Chapter 3 The Sun

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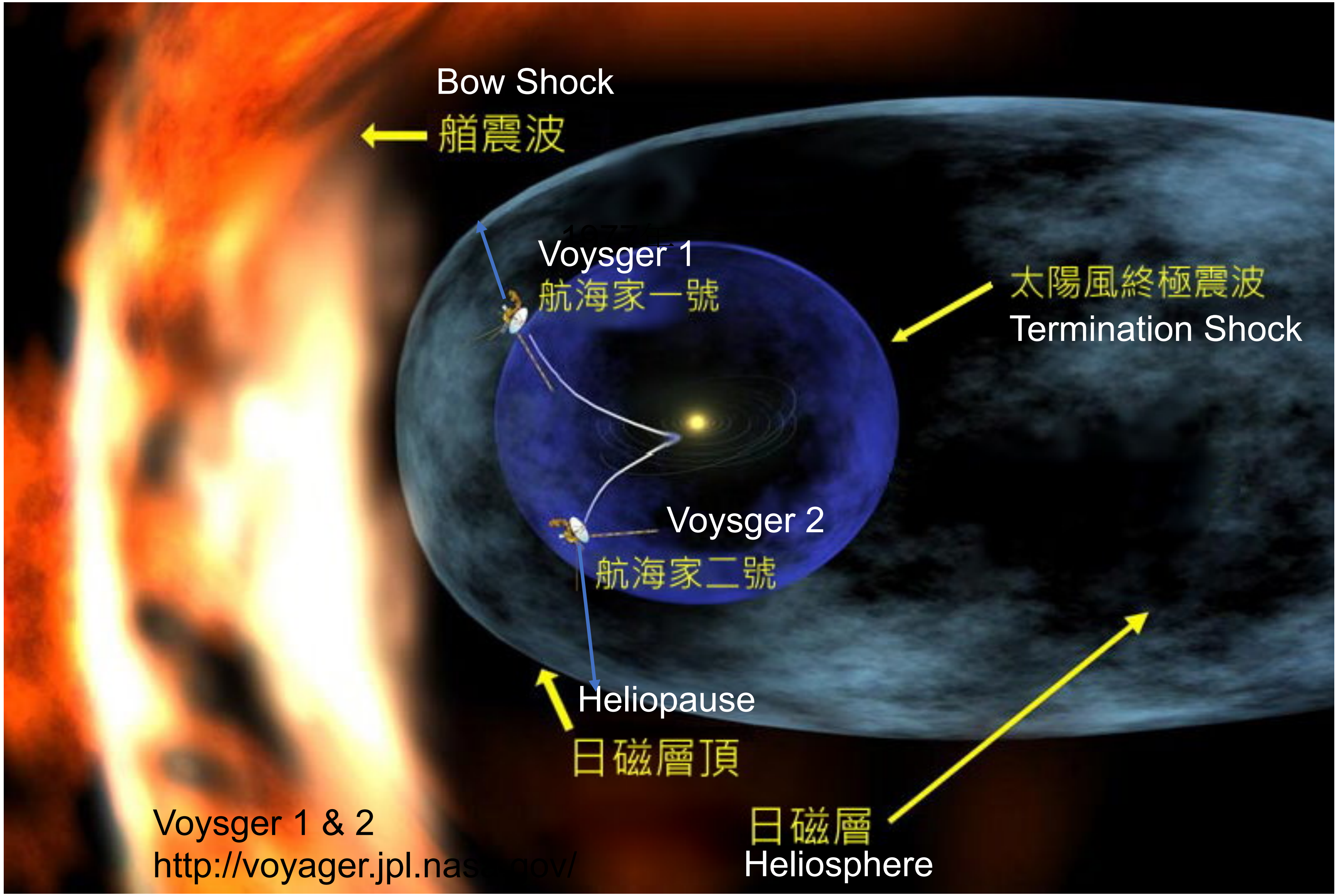
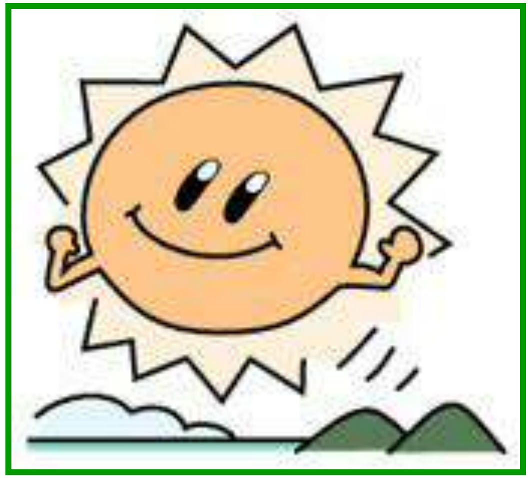

Bow Shock
艏震波
Voysger 1
航海家一號
太陽風終極震波
Termination Shock
Voysger 2
航海家二號
Heliopause
日磁層頂
日磁層
Heliosphere
Voysger 1 & 2
http://voyager.jpl.nasa.gov/

The Sun: Energy source of Space

Age = 4.5×10^9 yr
Mass = 1.99×10^{30} kg
Radius = 696,000 km (696 Mm)
Mean density = $1.4 \times 10^3\ \mathrm{kg \cdot m^{-3}}$ ($1.4\ \mathrm{g \cdot cm^{-3}}$)
Mean distance from earth (1 AU) = 150×10^6 km (215 solar radii)
Surface gravity = $274\ \mathrm{m \cdot s^{-2}}$
Escape velocity at surface = $618\ \mathrm{km \cdot s^{-1}}$
Radiation emitted (luminosity) = 3.86×10^{26} W ($3.86 \times 10^{33}\ \mathrm{erg \cdot s^{-1}}$)
Equatorial rotation period = 26 days
Mass loss rate = $10^9\ \mathrm{kg \cdot s^{-1}}$
Effective blackbody temperature = 5,785K
Inclination of sun's equator to plane of earth's orbit = 7°
Composition: approximately 90% H, 10% He, 0.1% other elements (C, N, O, . . .)

The Sun



- Age: 5×10^9 years
- Mass: $3.3 \times 10^5\ M_E$
- Radius: $100\ R_E$

- Density: $1.4\ g/cm^3$
- Gravitation: $2.7 \times 10^2\ m/s^2$
- Rotation Period: 27 days

- **$M_E = 5.97 \times 10^{27}$ Kg**
- **$R_E = 6400$ Km**

TABLE 3.1. Solar-system, Coronal, and Solar-Wind Compositions

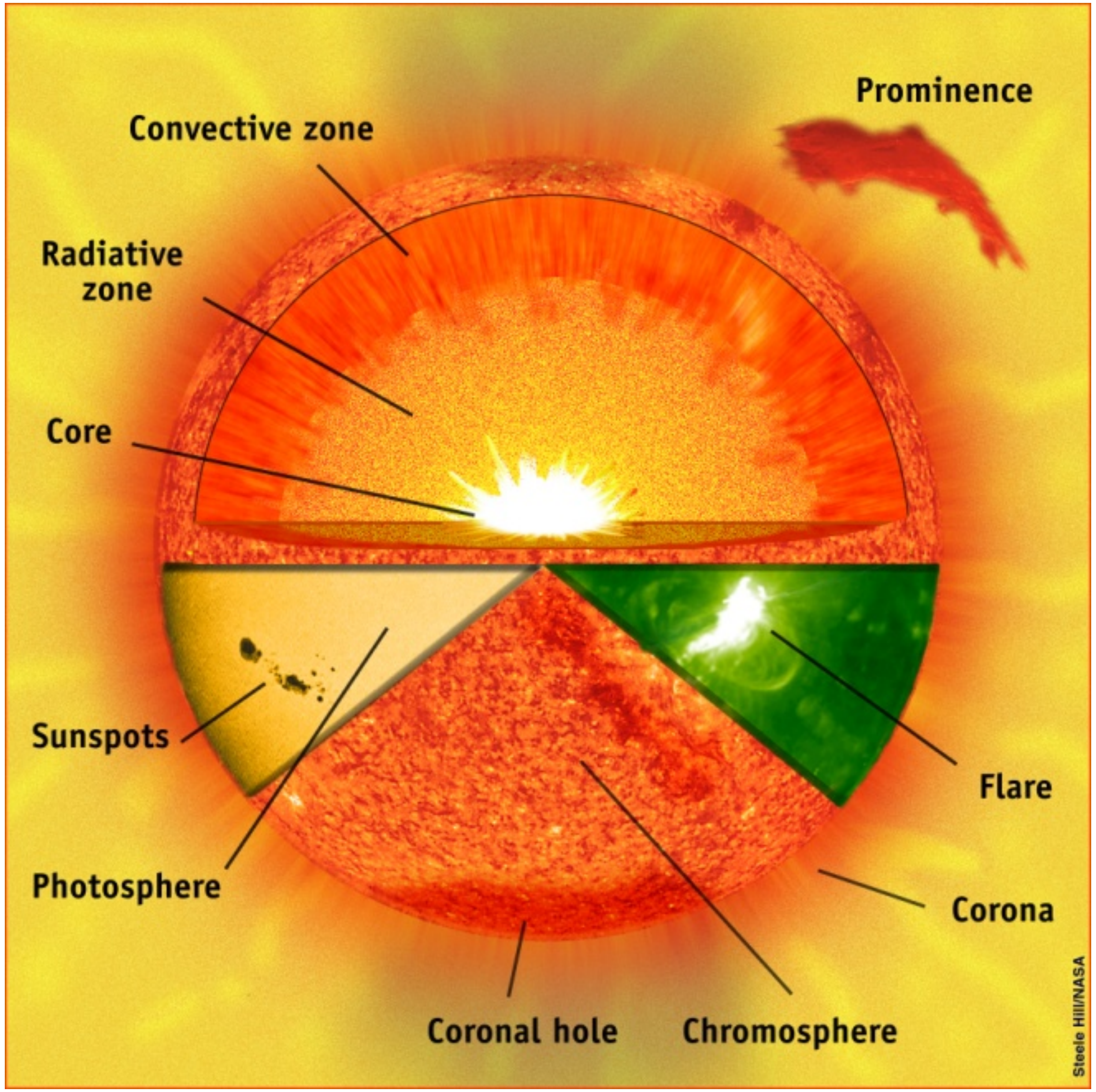
Element[a]	Solar System[b]	Corona[c]	Solar Wind[d]
H	1,350	—	1,900
He	108	72	75
C	0.60	0.41	0.43
N	0.12	0.12	0.15
O	1.00	1.00	1.00
Ne	0.14	0.14	0.17
Na	0.003	0.012	—
Mg	0.053	0.192	—
Al	0.004	0.147	—
Si	0.050	0.176	0.22
S	0.026	0.043	—
Ar	0.005	0.004	0.004
Ca	0.003	0.014	—
Fe	0.045	0.223	0.190
Ni	0.002	0.008	—

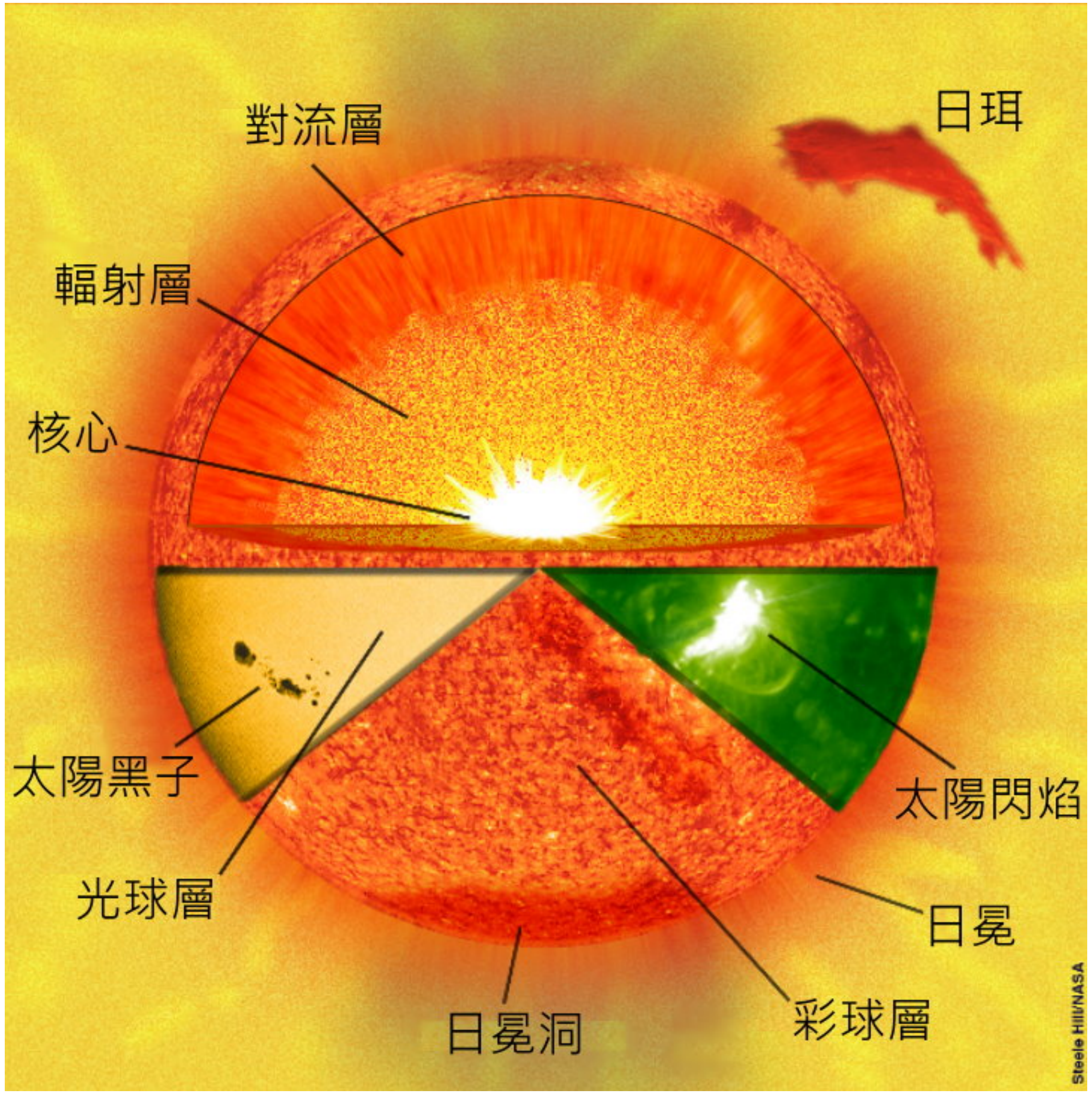
[a]Abundances referenced to that of oxygen. Only elements with abundances greater than 10^{-3} are listed.

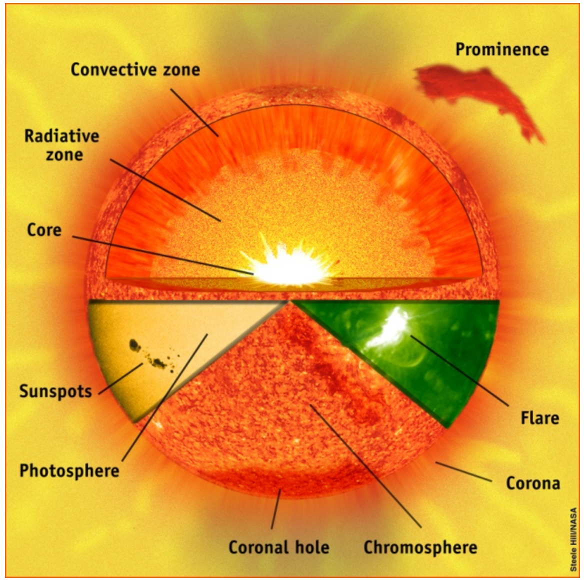
[b]Values from Anders and Ebihara (1982).

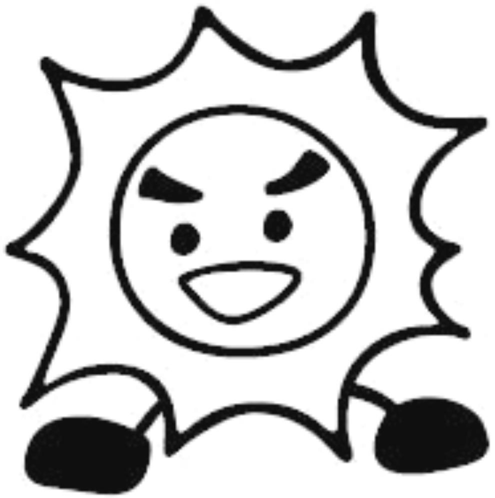
[c]Values derived from measurements of solar-energetic particles (Crook et al., 1984; Breneman and Stone, 1985).

[d]Values from Bochsler and Geiss (1989).


Prominence
Convective zone
Radiative zone
Core
Sunspots
Photosphere
Flare
Corona
Coronal hole
Chromosphere
Steele Hill/NASA


日珥
對流層
輻射層
核心
太陽黑子
光球層
太陽閃焰
日冕
日冕洞
彩球層
Steele Hill/NASA





- **Core**: energy source (nuclear fusion)
    - $0.3R_{\odot}$, 1.5×10^{7}K
- **Radiative Zone**: scattering
    - $0.5R_{\odot}$, 5.0×10^{5}K
- **Convective Zone**: convection
    - $0.2R_{\odot}$, 6.6×10^{5}K
- **Photosphere**: visible solar disc
    - $0.001R_{\odot}$, 5750K
- **Chromosphere**: thin, low temp
    - 10000KM, 4500-500000K
- **Corona**: Sun's atmosphere
    - $>R_{\odot}$,1.5×10^{6}K

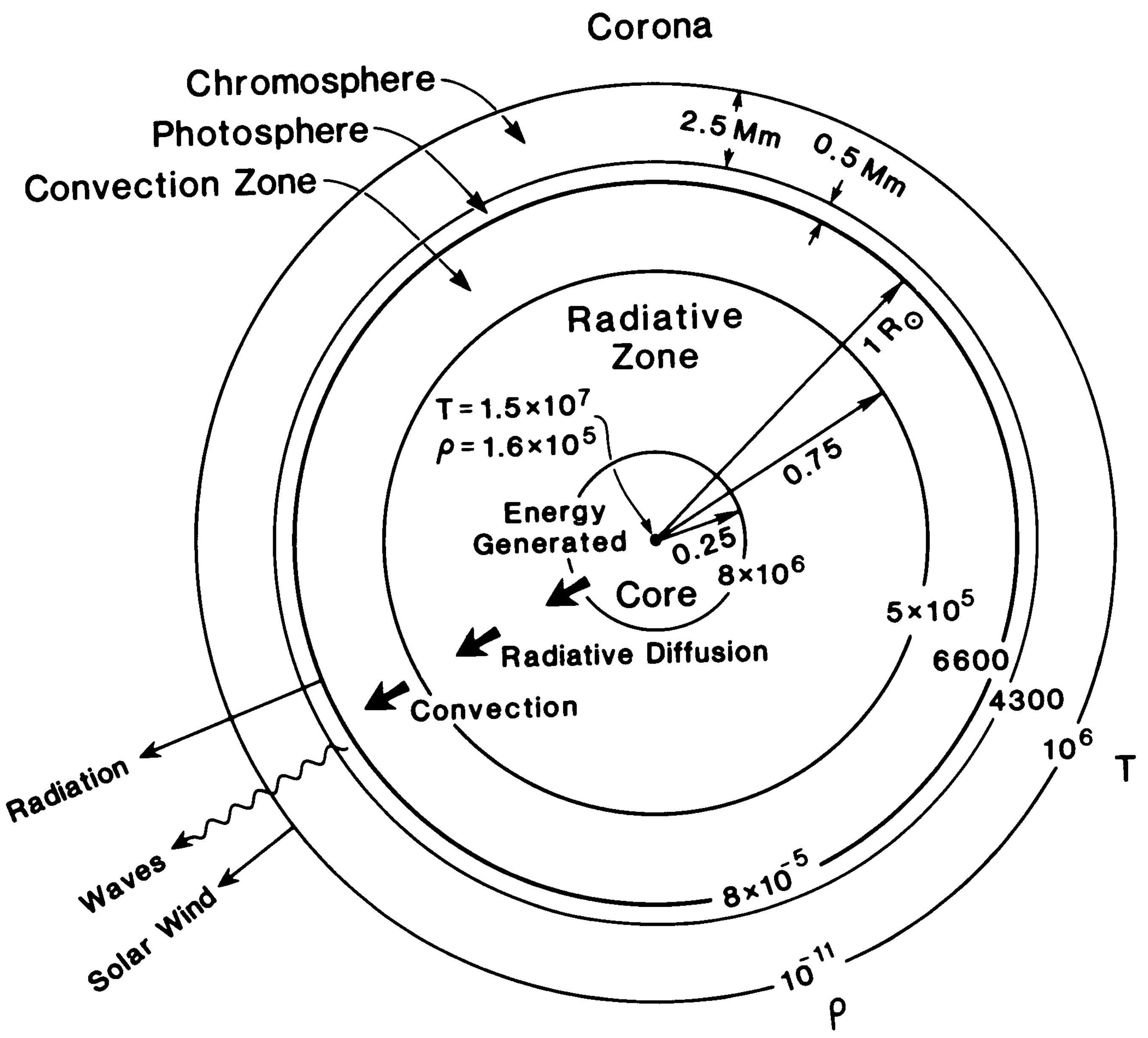


FIG. 3.2. Overall structure of the solar interior (including the core, the radiative zone, and the convection zone) and the solar atmosphere (i.e., the photosphere, chromosphere, and corona).

TABLE 3.2. Fusion Reactions in the Interior of the Sun

$$2({}^1H + {}^1H) \rightarrow 2({}^2H + e^+ + e^- + \nu)$$
$$2(e^+ + e^-) \rightarrow 2\gamma$$
$$2({}^2H + {}^1H) \rightarrow 2({}^3He + \gamma)$$
$${}^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H + \gamma$$

$$4\,{}^1H \rightarrow {}^4He + 5\gamma + 2\nu \qquad \text{(overall)}$$

$m_{4H} = 6.693*10^{-27}$ kg

$m_{He} = 6.645*10^{-27}$ kg

$\Delta m = 0.048*10^{-27}$ kg

6.2×10^{11}

The source of the Sun's energy is nuclear fusion
Proton-proton cycle, four protons merges to one α-particle, the mass difference between the four protons and the α-particle corresponds to an energy of $4.3*10^{-12}$J or 26.2 MeV.

The first step:

Two protons merge to a deuteron, emitting a positron and a neutrino.

