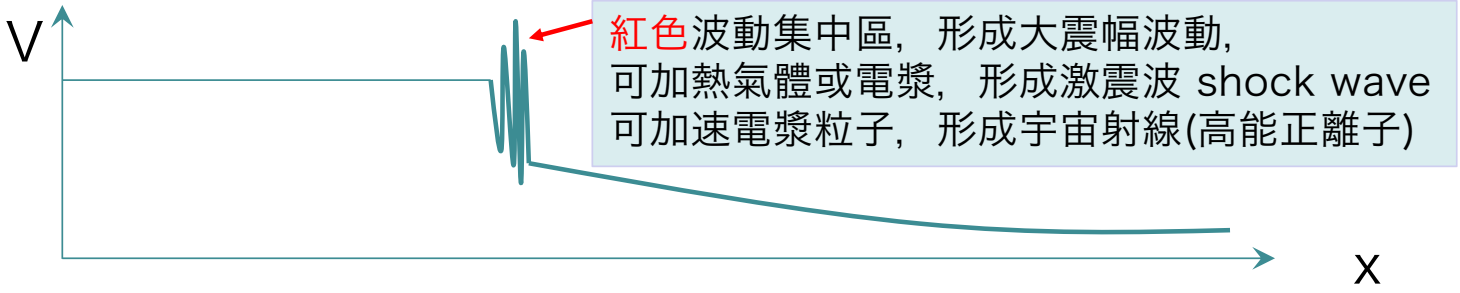


說明：考慮上下游有一些小擾動，有些擾動向下游傳播(綠色)，有些向上游傳播(紅色)



結果綠色波動可以順利被帶往下游，但是紅色波動集中在超音速流減速到次音速流的區域

(2) 流速在很窄的區域由超音速流V_1快速降到次音速流V_2, 再慢慢由V_2降到V_3

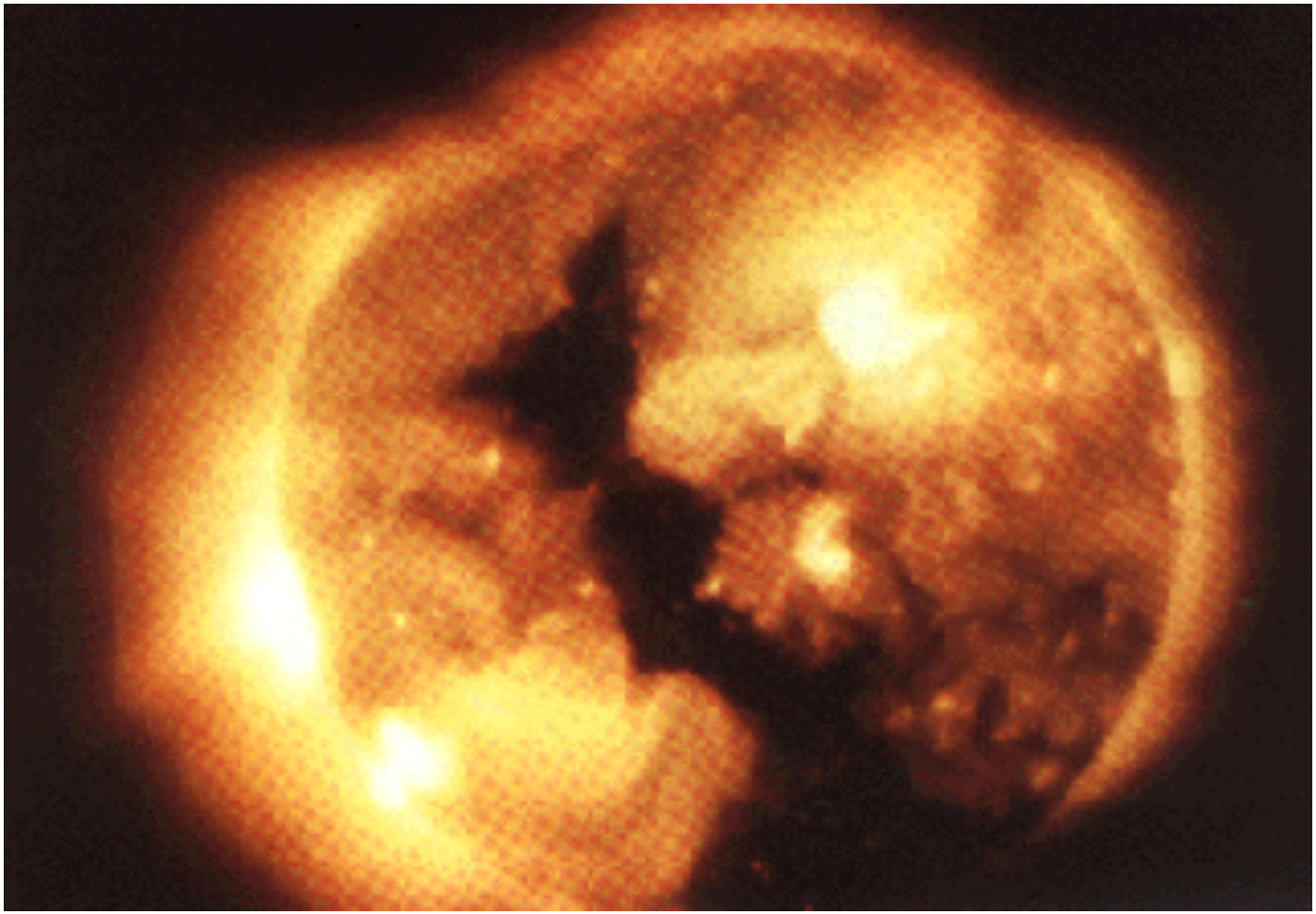


跨過激震波

- 流速減慢（in shock wave rest frame)
  - 跟著激震波走，會覺得上游的 超音速流 穿過激震波會減速 成為次音速流
- 密度增加
- 溫度增加 (聲速增加)
- 熱壓增加
- 熵值增加
  - 因為 entropy 熵 增加，所以是一種 不可逆反應！

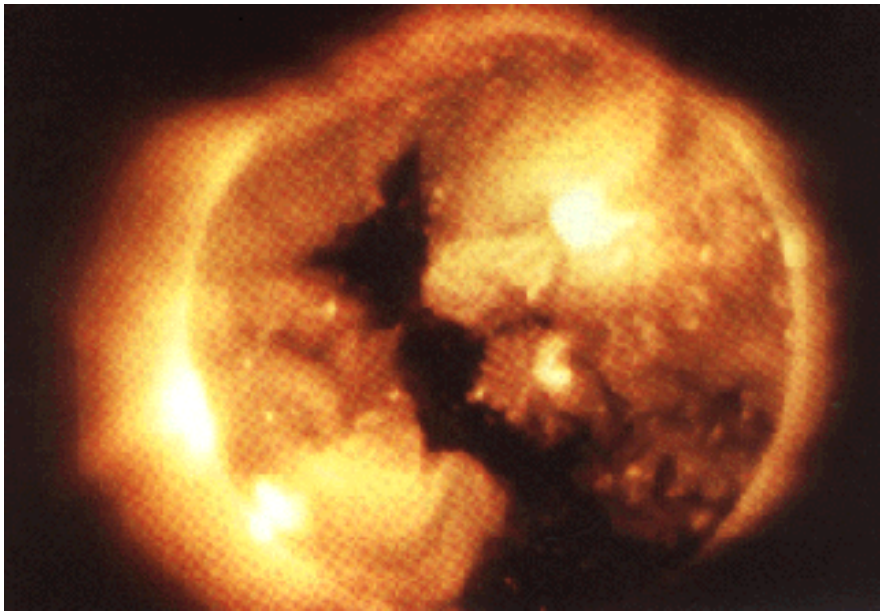
Skylab (1973) Hard-X ray image

Elephant-trunk distribution of coronal hole

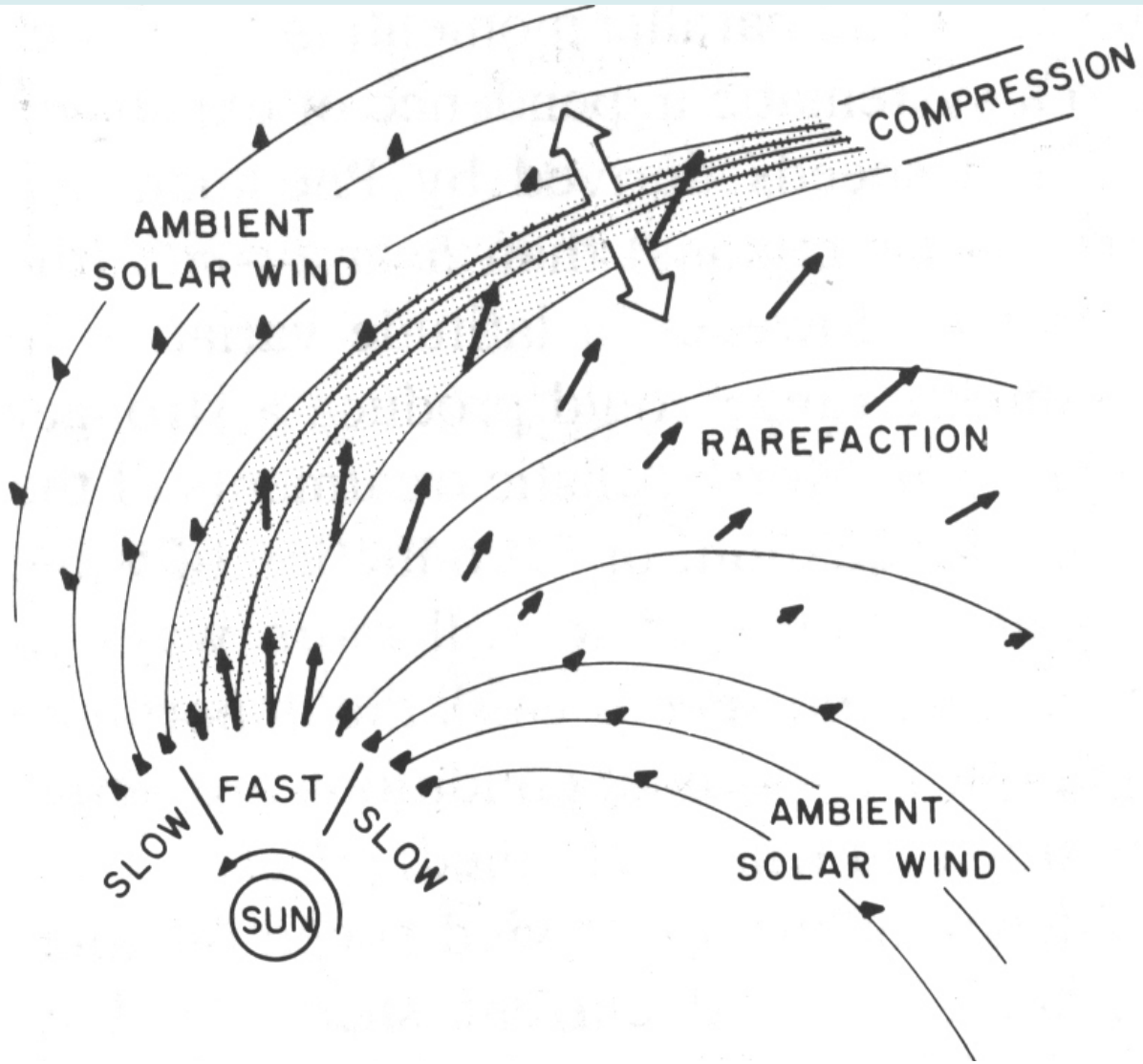


High Speed Solar Wind From Coronal Hole

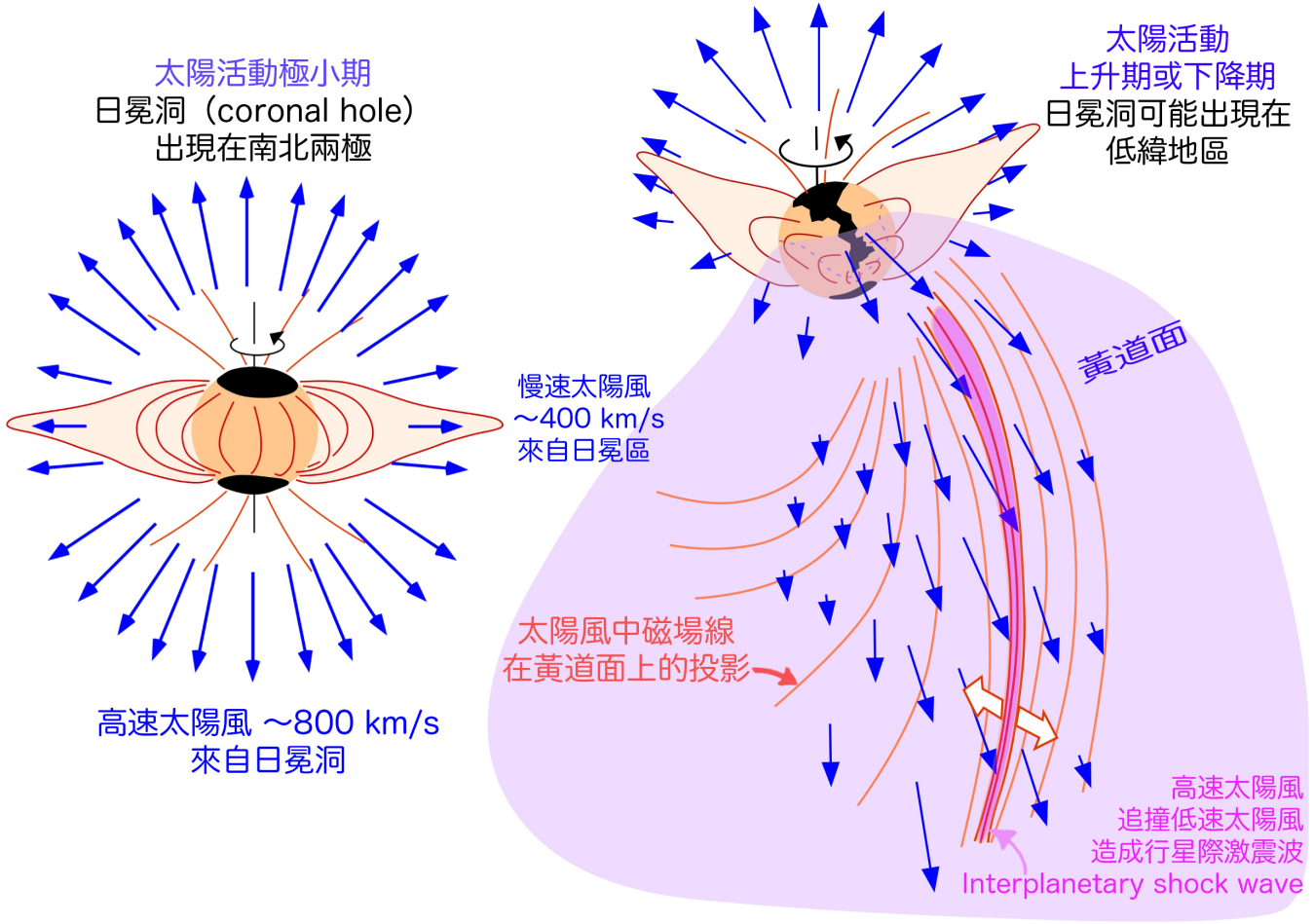
・High-speed solar wind from low-latitude coronal hole
・Slow solar wind from the corona region
・Solar rotation yields high-speed solar wind overtaking slow solar wind
→Co-rotating shocks in the interplanetary space

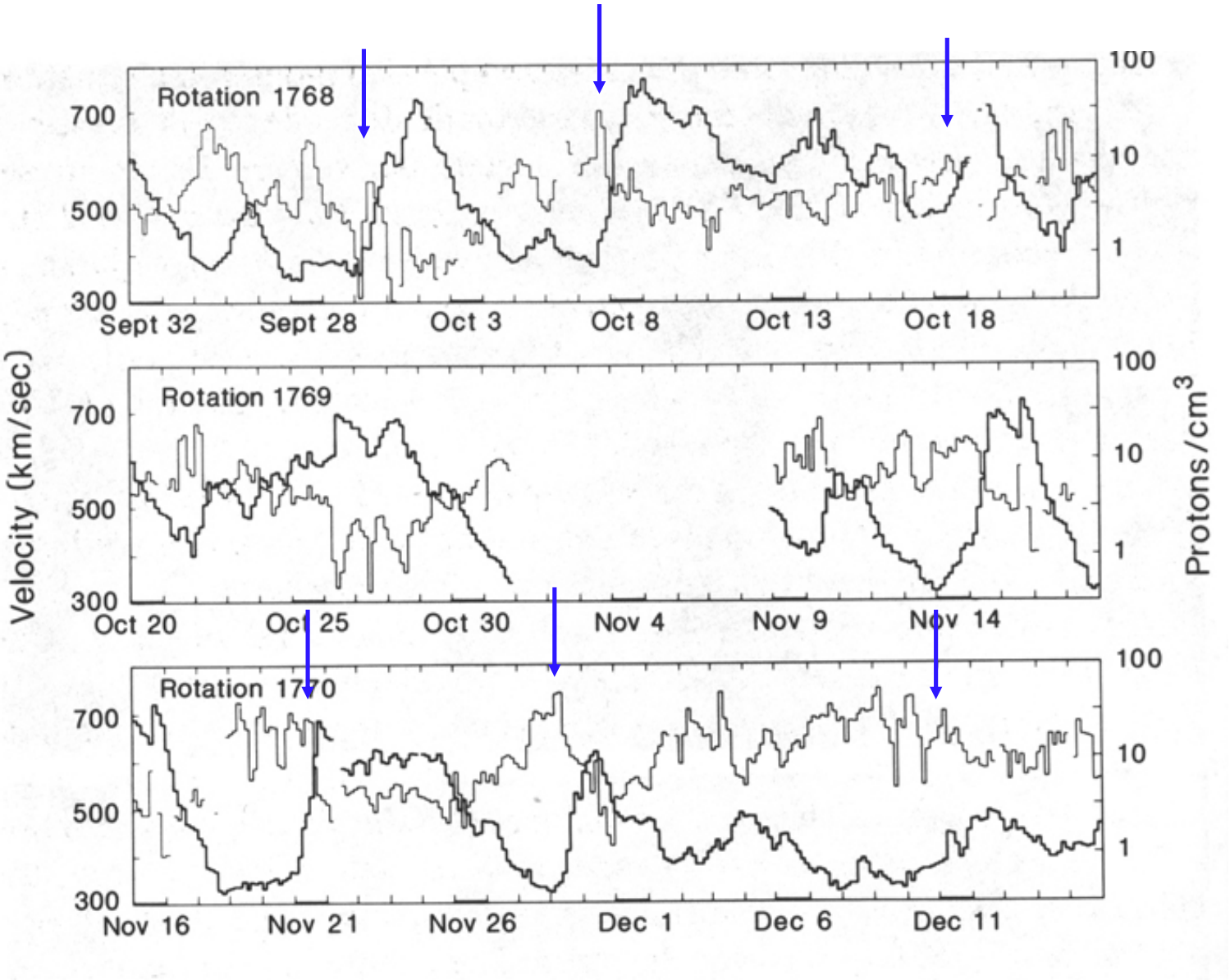


Co-rotating shocks



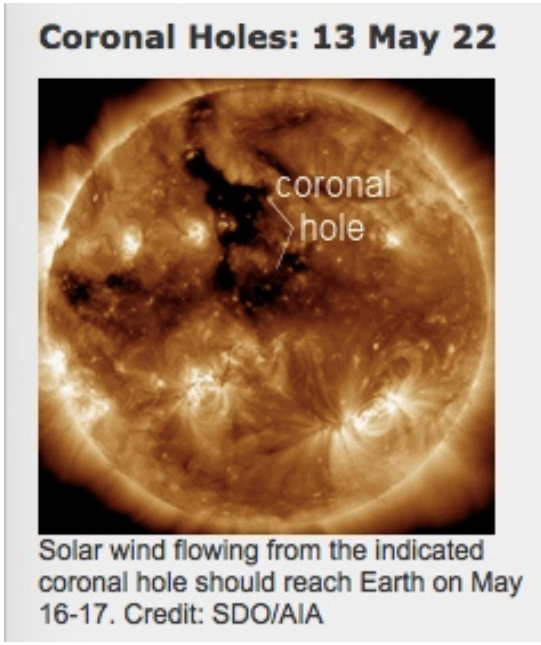
當「日冕洞」發生在太陽盤面中央區域時，行星際空間中會發生高速太陽風追撞低速太陽風，造成激震波

