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SMR/1328/14

School on the Physics of Equatorial Atmosphere

(24 September - 5 October 2001)

Sun and Solar Wind

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(Boston University)

LECTURE 1.1 : SUN + SOLAR WIND
(Mendillo) --- Context for Aeronomy

- Sun as a star — formation of Solar System
  ---"Nebula Hypothesis" — The gravitational contraction of an inter-stellar gas cloud (98% H+He, 2% other elements)

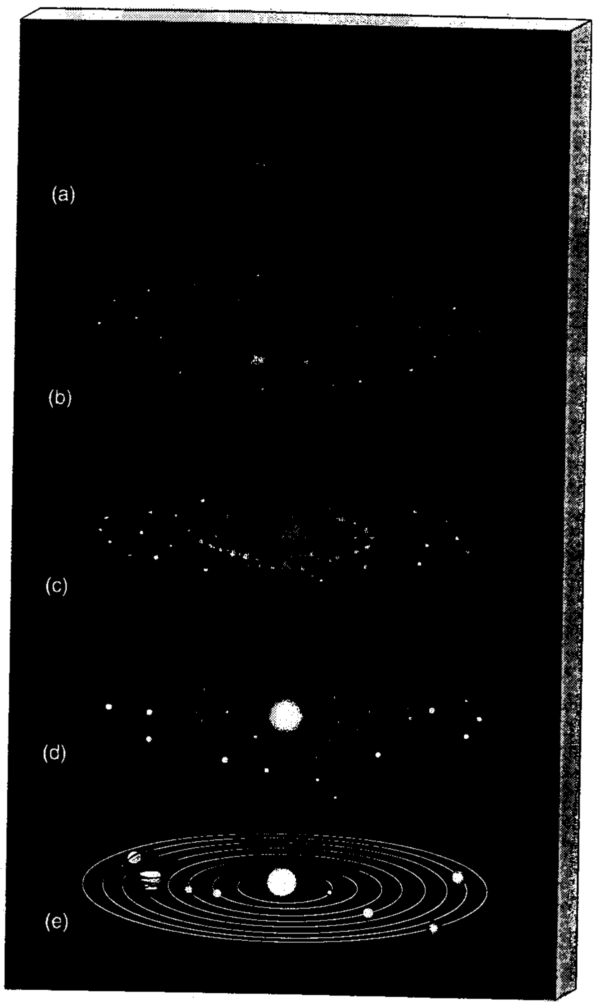
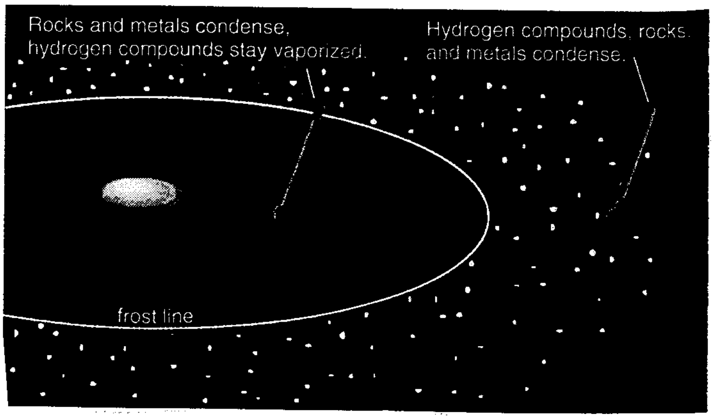


Figure 4.20 Solar System Formation The condensation theory of planet formation (not drawn to scale; Pluto not shown in part e). (a) The solar nebula after it has contracted and flattened to form a spinning disk (Figure 4.17b). The large blob in the center will become the Sun. Smaller blobs in the outer regions may become jovian planets. (b) Dust grains act as condensation nuclei, forming clumps of matter that collide, stick together, and grow into moon-sized planetesimals. (c) Strong winds from the still-forming Sun expel the nebular gas. (d) Planetesimals continue to collide and grow. (e) Over the course of a hundred million years or so, planetesimals form a few large planets that travel in roughly circular orbits.

[from ASTRONOMY, Chaisson + McMillan, 2001]

The Terrestrial (rocky) and Jovian (gaseous) planets formed in regions of different temperature

FIGURE 8.9 Temperature differences in the solar nebula led to different kinds of condensed materials, sowing the seeds for two different kinds of planets.