The second step:

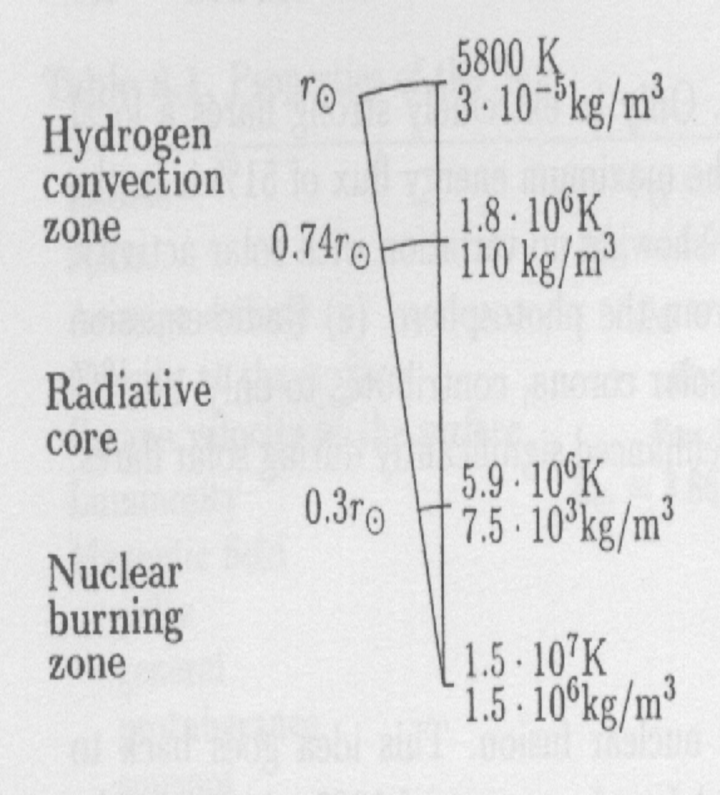
A proton collides and merges with the deuteron, forming a ^{3}He-nuclei under emission of a γ-quant.

The third step:

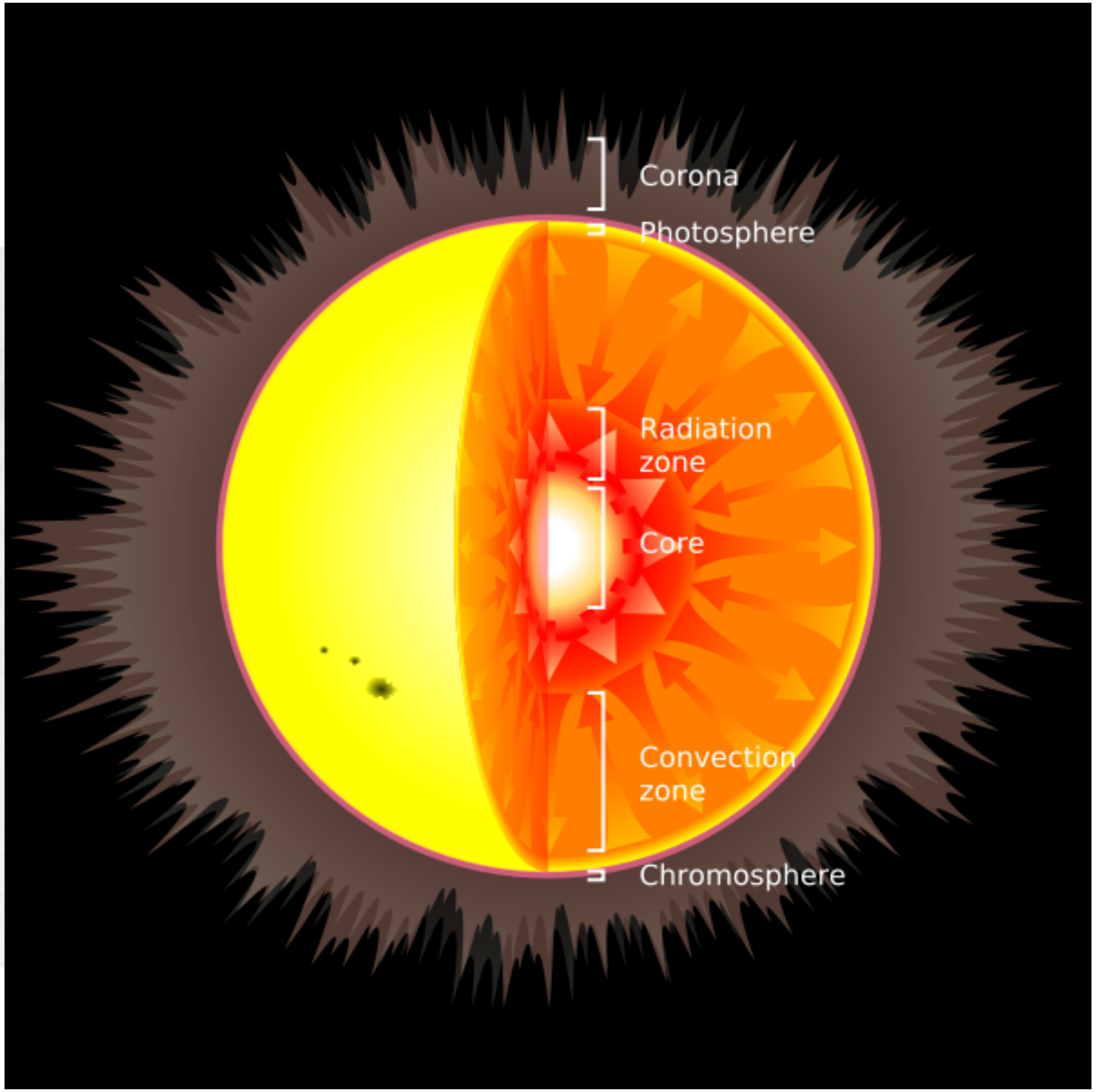
Two ^{3}He-nuclei collide, they merge to an α-particle, emitting two protons and a γ-quant .

The time scale of the proton-proton cycle basically is by the first step, half of the hydrogen initially present is converted into deuteron within 10^{10} year.

Although a photon travels with the speed of light, it needs about 100000 years to diffuse from the Sun's core to its surface.

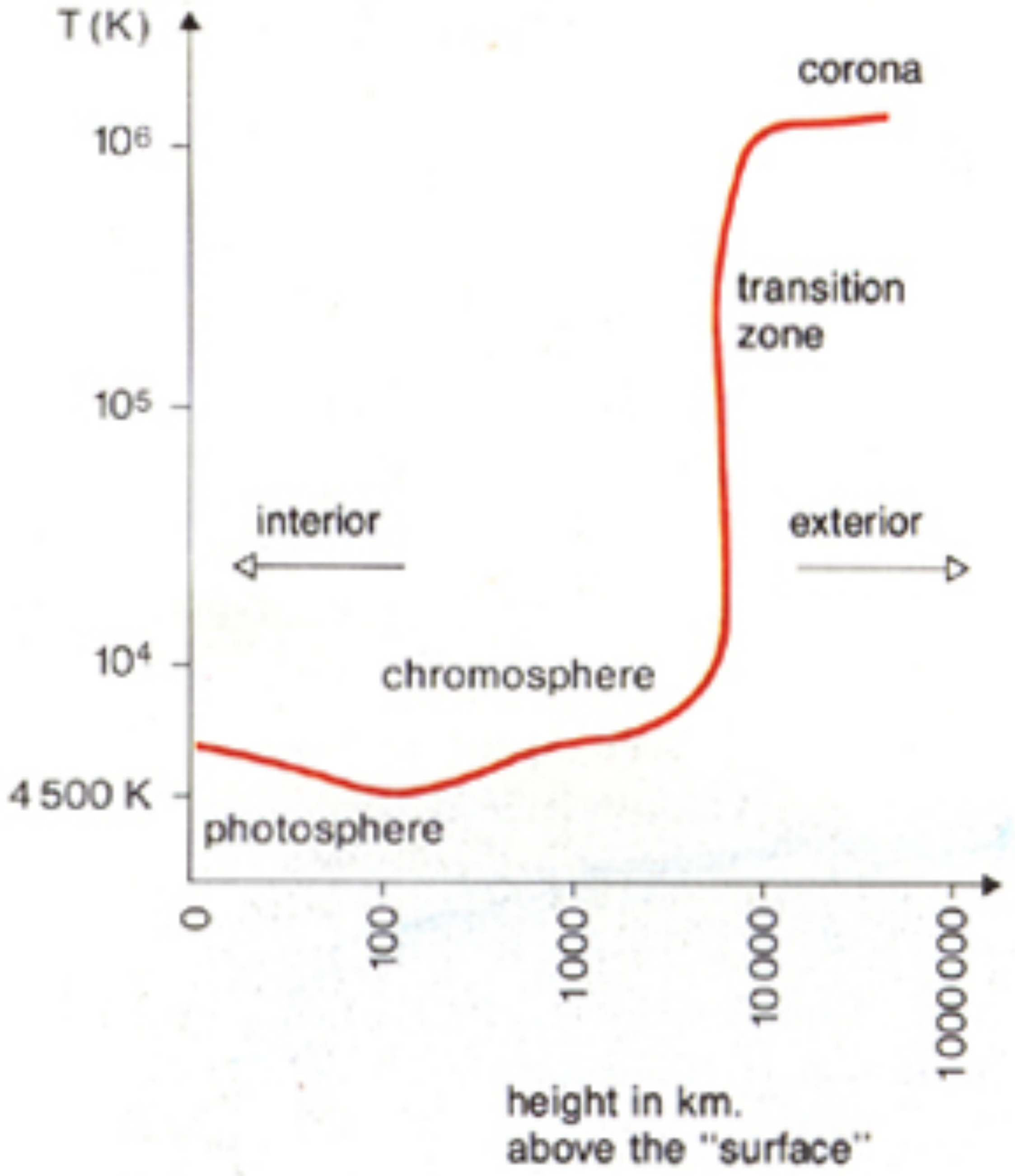


Hydrogen convection zone
Radiative core
Nuclear burning zone
$r_\odot$
$0.74r_\odot$
$0.3r_\odot$
5800 K
$3 \cdot 10^{-5}\,\mathrm{kg/m^3}$
$1.8 \cdot 10^6\,\mathrm{K}$
$110\ \mathrm{kg/m^3}$
$5.9 \cdot 10^6\,\mathrm{K}$
$7.5 \cdot 10^3\,\mathrm{kg/m^3}$
$1.5 \cdot 10^7\,\mathrm{K}$
$1.5 \cdot 10^6\,\mathrm{kg/m^3}$



Corona
Photosphere
Radiation zone
Core
Convection zone
Chromosphere

Wiki


T (K)
corona
10^6
transition
zone
10^5
interior
exterior
10^4
chromosphere
4 500 K
photosphere
0
100
1000
10 000
1 000 000
height in km.
above the "surface"

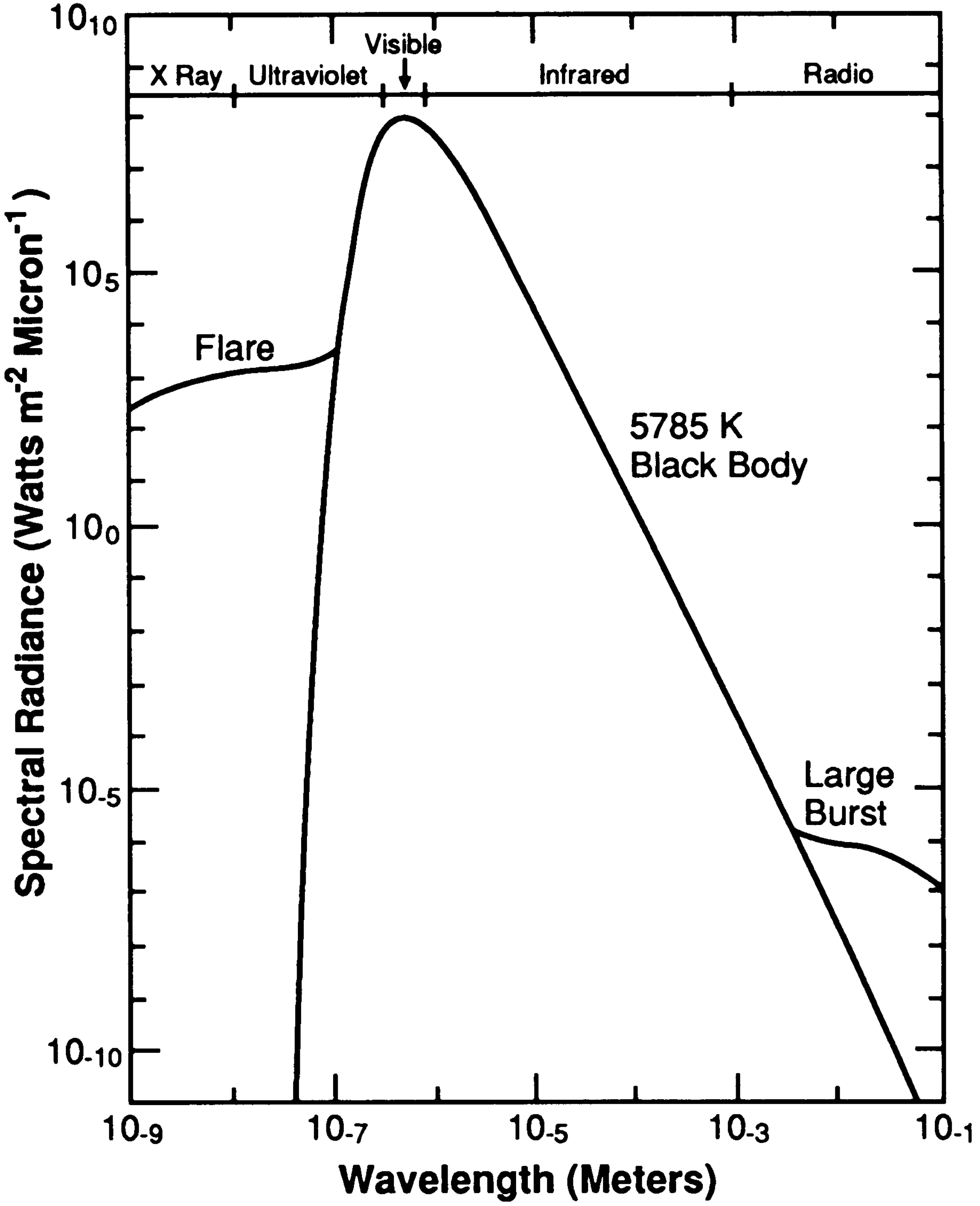
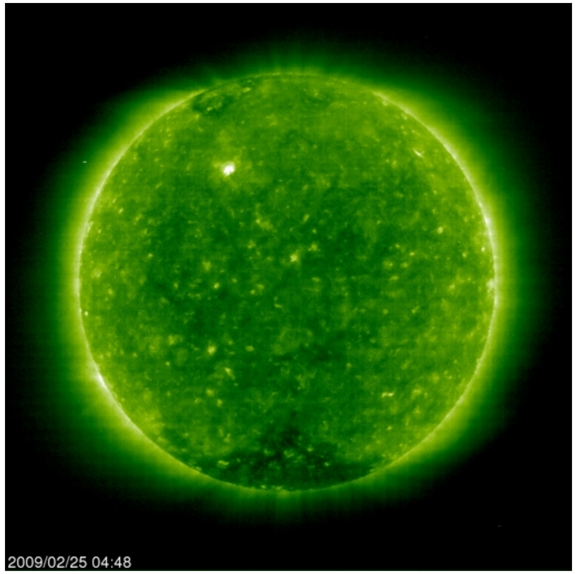
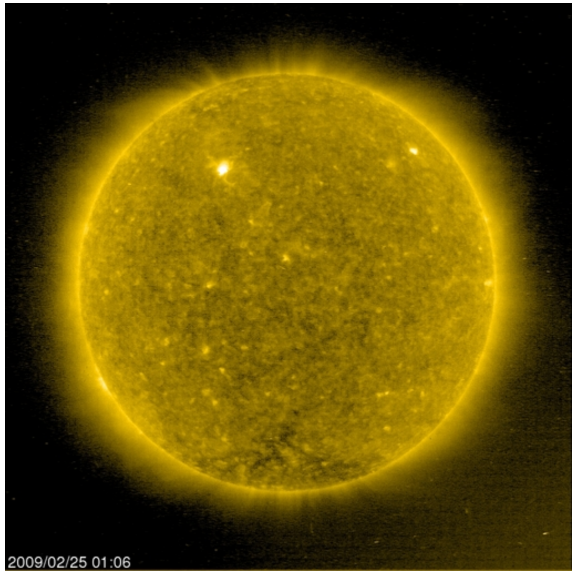
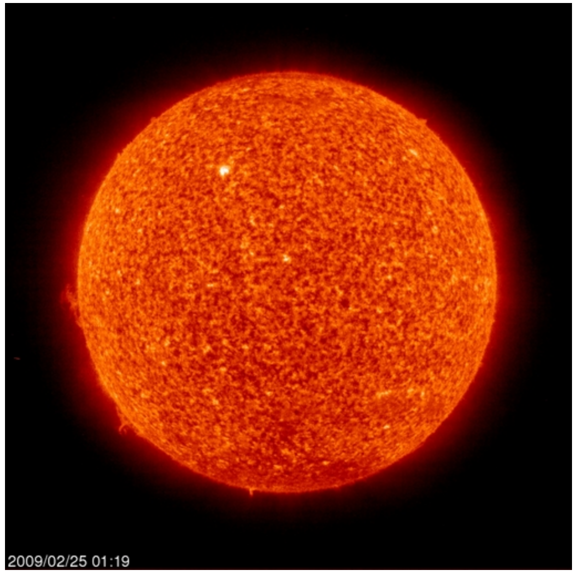


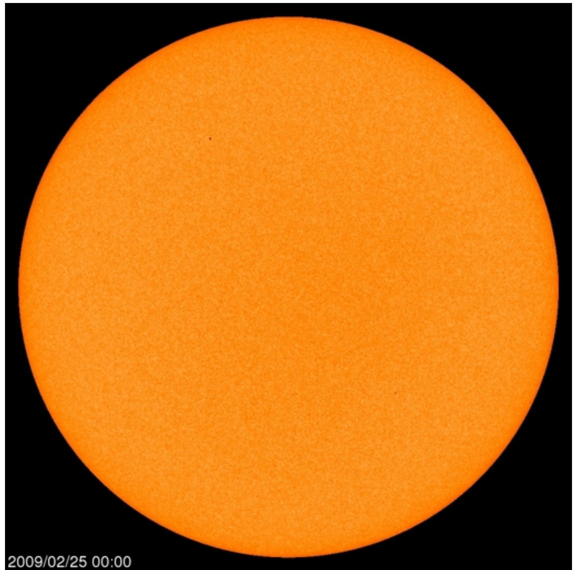
FIG. 3.1. Spectral radiance of the surface of the sun as a function of wavelength.

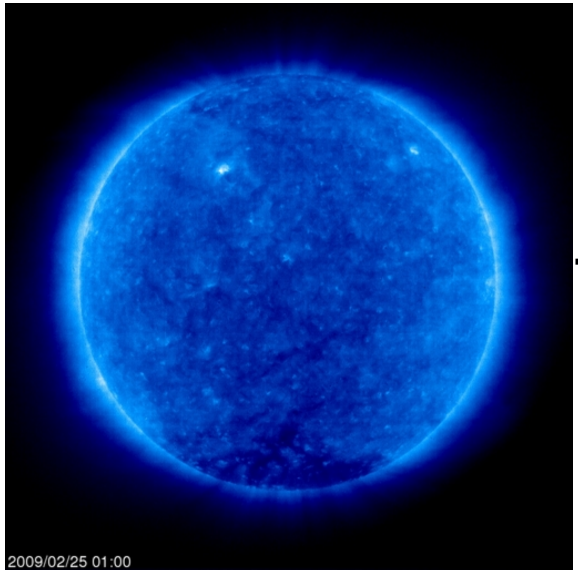
Solar under various temperatures











EIT195	EIT284	EIT304
1.5 million	2 million	80,000

MDI	EIT171
6000	1million

The Sun’s composition:

hydrogen 92% in terms of particle number or 72% in terms of mass
helium 8%
oxygen 0.06%
carbon 0.03%
the rest<0.01%.

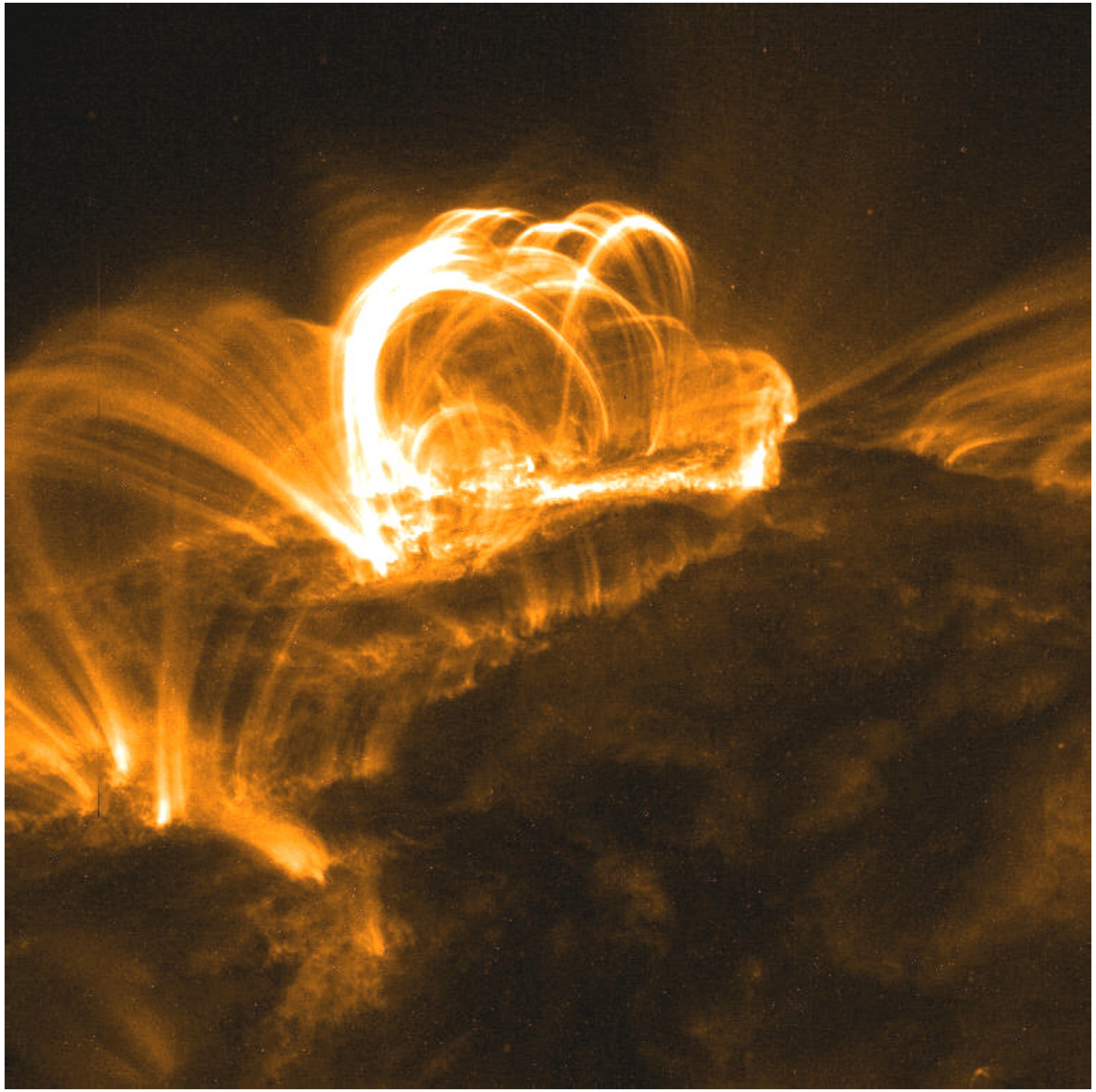
The Sun radiates as a black body at about 6000 K.