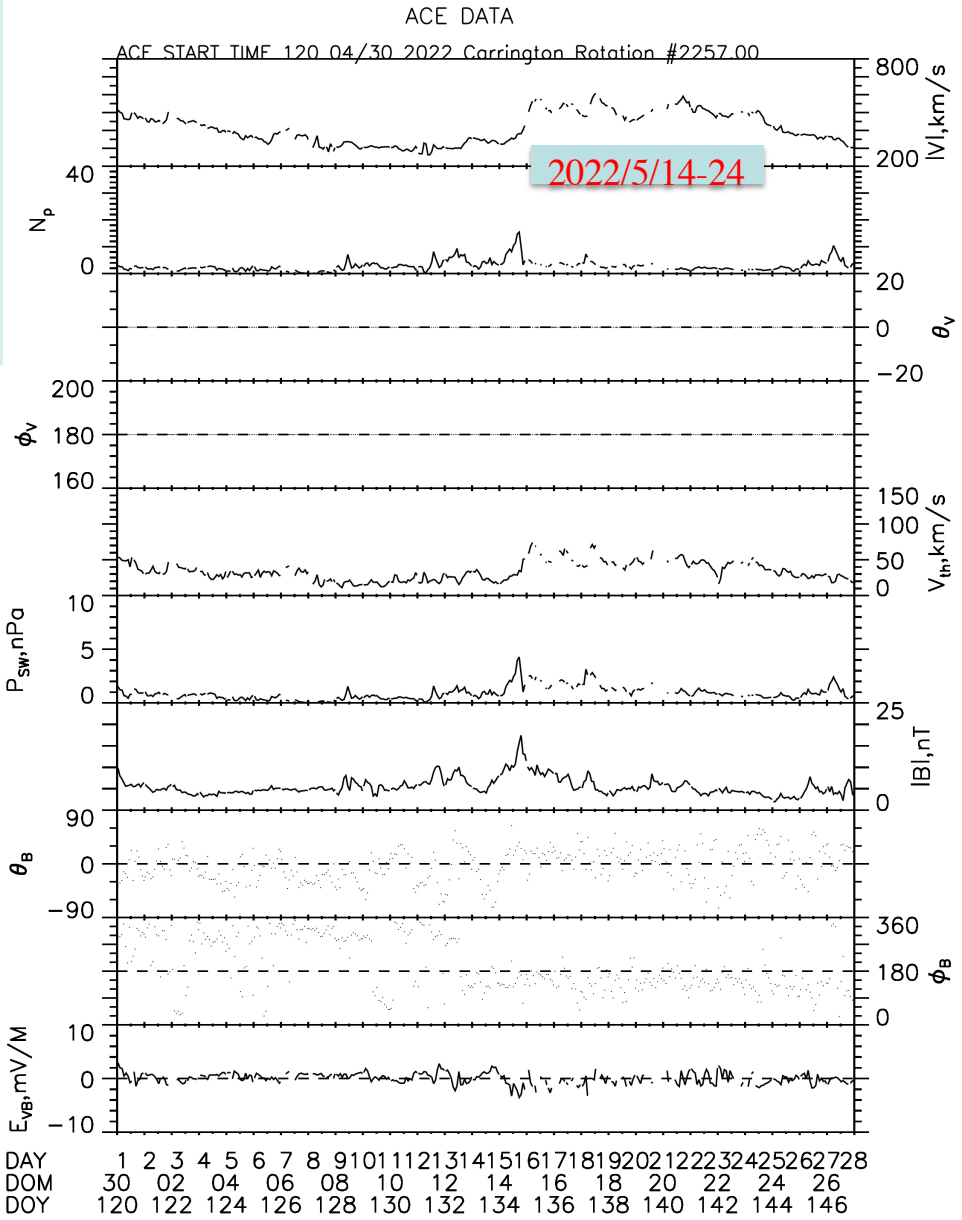



Rotation 1768
Rotation 1769
Rotation 1770
Velocity (km/sec)
Protons/cm3
700
500
300
100
10
1
Sept 32
Sept 28
Oct 3
Oct 8
Oct 13
Oct 18
Oct 20
Oct 25
Oct 30
Nov 4
Nov 9
Nov 14
Nov 16
Nov 21
Nov 26
Dec 1
Dec 6
Dec 11

Observations of Solar Wind

- ACE spacecraft Observations (ACE 太空船 的觀測結果)





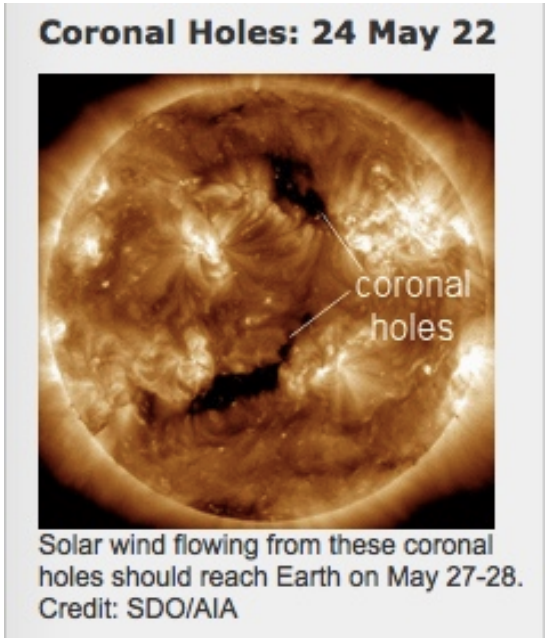
太陽風速度

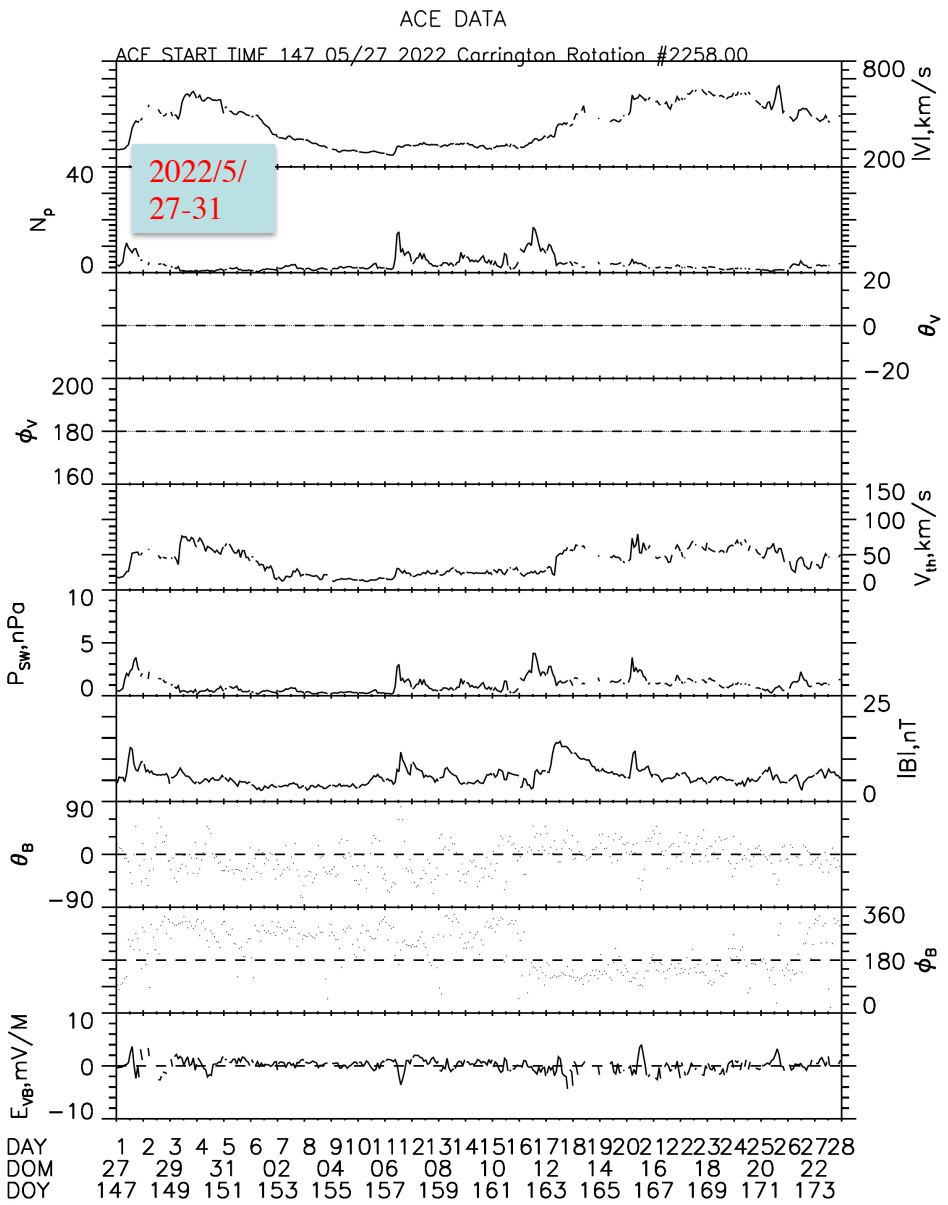
太陽風熱速度

ANTARCTIC LUNAR ECLIPSE: Around the world, millions of people saw the May 15th lunar eclipse. Only a few saw it from Antarctica. Thomas Leps sends this picture from the geographic South Pole:

Observations of Solar Wind

- ACE spacecraft Observations (ACE 太空船 的觀測結果)





太陽風速度

太陽風熱速度

高速太陽風 追撞 低速太陽風會形成一個「與太陽自轉一起旋轉」的交互作用區 (co-rotating interaction region, CIR) 。這個CIR區域，會有激震波形成 (co-rotating shocks)。

這張 2022-05-27 的照片是 當 CIR & co-rotating shock 撞擊地球磁層期間，在紐西蘭所拍攝到的南極光

注意：南半球的星空 與 北半球所看到的星空 不同

SOUTHERN LIGHTS: A co-rotating interaction region (CIR) hit Earth's magnetic field on May 27th. The impact sparked 12 hours of geomagnetic storming (G1-class) and a rare display of Southern Lights. Minoru Yoneto sends this deep-sky exposure from Queenstown, New Zealand:

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Ans.: Coronal Hole 日冕洞

- Origin of the transient high-speed high-density solar wind
- 高速、高密度的暫態太陽風 是源自何處？

Ans.: 日珥/暗紋 的噴發 導致上方 日冕物質拋射
Eruption of Solar Prominence (or Filament) leads to Coronal Mass Ejection (CME)

Solar-flare associated shocks

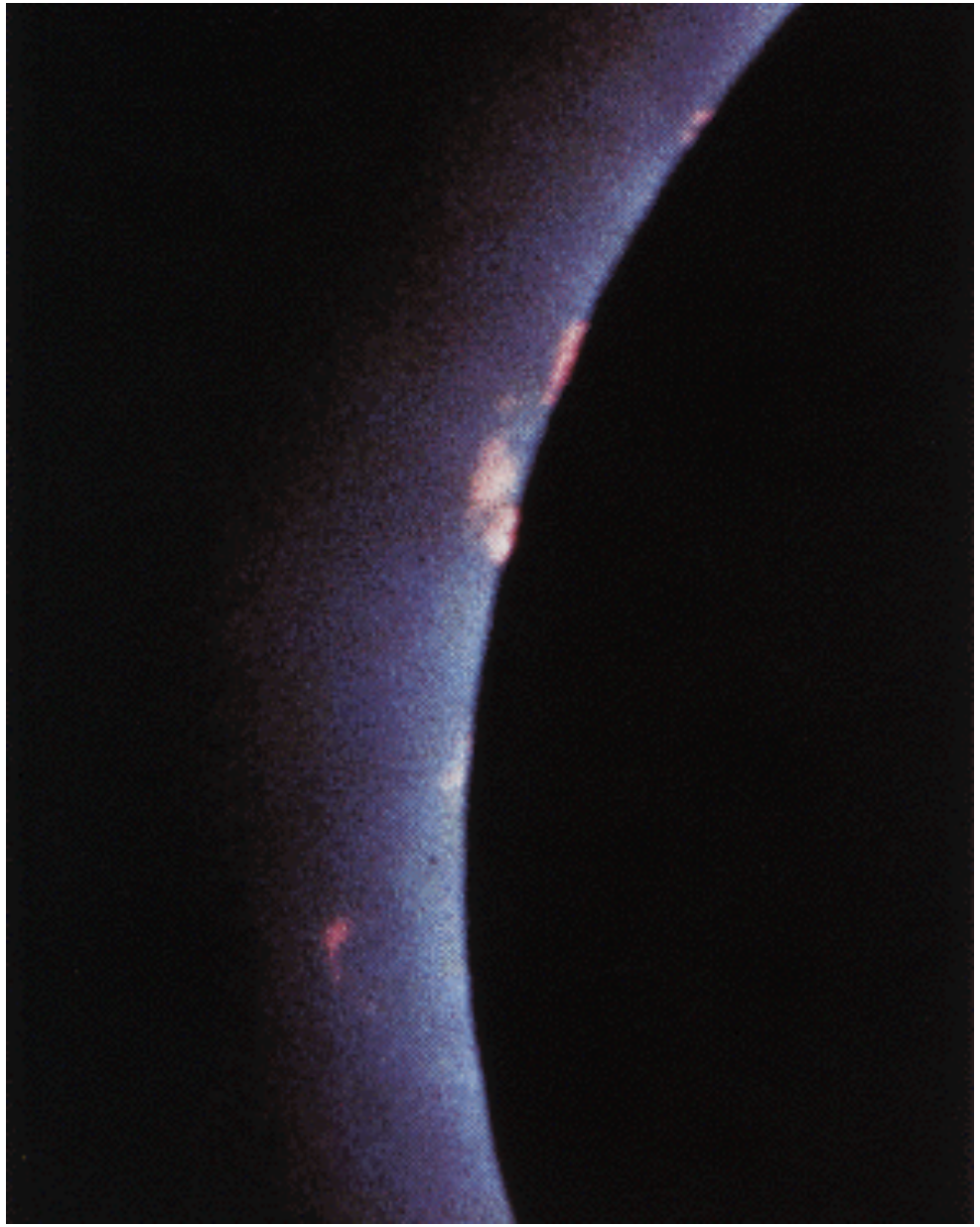
1. Eruption of **Prominences**/ **Filaments**
日珥噴發

2. Solar flare / CME (Coronal mass ejection)
太陽閃焰＋日冕物質拋射

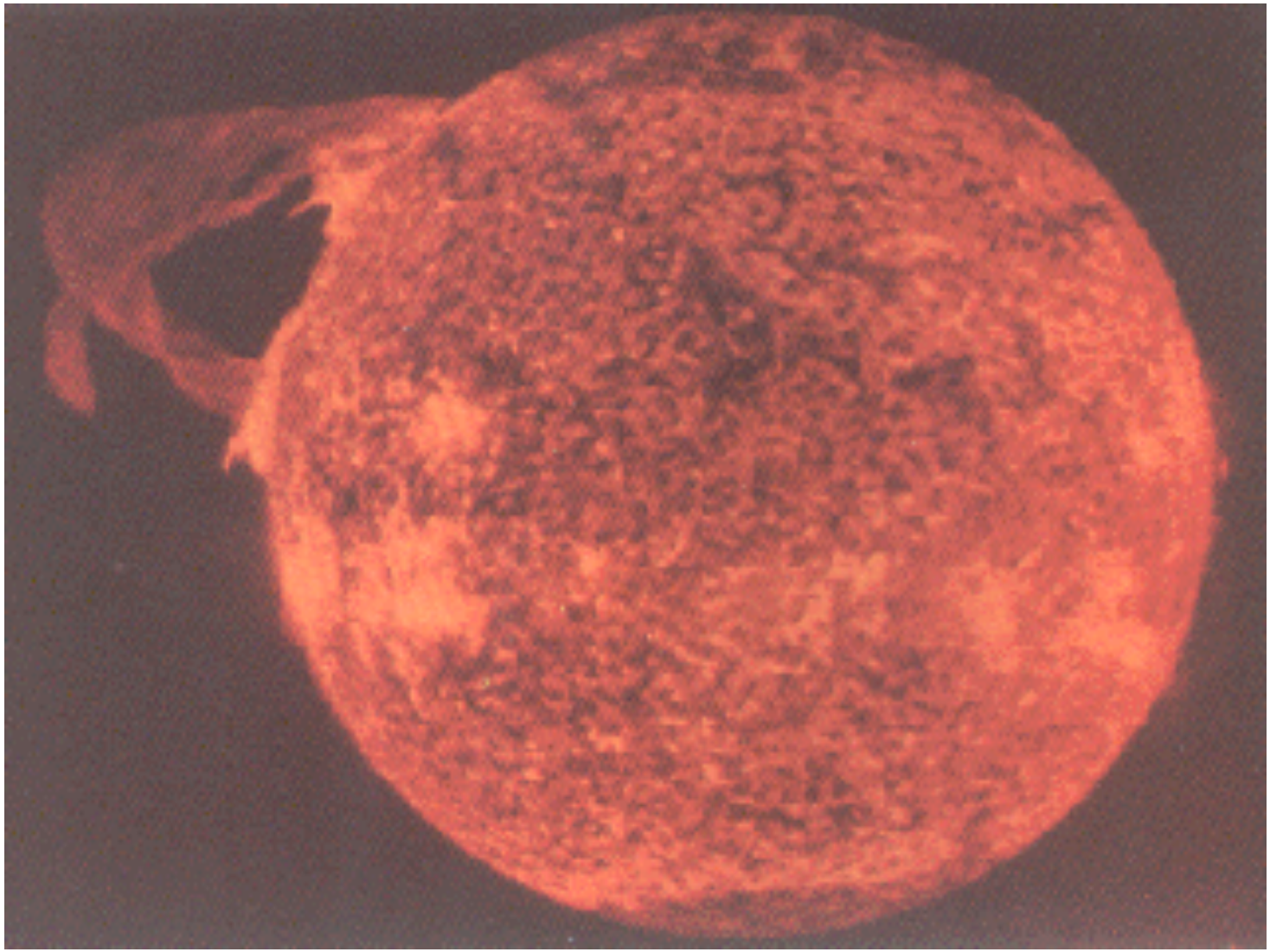
3. Interplanetary shock followed by magnetic cloud in the solar wind
行星際空間激震波，後面跟著磁雲