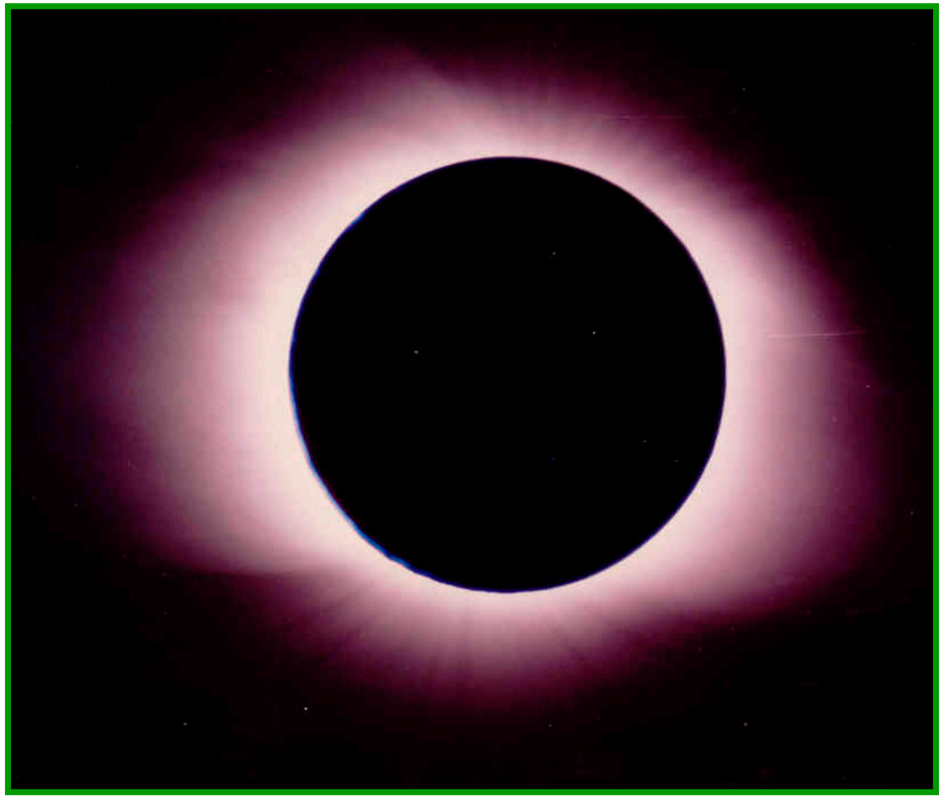
The flux of visible solar energy varies very little and, however, the emissions at shorter wavelengths, the EUV and X-ray, vary by orders of magnitude depending on sunspot number and solar activity.

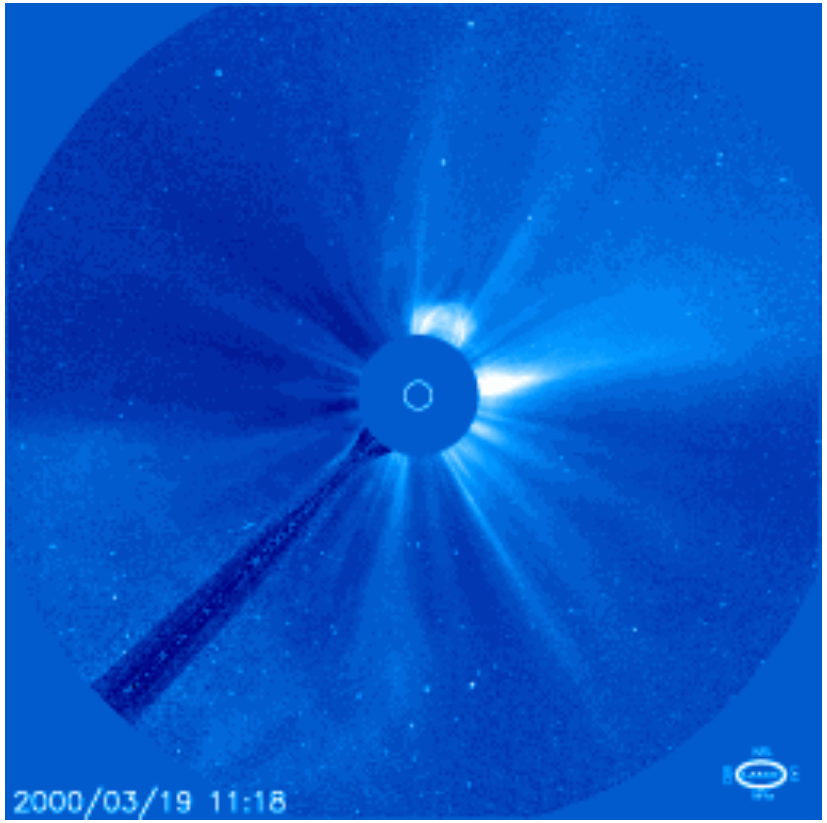
Table 6.1. Properties of the Sun

Radius	$r_\odot = 696\,000$ km
Mass	$M_\odot = 1.99 \times 10^{31}$ kg
Average density	$\varrho_\odot = 1.91$ g/cm^3
Gravity at the surface	$g_\odot = 274$ m/s^2
Escape velocity at the surface	$v_{esc} = 618$ km/s
Luminosity	$L_\odot = 3.86 \times 10^{23}$ kW
Magnetic field	
polar	1 G
general	some G
protuberance	10–100 G
sunspot	3 000 G
Temperature	
core	15 million K
photosphere	5780 K
sunspot (typical)	4200 K
chromosphere	4400–10 000 K
transition region	10 000–800 000 K
corona	2 million K
Sidereal rotation	
equator	26.8 d
30° latitude	28.2 d
60° latitude	30.8 d
75° latitude	31.8 d

Differential rotation



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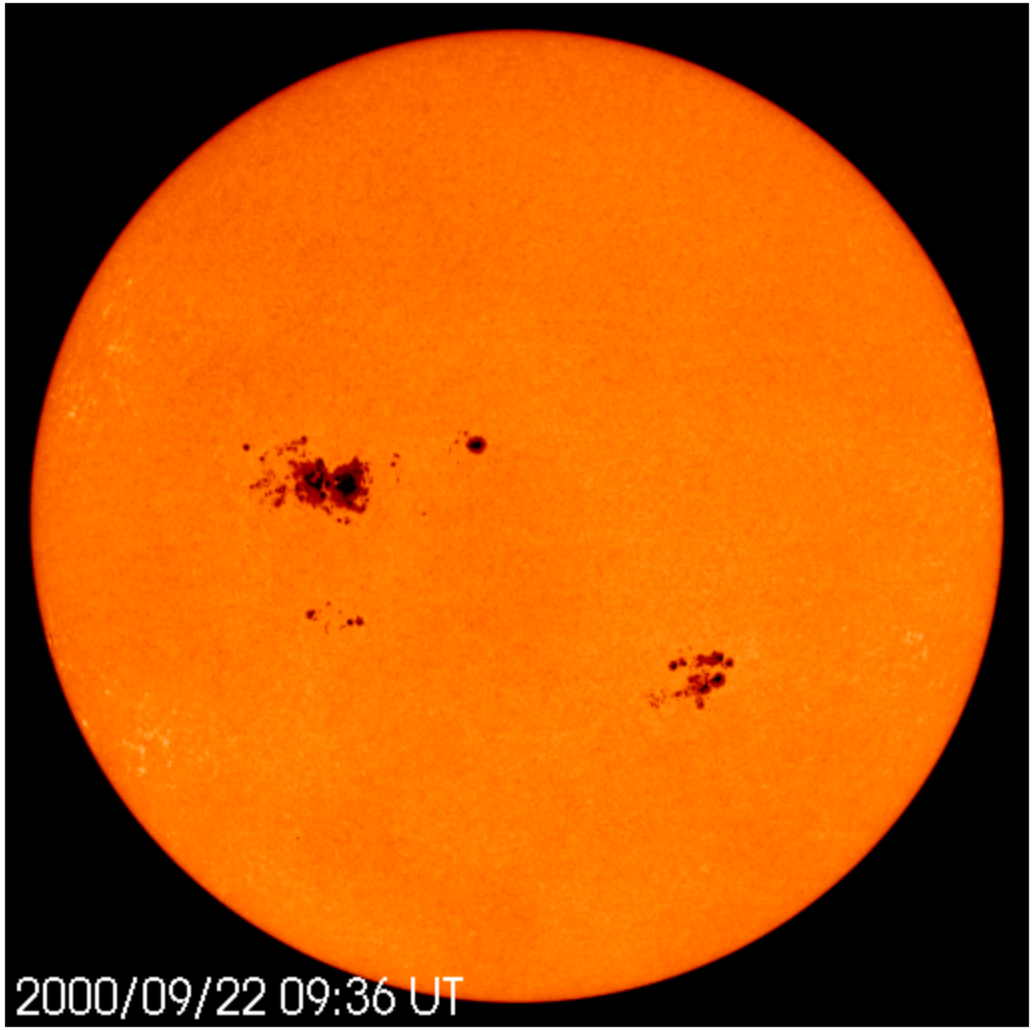
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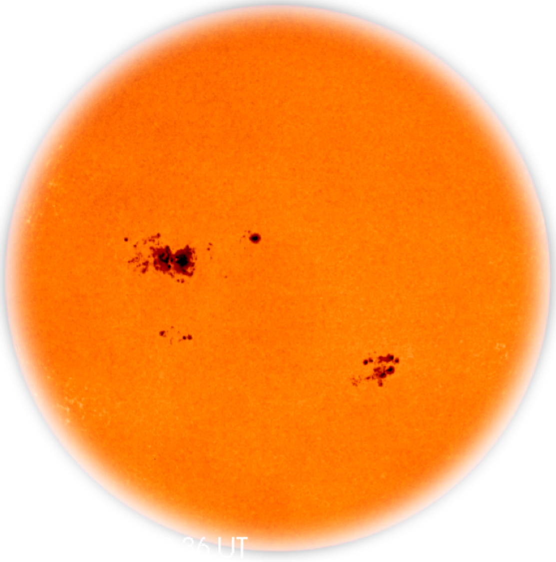
Sunspot characteristics:



(i) Low temperature: 3900°K
(ii) Intense magnetic field: 200gauss
(iii) Pair
(iv) Cycle~11.25 years

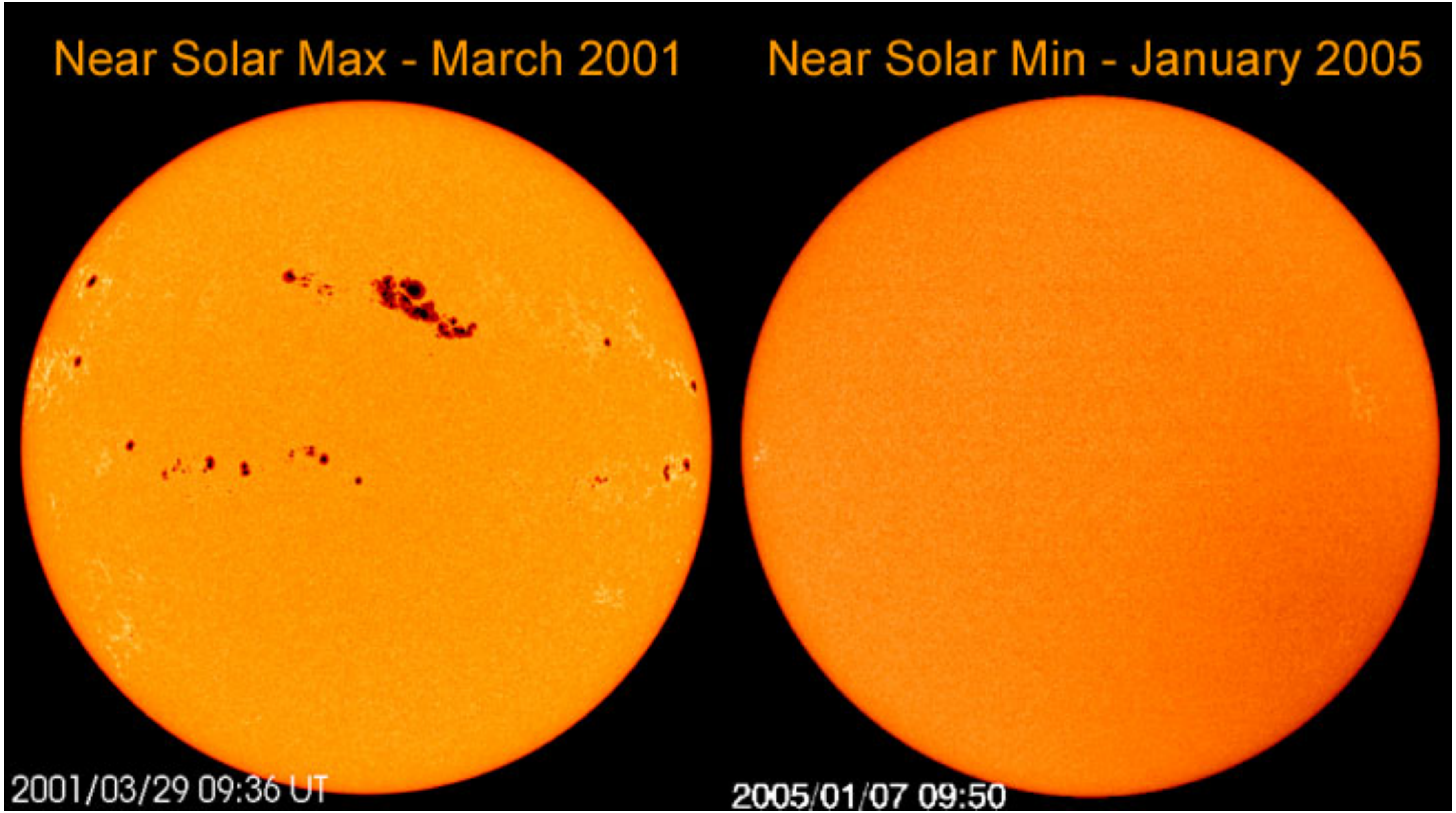
Wolf Sunspot number (Solar activity index, **SSN, R)**

Wolf number: $R=k(10*g+f)$

f: number of individual spot   g: number of group
k: comparison constant ~1   Solar min R~0   Solar max R~200

R_{12}: Sum 12 monthly mean of R and then divide by 12

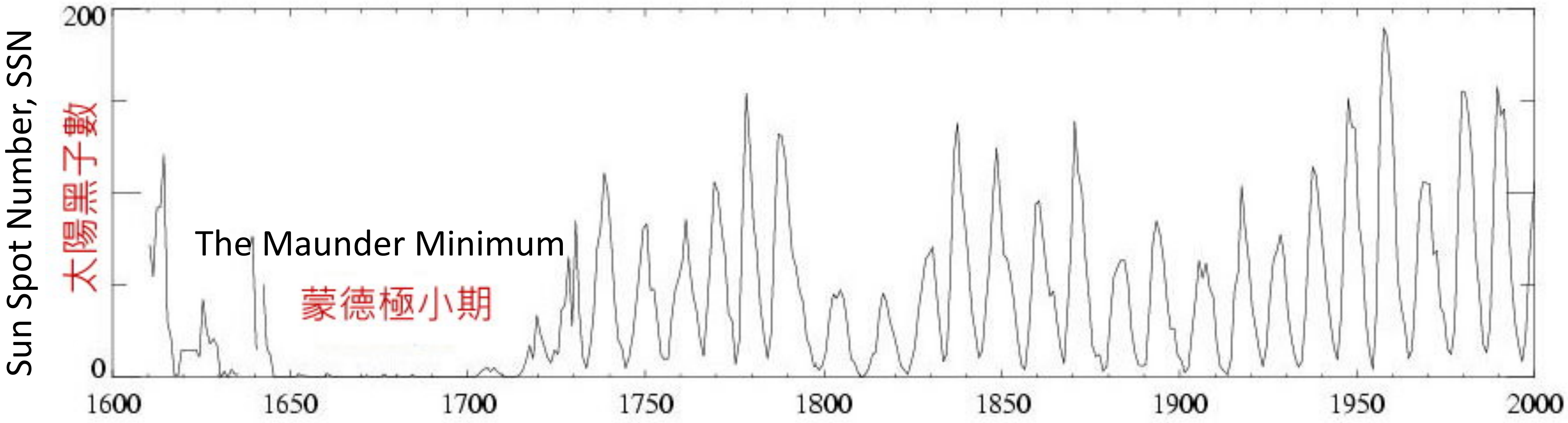
$$R12=(0.5R_{-6} +R_{-5} +R_{-4} +R_{-3} +R_{-2} +R_{-1} +R_0+R_1+R_2+R_3+R_4+R_5 +0.5R_6)/12$$



The 1st cycle: 1755~1766

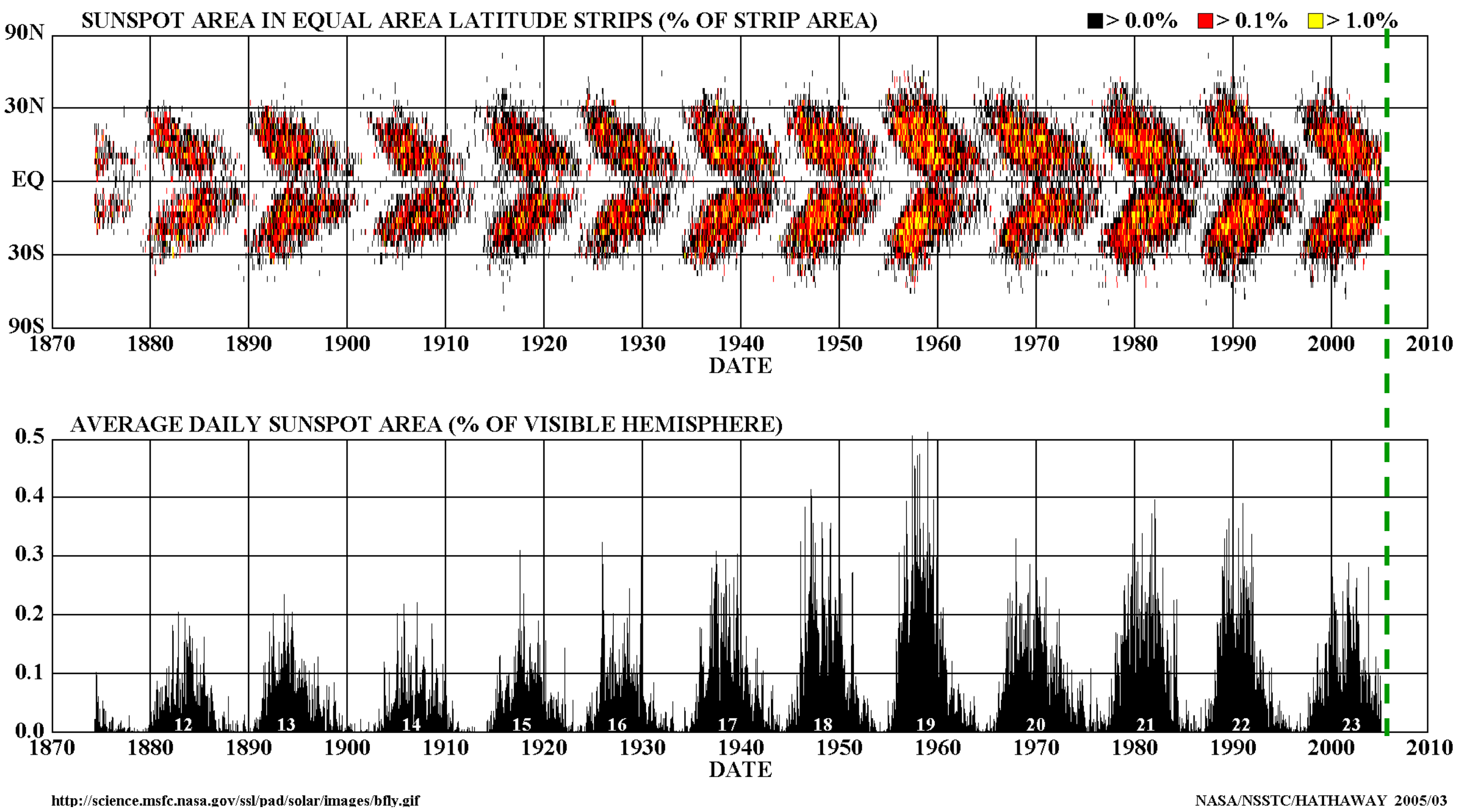
Now: 24th cycle, 2008.01.04 ~

The Maunder Minimum: 1645~1715

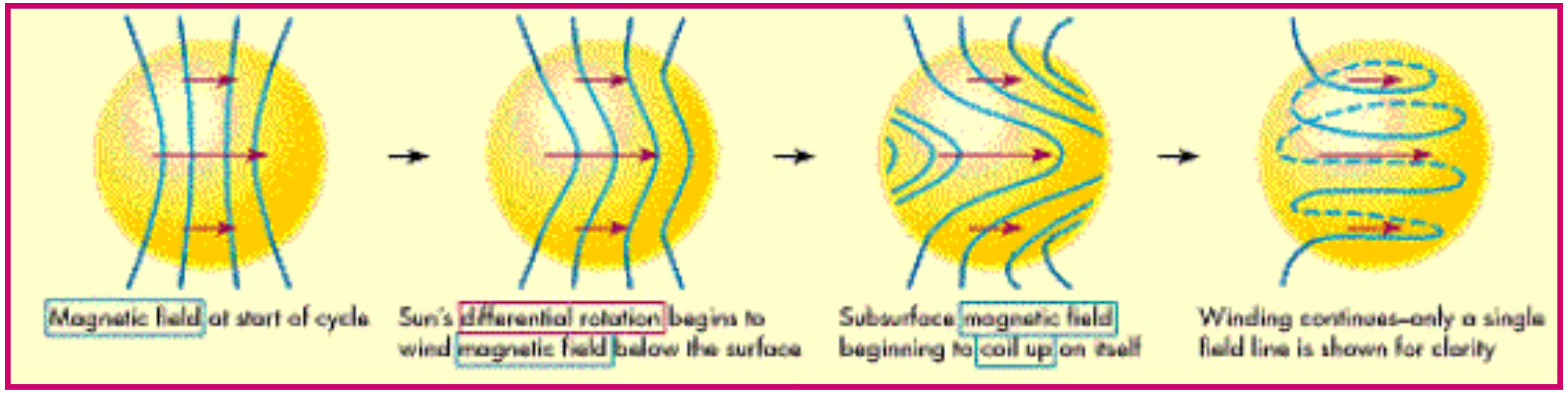


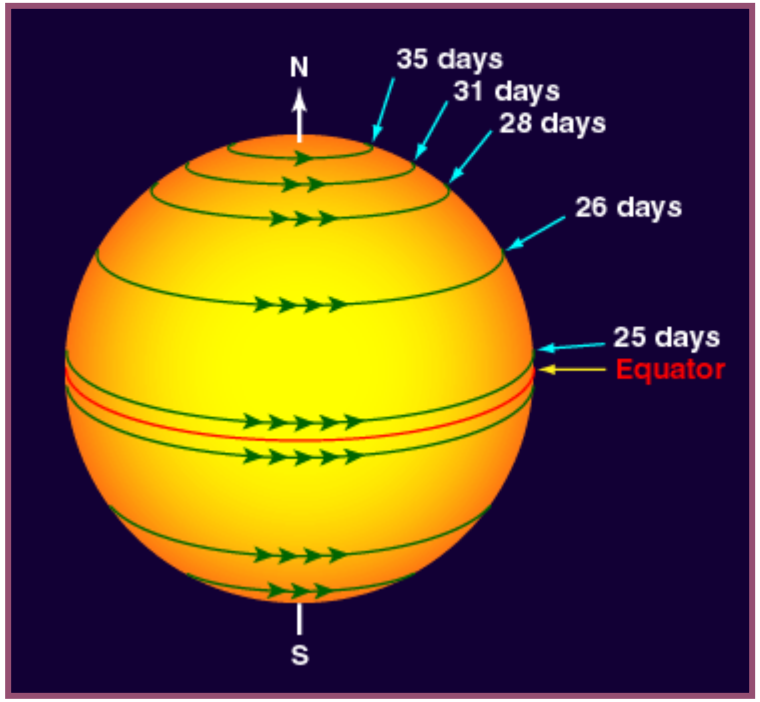
Sun Spot Number, SSN
太陽黑子數
200
0
The Maunder Minimum
蒙德極小期
1600
1650
1700
1750
1800
1850
1900
1950
2000

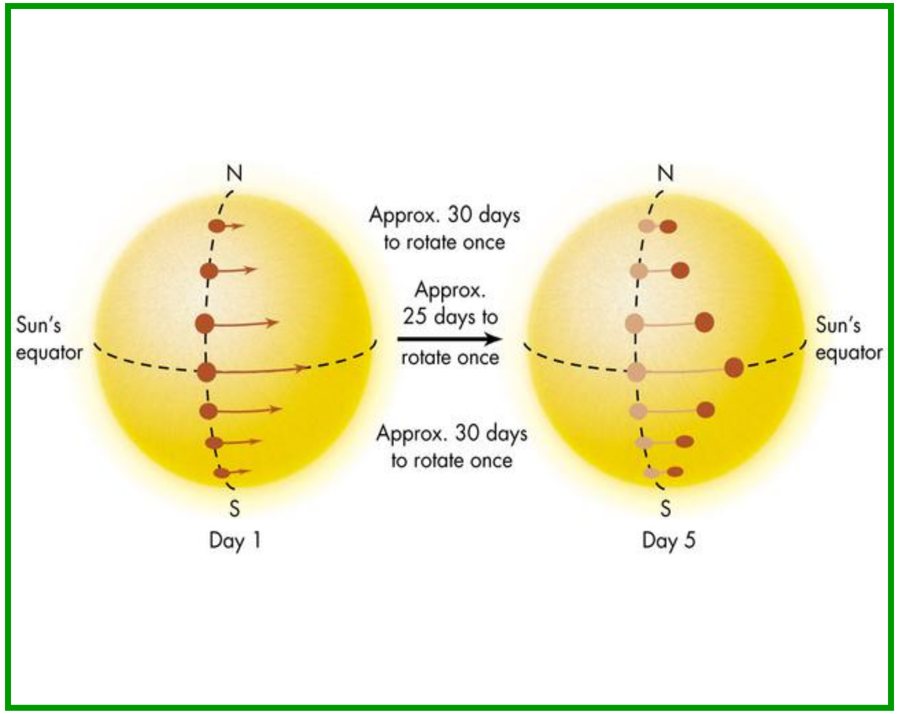
DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



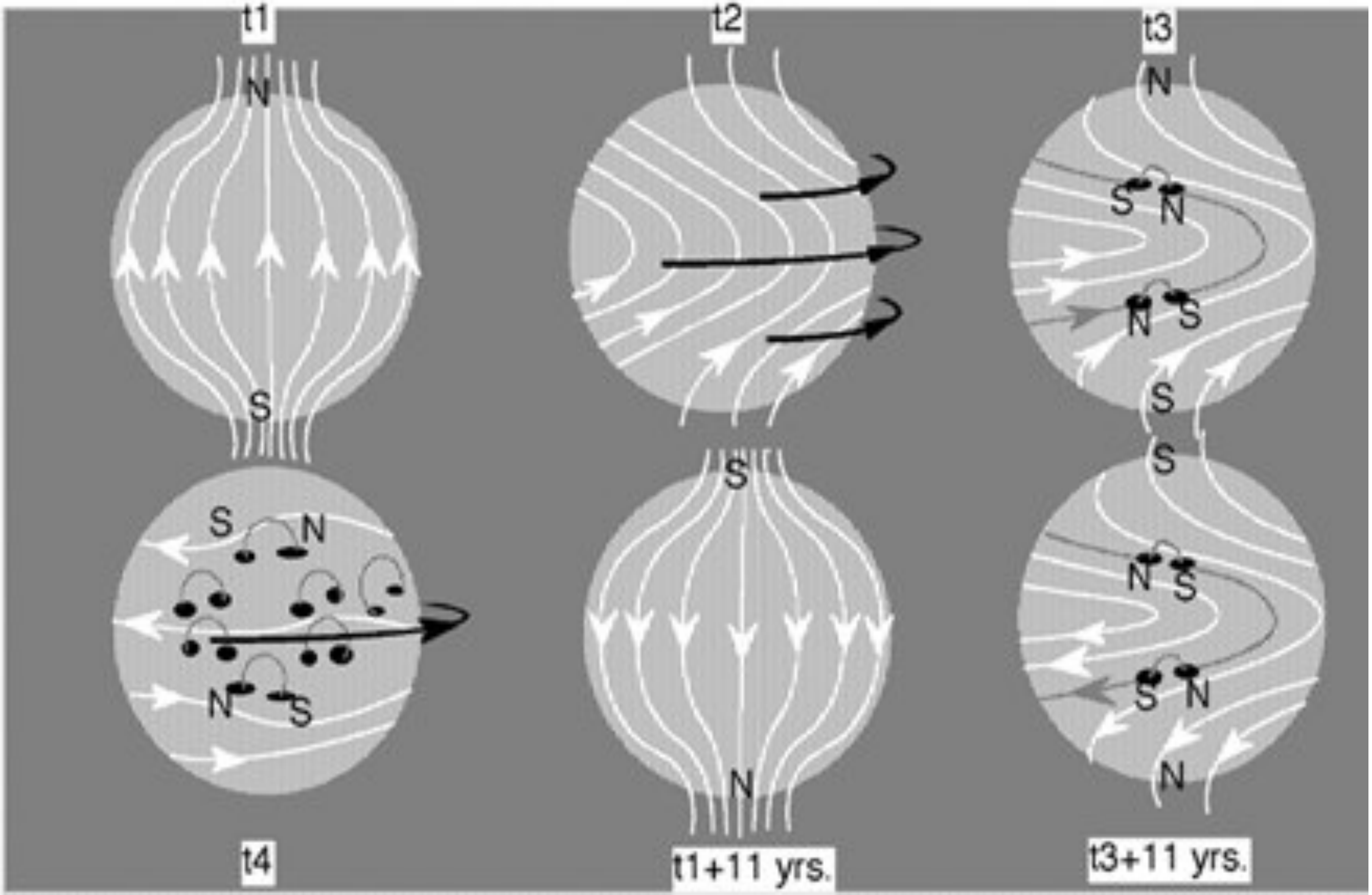
The Sun's rotation – differential rotation







A sketch of the formation of sunspots and the 22-years sunspot cycle due to the differential rotion of plasma in the photosphere



Sunlight and Solar wind

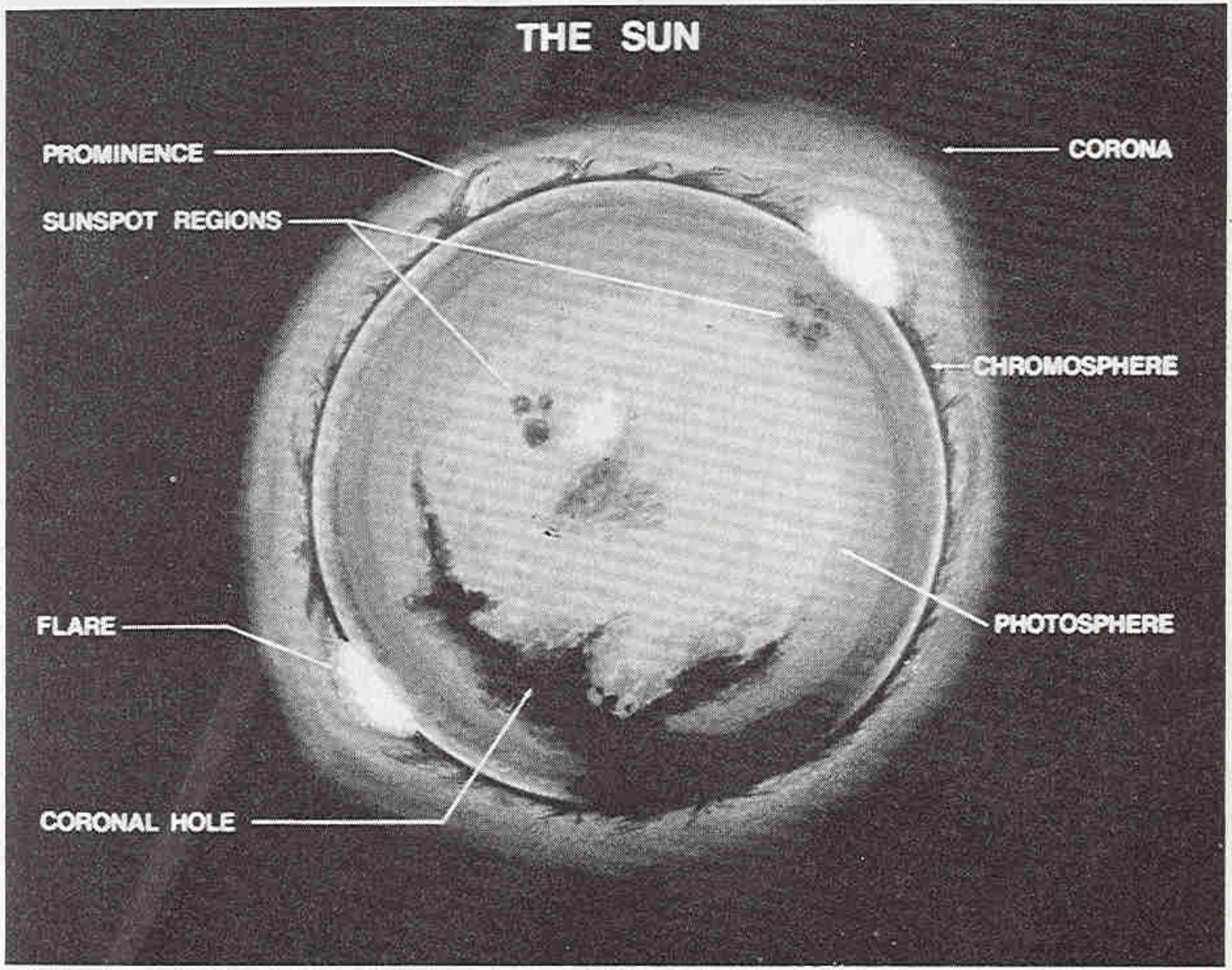


Fig. 2.2 *Solar features (observed at various times on different wavelengths) that can have important consequences on the ionosphere (NASA photograph MSFC–5/80–STE 3826)*

The solar-terrestrial system

- The Earth’s upper atmosphere is ionized by solar radiations

 (a) electromagnetic: radio - - X-ray; speed 300000 km/s, traveling time 8.3 min.

 (b) particle (corpuscular): solar wind (H^+ and e^- mainly); speed 300-800 km/s

- Solar terrestrial system: The Sun, the interplanetary medium, and the Earth’s magnetosphere, Ionosphere and neutral atmosphere.

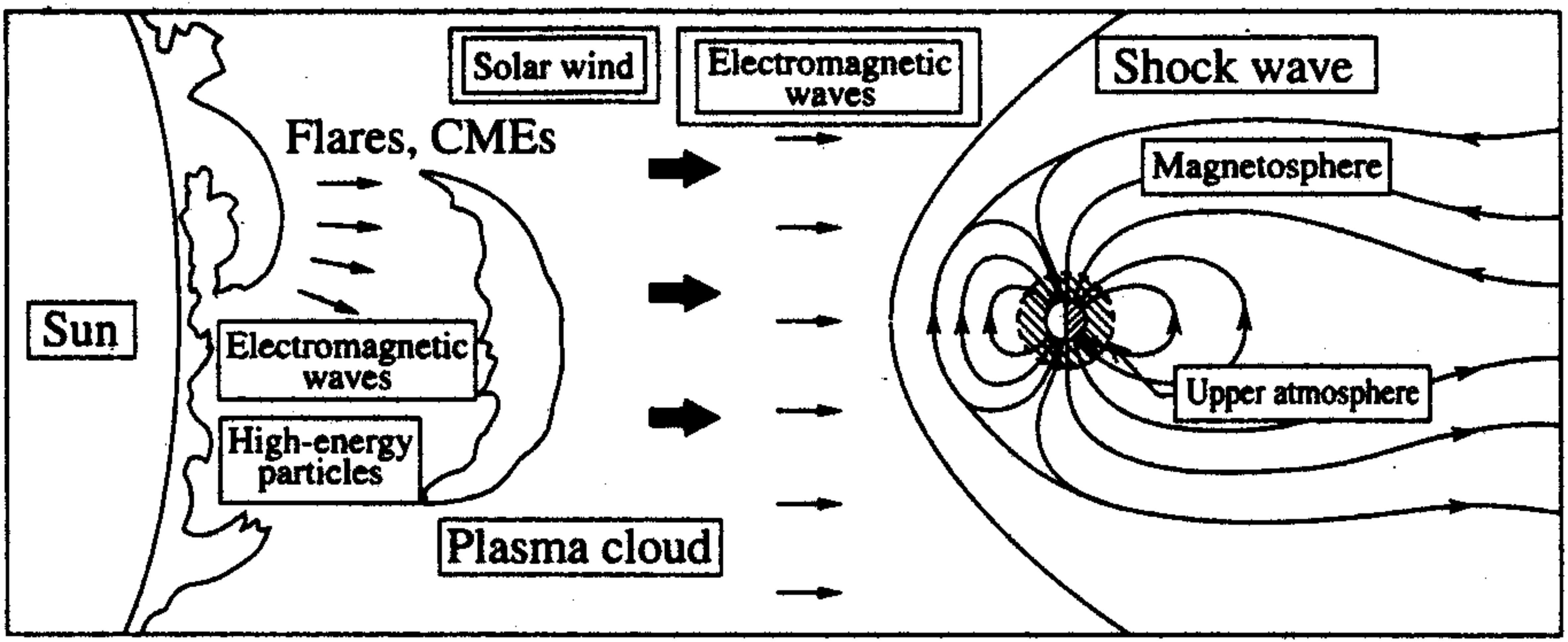
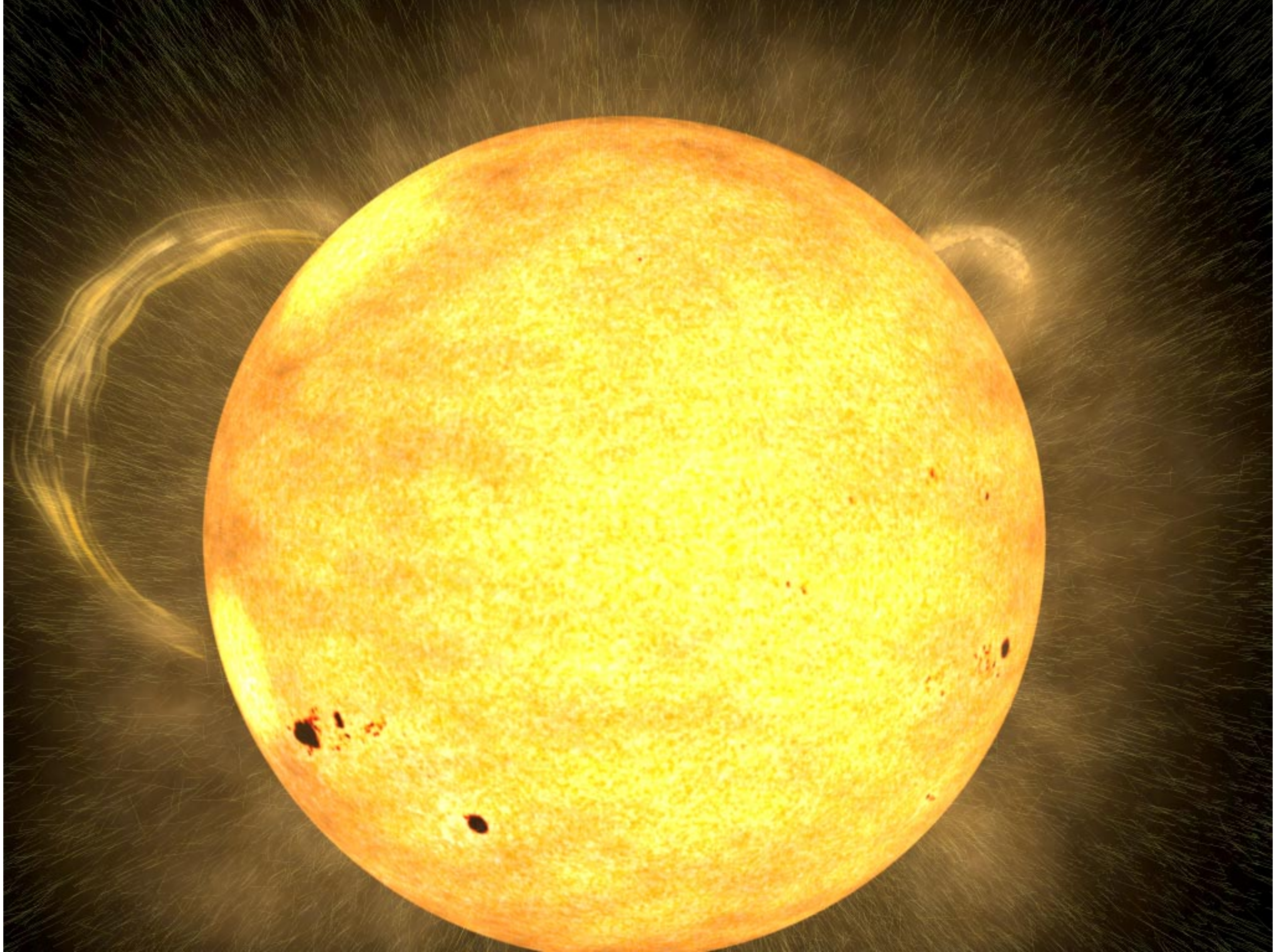


Fig. 1.1 The various forms of solar energy and the space environment

- Sunspots: low temp ~3000 K, strong magnetic field 0.4 T (4000 G), cycle ~ 11 yrs.
- The period between about 1640 and 1710 is called the Maunder minimum. Solar activity vs. climate.
- The Wolf (or Zurich) sunspot number $R=k(10g+s)$, where g and s are the group and individual spot number, and k denotes the correction factor.
- The spots, after a sunspot min., occur at the latitudes of 20° to 30° north and south whereas at sunspot max. spots occur at $\pm 15^\circ$ and, as the sunspot number declines, spots occur in the latitudes of 5° and 10°.
- The 12-month smoothed relative sunspot number

$$R_{12} = (0.5R_{-6} + R_{-5} + - - - + R_5 + 0.5\, R_6)/12$$

- Solar activity index: sunspots, F10.7



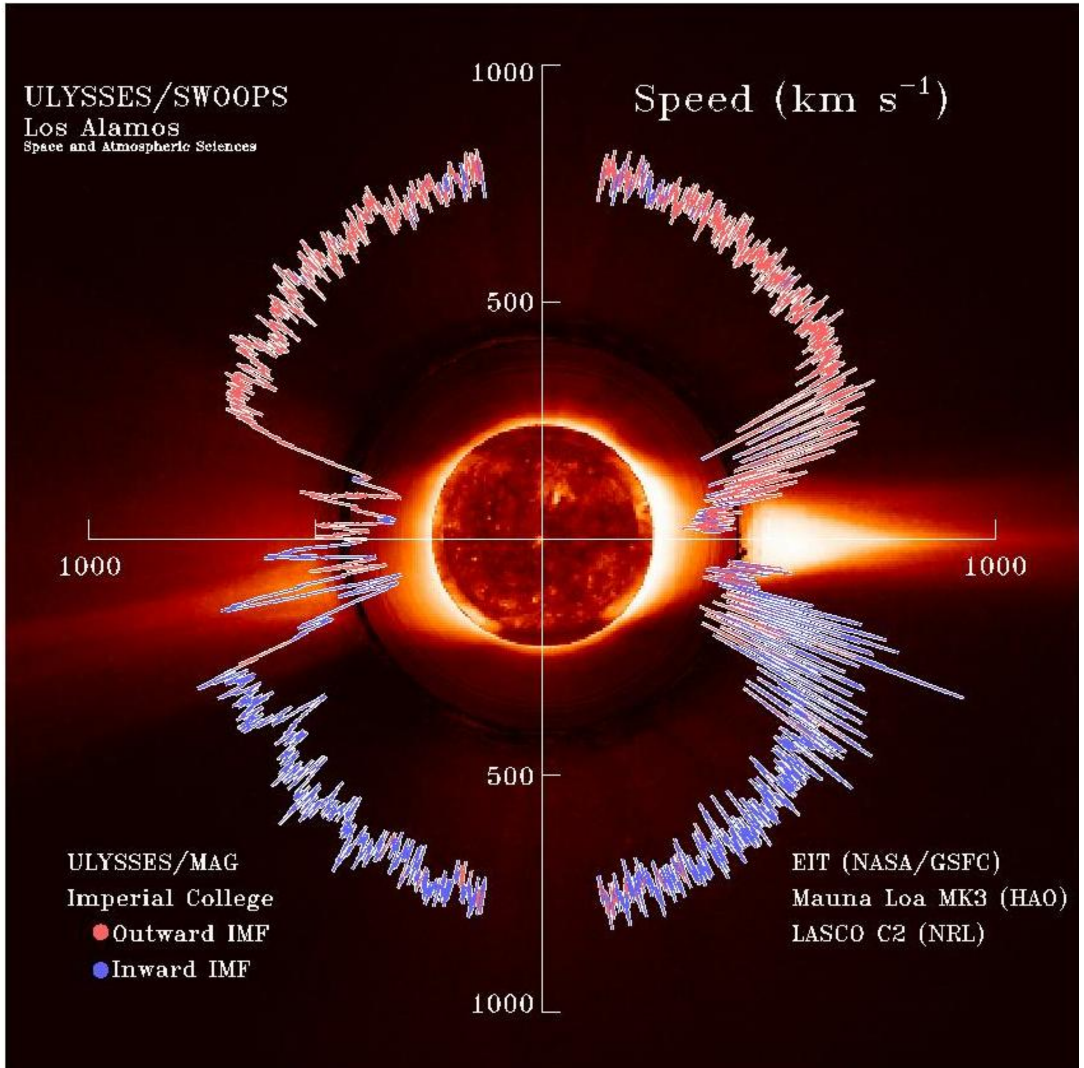
The solar wind

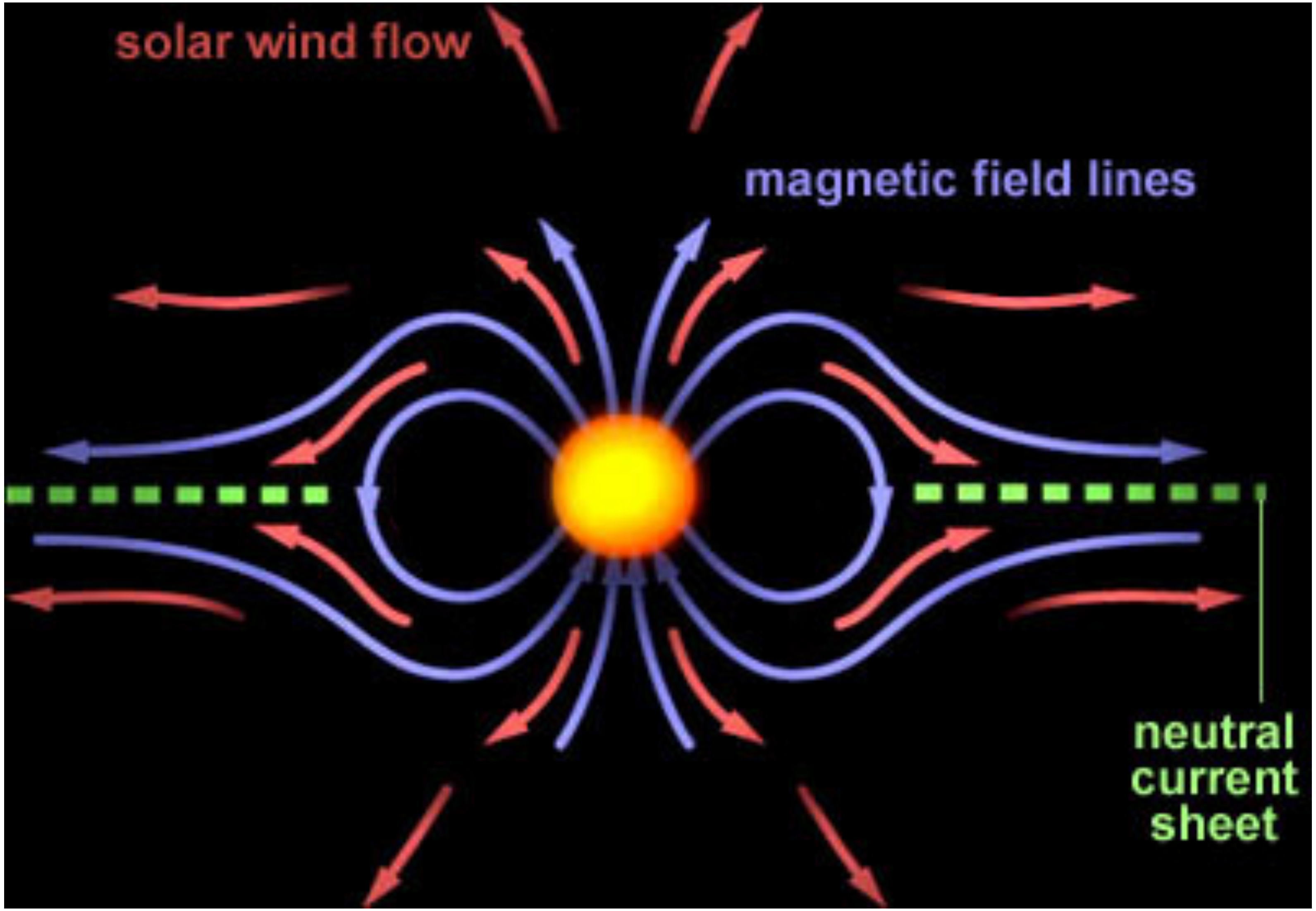
The solar wind is a continuous flow of charged particle