Red: Prominences

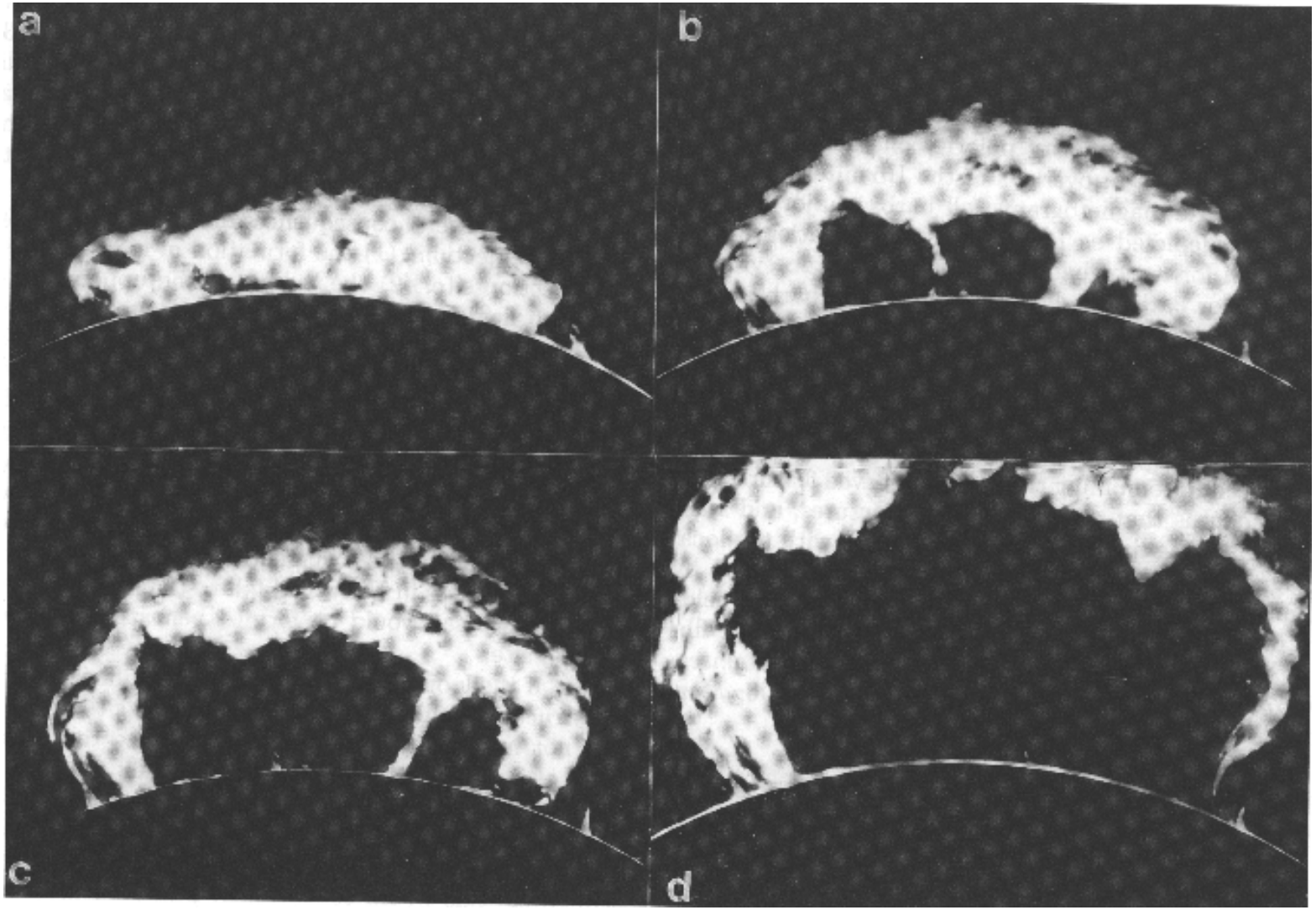
Blue: Corona



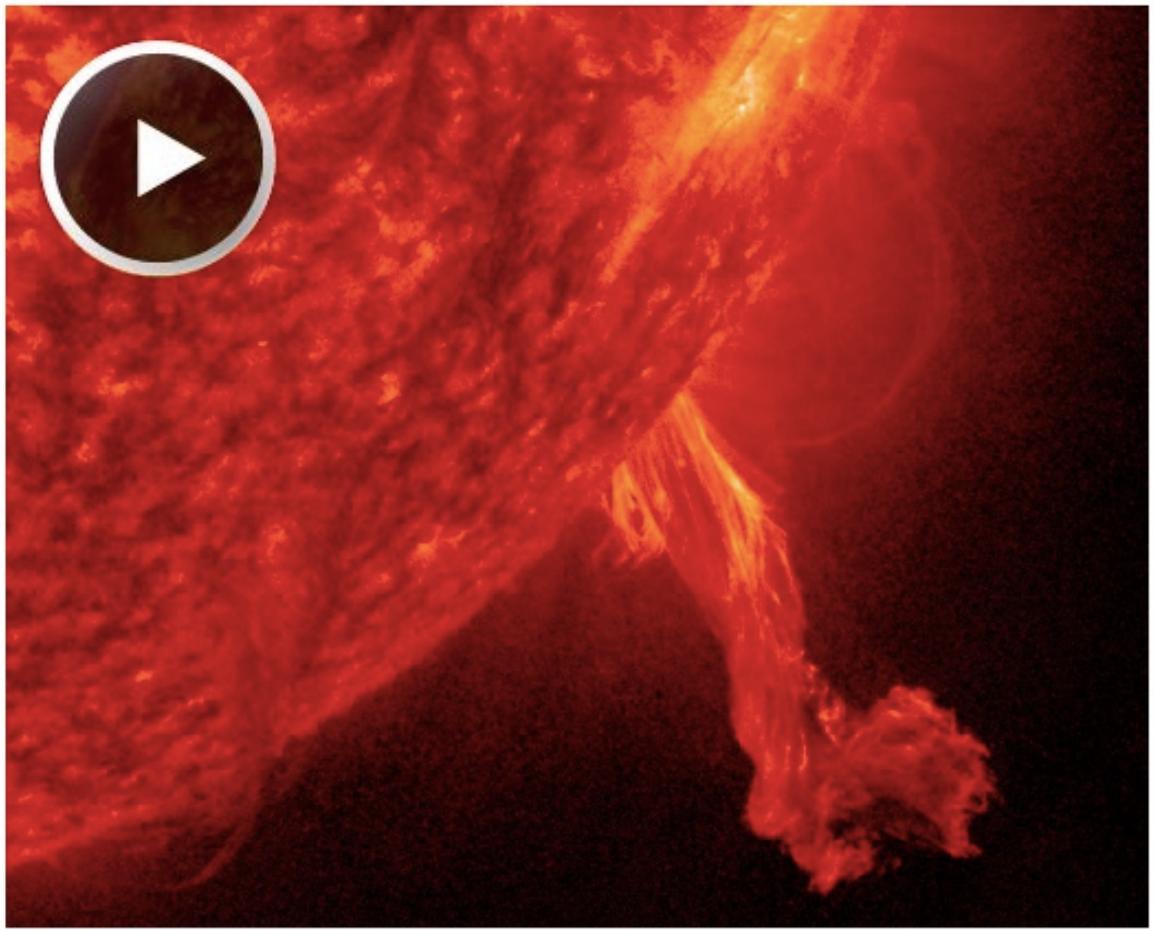
Prominences (UV observation)



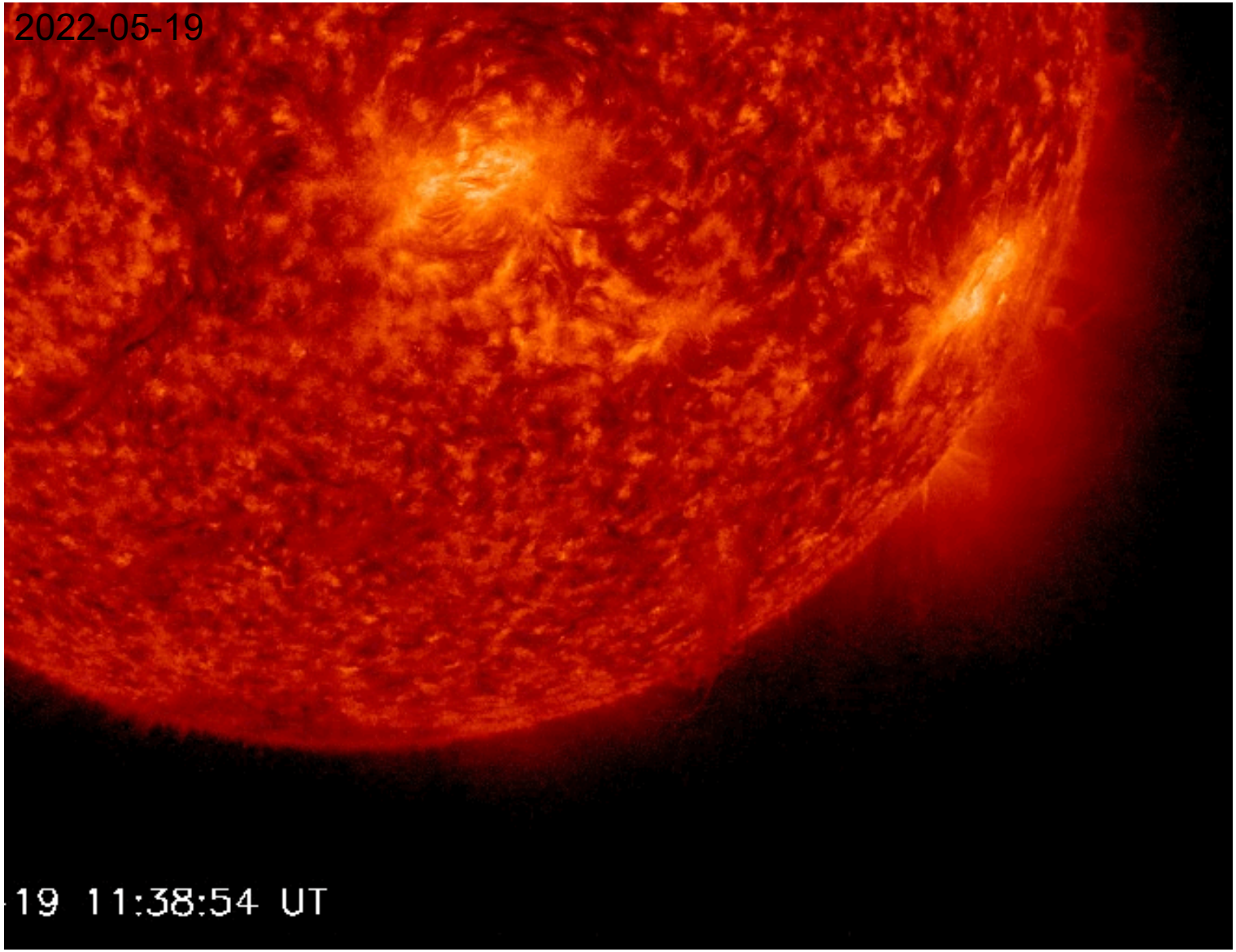
Prominence eruption



JUMPING PLASMA FOUNTAINS: Today, a massive jet of plasma shot out of the sun's southwestern limb. NASA's Solar Dynamics Observatory recorded the eruption: 2022-05-19



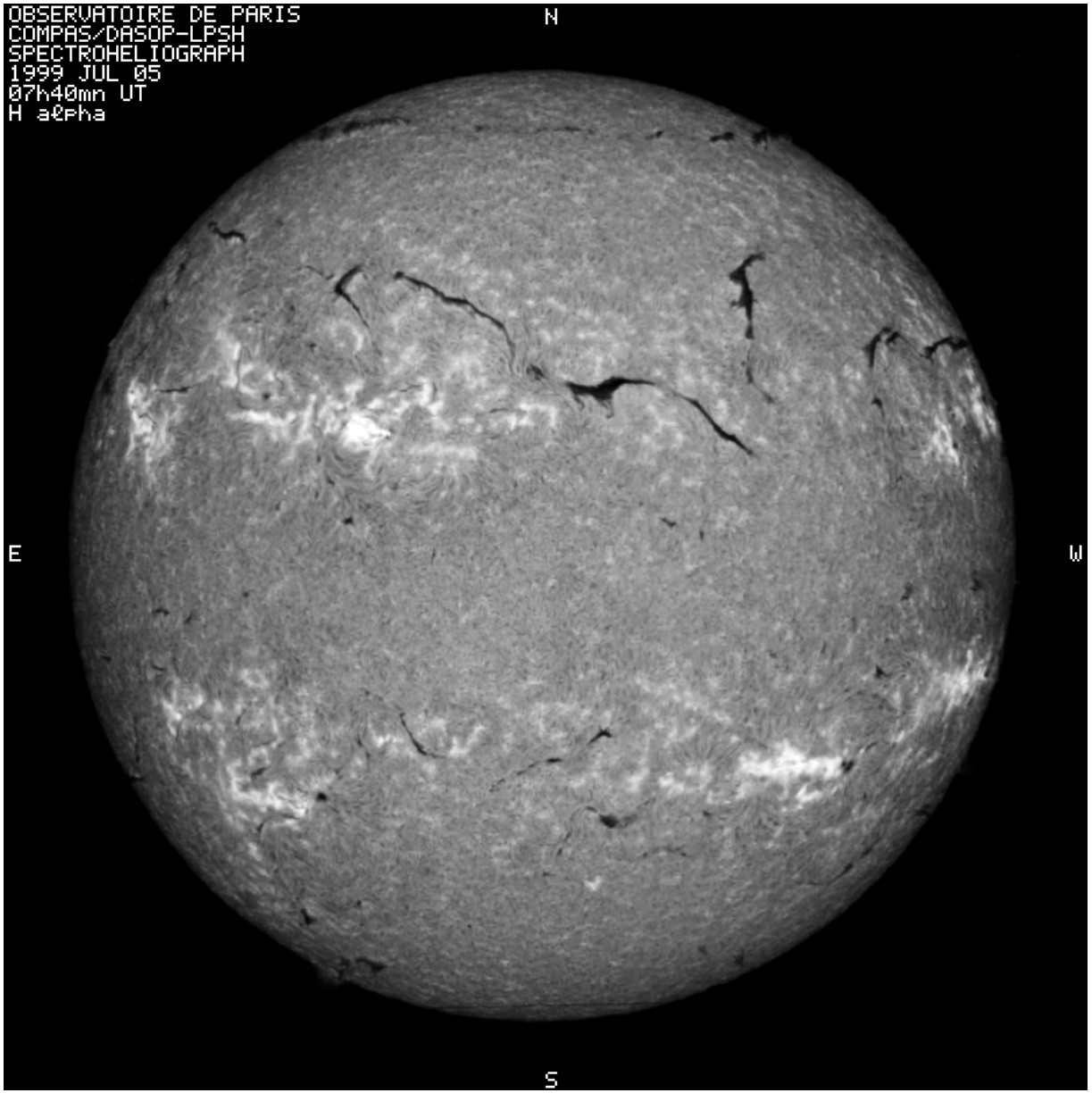
The base of the jet is twice as wide as Earth, and its apex is 10 times as tall. The towering plume almost certainly propelled a CME away from the sun (confirmation awaits fresh data from SOHO coronagraphs). It won't hit Earth.


2022-05-19
19 11:38:54 UT

Filaments

The Observatoire de Paris

H-alpha image
05 July 1999



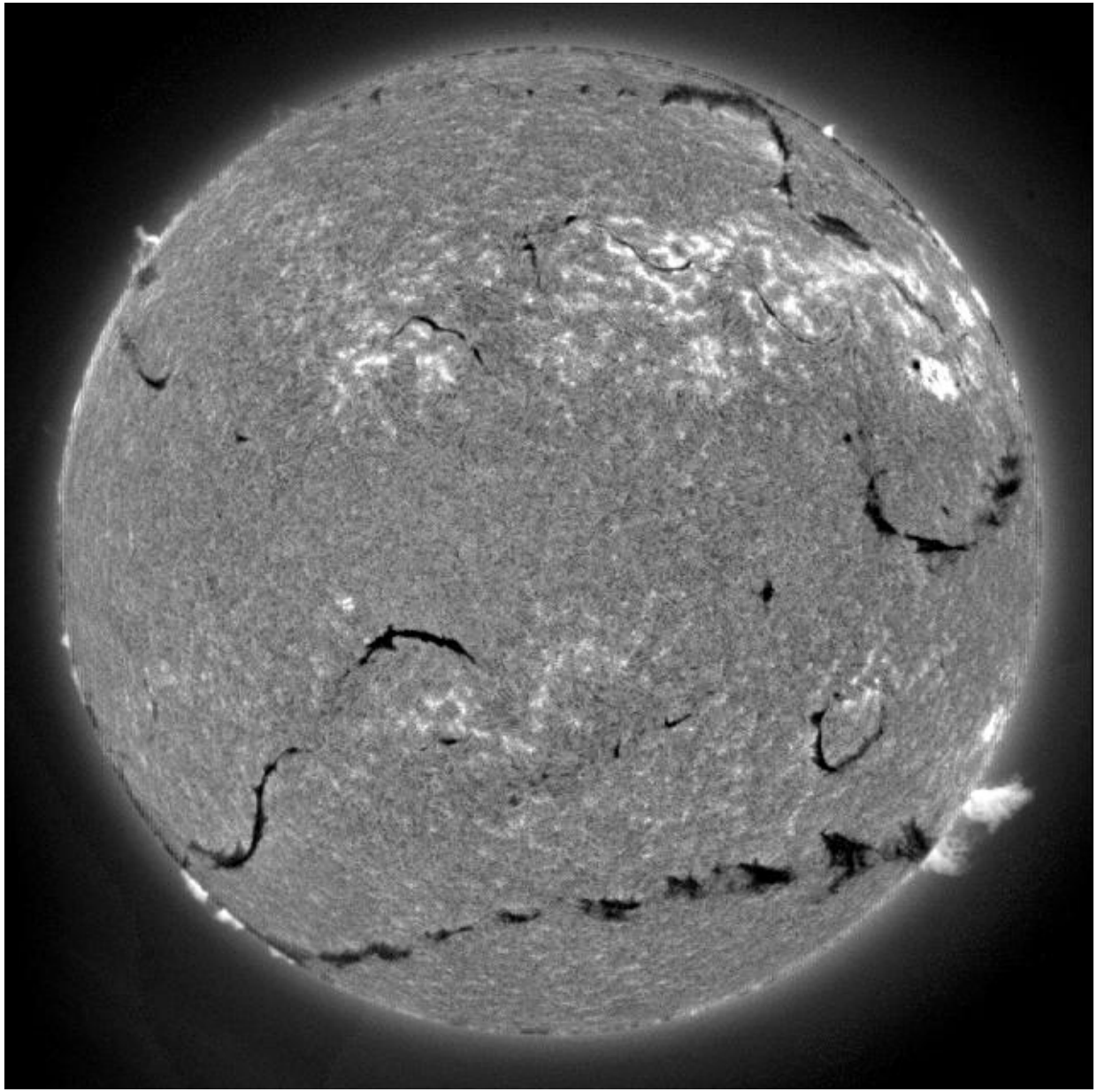
- 氫-阿法光 (H-alpha) 是一種深紅色的可見光，波長約為656.3奈米(nm) 也就是 6563 埃(Å, Angstroms)。屬於巴爾麥系列（Balmer series, from n ≥ 3 to n = 2）的光子。（可見光波長約 760-380 nm）
- 這樣波長的 氫-阿法 光子，只能把 氫原子裡的價電子 從 n=2 的激發態，往上激發到 n=3 的激發態，但還不足以使這些氫原子游離。
- 這些處在 n=3 激發態的氫原子，很容易 (朝其他方向) 重新放出一個 氫-阿法光 的光子，讓價電子回到 n=2 的激發態，甚至再放出一個 紫外線 光子讓價電子回到 n=1 的基礎態 （萊曼系列 Lyman series, from n ≥ 2 to n = 1 ）
- 因為**萊曼系列**的**紫外線**會被大氣臭氧層吸收，所以通常**要在太空中觀測**。但是**巴爾麥系列**的可見光，尤其**紅光**，不會被大氣吸收或散射，所以**地面觀測站**，可以鎖定接收波長為656.3nm 附近的光，來觀測太陽，就可以很輕鬆的觀測太陽光盤上的「暗紋」分佈。
- 如果把太陽光盤遮住，還可以很清晰的觀測到太陽光盤邊緣浮起來的日珥結構。如下一張

Filaments & Prominences

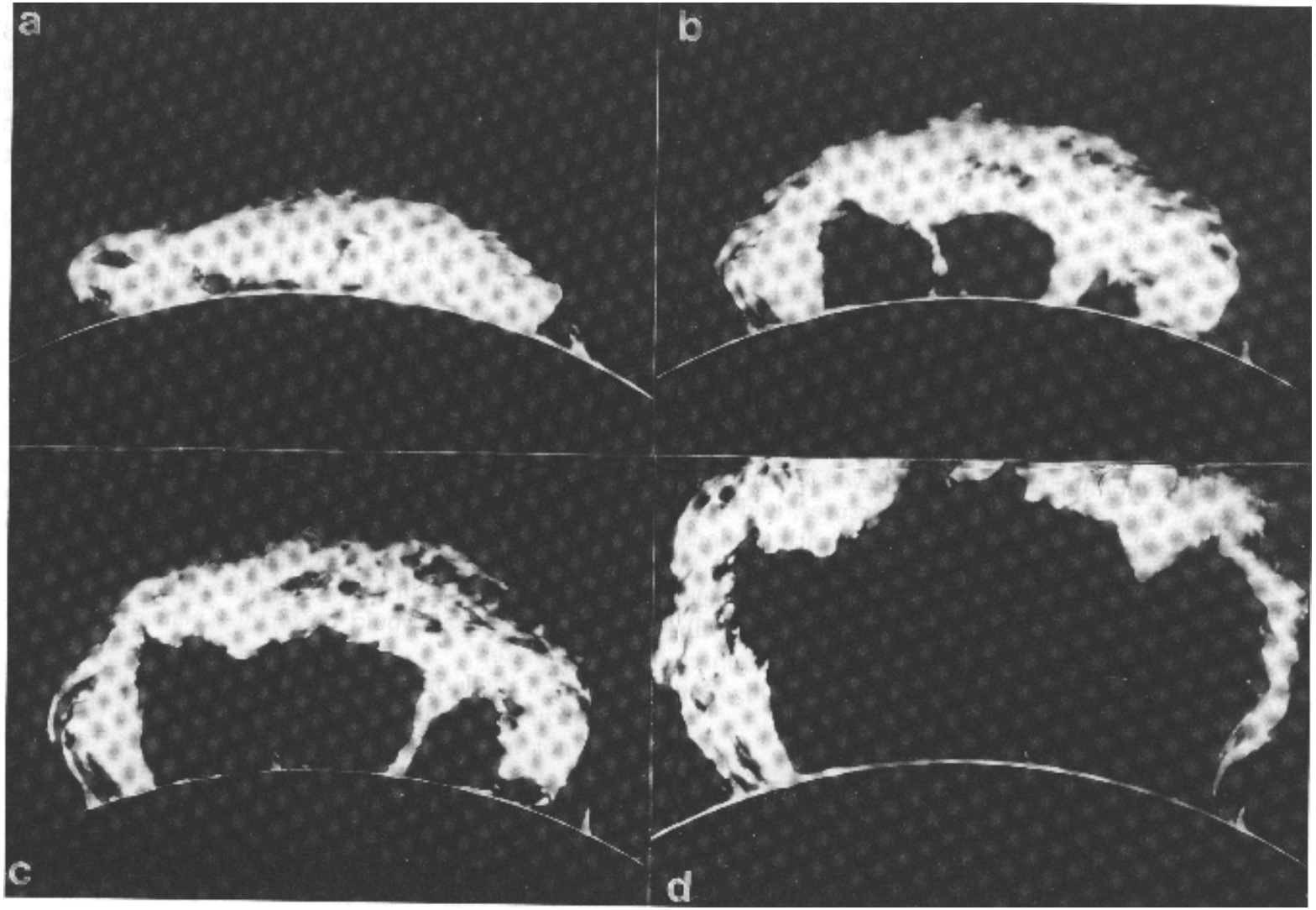
The Big Bear Solar Observatory (BBSO)