Slow solar wind 250-400 km/s, 8 ions/cm^3 at 1AU, Streamer belt

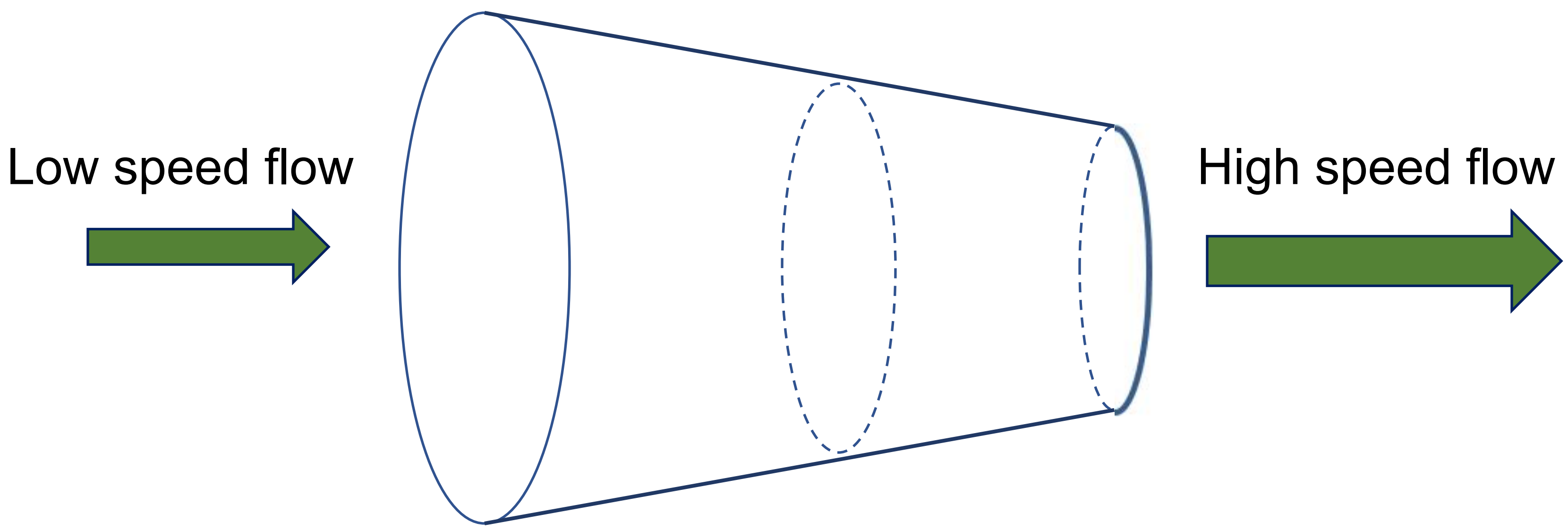
Strongly overexpending flux tubes

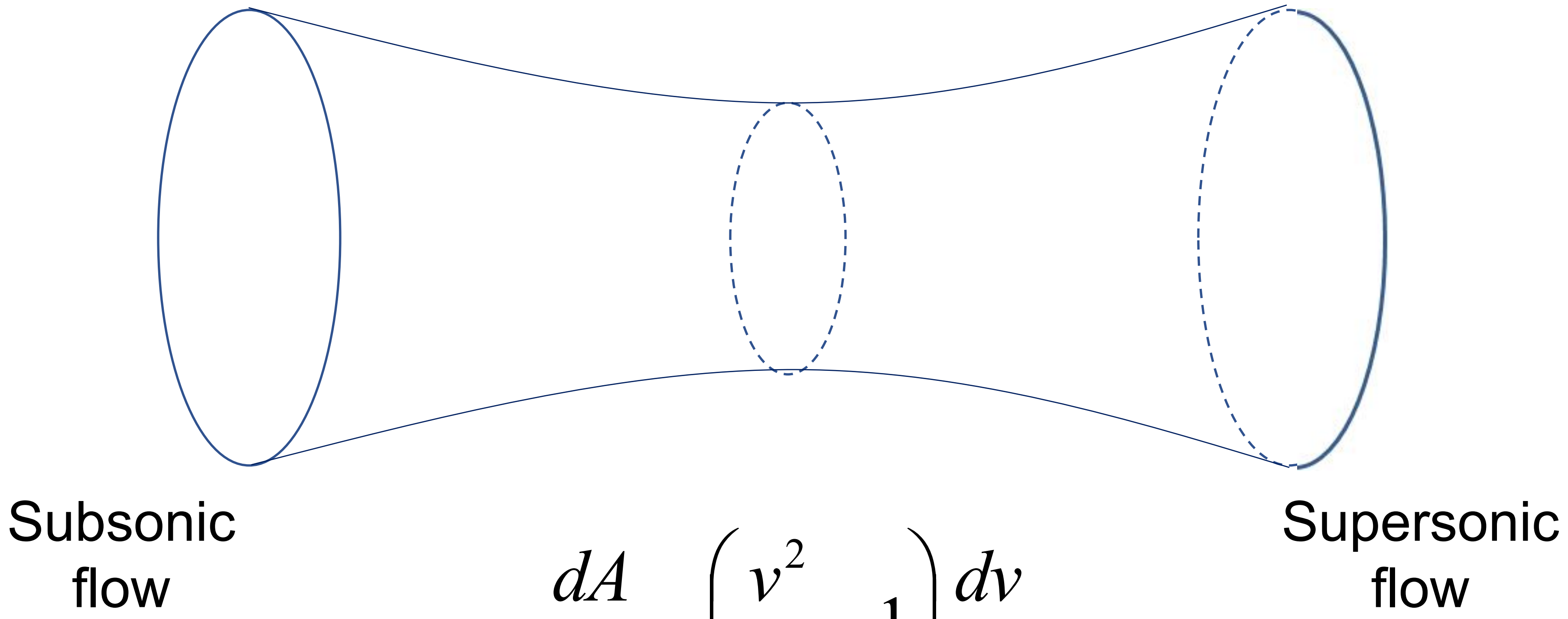
Fast solar wind 400-800 km/s, 3 ions/cm^3 at 1AU, Coronal hole




solar wind flow
magnetic field lines
neutral current sheet

Laval's nozzle





$$\frac{dA}{A} = \left(\frac{v^2}{c_s^2} - 1 \right) \frac{dv}{v}$$

$$c_s = \sqrt{\frac{p}{\rho}} = \sqrt{\frac{2k_B T}{m}}$$

Equation of motion:

$$\rho(\vec{u}\cdot\nabla)\vec{u} = -\nabla p - \frac{\rho M_\Theta G}{r^2} \qquad (4.16)$$

$$u_r \frac{du_r}{dr} = \frac{1}{nm}\frac{d}{dr}(2nk_B T) - \frac{GM_\Theta}{r^2} \qquad (4.17)$$

Continuity Equation:

$$n(r)\cdot u_r(r)\cdot r^2 = n_0 \cdot u_{r0} \cdot r_0^2 \qquad (4.18)$$

$$\boxed{\frac{du_r}{dr}\left[u_r - \frac{2k_B T}{mv_r}\right] = \frac{2k_B r^2}{m}\frac{d}{dr}\frac{T}{r^2} - \frac{GM_\Theta}{r^2} \qquad (4.19)}$$

$$\left[\frac{v}{v_c}-1\right]\frac{dv}{v}=2\left[1-\frac{r_c}{r}\right]\frac{dr}{r}$$

$$r_c=\frac{GM_\Theta m}{4k_BT} = \frac{GM_\Theta}{2c_s}$$

$$u_c=\sqrt{\frac{2k_BT_0}{m}}$$

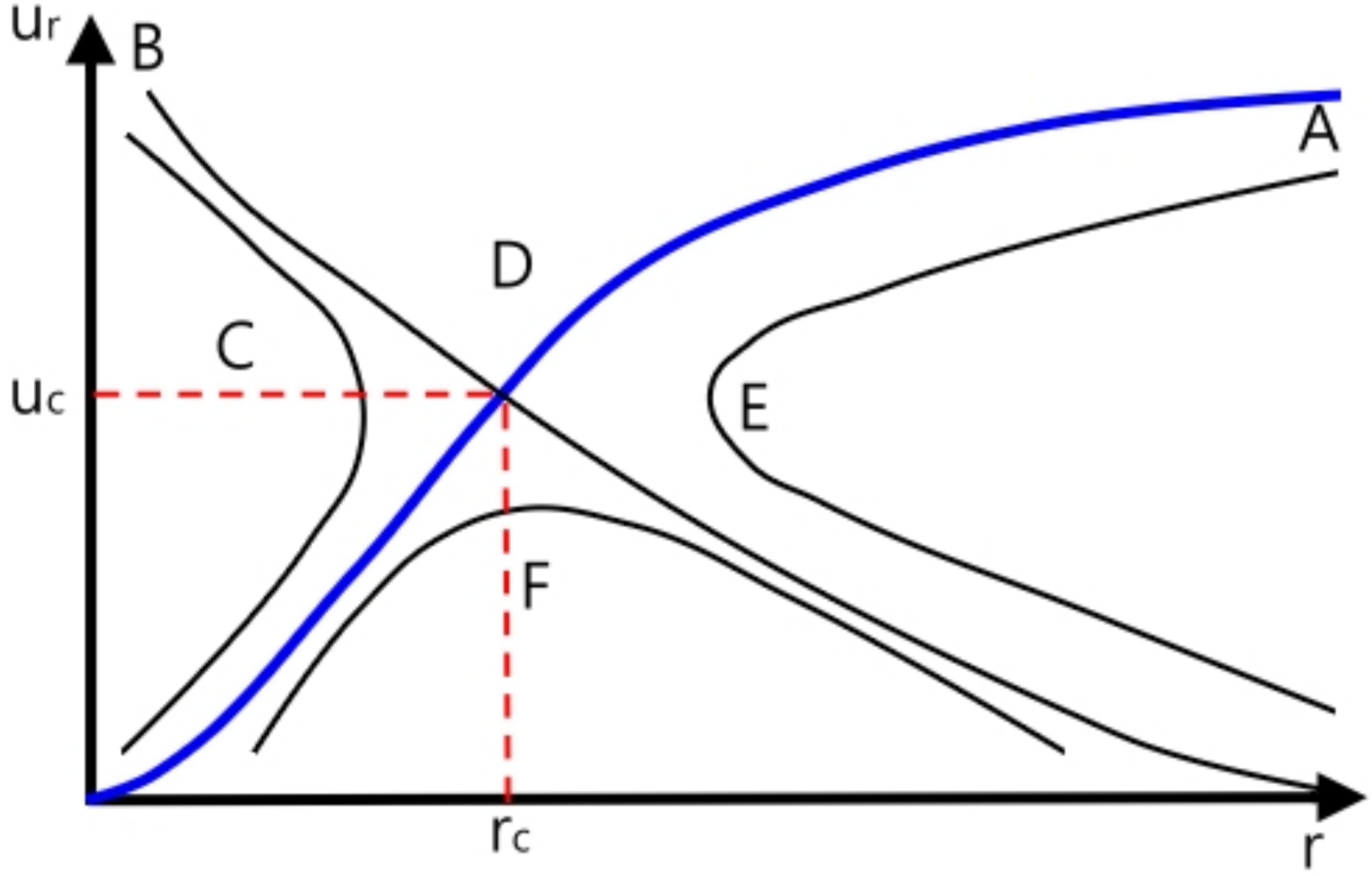


TABLE 4.2. Solar-Wind Flux Densities and Fluxes near the Orbit of the Earth

	Flux Density	Flux Through Sphere at 1 AU
Protons	$3.0 \times 10^{8}\ \mathrm{cm^{-2} \cdot s^{-1}}$	$8.4 \times 10^{35}\ \mathrm{s^{-1}}$
Mass	$5.8 \times 10^{-16}\ \mathrm{g \cdot cm^{-2} \cdot s^{-1}}$	$1.6 \times 10^{12}\ \mathrm{g \cdot s^{-1}}$
Radial momentum	2.6×10^{-9} pascal (Pa)	7.3×10^{14} newton (N)
Kinetic energy	$0.6\ \mathrm{erg \cdot cm^{-2} \cdot s^{-1}}$	$1.7 \times 10^{27}\ \mathrm{erg \cdot s^{-1}}$
Thermal energy	$0.02\ \mathrm{erg \cdot cm^{-2} \cdot s^{-1}}$	$0.05 \times 10^{27}\ \mathrm{erg \cdot s^{-1}}$
Magnetic energy	$0.01\ \mathrm{erg \cdot cm^{-2} \cdot s^{-1}}$	$0.025 \times 10^{27}\ \mathrm{erg \cdot s^{-1}}$
Radial magnetic flux	5×10^{-9} T	1.4×10^{15} weber (Wb)

TABLE 4.3. Some Derived Properties of the Solar Wind near the Orbit of the Earth

Gas pressure	30 pPa
Sound speed	60 $km \cdot s^{-1}$
Magnetic pressure	19 pPa
Alfvén speed	40 $km \cdot s^{-1}$
Proton gyroradius	80 km
Proton–proton collision time	4×10^6 s
Electron–electron collision time	3×10^5 s
Time for wind to flow from corona to 1 AU	$\sim$4 days $= 3.5 \times 10^5$ s

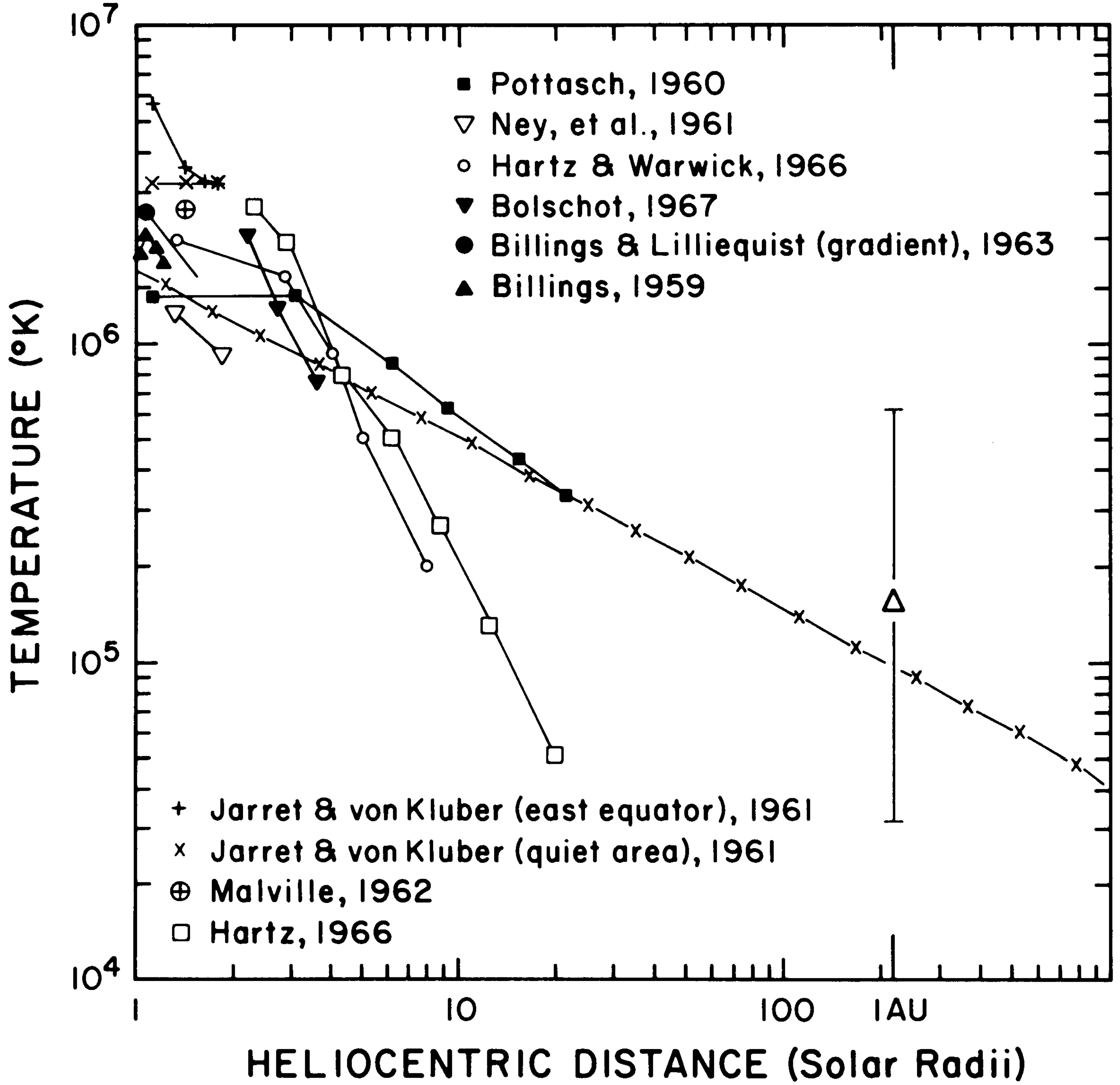


FIG. 4.1. Coronal temperature measurements at various heliocentric distances. (Adapted from Newkirk, 1967.)

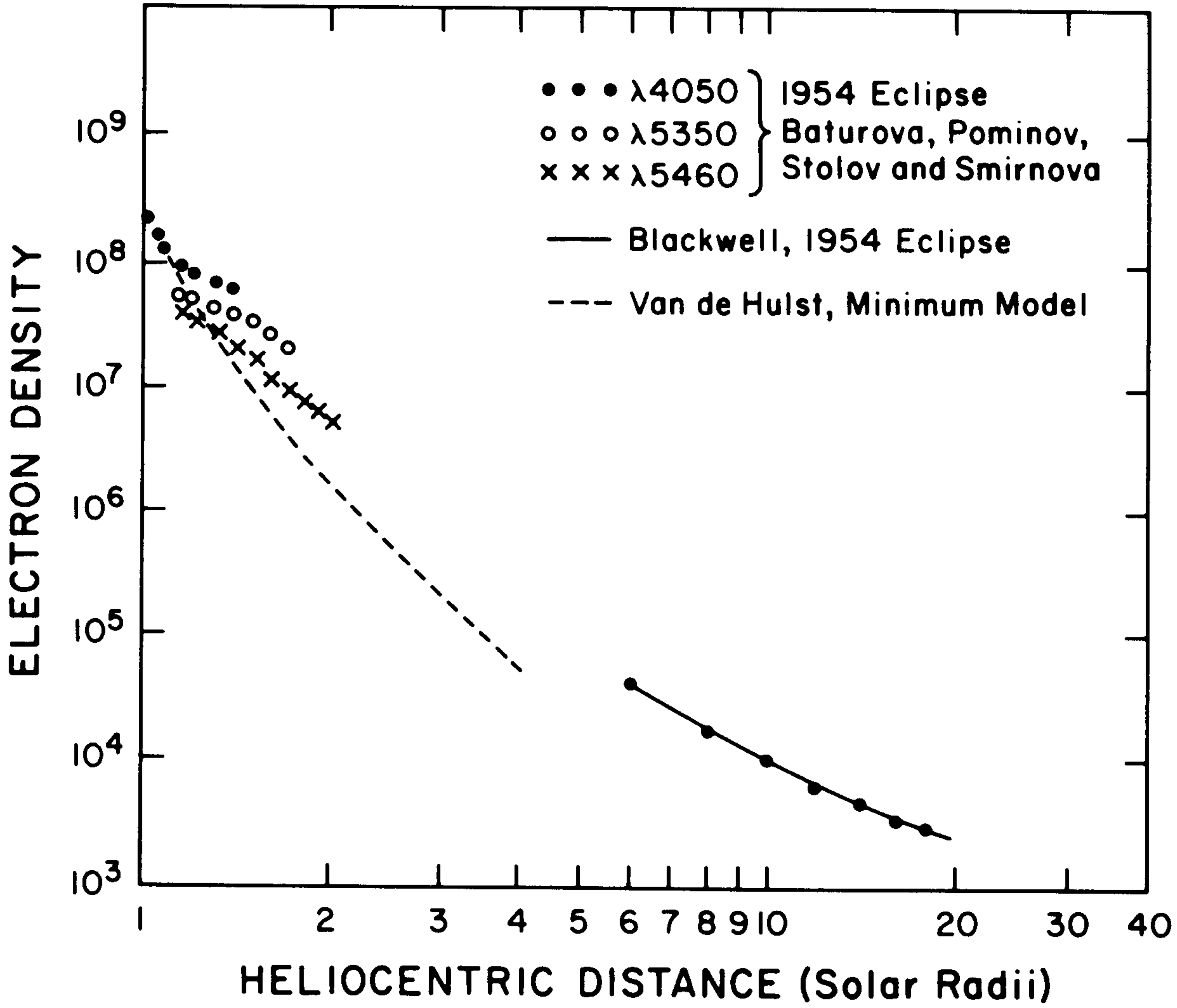


FIG. 4.2. Equatorial electron density for 1954 corona. Number density of electrons (cm^{-3}) inferred by different observers from data obtained at a single eclipse of the sun. (Adapted from Billings, 1966.)