H-alpha full disk image
30 January 1999

http://www.bbso.njit.edu/brochure.html

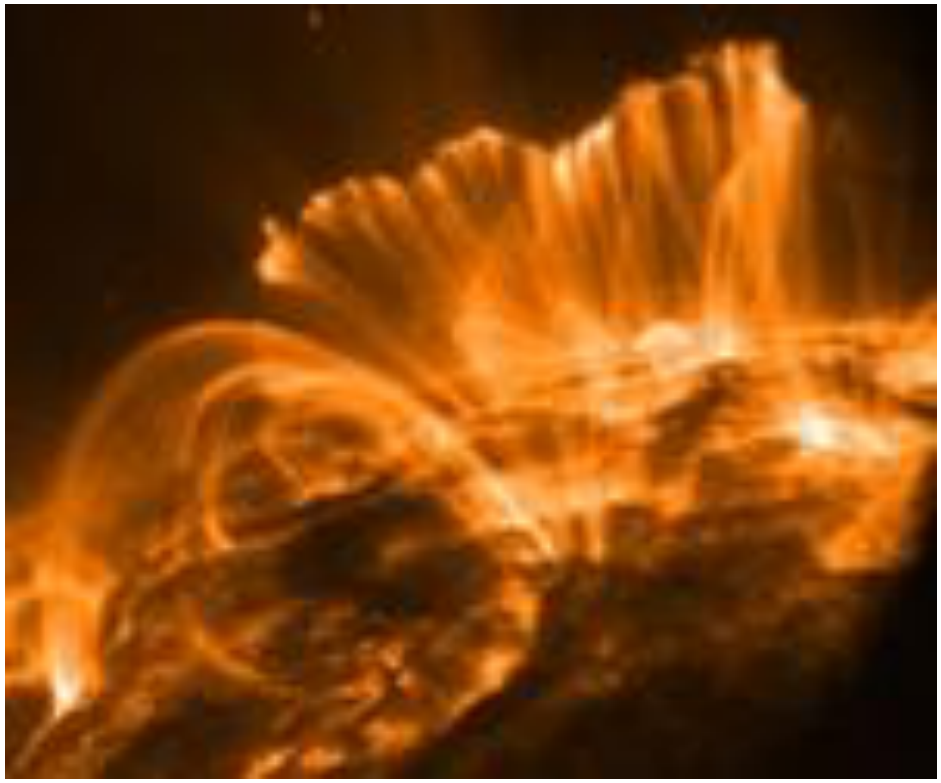


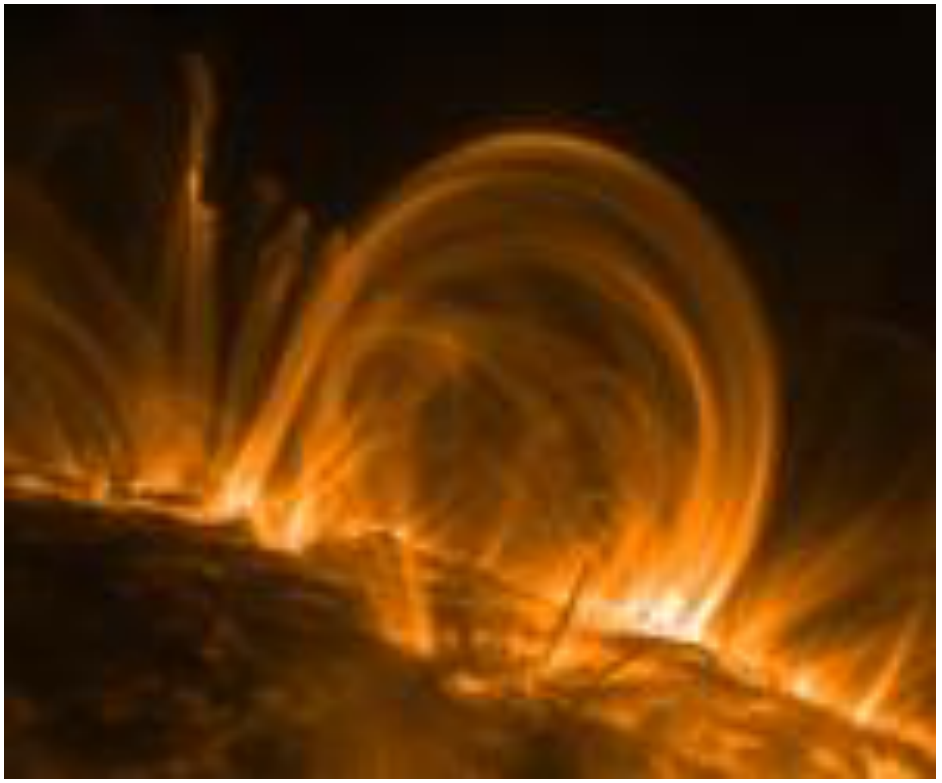
Prominence eruption



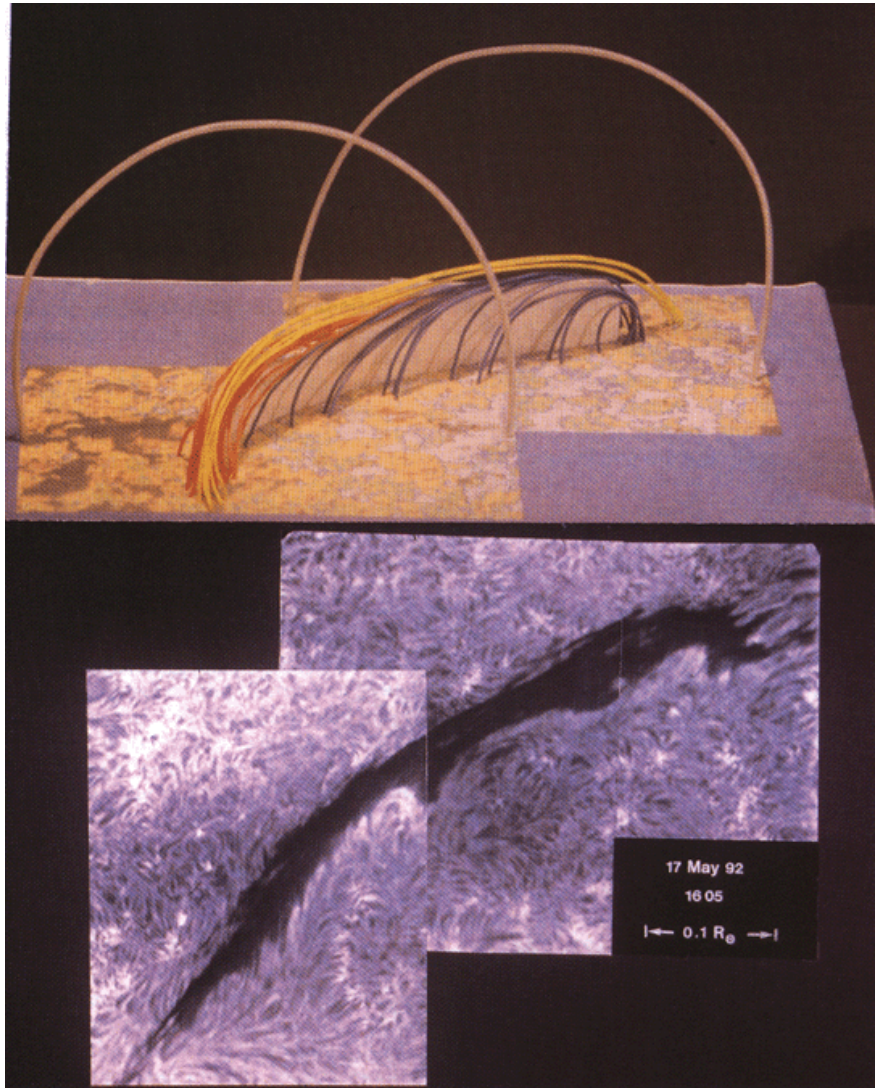
EUV Images from the Transition Region And Coronal Explorer (TRACE) spacecraft
Coronal Loops 日冕中的拱門結構(Fully ionized gas)

https://www.nasa.gov/mission_pages/stereo/multimedia/TRACE_images.html

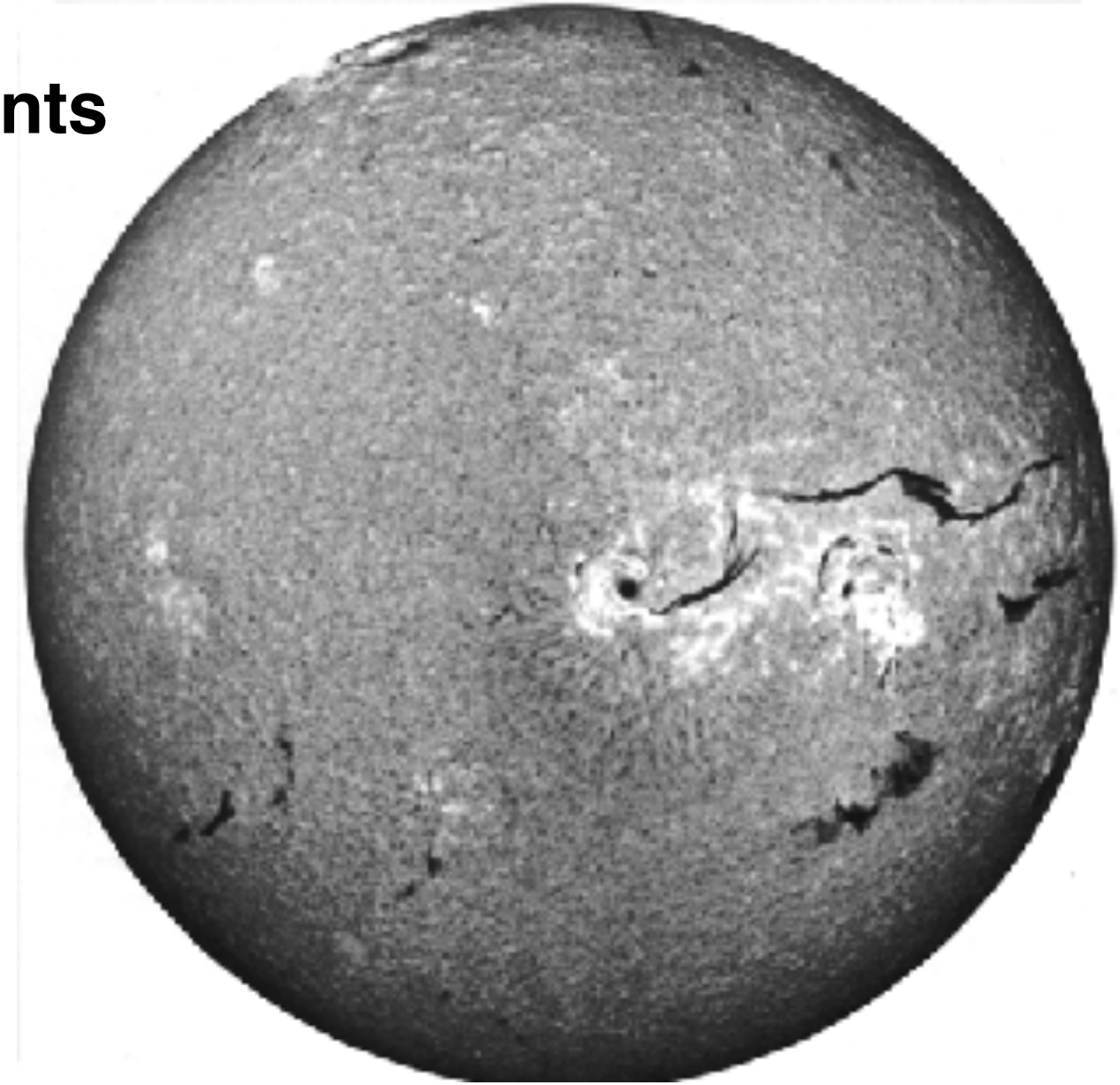




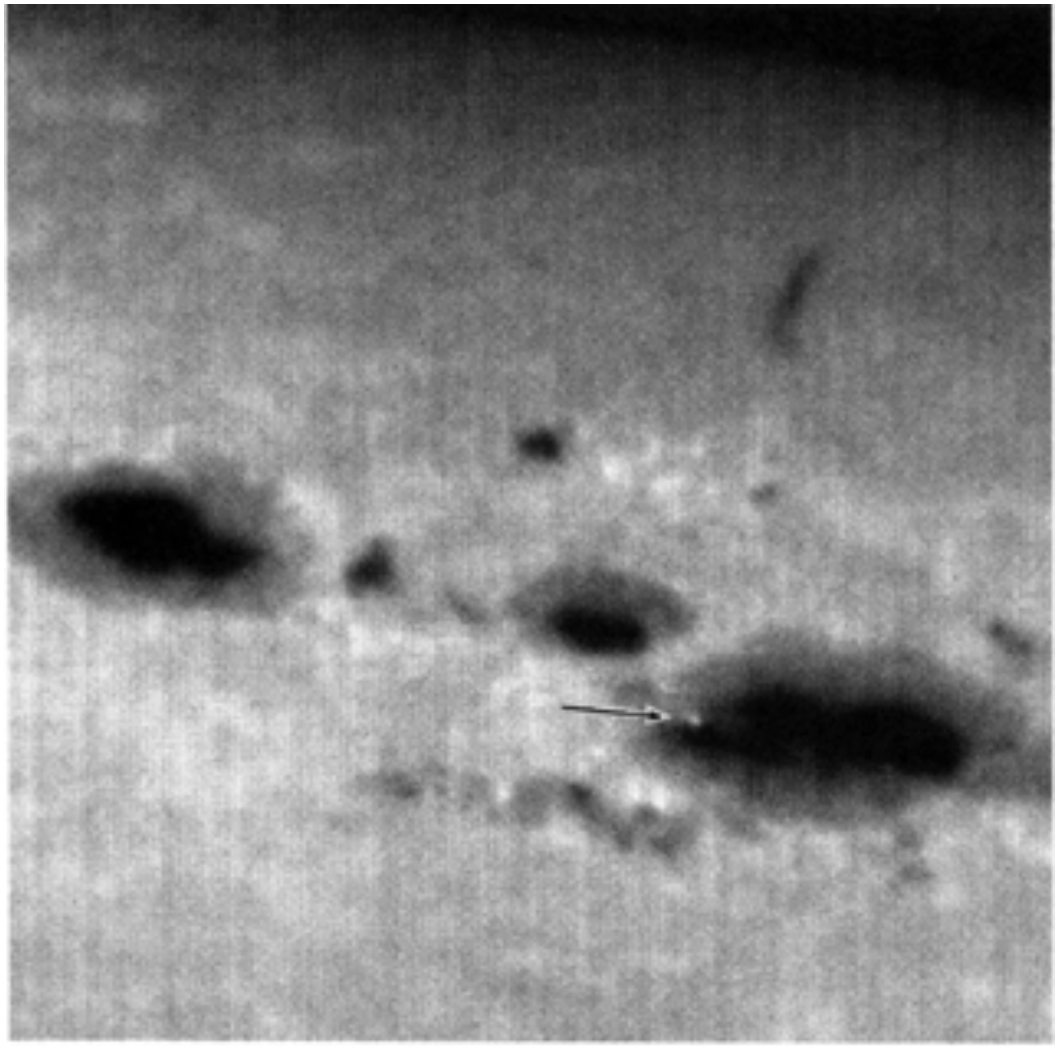
Filaments magnetic field and coronal loop