The Fluid Theory of Solar Wind Formation

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{F}_g \qquad \text{(momentum)}$$

For a plasma flow that is *steady* or independent of time, all time derivatives are zero, and we need deal only with simpler equations:

$$\nabla \cdot \rho \mathbf{u} = 0 \tag{4.1}$$

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{F}_g \tag{4.2}$$

$$\nabla \cdot \rho \mathbf{u} = \frac{1}{r^2} \frac{d}{dr} \rho u r^2$$

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = \rho u \frac{du}{dr} \; \hat{\mathbf{e}}_r$$

we can write the flow speed as

$$\mathbf{u} = u(r)\hat{\mathbf{e}}_r$$

and express the sun's gravitational field as

$$\mathbf{F}_g = -\frac{GM_\odot}{r^2}\hat{\mathbf{e}}_r$$

where G is the gravitational constant, and $M_\odot$ is the mass of the sun. The pressure gradient is

$$\nabla p = \frac{dp}{dr}\hat{\mathbf{e}}_r$$

$$\frac{1}{r^2}\frac{d}{dr}\rho u r^2 = 0 \tag{4.3}$$

$$\rho u \frac{du}{dr} = -\frac{dp}{dr} - \rho \frac{GM_\odot}{r^2} \tag{4.4}$$

$$-\frac{dp}{dr} - \rho \frac{GM_\odot}{r^2} = 0 \tag{4.5}$$

$$p = nk(T_e + T_i) = 2nkT$$

Solving for the mass density $\rho = n(m_e + m_p) = nm$, where m is the sum of the proton and electron masses, yields

$$\rho = m \cdot \frac{p}{2kT}$$

Substitution into (4.5), assuming that the temperature T is constant, finally gives the equation for pressure in a *static*, *isothermal* atmosphere:

$$\frac{1}{p}\frac{dp}{dr} = -\frac{GM_{\odot}m}{2kT}\frac{1}{r^2}$$

The solution to this differential equation for $p(r)$ is

$$\ln p = \frac{GM_{\odot}m}{2kT}\frac{1}{r} + K$$

where K is an arbitrary constant. Setting $p(r) = p_0$ at the base of the corona, $r = R$, gives the value of the constant

$$K = \ln p_0 - \frac{GM_\odot m}{2kT}\frac{1}{R}$$

and allows us to write the solution as

$$\ln \frac{p}{p_0} = \frac{GM_\odot m}{2kT}\left(\frac{1}{r} - \frac{1}{R}\right)$$

or

$$p(r) = p_0 \exp\left\{\frac{GM_\odot \mathrm{m}}{2kT}\left(\frac{1}{r} - \frac{1}{R}\right)\right\} \tag{4.6}$$

For $r > R$, $1/r - 1/R$ is negative, and $p < p_0$; that is, solution (4.6) shows what we would expect, that $p(r)$ decreases with increasing distance from the sun.

that is of interest. The more familiar form can be recovered from (4.6) by measuring r from the base of the corona, in terms of the height

$$h = r - R$$

and considering only $h << R$. Then

$$\frac{1}{r} = \frac{1}{R+h} = \frac{1}{R(1+h/R)} \approx \frac{1}{R}\left(1 - \frac{h}{R}\right)$$

In this approximation, equation (4.6) becomes

$$p = p_0 \exp\left\{\frac{GM_\odot m}{2kT}\left(\frac{1}{R} - \frac{h}{R^2} - \frac{1}{R}\right)\right\} = p_0 \exp\left\{-\frac{GM_\odot m}{2kTR^2} \cdot h\right\} = p_0 e^{-h/\lambda} \quad (4.7)$$

where $\lambda = 2kTR^2/GM_\odot m = 2kT/mg$ is the *scale height* given in terms of the acceleration due to gravity g at the base of the atmosphere.

The deficiency of equation (4.6) as a model for the equilibrium state of the corona stems from the variation in gravity over the great heliocentric distance spanned by the corona. If we let $r \to \infty$, the pressure given by (4.6) does not continue to decay exponentially as in (4.7); rather, it approaches the value

$$p_\infty = p_0 \exp\left\{-\frac{GM_\odot m}{2kTR}\right\}$$

For a coronal temperature of 10^6K, this is only about e^{-8} or 3×10^{-4} of the high pressure at the base of the corona. It is many orders of magnitude higher than the pressure thought to exist in the interstellar medium ($p_{\mathrm{int}} \approx 10^{-13} - 10^{-14}$ Pa), and thus could not represent an equilibrium state between the corona and that distant medium.

It was this problem that motivated E. N. Parker in the 1950s to reexamine the equilibrium states implied by equations (4.3) and (4.4) by considering solutions with nonzero flow speeds. The first of these equations is satisfied if

$$\rho u r^2 = C \qquad \text{(a constant)}$$

The meaning of this expression becomes clear if it is multiplied by 4π to give

$$4\pi r^2 \cdot \rho u = I \qquad \text{(a constant)} \tag{4.8}$$

The momentum equation (4.4) involves the same two fluid properties, ρ and u, as our first integral (4.8), plus the pressure p. Under the same isothermal assumption made in our analysis of a static equilibrium,

$$p = 2nkT$$

can be differentiated and substituted into (4.4) to give

$$\rho u \frac{du}{dr} = -2kT \frac{dn}{dr} - \rho \frac{GM_\odot}{r^2}$$

or, using $\rho = nm$ and dividing through by ρ,

$$u \frac{du}{dr} = -\frac{2kT}{m} \frac{1}{n} \frac{dn}{dr} - \frac{GM_\odot}{r^2} \tag{4.9}$$

This equation can be written with the speed $u(r)$ as the only remaining fluid property by writing (4.8) as

$$4\pi r^2 mnu = I$$

solving for

$$n = \frac{I}{4\pi m}\frac{1}{ur^2}$$

and differentiating to obtain

$$\frac{dn}{dr} = \frac{I}{4\pi m}\left\{-\frac{1}{u}\cdot\frac{2}{r^3} - \frac{1}{r^2}\frac{1}{u^2}\frac{du}{dr}\right\} \tag{4.10}$$

$$\frac{1}{n}\frac{dn}{dr}=\frac{4\pi m}{I}\cdot ur^2\cdot\frac{I}{4\pi m}\left\{-\frac{2}{ur^3}-\frac{1}{r^2u^2}\frac{du}{dr}\right\}=-\frac{2}{r}-\frac{1}{u}\frac{du}{dr}$$

Substitution into (4.9) then reduces the momentum equation to

$$u\frac{du}{dr}=\frac{4kT}{mr}+\frac{2kT}{m}\frac{1}{u}\frac{du}{dr}-\frac{GM_\odot}{r^2} \tag{4.11}$$

This is a differential equation for $u(r)$ and its derivative du/dr in an *expanding, isothermal* atmosphere.

Analysis of equation (4.11) is facilitated by moving all terms involving $u(r)$ to the left-hand side to give

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

$$\left(u^2 - \frac{2kT}{m}\right)\frac{1}{u}\frac{du}{dr} = \frac{4kT}{mr} - \frac{GM_\odot}{r^2} \tag{4.12}$$

This form of the momentum equation was recognized by Parker (1958) as revealing the existence of a solar wind. For any realistic coronal temperature T, the second term on the right-hand side of (4.12), GM/r^2, is larger than the first term, $4kT/mr$, at the base of the corona. This is basically a statement that despite its high temperature, the corona is gravitationally bound. Thus the right-hand side of (4.12) is negative near the base of the corona. However, GM/r^2 falls off more rapidly with r than does $4kT/mr$, so that the right-hand side grows with increasing r, passes through zero at the radius

$$r_c = \frac{GM_\odot m}{4kT} \qquad\qquad \left.\frac{du}{dr}\right|_{r_c} = 0$$

Section 4.2, the sound speed in the corona is given by

$$c_s^2 = \frac{\gamma p}{\rho} = \gamma \frac{2nkT}{nm} = \gamma \frac{2kT}{m}$$

For an isothermal plasma, $\gamma = 1$. All other solutions (that start with small

It is not difficult to write down actual solutions to equation (4.12). The reader can easily verify by differentiation that the expression

$$\frac{1}{2} u^2 - \frac{2kT}{m} \ln u = \frac{4kT}{m} \ln r + \frac{GM_\odot}{r} + K'$$

where K' is again an arbitrary constant, is a solution of (4.12). Imposition of the requirement that $u^2 = 2kT/m$ where $r = r_c = GM_\odot\, m/4kT$ determines the constant K' and gives the explicit form of the special *solar-wind solution*

$$u^2-\frac{2kT}{m}-\frac{2kT}{m}\ln\frac{mu^2}{2kT}=8\frac{kT}{m}\ln\left(\frac{r}{r_c}\right)+2GM_{\odot}\left(\frac{1}{r}-\frac{1}{r_c}\right) \tag{4.13}$$

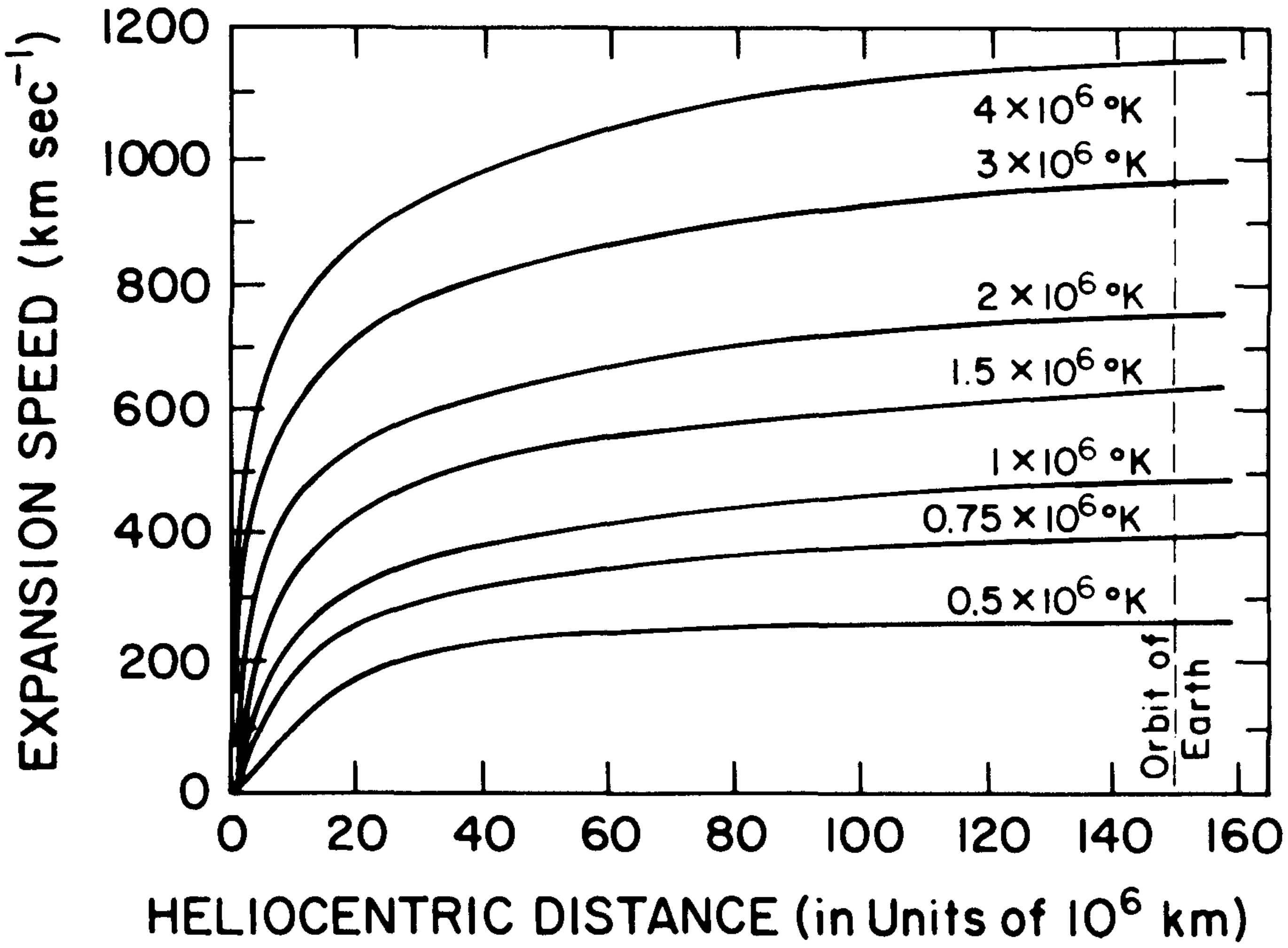


FIG. 4.3. Radial-expansion speed $u(r)$ derived from isothermal coronal-expansion models with coronal temperatures ranging from 5×10^5K to 4×10^6K (Adapted from Parker, 1958.)

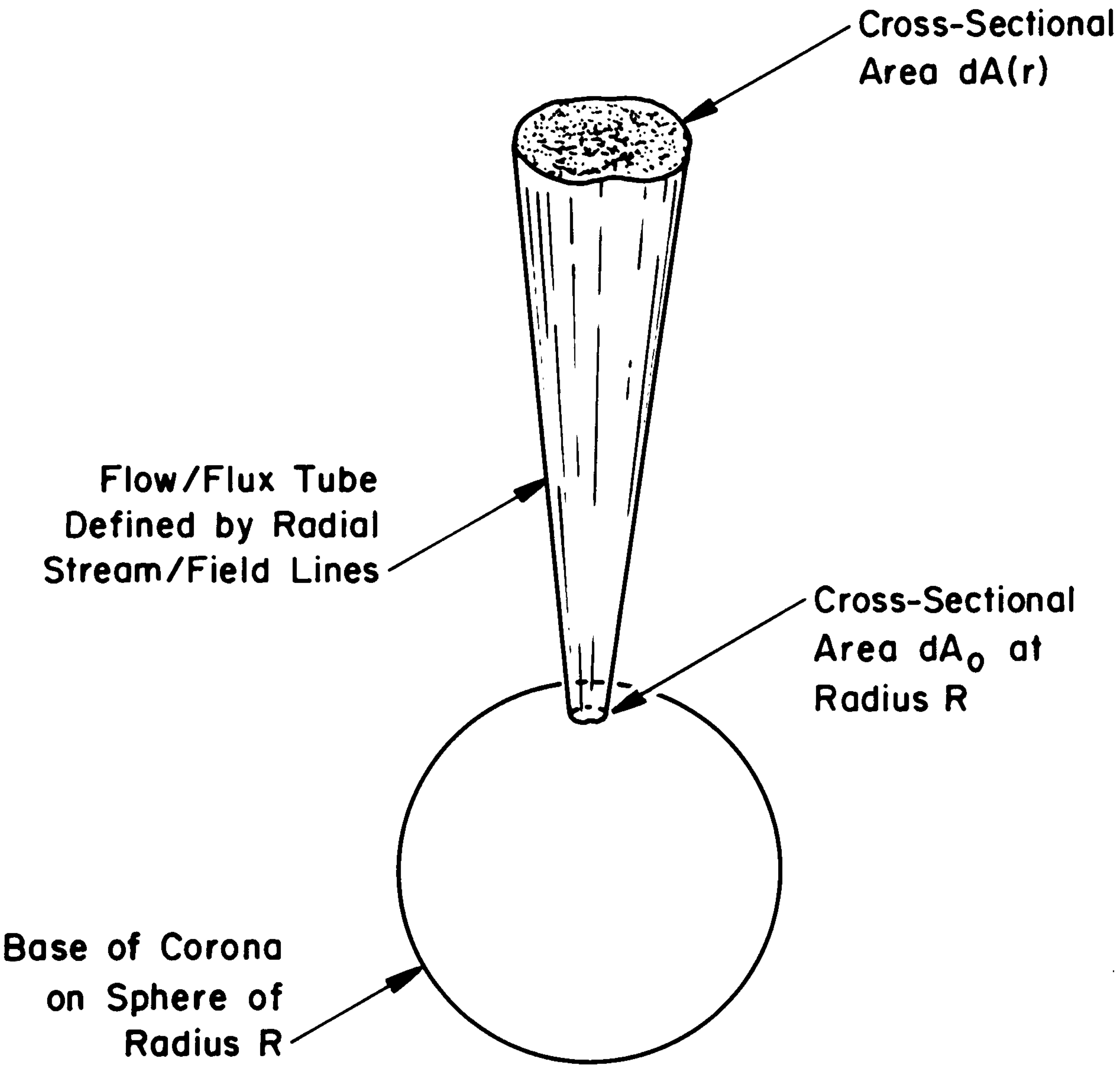


FIG. 4.4. Geometry of a flow (or flux) tube defined by radial streamlines (or magnetic-field lines).

magnetic flux within the tube (as implied by $\nabla \cdot \mathbf{B}=0$) then would require that if B_0 were the (radial) field at the base of the flux tube, and $B(r)$ were the field at any radius r,

$$B(r)\left(\frac{r}{R}\right)^2 dA_0 = B_0\, dA_0$$

or

$$B(r) = B_0\left(\frac{R}{r}\right)^2$$

That is, the intensity of the purely radial magnetic field would fall off as $1/r^2$.

$$\omega = \frac{2\pi \text{ rad}}{25.4 \text{ days}} = 2.7 \times 10^{-6} \text{ rad} \cdot \text{s}^{-1}$$

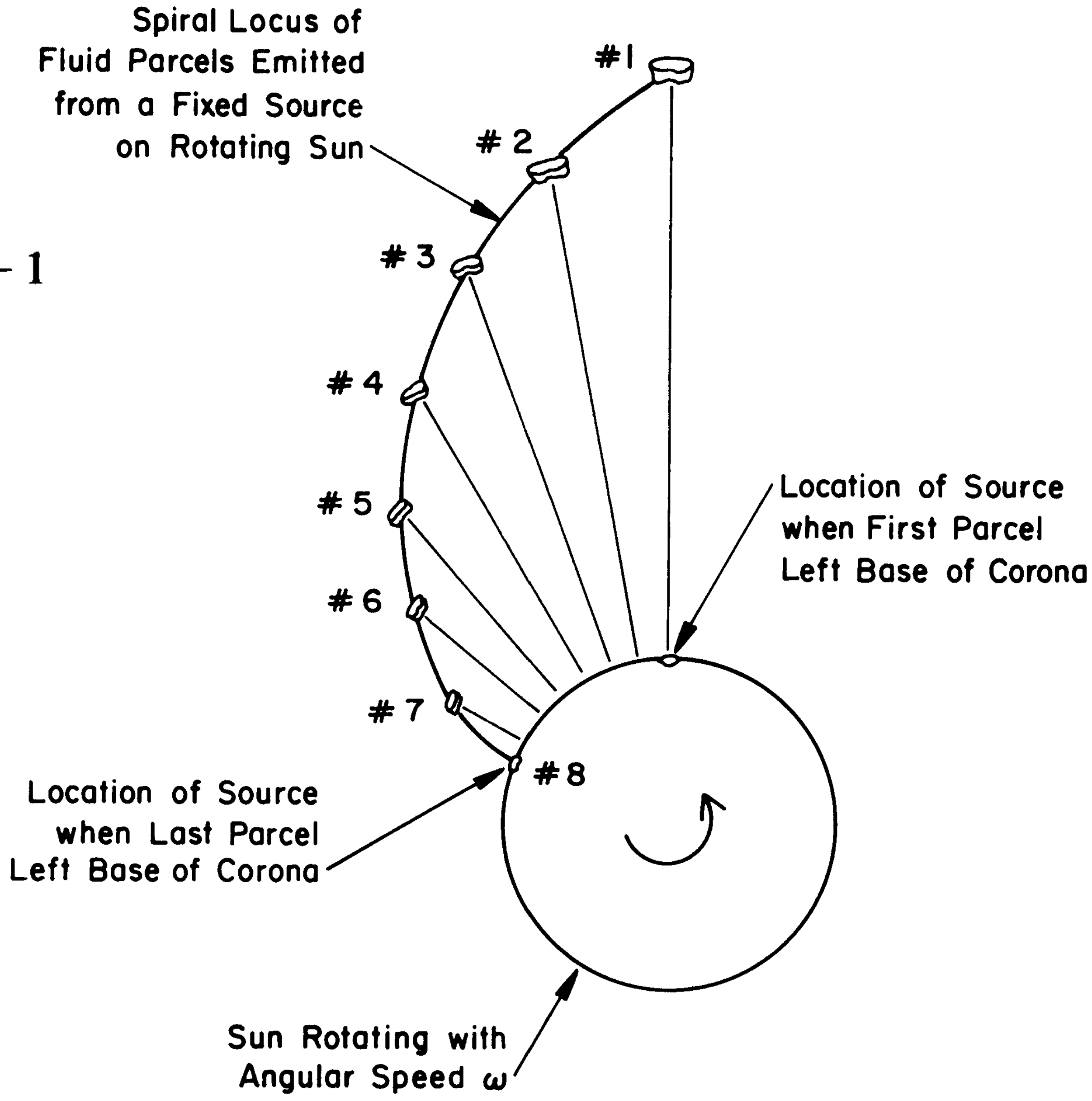


FIG. 4.5. Loci of a succession of fluid parcels (eight of them in this sketch) emitted at constant speed from a source fixed on the rotating sun.

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

Then the magnetic field stretched out along the path of plasma flowing from the fixed source in this coordinate system has components related by

$$\frac{B_\varphi}{B_r}=\frac{U_\varphi}{U_r}=\frac{-\omega r}{u(r)} \tag{4.14}$$

This gives a differential equation for the field lines near the solar equator (solar latitude = 0) as

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

If the radial-expansion speed is constant, as in the solar wind well out in interplanetary space, this equation becomes

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

and has the obvious solution

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

Specification of the location of the source of a field line at longitude φ_0 at $r = R$ then yields

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

This is in fact a geometric figure of Grecian antiquity and respectability known as the spiral of Archimedes.

$$B_r(r)\frac{r^2}{R^2}dA_0 = B_0 dA_0$$

or

$$B_r(r) = B_0\left(\frac{R^2}{r^2}\right)$$

The longitude (or azimuthal) component of the field can then be derived from (4.14):

$$B_\varphi(r) = -\frac{\omega r}{u}B_r = -B_0\frac{\omega R}{u}\frac{R}{r}$$

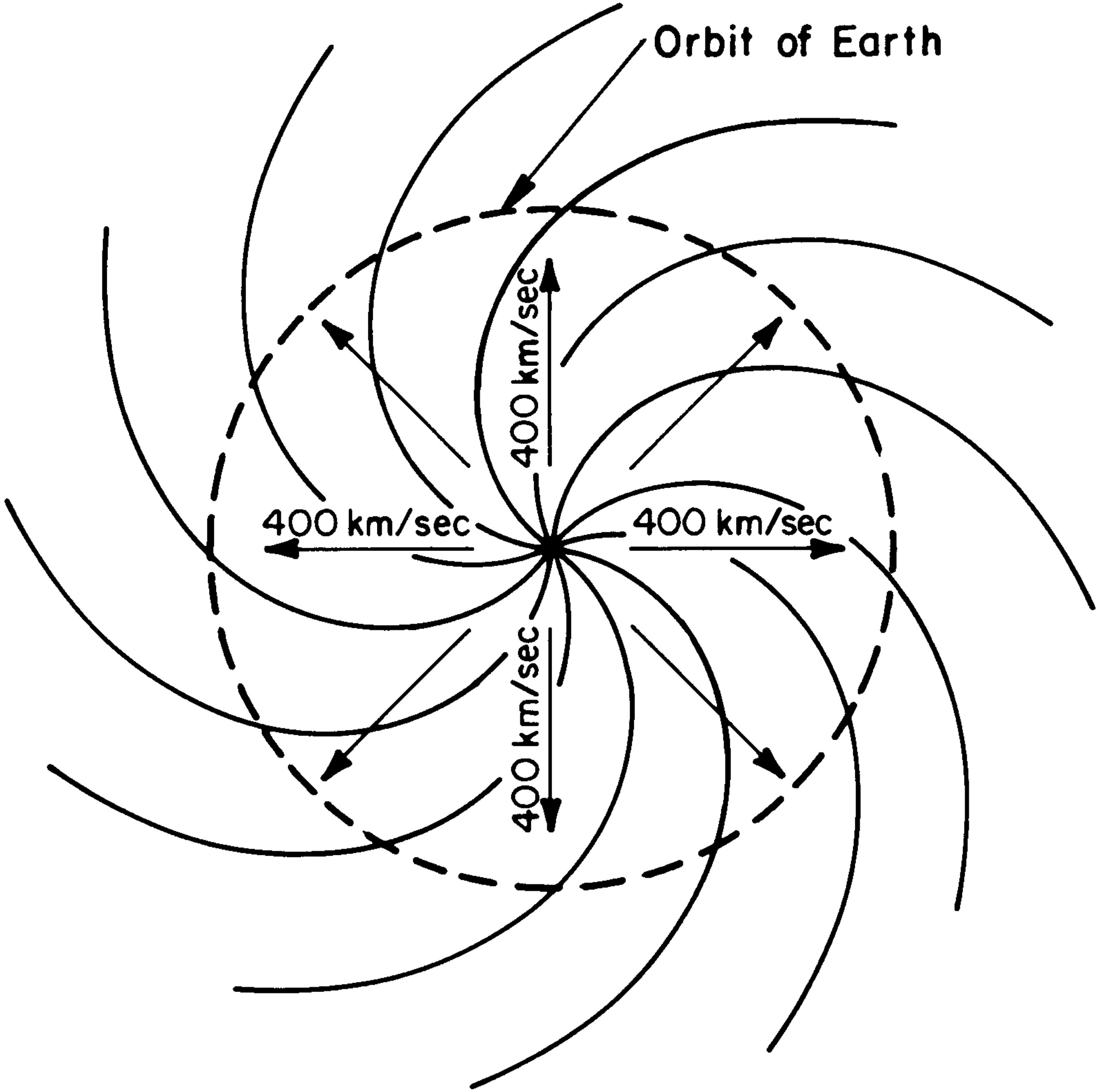
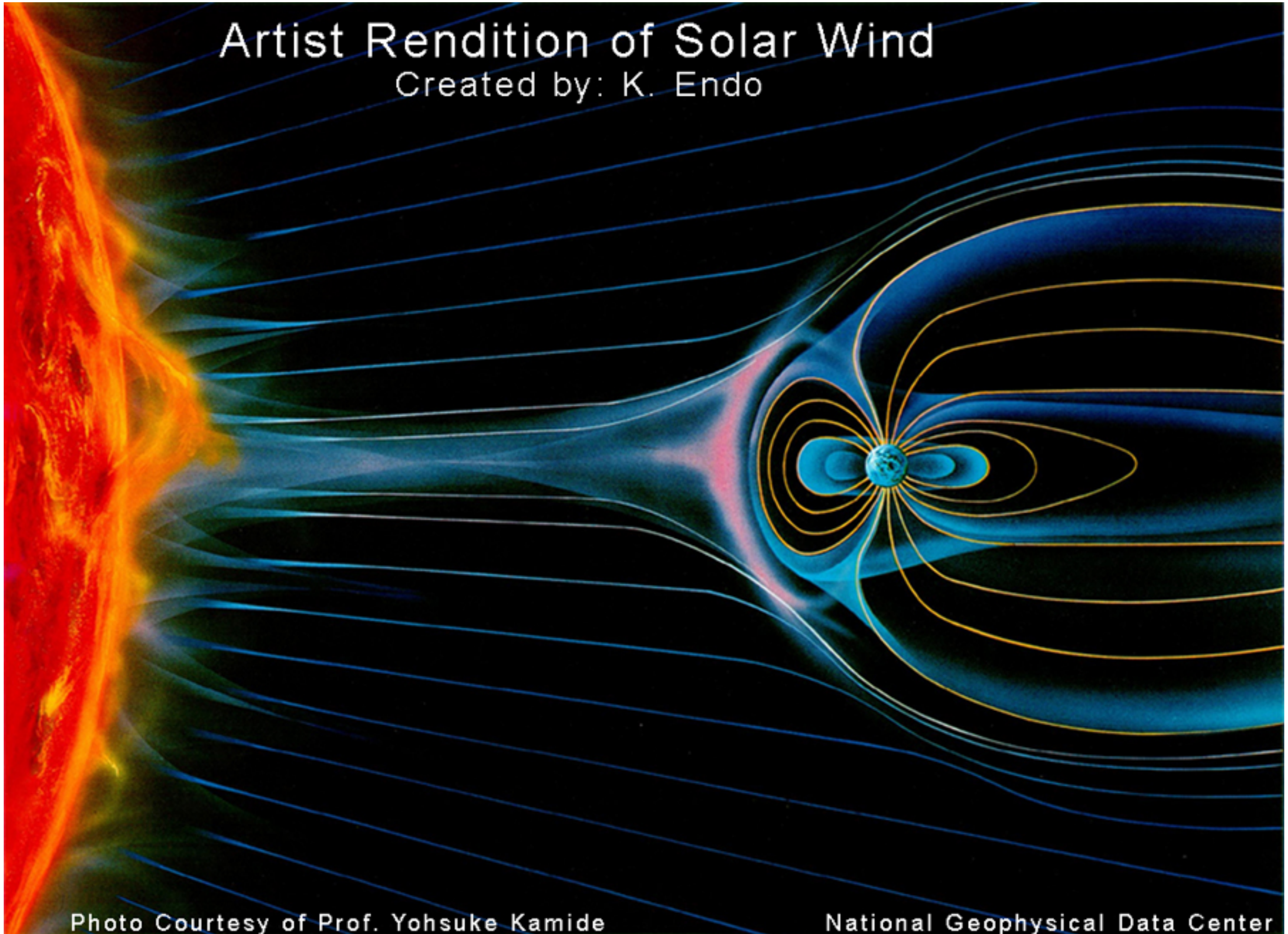
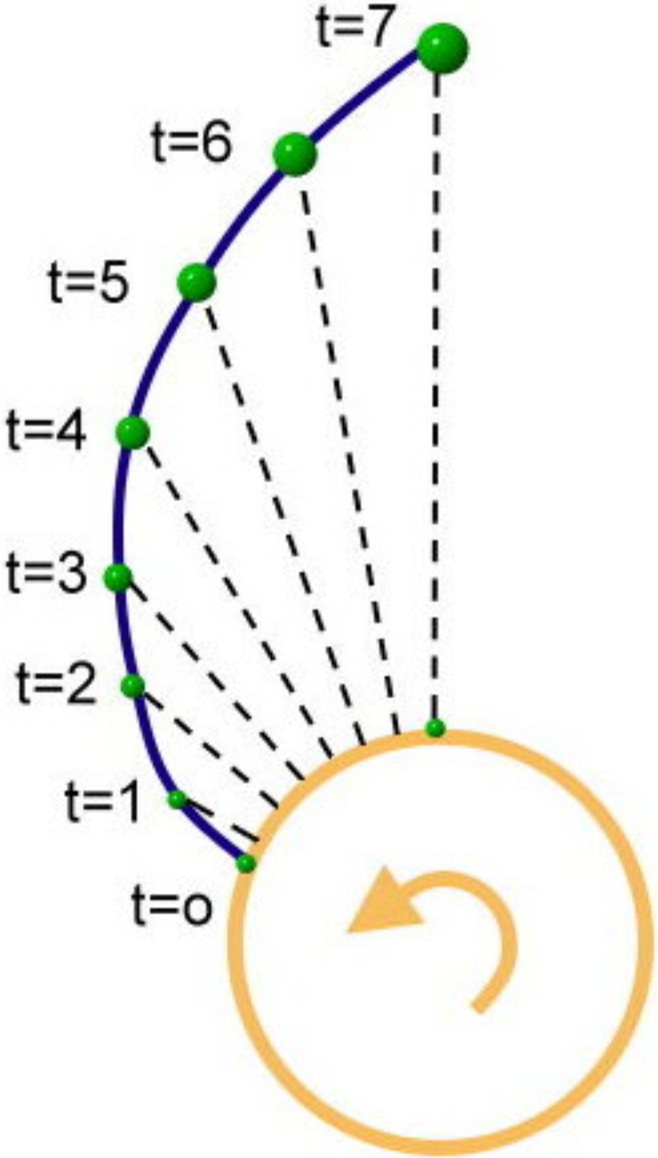
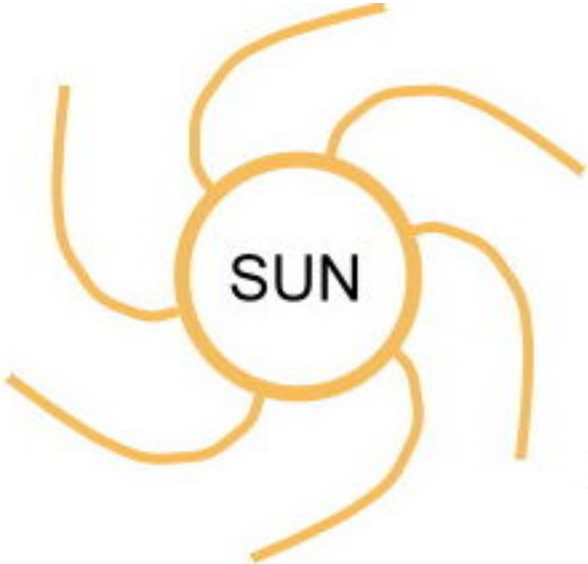


FIG. 4.6. Spiral interplanetary magnetic-field lines frozen into a radial solar-wind expansion at 400 $km \cdot s^{-1}$.

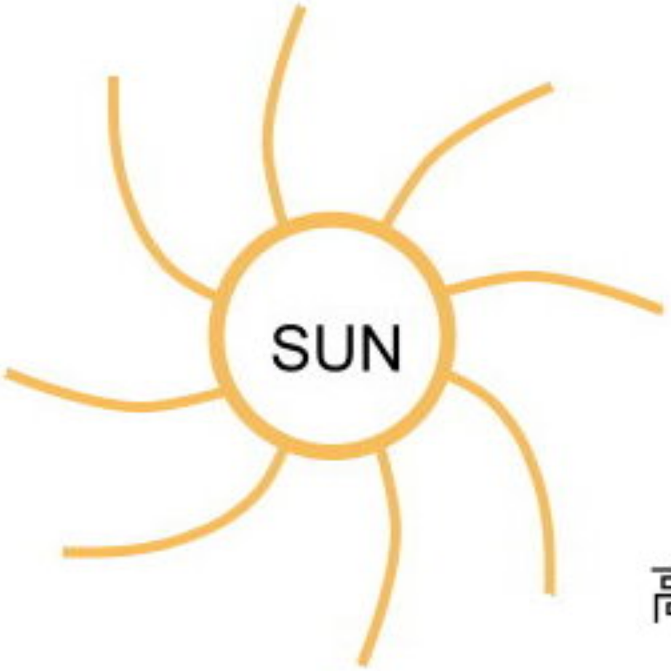
Solar Terrestrial Environment



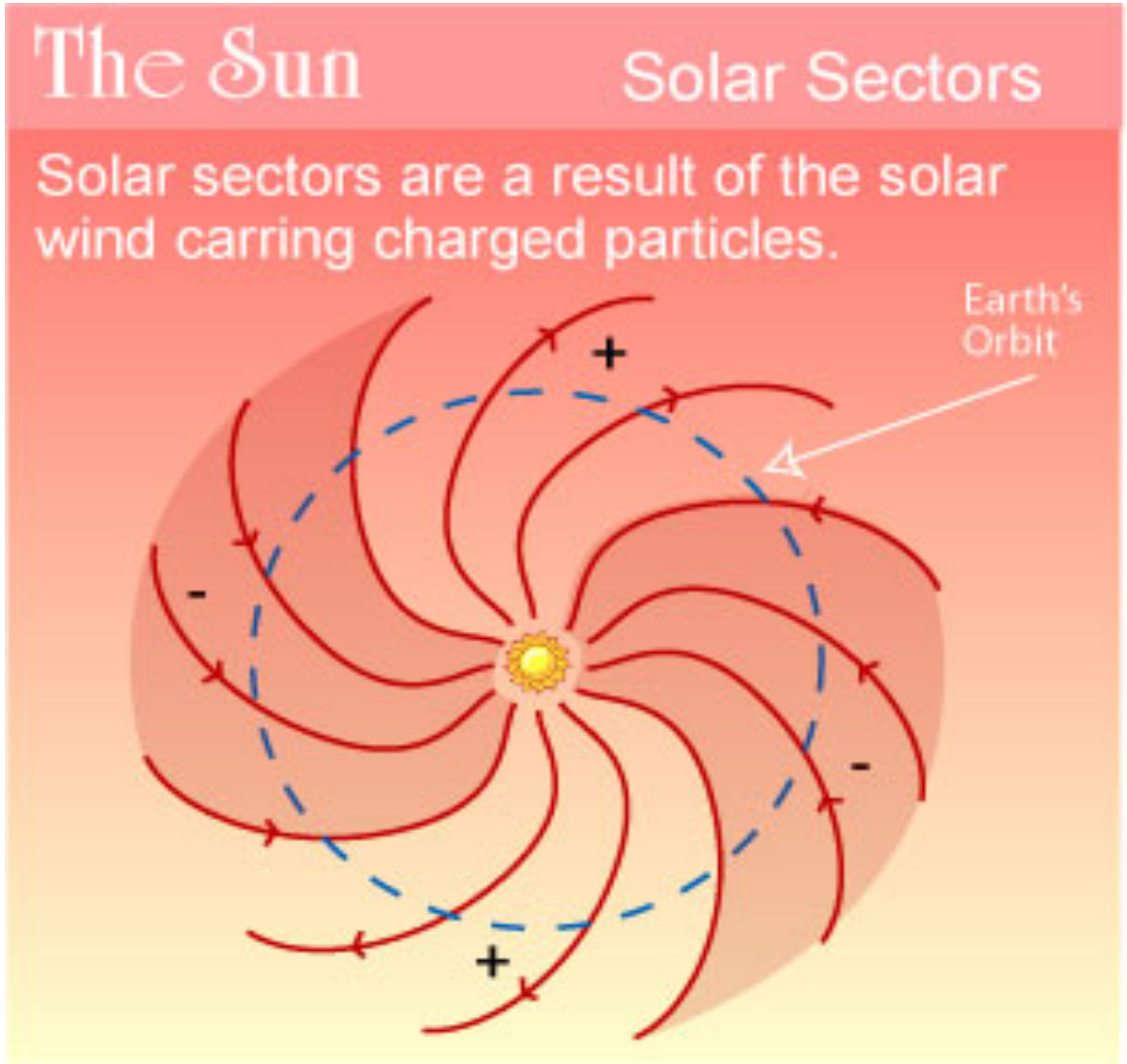




低速太陽風



高速太陽風



$$\tan\theta = r\omega / V_{sw}$$

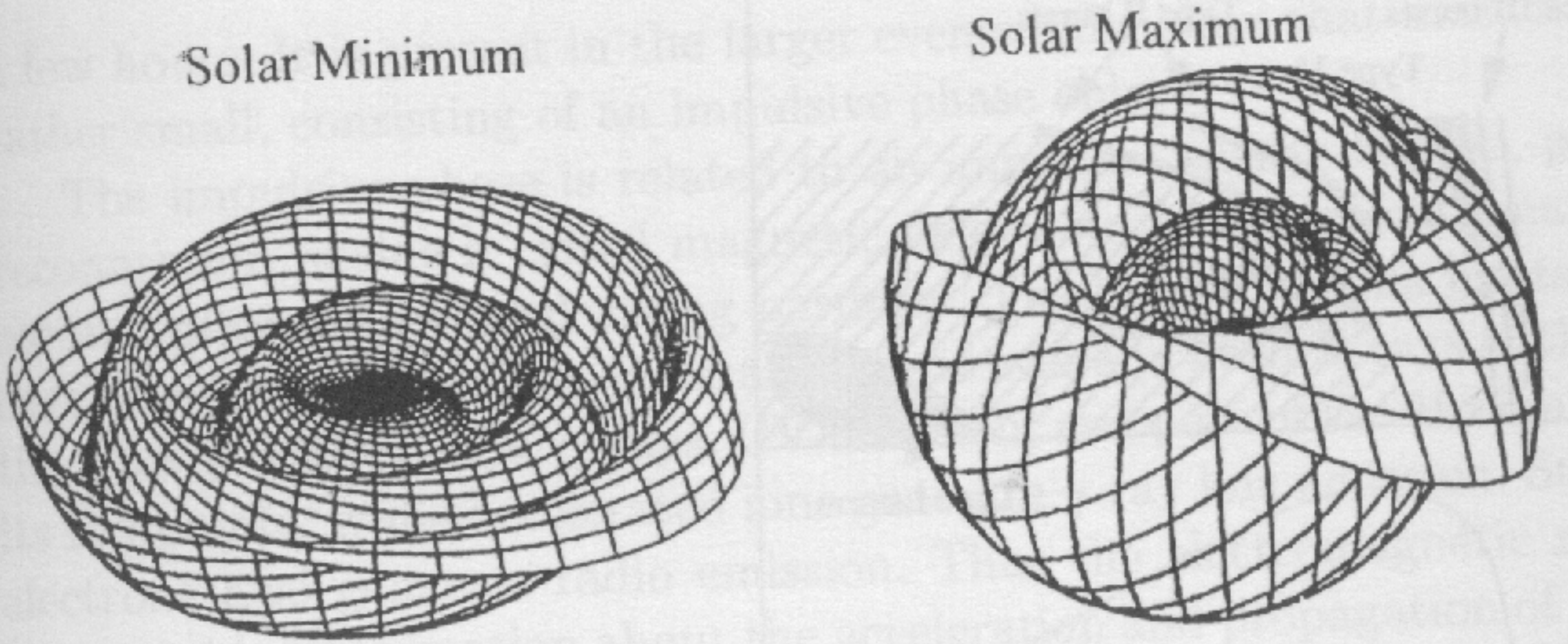


Fig. 6.20. Waviness of the heliospheric current sheet during solar minimum and maximum conditions, based on a sketch by R. Jokipii, University of Arizona