Filaments

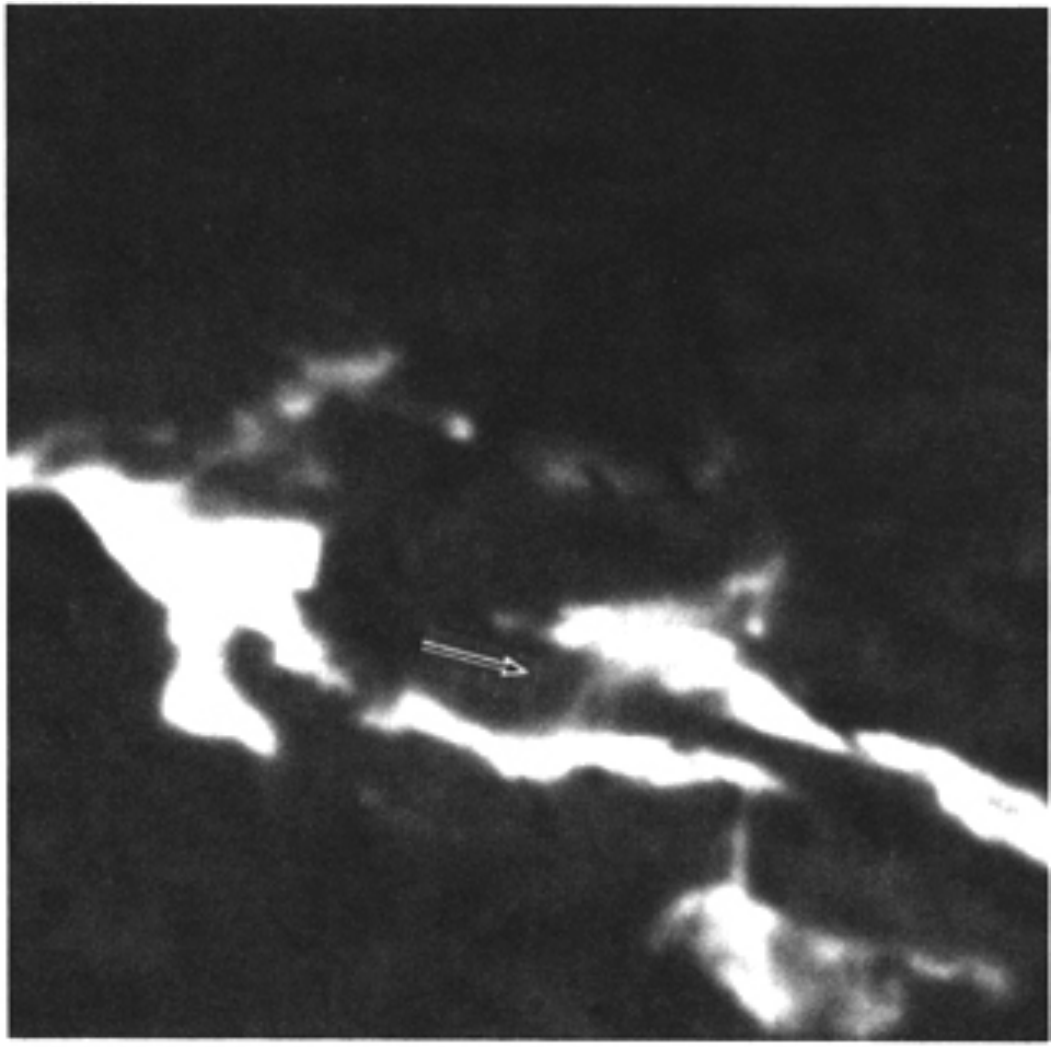


White light Image taken prior to solar flare

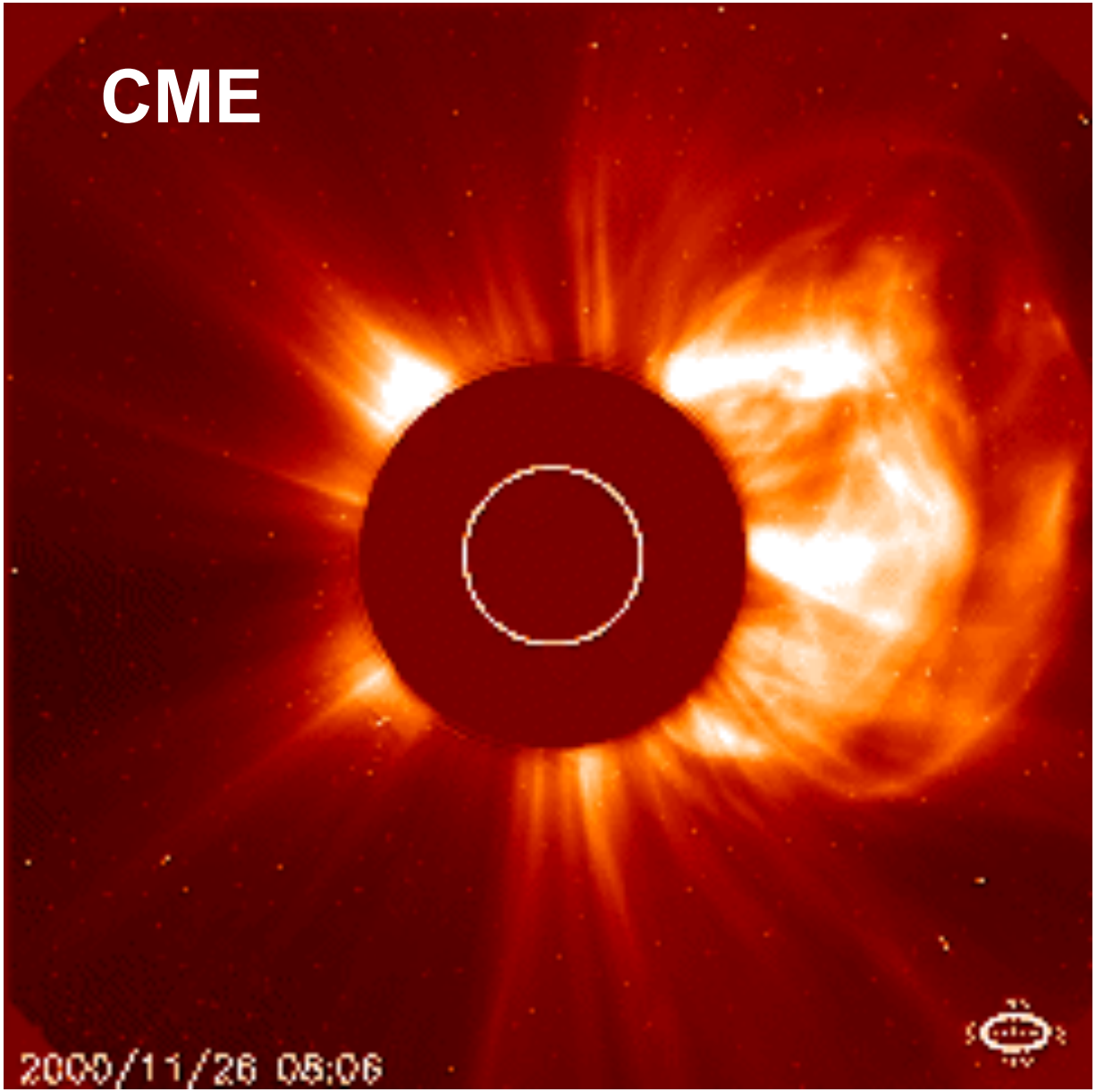


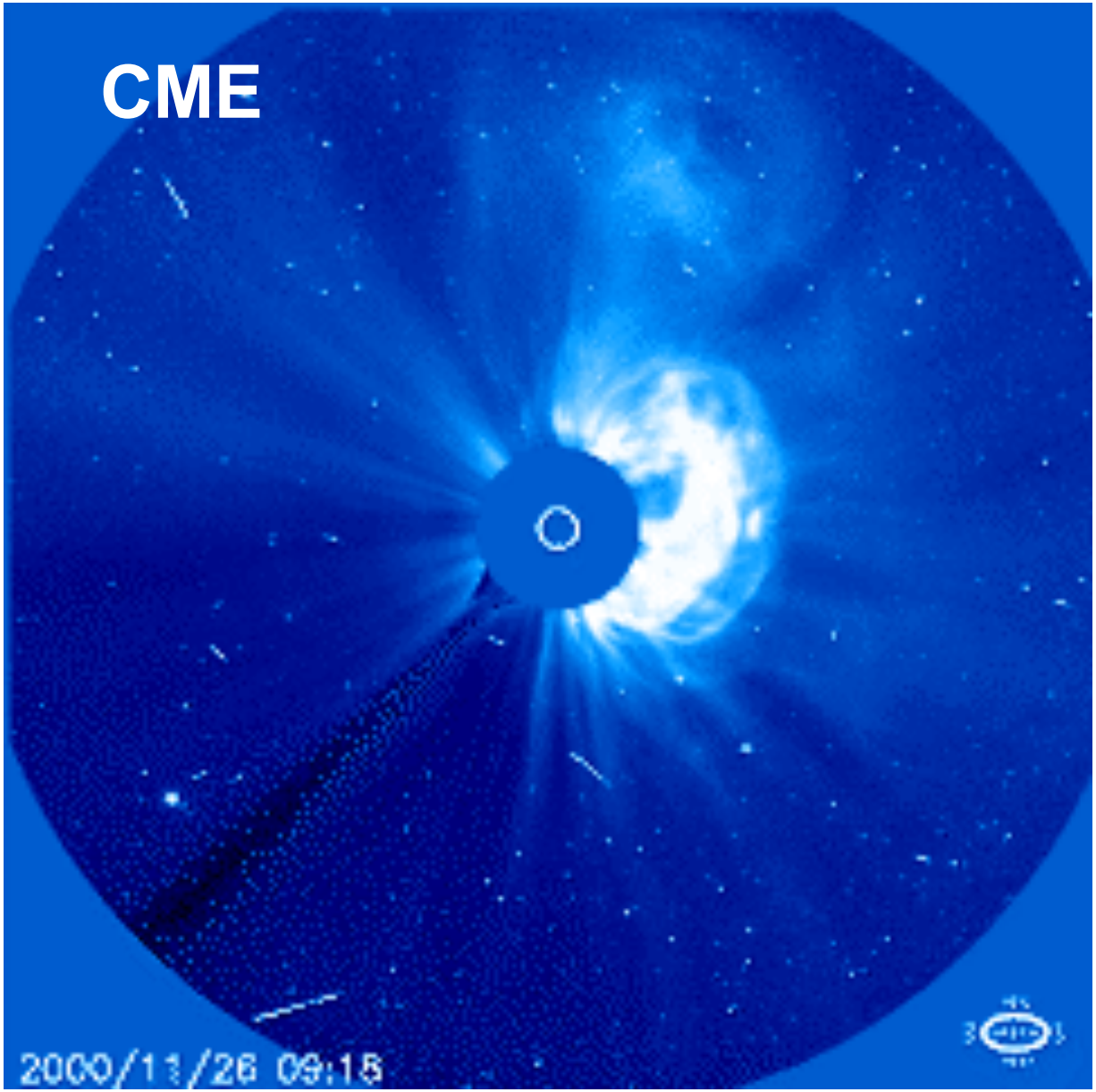
17:37:19 UT

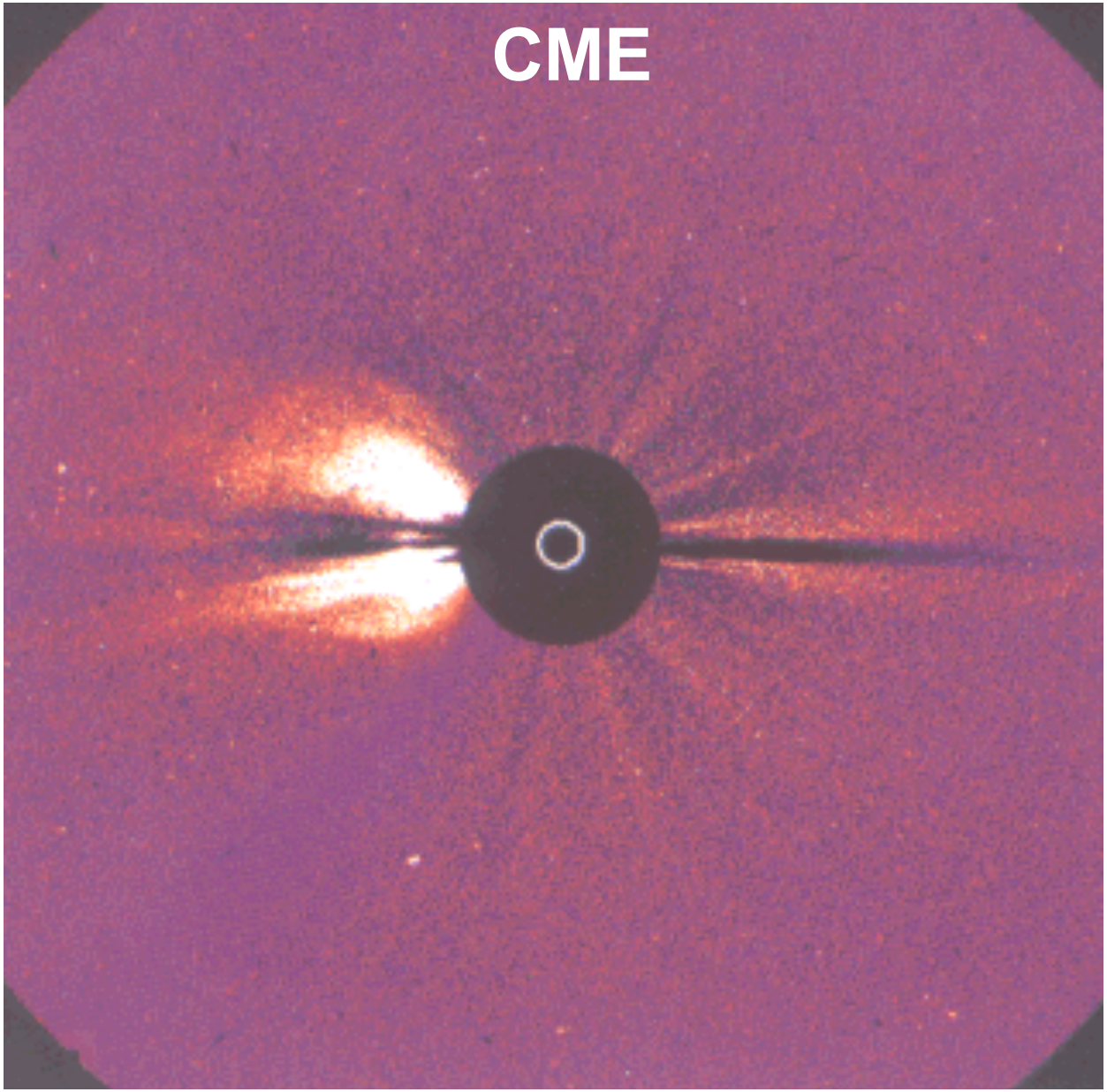
White light Image taken during the solar flare



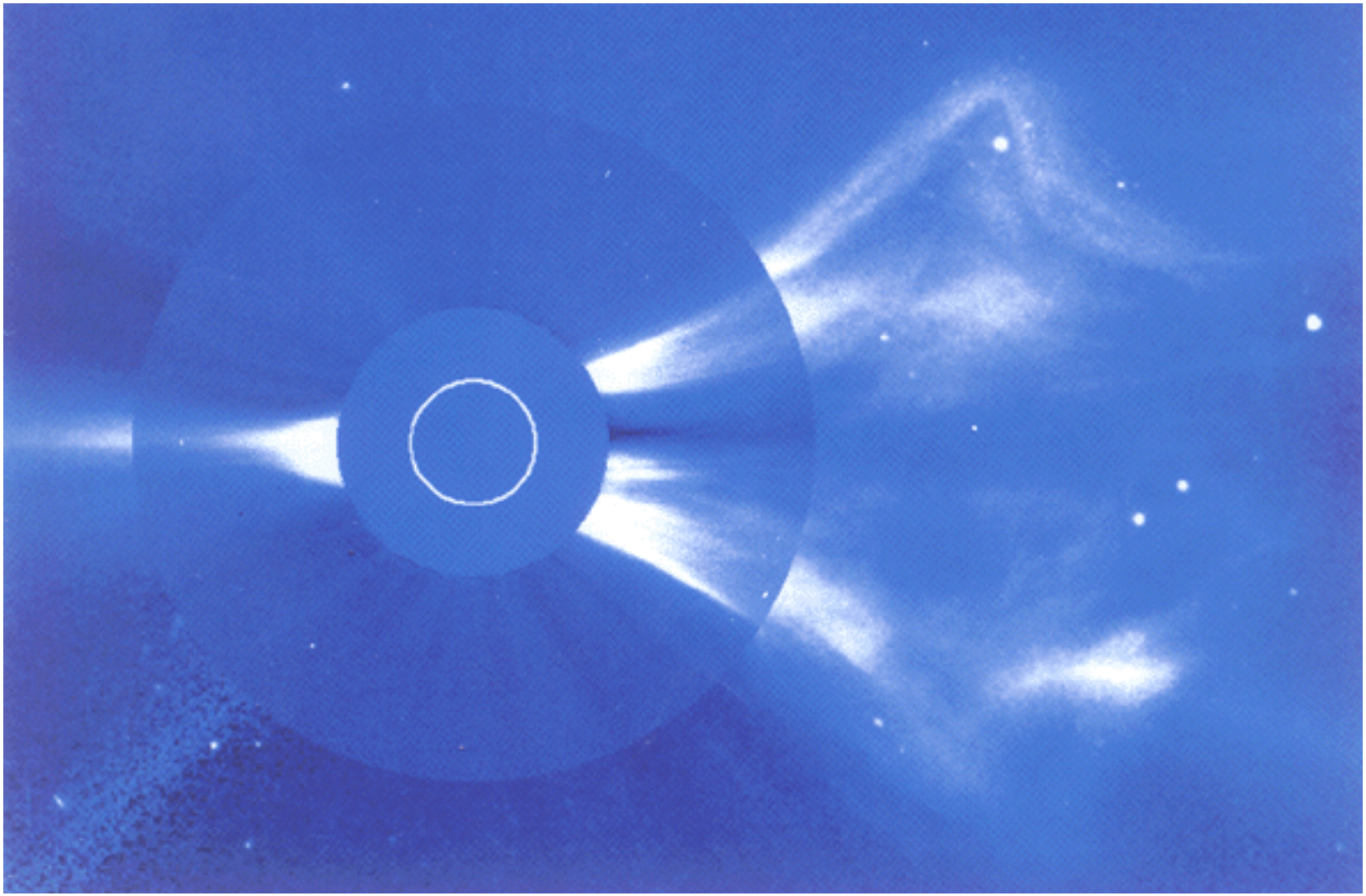
18:23:59 UT


CME
2000/11/26 06:06


CME
2000/11/26 09:15


CME

CME



Magnetic cloud

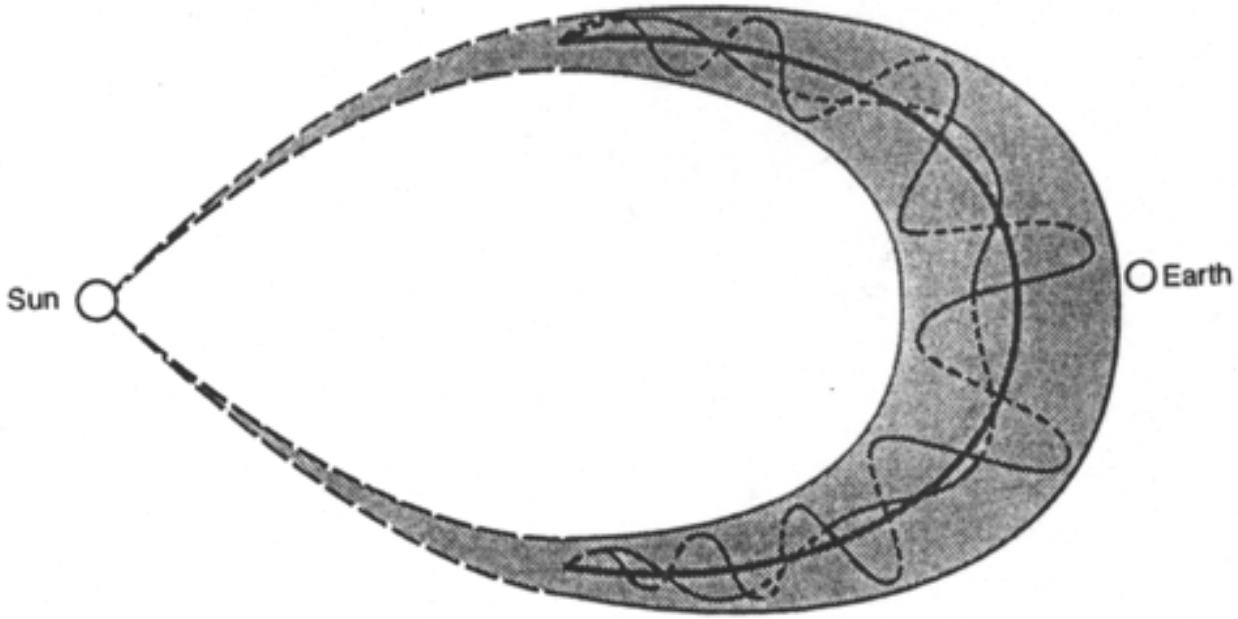
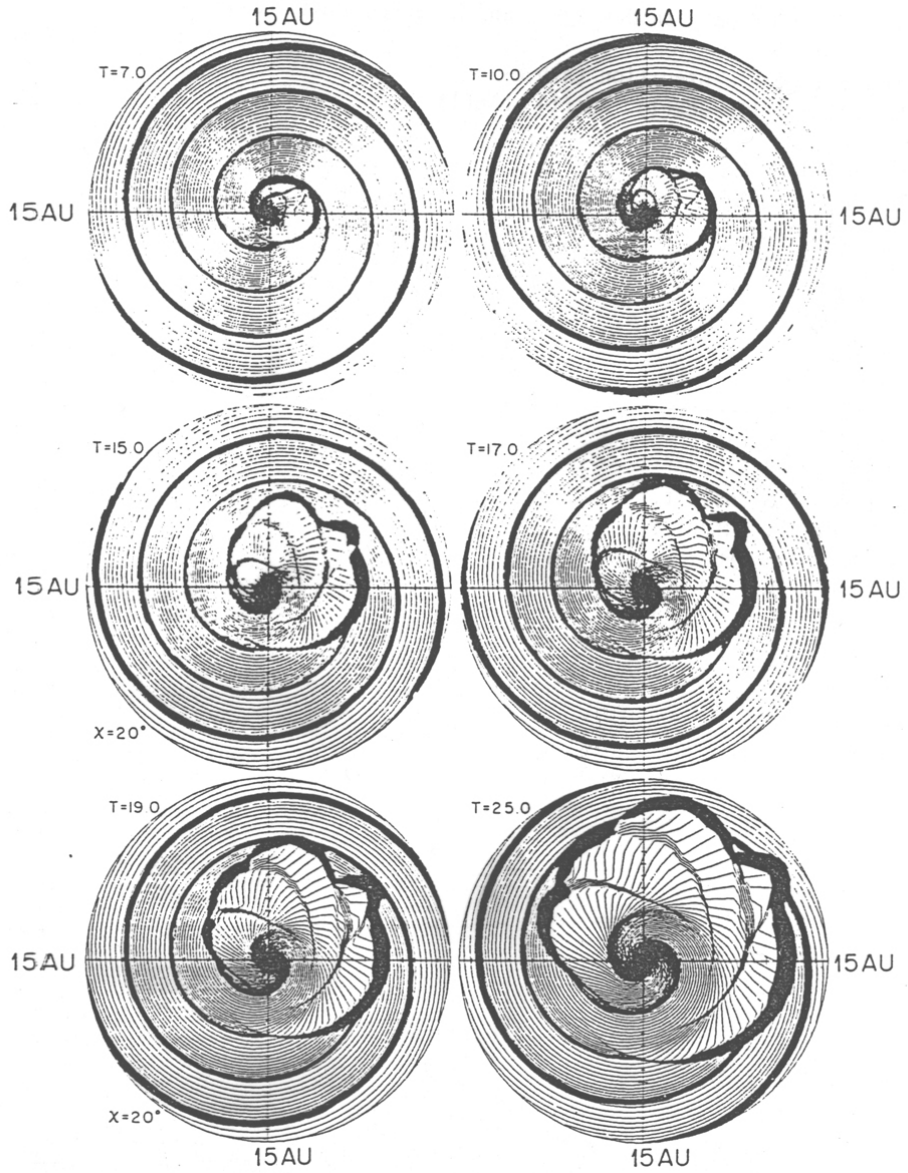
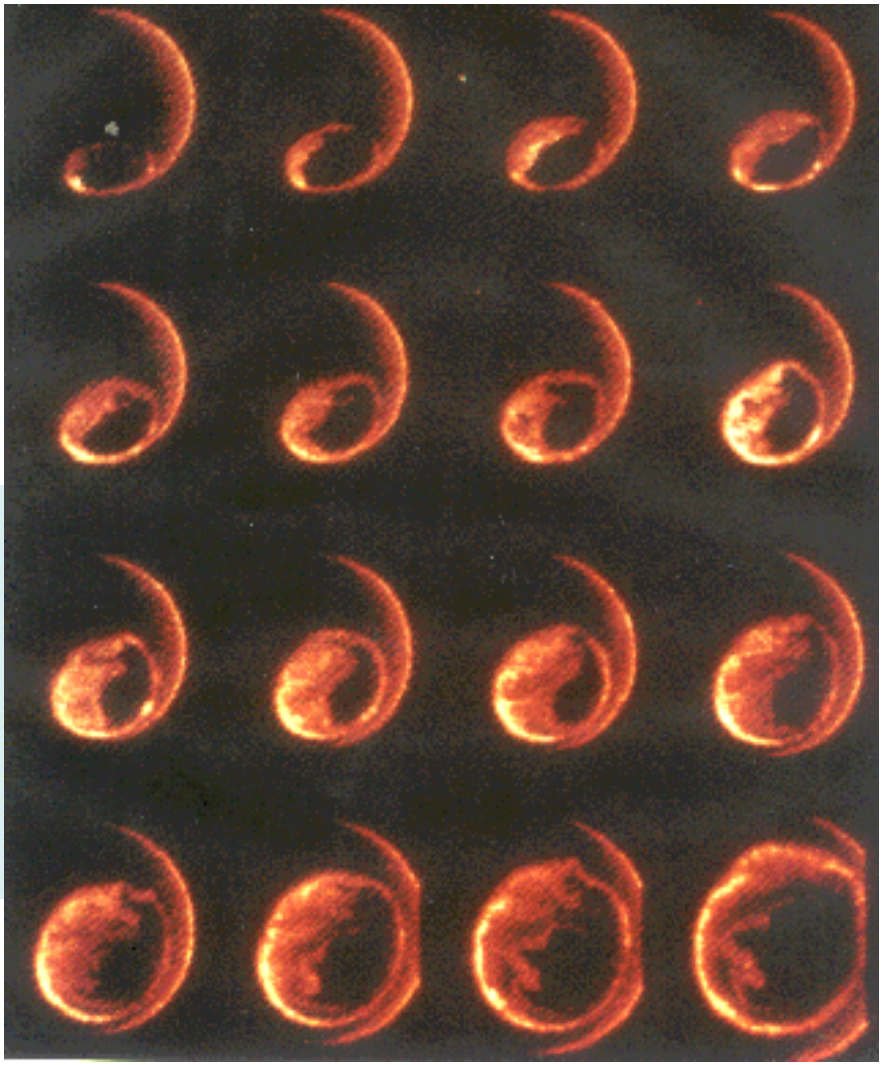


Figure 1. Idealized view of a magnetic cloud with a relaxed force-free field, given by *Lundquist* [1950].


15AU
15AU
T=7.0
T=10.0
15AU
15AU
T=15.0
T=17.0
15AU
15AU
X=20°
T=19.0
T=25.0
15AU
15AU
X=20°
15AU
15AU

40~50hrs after CME:

Substrom Auroral (UV Images)



1AU=8 min * 300000 km/s
If
Vshock = 800~1000 km/s
then
Traveling time=1AU/Vshock
=50~40hrs

Shock Waves in the Heliosphere
日磁層中的激震波

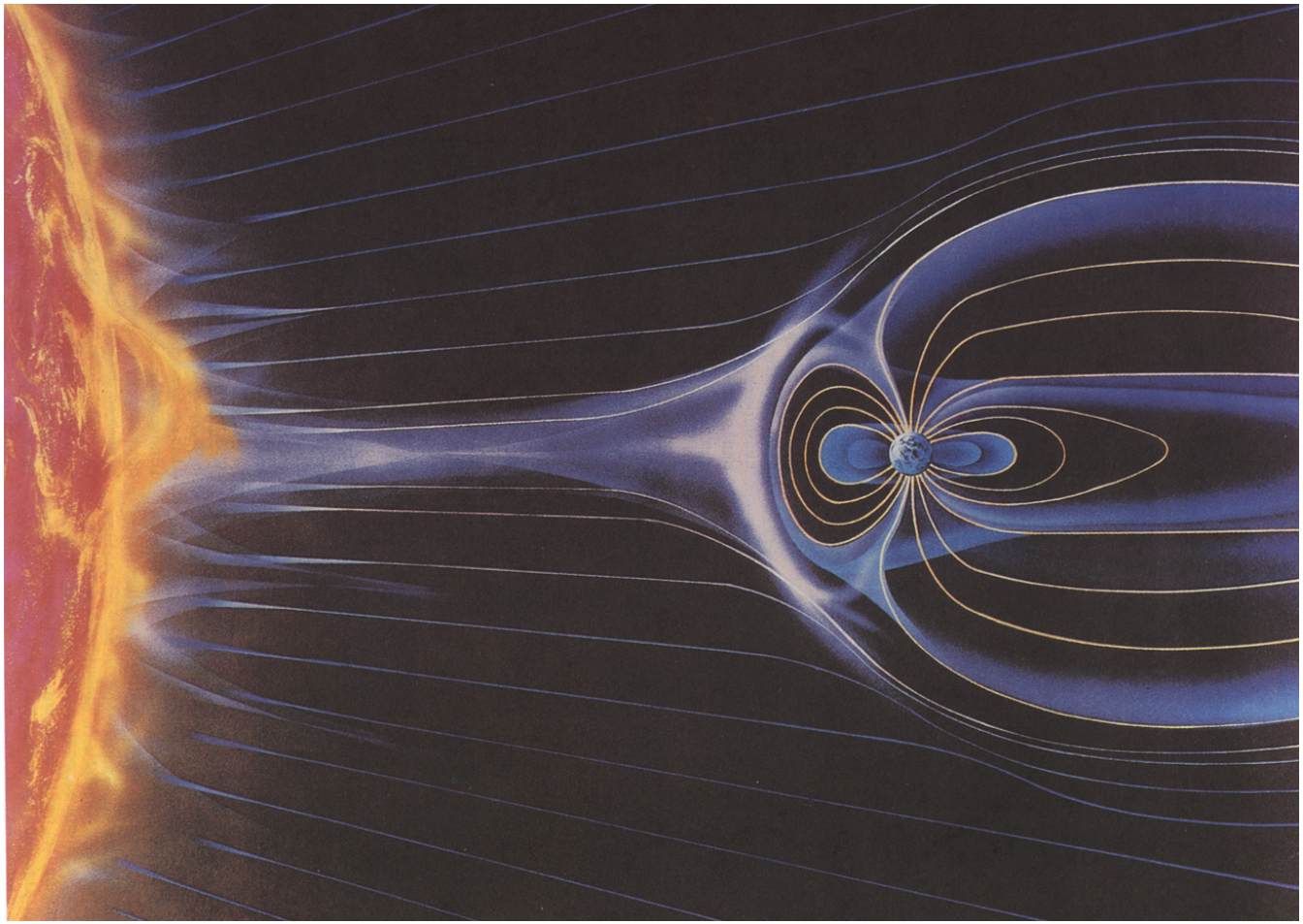
✓ · Co-rotating shocks （與太陽共轉的 行星際激震波）
A pair of shocks which are generated when high-speed solar wind overtaking slow solar wind

✓ · Solar-flare/CME associated shocks
（與 太陽閃焰/日冕物質拋射 相關的 行星際激震波）
Eruption of solar prominence/filament
→ Coronal Mass Ejection (CME) & Solar Flare
→ Interplanetary shock followed by Magnetic Cloud

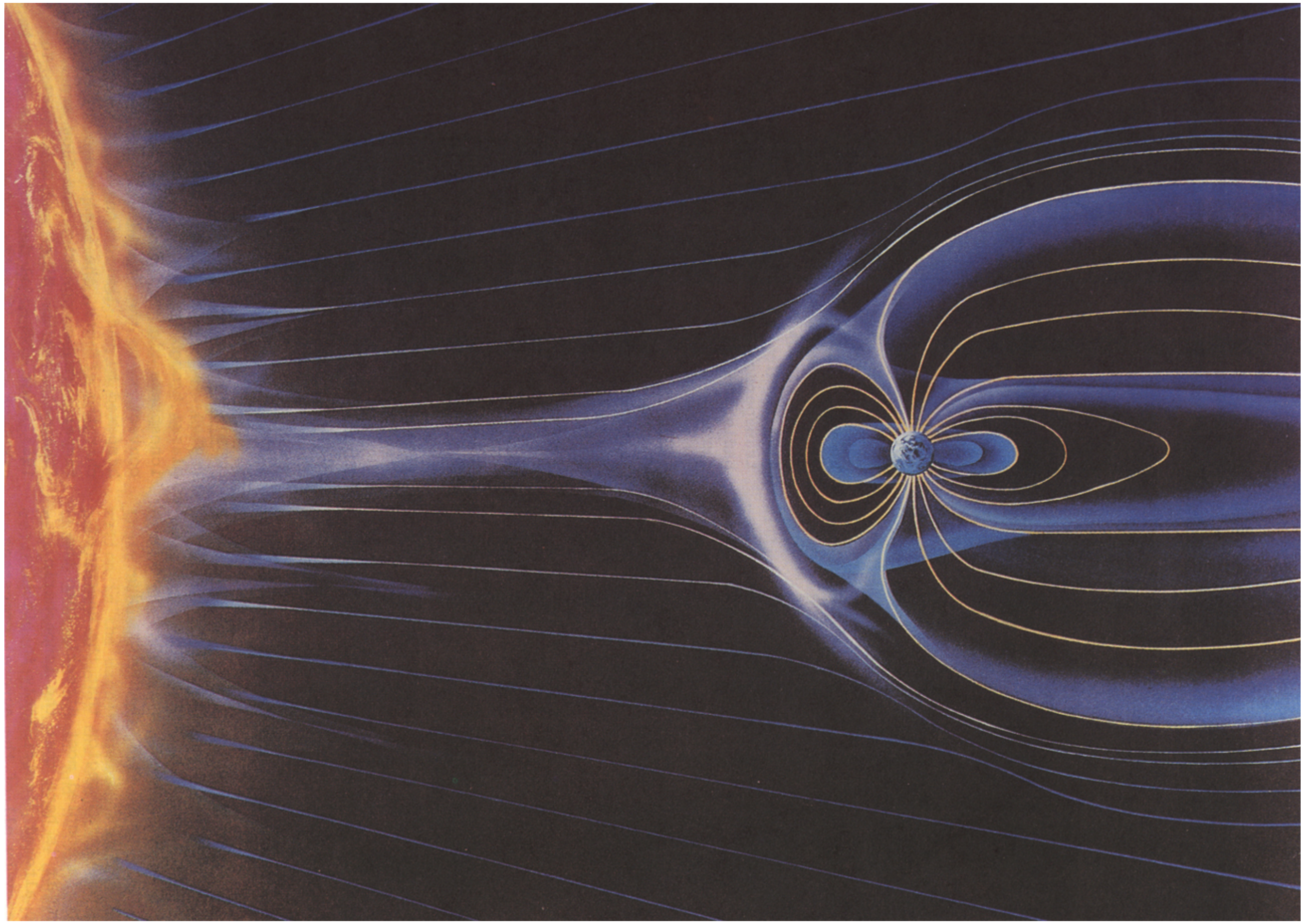
→ · Planetary bow shocks (行星 艏震波)

· Termination shock （太陽風 終止震波）
Termination of supersonic solar wind

Bow Shock 示意圖



Bow Shock 示意圖



$15R_E$

$30R_E$

磁頭寬度比地球寬度 放大15倍 截面積放大225倍

$30R_E$

磁尾寬度比地球寬度 放大30倍

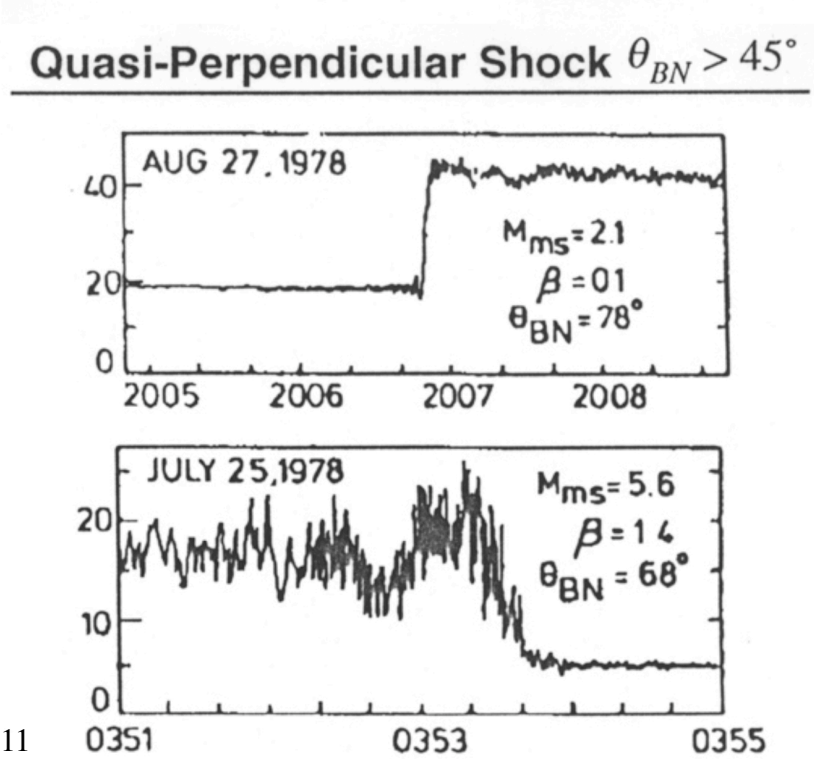
$10R_E$

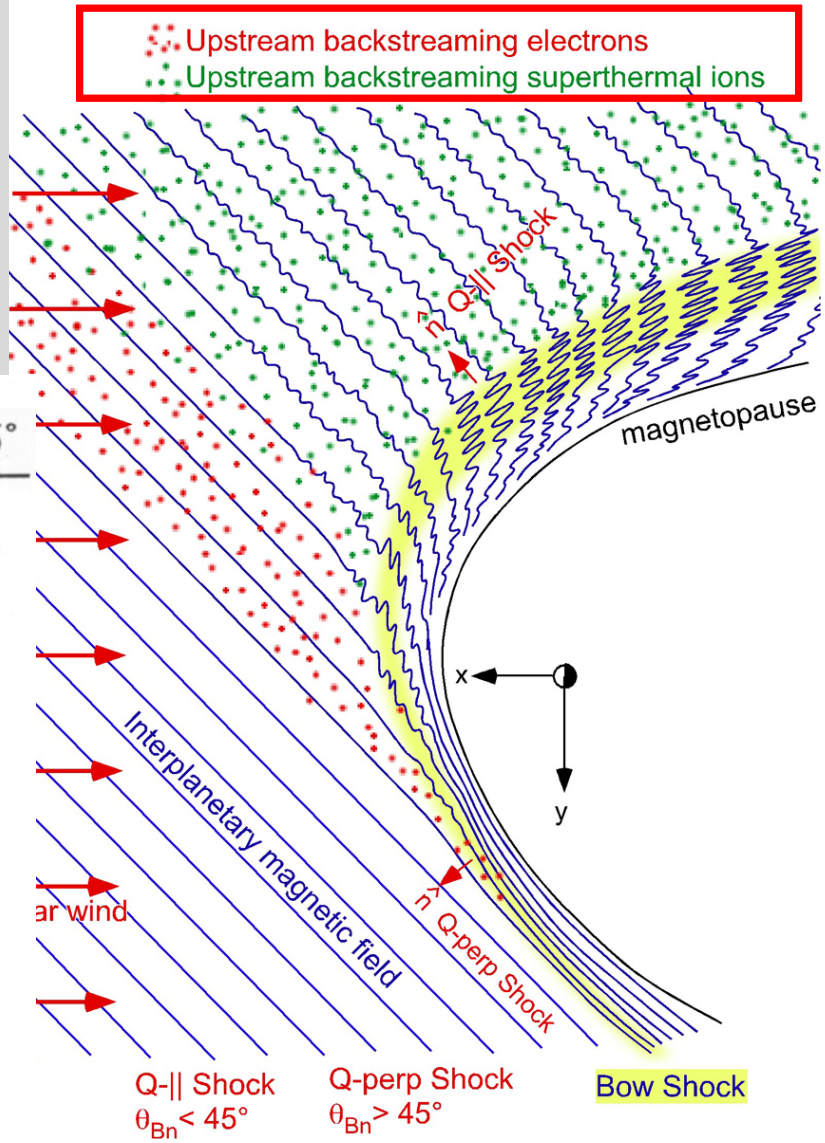
Planetary bow shocks（行星艏震波）

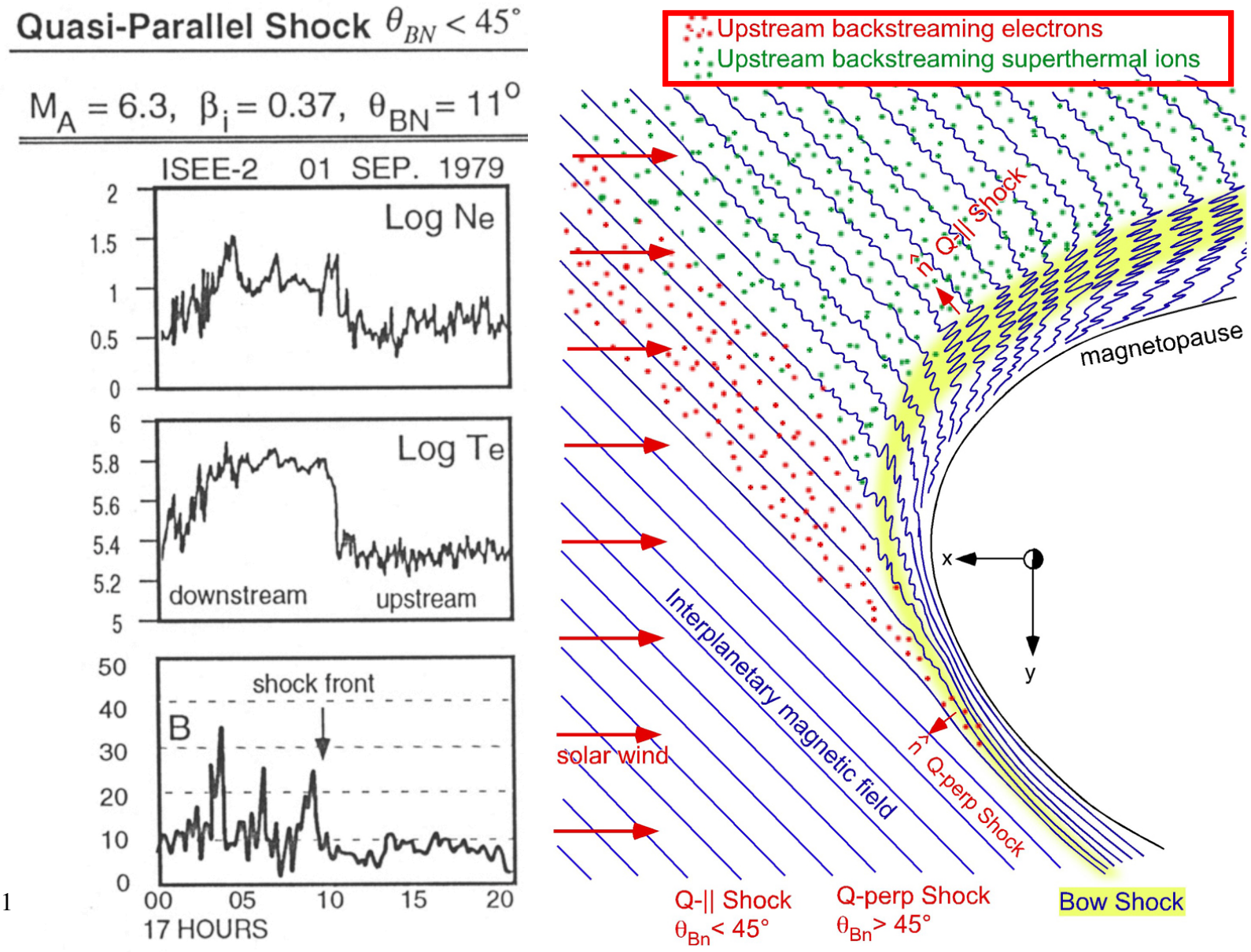
- Supermagnetosonic solar wind encounter planetary magnetosphere 當超音速太陽風遇到行星磁層
- Almost stationary --> easy to study
  但 Bow shock 與磁層頂之間距離，會隨太陽風速度減小而增加
- Quasi-perpendicular shock（準垂直激震波）
- Quasi-parallel shock（準平行激震波）
- Supercritical shock (high Mach number M>3)