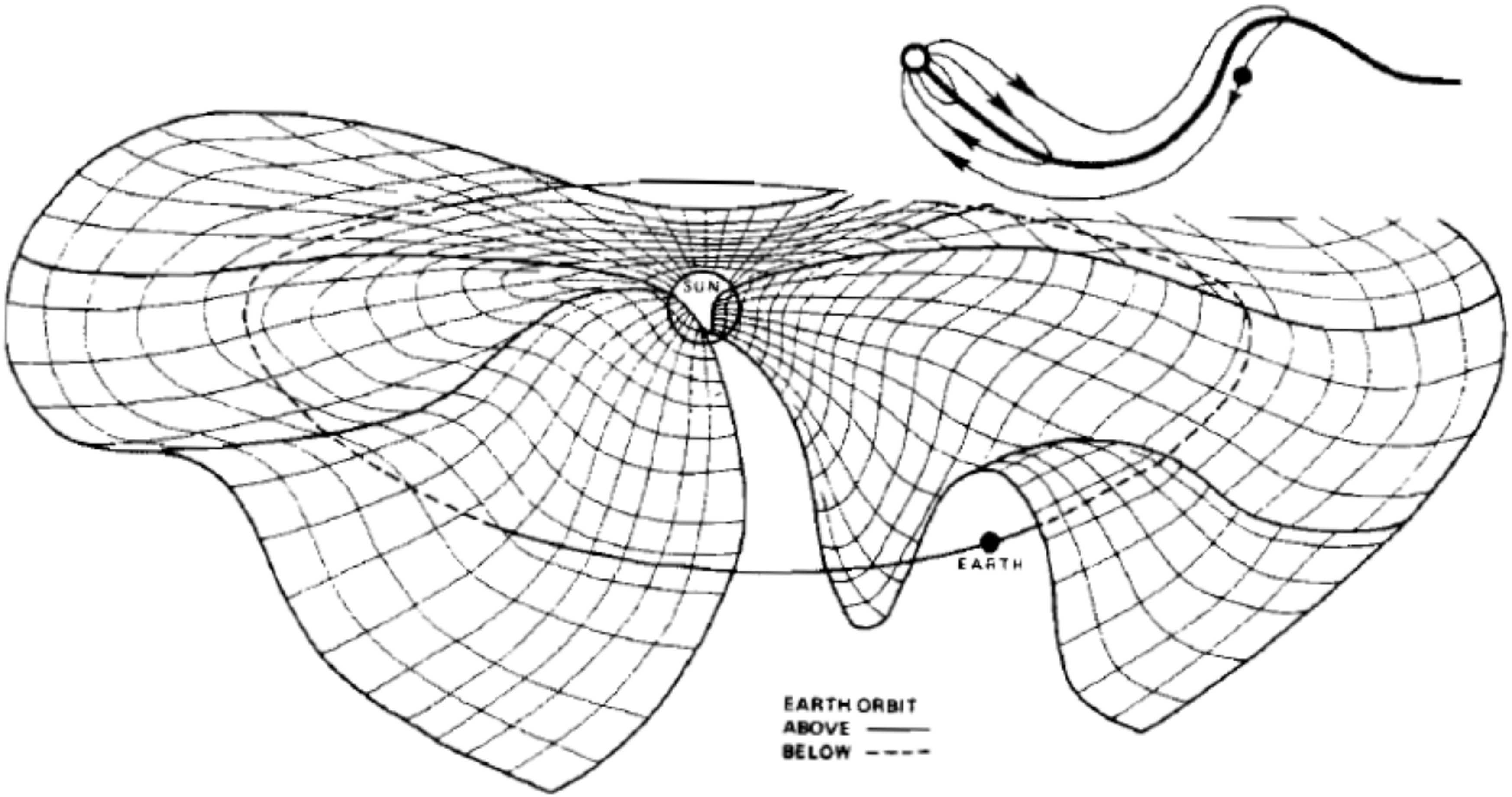
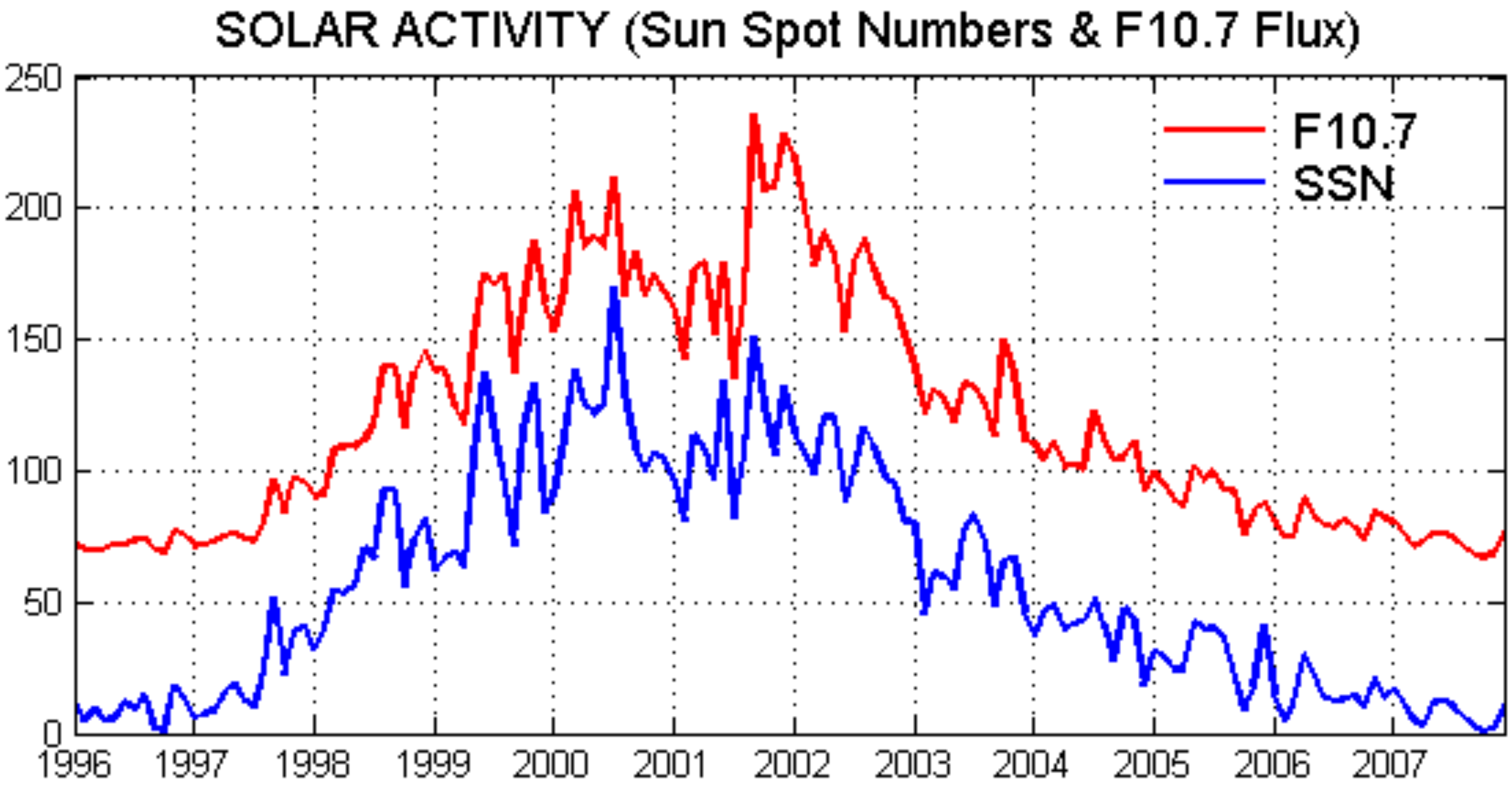


Fig. 1.10. Three-dimensional sketch of the solar equatorial current sheet and associated magnetic field lines. The current sheet is shown as lying near the solar equator with spiraled, outward-pointing magnetic fields lying above it and inward-pointing fields lying below it. The current sheet contains folds or flutes. When the sun rotates, an observer near the ecliptic will alternately lie above and below the current and will see a changing sector pattern. The inset above shows a meridional cross section with the earth below the current sheet. (Figure courtesy of S.-I. Akasofu.)

Solar Storm

Solar energy	Effects on space environment
<u>Steady energy radiation</u>	Control of the structure and dynamics of the atmosphere.
Electromagnetic waves	Formation of the ionosphere, production of ionospheric currents.
Particle radiation (solar wind)	Formation of the magnetosphere, drives magnetospheric convection.
<u>Transient energy radiation</u>	
Electromagnetic waves (flares)	Anomalous ionization of the ionosphere, radio noise.
	Magnetocspheric and ionospheric storms.
Plasma cloud (CME)	Production of high-energy particles.
High-energy particles	Radiation, anomalous ionization in the polar ionosphere.

- Solar index, F10.7: Solar radiation intensity of wavelength 10.7cm(2800MHz) and SSN (Sunspot number)



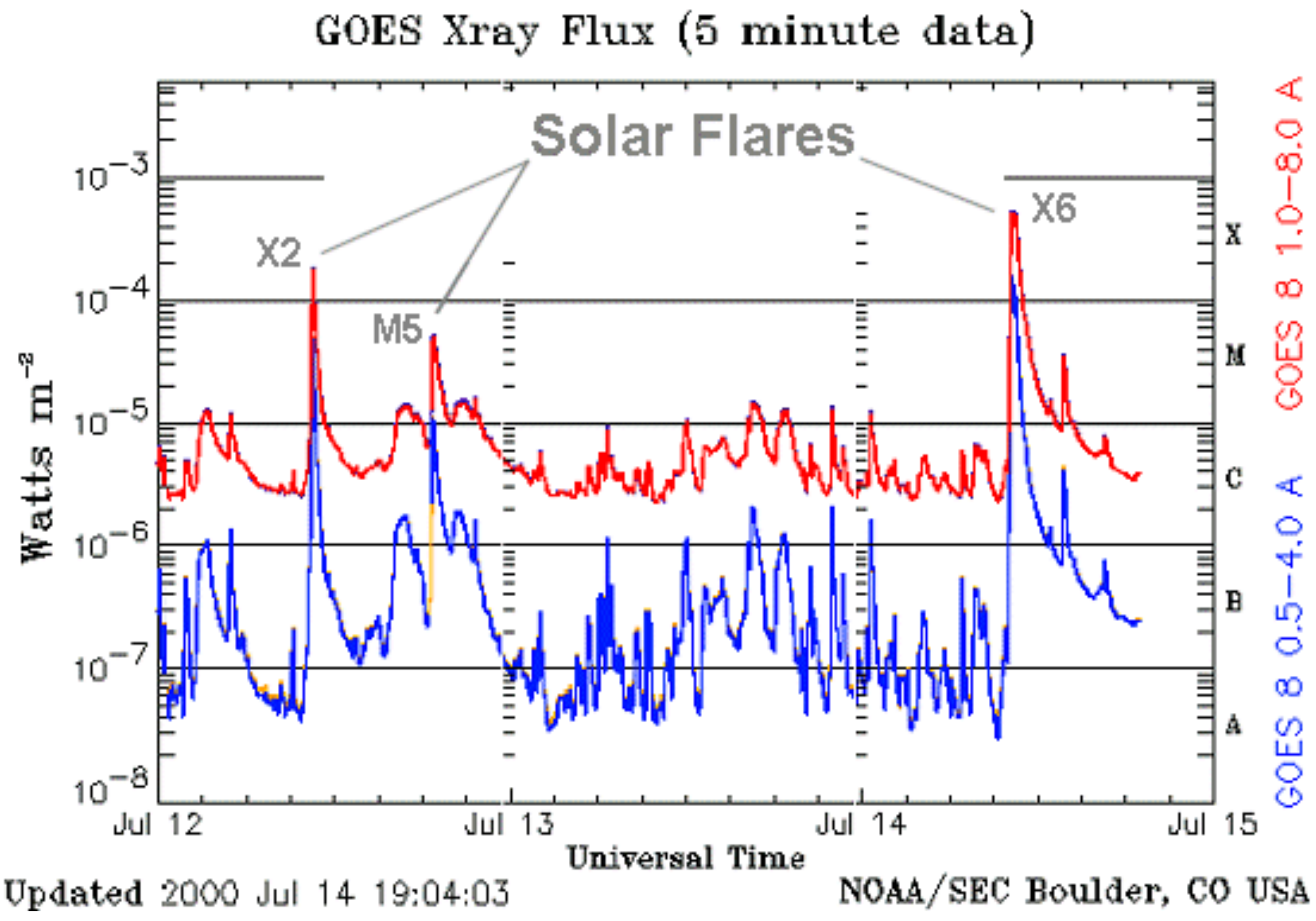
- <u>The active Sun</u>

- <u>Flare</u>
- A flare is a burst of “light” (easily observed at red Hα 6563A) occurring in the chromosphere near a sunspot. Life time 3 min up to 2 hr.
- Hα-flares are ranked in the size (importance, 1-4) and brilliance (f, n, b).
- X-ray flares are classified by power flux level of 1-8A (C, M, X).

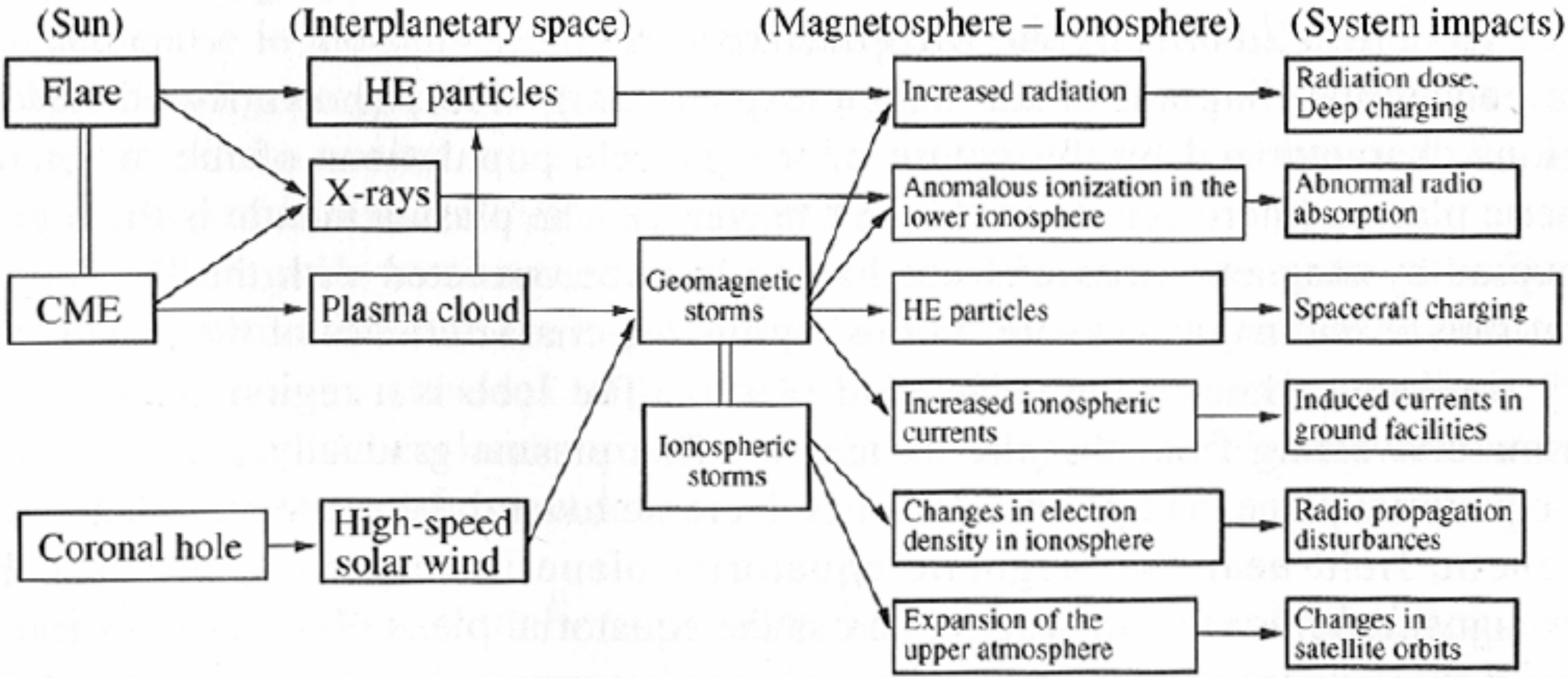
- <u>Radio burst</u>
- Radio bursts are generally associated with flares and originate from all levels of the solar atmosphere.

- X-Ray lare classification

Class	Peak (W/m^2) between 1 and 8 Angstroms
B	$I < 10^{-6}$
C	$10^{-6} < = I < 10^{-5}$
M	$10^{-5} < = I < 10^{-4}$
X	$I > = 10^{-4}$



GOES Xray Flux (5 minute data)
Solar Flares
X2
M5
X6
Watts m^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
X
M
C
B
A
GOES 8 1.0-8.0 A
GOES 8 0.5-4.0 A
Jul 12
Jul 13
Jul 14
Jul 15
Universal Time
Updated 2000 Jul 14 19:04:03
NOAA/SEC Boulder, CO USA


(Sun)
(Interplanetary space)
(Magnetosphere – Ionosphere)
(System impacts)
Flare
CME
Coronal hole
HE particles
X-rays
Plasma cloud
High-speed solar wind
Geomagnetic storms
Ionospheric storms
Increased radiation
Anomalous ionization in the lower ionosphere
HE particles
Increased ionospheric currents
Changes in electron density in ionosphere
Expansion of the upper atmosphere
Radiation dose, Deep charging
Abnormal radio absorption
Spacecraft charging
Induced currents in ground facilities
Radio propagation disturbances
Changes in satellite orbits

Type	Time to earth	Consequence
Solar flare	8.5 minute	Sudden ionospheric disturbance Short wave (1-30MHz) fadeout
CME	1-2 day	Magnetic storm Ionospheric storm (1-2 day later)
High-energy particle	1-2 hour	Electronic equipment damage

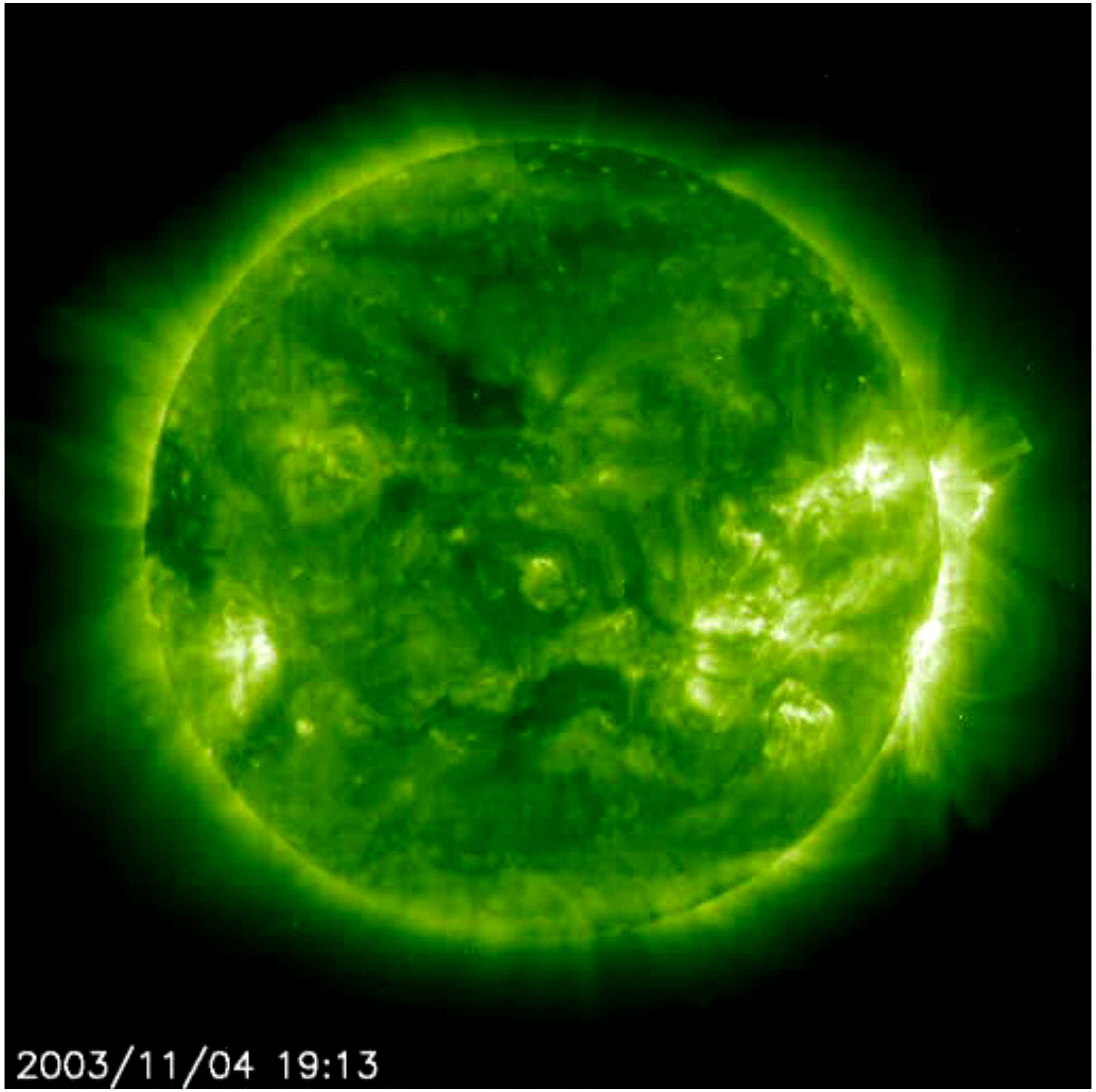
	Type	Rate
Energy radiation from sun	Electromagnetic wave	3.8×10^{26} W/sec
	Solar wind	4.1×10^{20} W/sec
	Explosive event	7×10^{18} W/sec
Rate of mass-lose from sun	Electromagnetic wave	4.2×10^{9} kg/sec
	Solar wind	1.4×10^{9} kg/sec

TABLE 2. *Spectral density of power in solar radiation*

A	100	500	1000	1216	2000	3000	5000	10000
B	10	50	100	121.6	200	300	500	1000
C	10^{-5}	5×10^{-5}	3×10^{-5}	(Ly α)	10^{-2}	0.6	2	0·7
D	10^{-80}	10^{-12}	10^{-4}		0.7	1.5	2	0.5
E		3×10^{-3}		5×10^{-3}			1200	

Line A Wavelength in Å.
Line B Wavelength in nm.
Line C Observed spectral density (W m^{-2} nm^{-1}).
Line D Spectral density from black body at 6000 °K normalized to equal observed density at 500 nm.
Line E Observed total power flux in part of spectrum indicated (W m^{-2}).

Solar flare



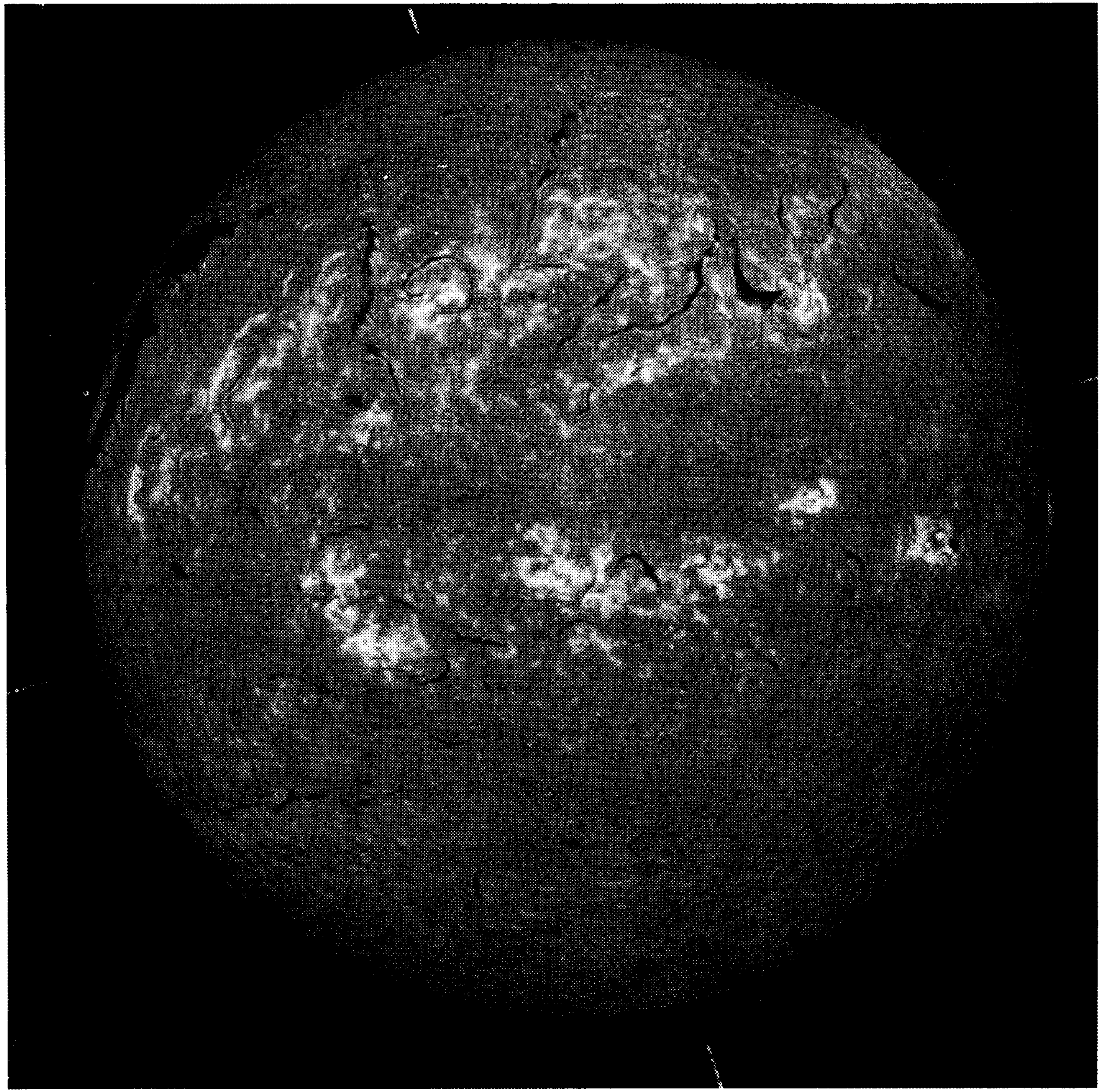


FIG. 3.3. Chromosphere in Hα, showing active regions (bright) and filaments or prominences (thin dark ribbons on the disk). (Courtesy B. Schmieder, Meudon Observatory.)

Corona Mass Ejection (CME)