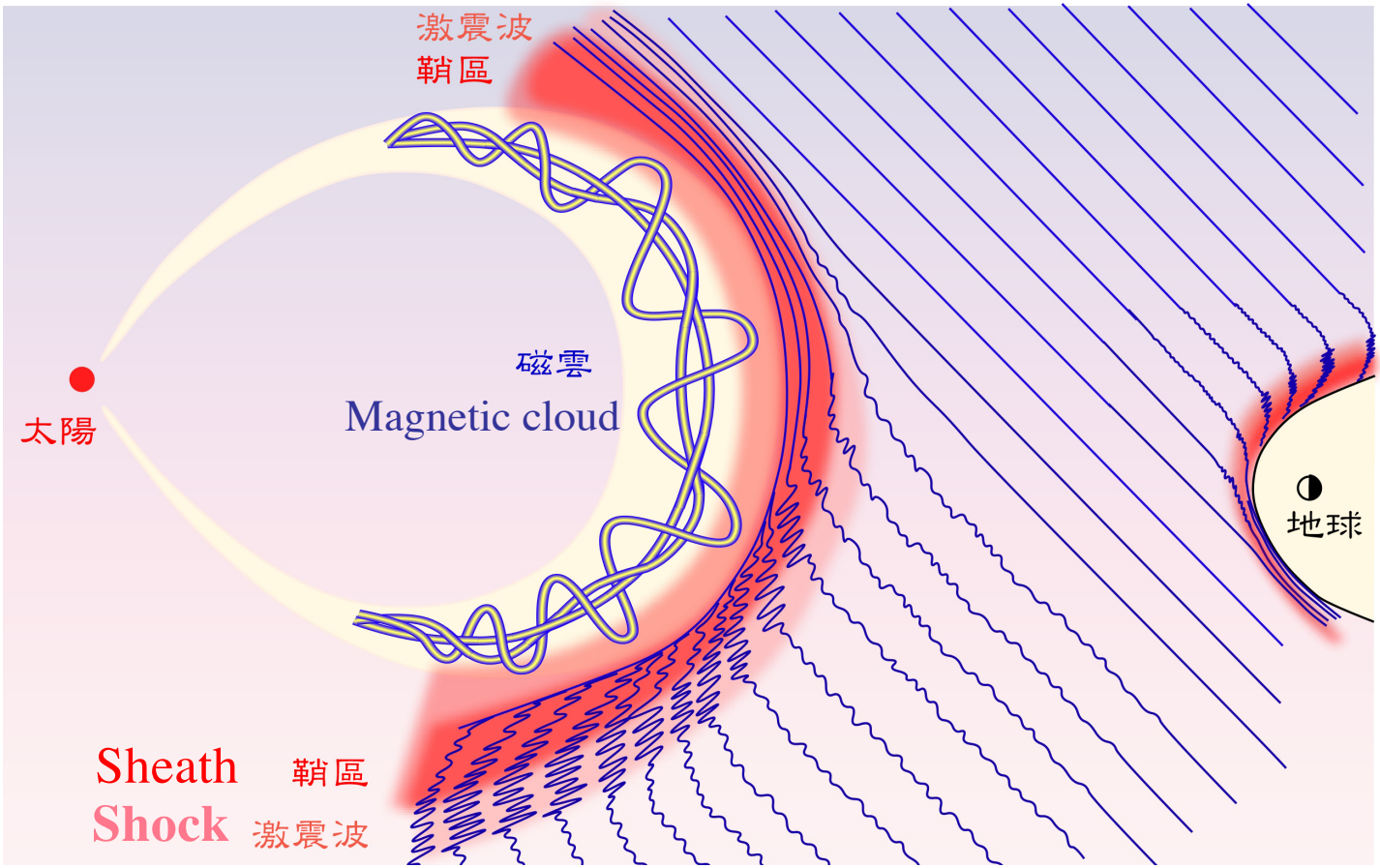
馬赫數M = 流速/聲速

Observations of Earth Bow Shock






Quasi-Parallel Shock $\theta_{BN} < 45°$
$M_A = 6.3,\ \beta_i = 0.37,\ \theta_{BN} = 11^o$
ISEE-2 01 SEP. 1979
Log Ne
Log Te
downstream
upstream
shock front
B
00 05 10 15 20
17 HOURS
Upstream backstreaming electrons
Upstream backstreaming superthermal ions
Q-|| shock
magnetopause
x
y
Interplanetary magnetic field
solar wind
Q-perp Shock
Q-|| Shock
$\theta_{Bn} < 45°$
Q-perp Shock
$\theta_{Bn} > 45°$
Bow Shock


激震波
鞘區
磁雲
Magnetic cloud
太陽
地球
Sheath 鞘區
Shock 激震波

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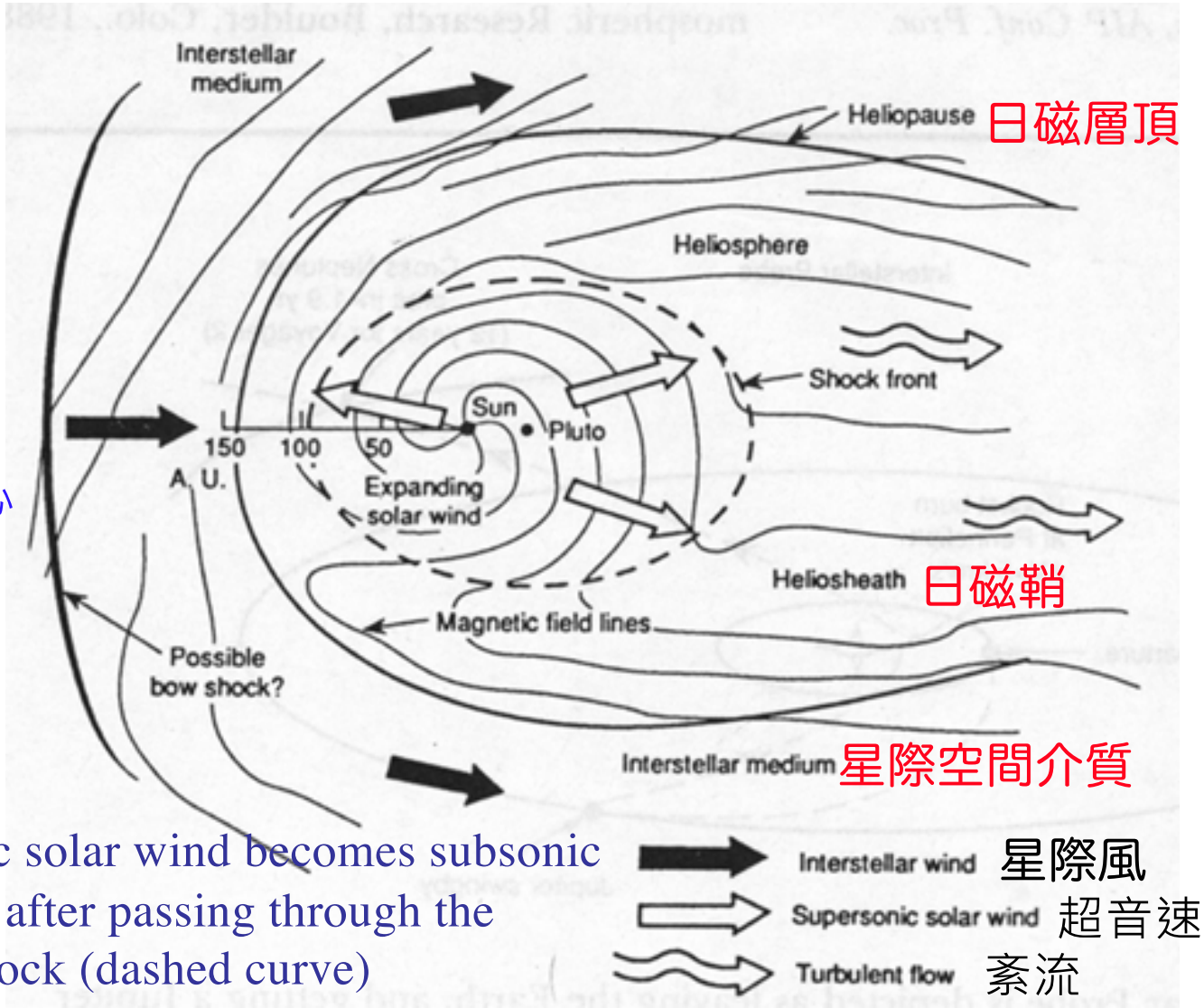
Heliomagnetosphere (Heliosphere) 日磁層的黃道面示意圖

Toward the center of milky way

朝向本星系中心



The supersonic solar wind becomes subsonic turbulent flow after passing through the termination shock (dashed curve)

Bow wave? or Bow shock? We don't know yet.

日磁層 立體 示意圖：極區
太陽風速大，TS靠近日磁層頂

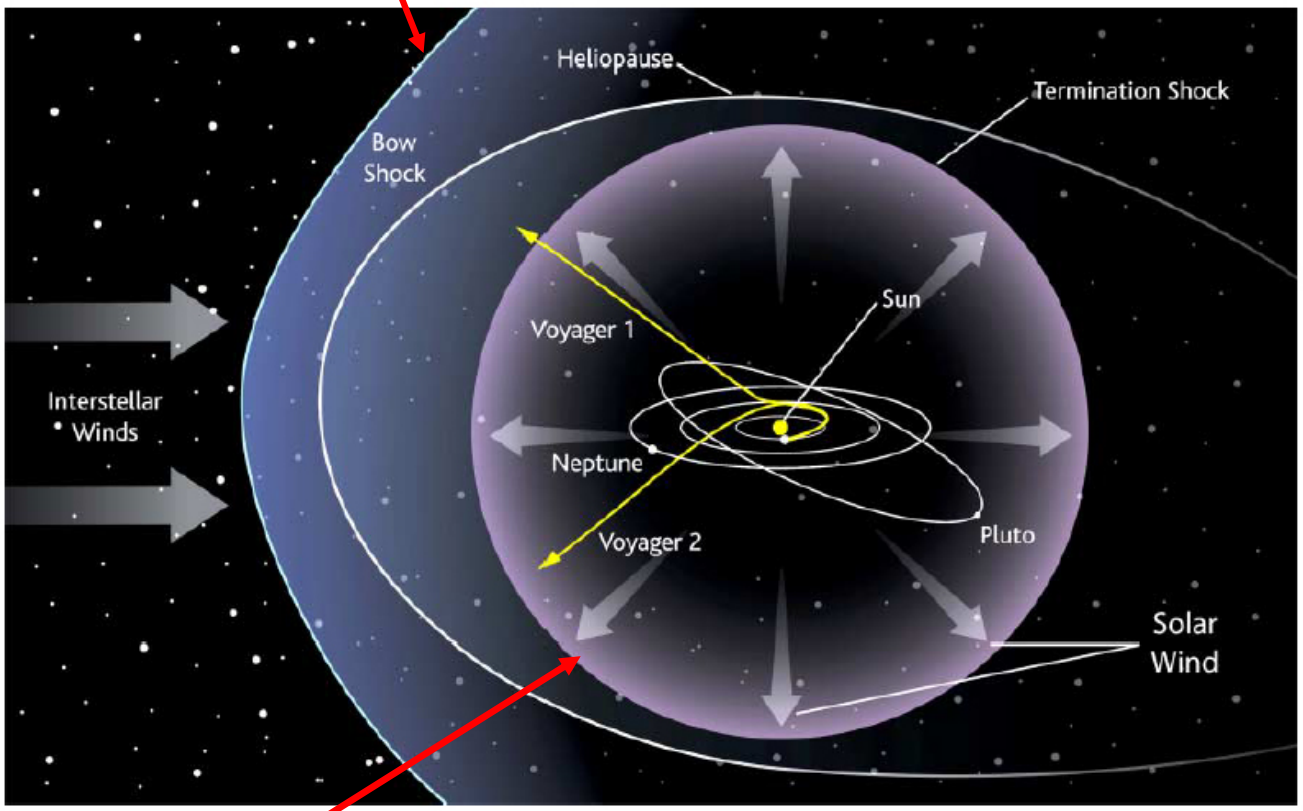


Fig. 1. Voyagers 1 and 2 have flown on different trajectories past the outer planets of the solar system since 1977, and Voyager 1 is reported to have crossed the termination shock of the solar wind at 94 AU from the Sun in December 2004. The solar wind is a supersonic flow, and a shock—the termination shock—is required for the wind to decelerate and merge with the local interstellar medium that bounds the solar system. The solar wind and interstellar gas do not merge easily, so further out beyond the termination shock, there is a true boundary between the solar wind and the interstellar medium: the heliopause. Further out still, if the solar system is itself moving supersonically relative to the interstellar medium, there may be a large bow shock.

Temination shock has been observed by Voyager 1 and Voyager 2.
太陽風終止震波

Termination Shock (TS) 太陽風終止震波

- 太陽風到達日磁層頂，速度必須降到 0, 所以從超音速太陽風變成次音速流 (wind --> breathing)，一定要經歷一個激震波結構。這個激震波結構 就被稱為 太陽風終止震波 Termination shock
- Termination shock 中的波動來自日磁層頂(heliopause)與日磁鞘區
- Voyager 1 crossed TS at 94.0 AU on December 16, 2004.
- Voyager 2 crossed TS at 83.7 AU on August 30, 2007.
- Voyager 1 crossed the heliopause at 121.6 AU in 2012.
- Voyager 2 crossed the heliopause at ~119 AU in late 2018.
- Termination shock, a source of cosmic ray?
- Sunspot numbers v.s. cosmic ray

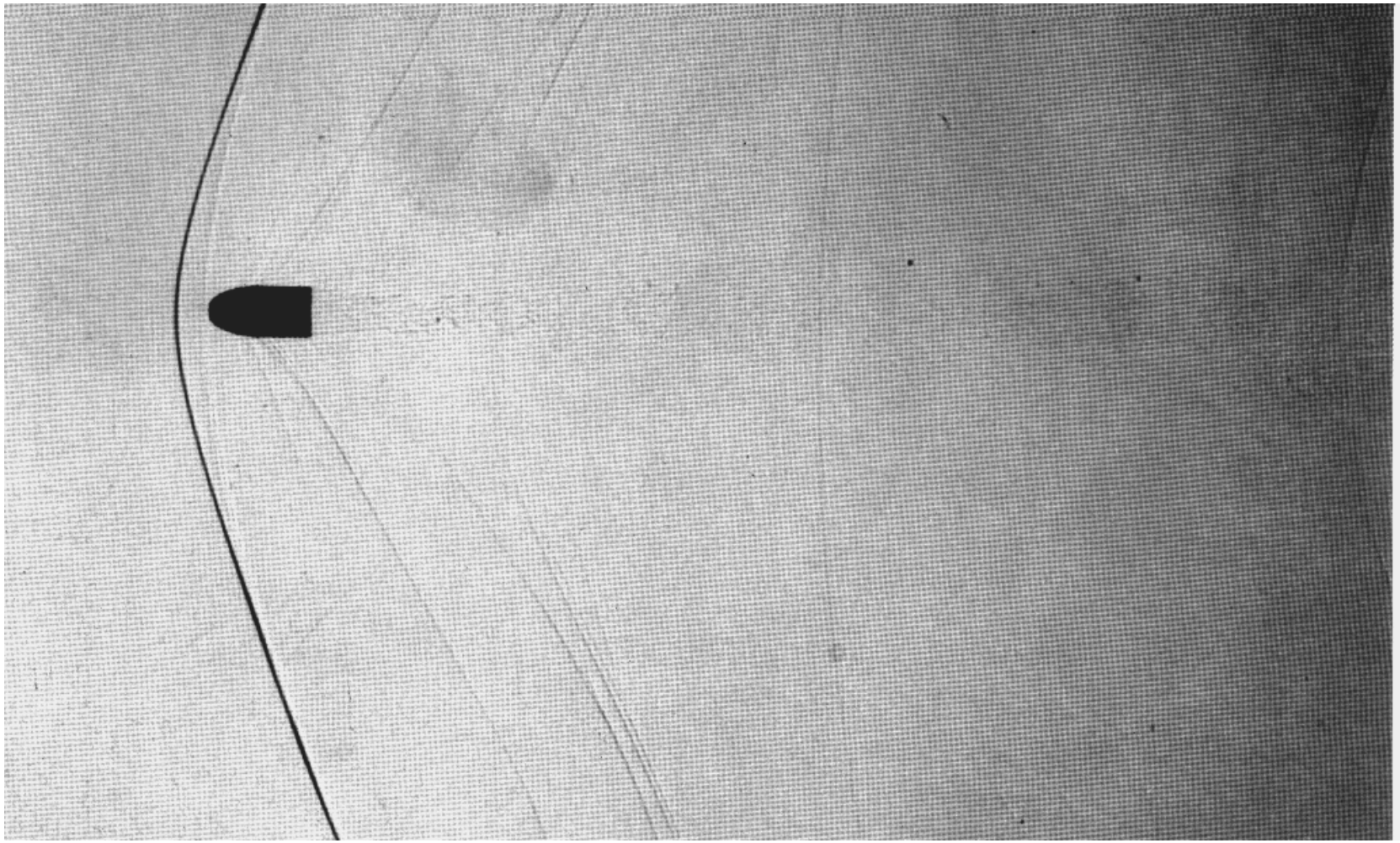
Examples of Shock Waves
激震波 的 範例

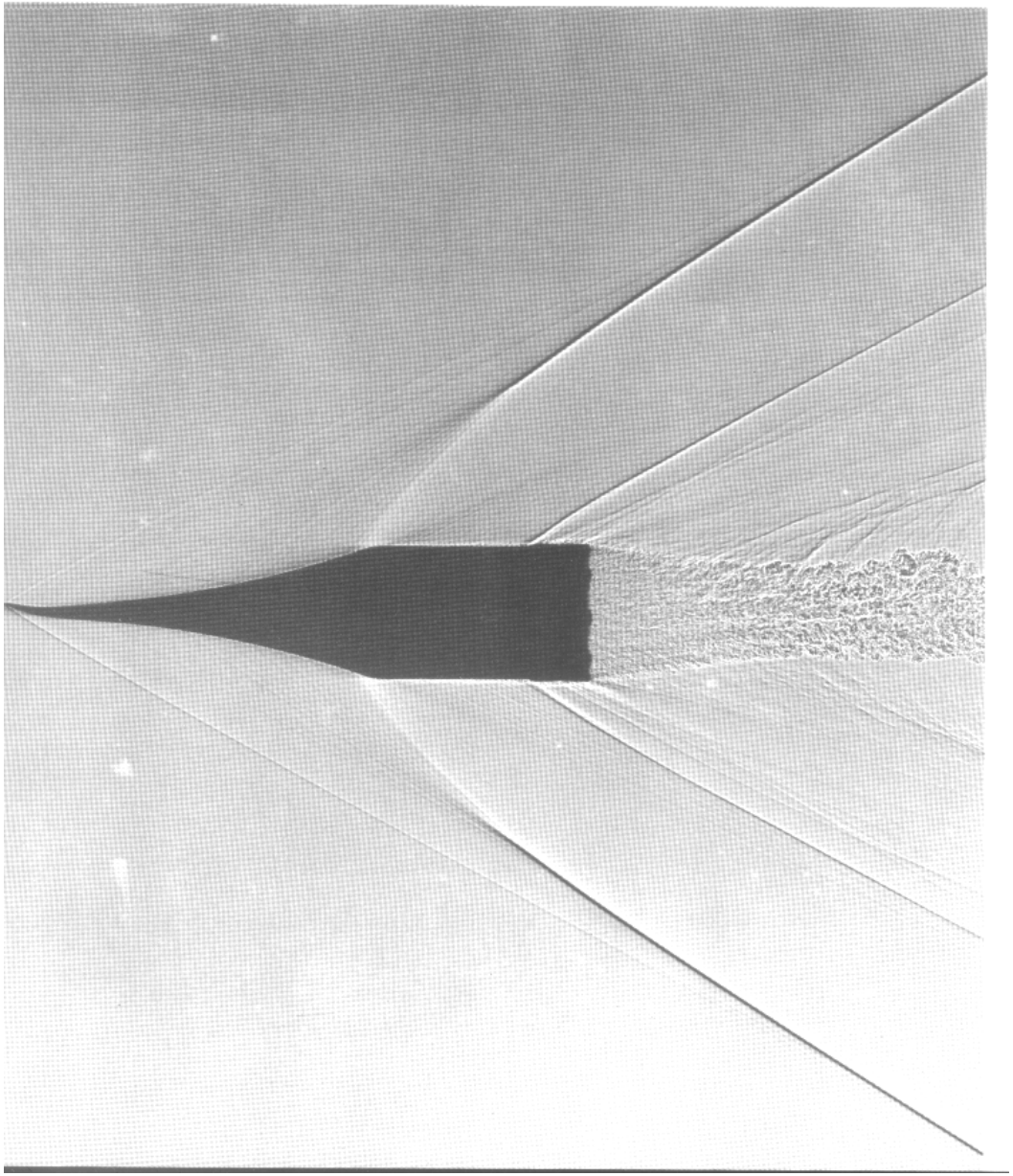
- 當超音速氣流 遇到 障礙物， 會形成 激震波 shock wave
- Shock Wave ：Mach number >1

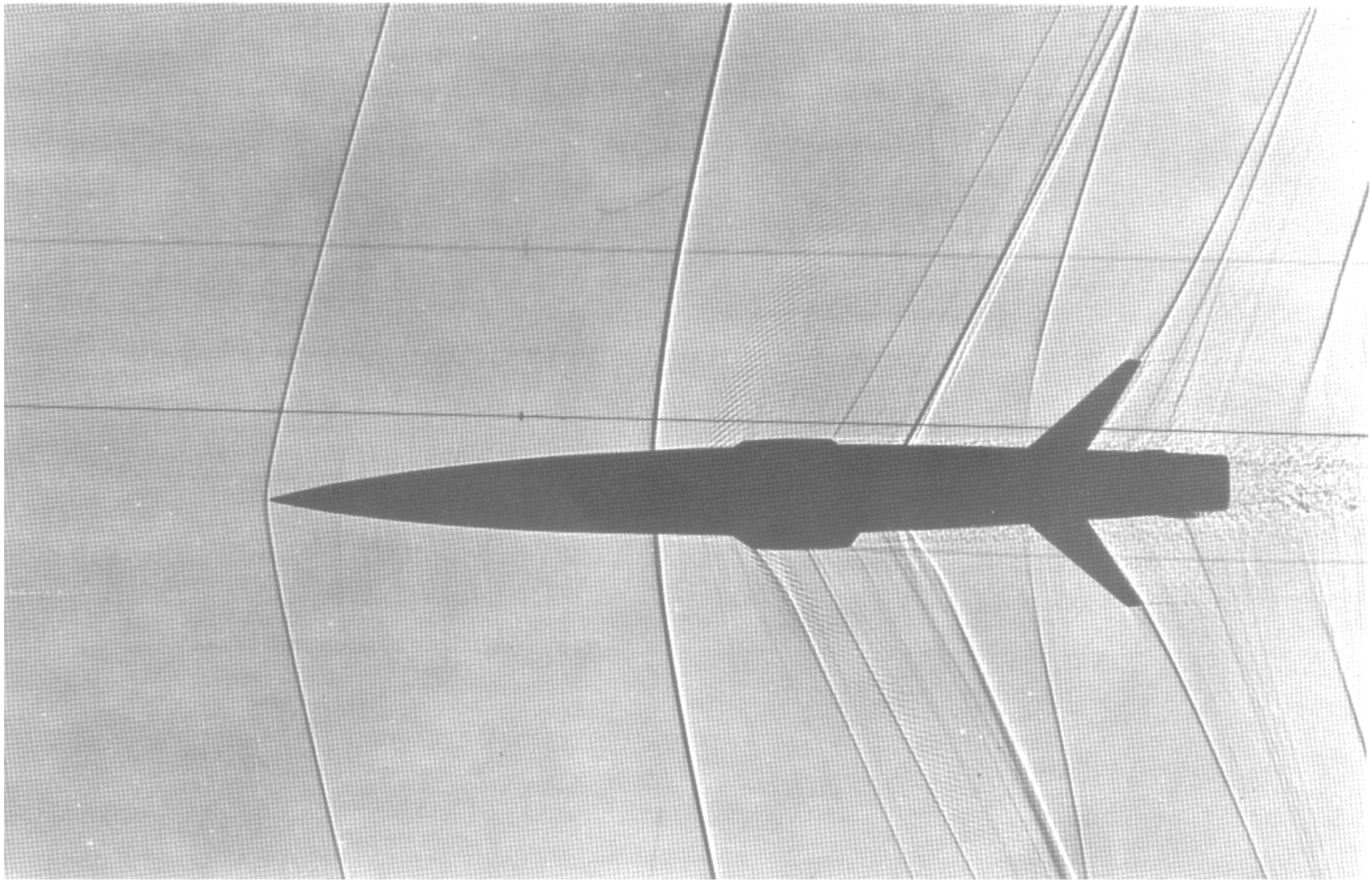
次音速飛機 超音速飛機 造型不同
根據 超音速風洞實驗的結果

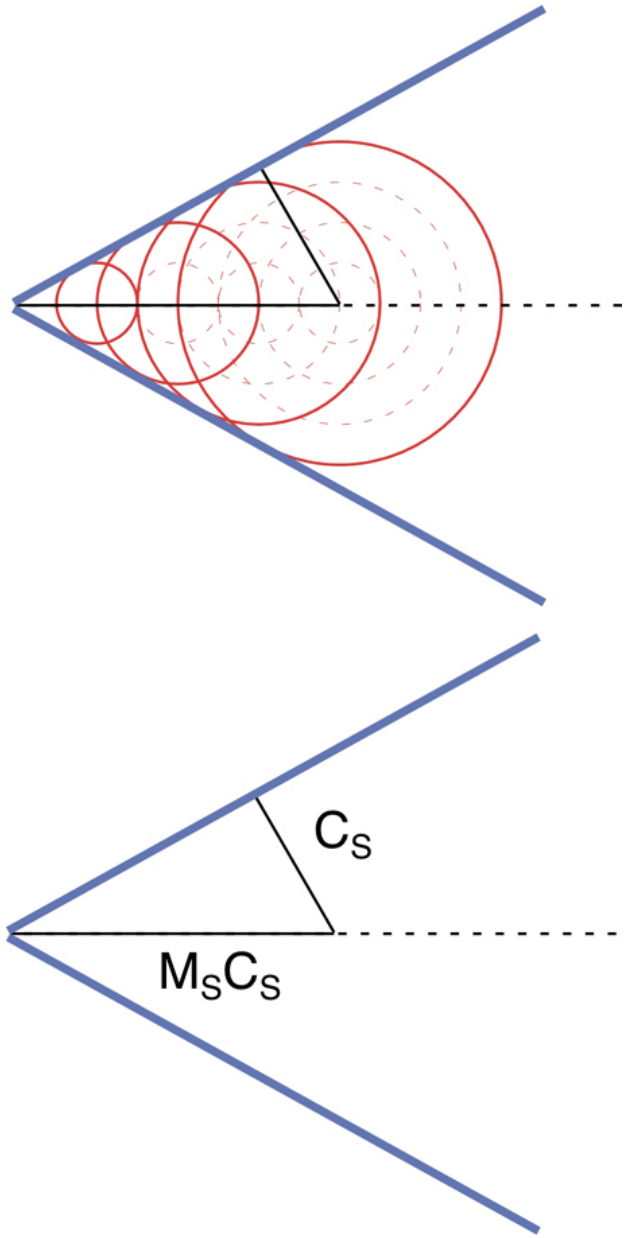
- **Supersonic flight**
- https://youtu.be/TrFW_Z8grnI
- https://youtu.be/OlBH81iKDew Boom! Breaking the sound barrier
- https://www.aerospaceutah.org/boom-breaking-the-sound-barrier/
- https://youtu.be/i_rFAo358bU
- https://youtu.be/0lwHMLG9moU
- https://youtu.be/QOzdY3m-la8 High speed flight / Part 2: Transonic flight
- https://youtu.be/jfic0f0eJm4 High speed flight / Part 1: Approaching the speed of sound
- https://youtu.be/smPeaXbJyn4 High speed flight / Part 3: Beyond the speed of sound

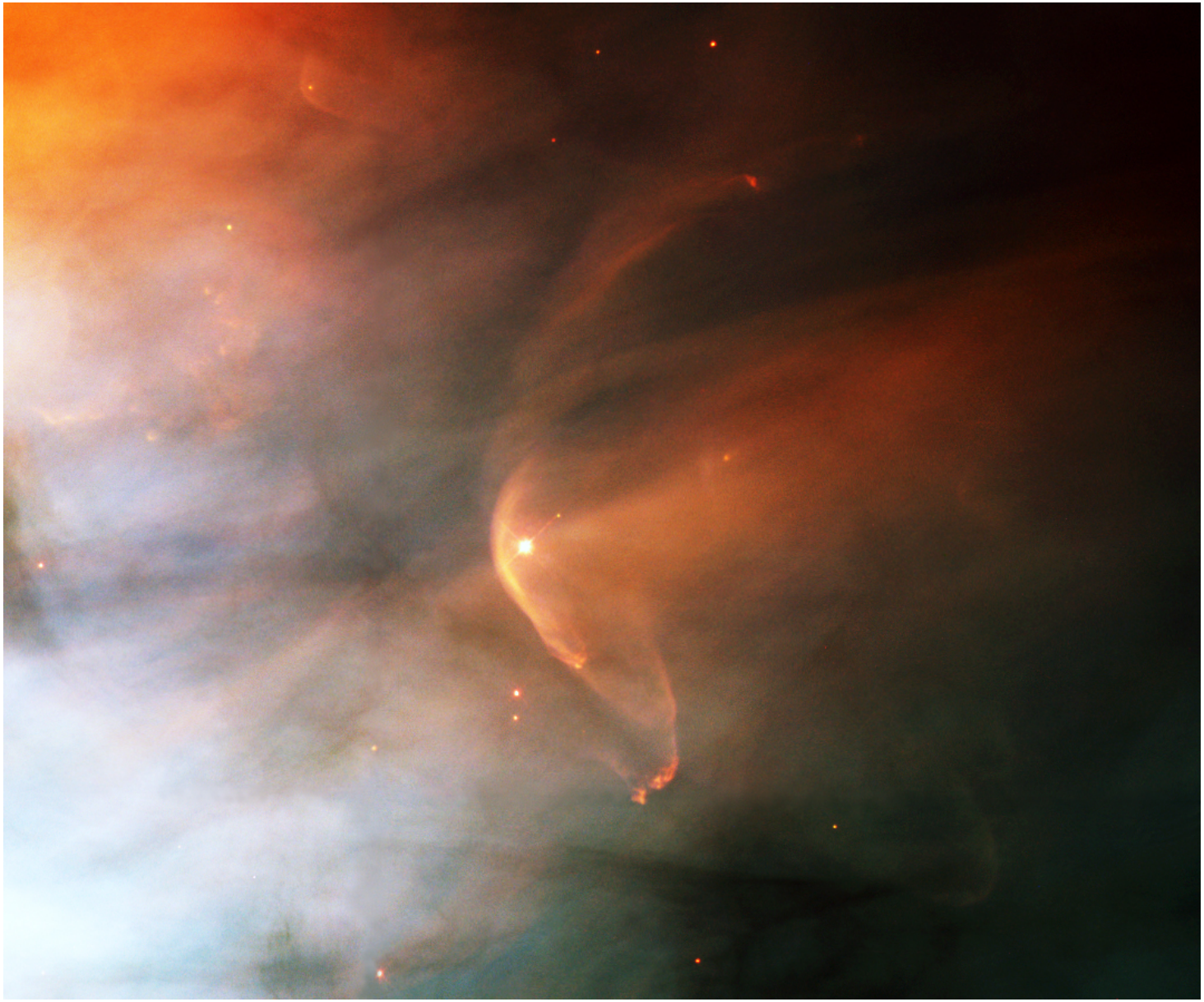
The thickness of the shock layer is a few “mean free path” of the gas.

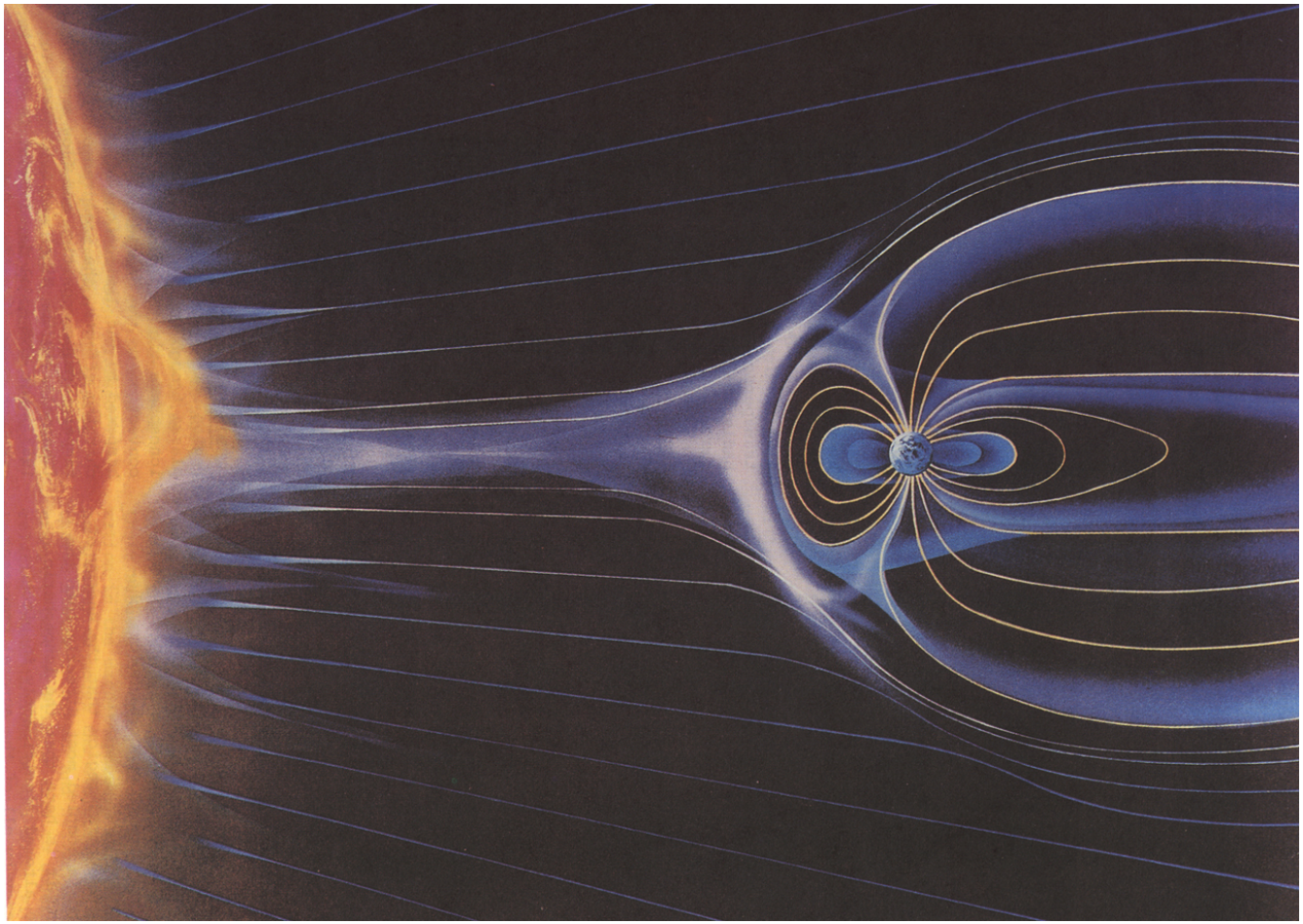


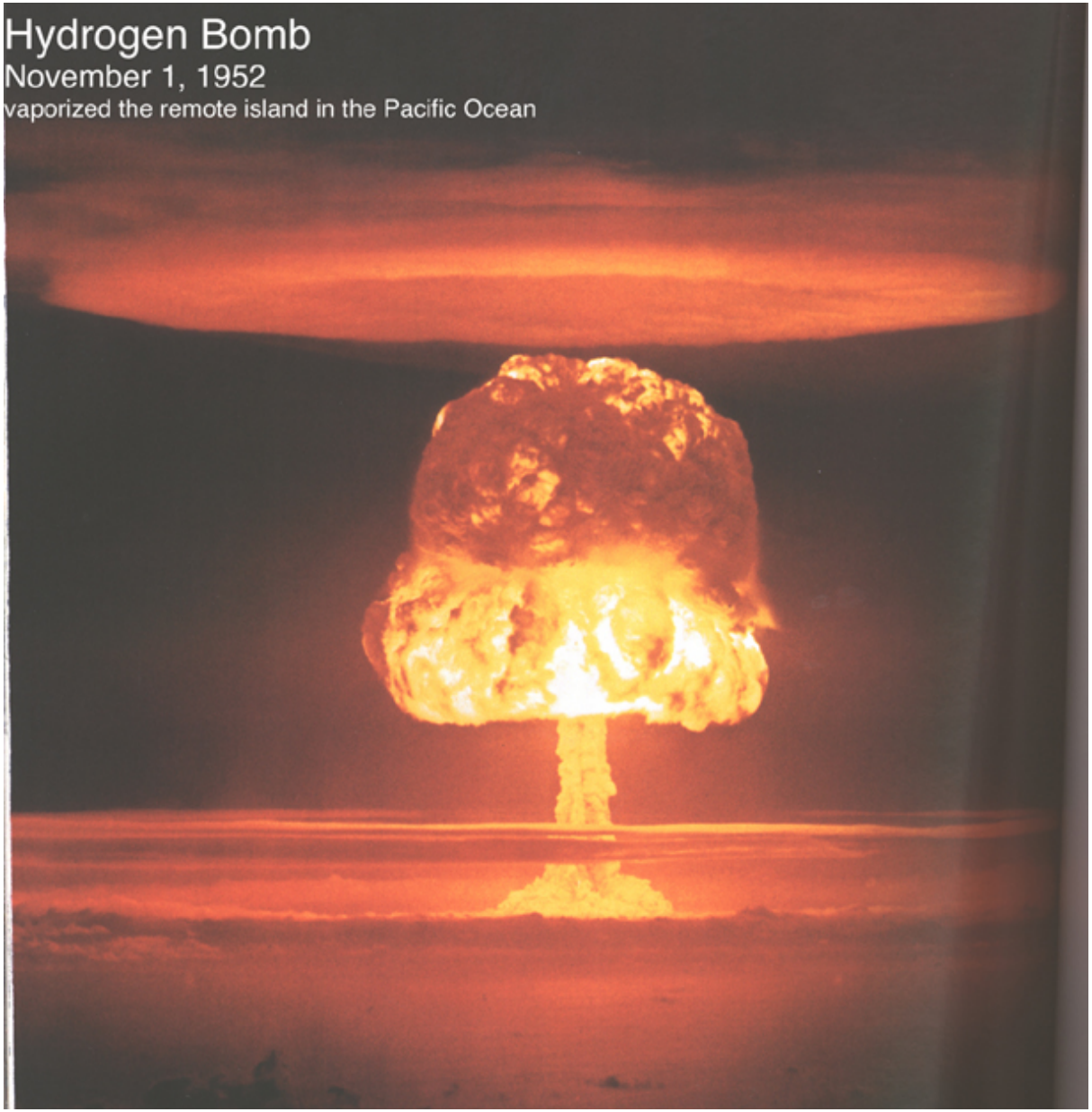





C_S
$M_S C_S$

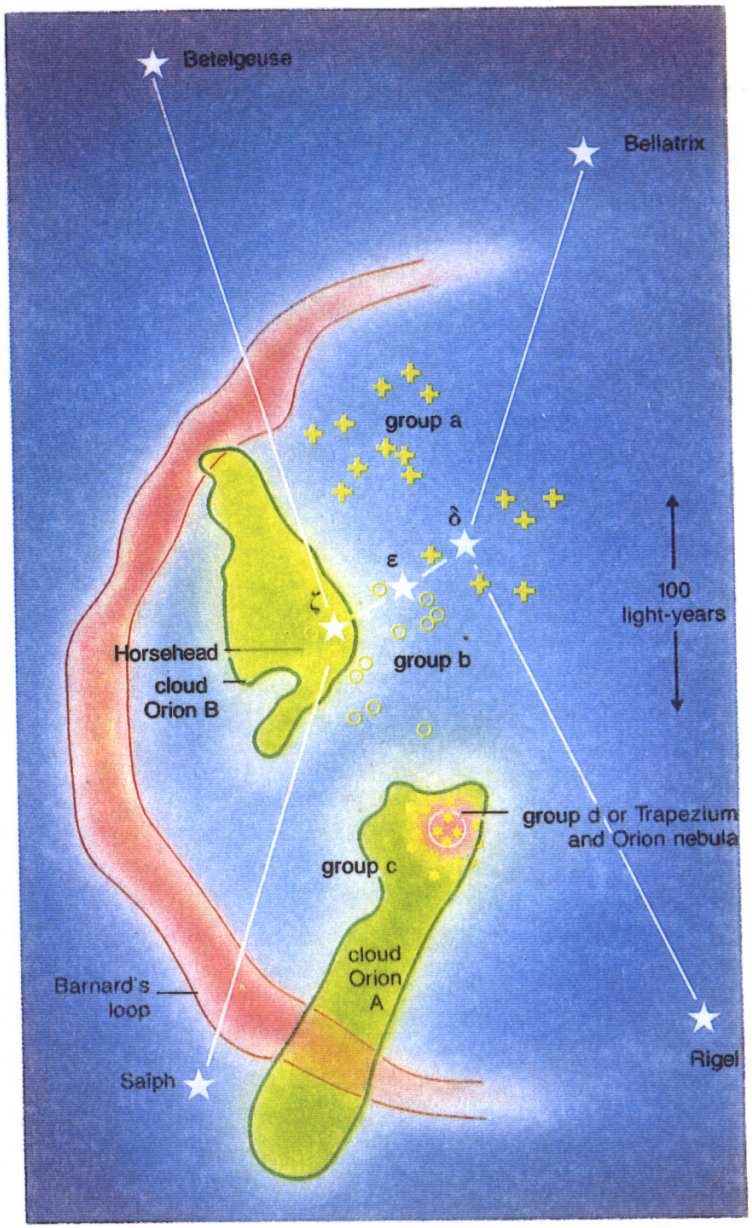





Hydrogen Bomb
November 1, 1952
vaporized the remote island in the Pacific Ocean


PORTRAITS
OF
MOUNT ST. HELENS
an awesome beauty
A UNIQUE PHOTOGRAPHIC HISTORY OF BEFORE, DURING AND AFTER THE VOLCANIC ERUPTION. INCLUDING RECENT PHOTOGRAPHS OF NATURE'S RE-GROWTH.

The Windy Ridge forest was flattened by the exploding volcano, Mt. St. Helens National Monument, Washington.


Betelgeuse
Bellatrix
group a
δ
ε
ζ
100
light-years
Horsehead
cloud
Orion B
group b
group d or Trapezium
and Orion nebula
group c
cloud
Orion
A
Barnard's
loop
Saiph
Rigel

總結

- 超音速太陽風的成因
- 激震波的成因與特性
- 行星際空間中的各種激震波的成因
- 自然界中的各種激震波
- 超音速飛機
- 激震波與宇宙射線（高能的帶正電離子）
- 最有建設性的激震波：star formation