[from COSMIC PERSPECTIVE, Bennett et al., 2001]

Planet	Average Distance from Sun (AU)	Temperature†	Relative Size	Average Equatorial Radius (km)	Average Density (g/cm³)	Composition	Moons	Rings?
Mercury	0.387	700 K	·	2,440	5.43	Rocks, metals	0	No
Venus	0.723	740 K	•	6,051	5.24	Rocks, metals	0	No
Earth	1.00	290 K	•	6,378	5.52	Rocks, metals	1	No
Mars	1.52	240 K	·	3,397	3.93	Rocks, metals	2 (tiny)	No
Most asteroids	2–3	170 K	·	≤ 500	1.5–3	Rocks, metals	?	No
Jupiter	5.20	125 K	⬤	71,492	1.33	H, He, hydrogen compounds‡	16	Yes
Saturn	9.53	95 K	⬤	60,268	0.70	H, He, hydrogen compounds‡	18	Yes
Uranus	19.2	60 K	●	25,559	1.32	H, He, hydrogen compounds‡	17	Yes
Neptune	30.1	60 K	●	24,764	1.64	H, He, hydrogen compounds‡	8	Yes
Pluto	39.5	40 K		1,160	2.0	Ices, rock	1	No
Most comets	0–50,000	a few K§		a few km?	<1?	Ices, dust	?	No

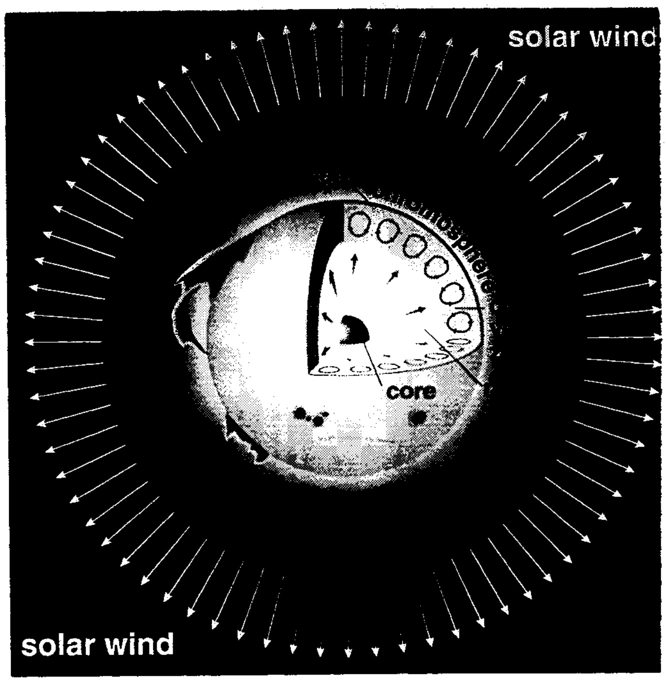
Table 14.1 Basic Properties of the Sun

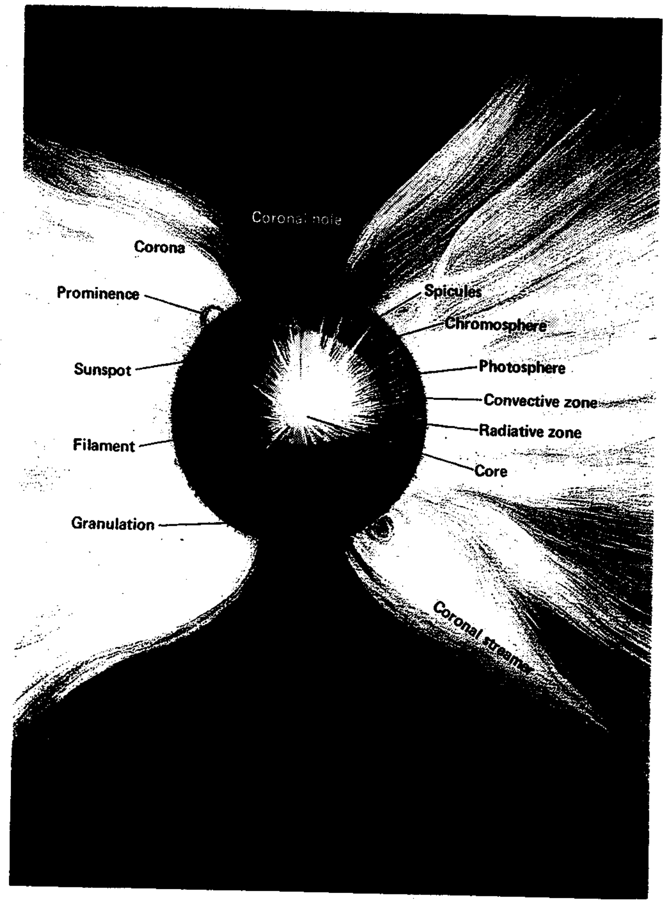
Radius (R_{Sun})	696,000 km (about 109 times the radius of the Earth)
Mass (M_{Sun})	2×10^{30} kg (about 300,000 times the mass of the Earth)
Luminosity (L_{Sun})	3.8×10^{26} watts
Composition (by percentage of mass)	70% hydrogen, 28% helium, 2% heavier elements
Rotation rate	27 days (equator) to 31 days (poles)
Surface temperature	5,800 K (average); 4,000 K (sunspots)
Core temperature	15 million K

Distance from Earth
(mean = 1 A.U.) = 150×10^6 Km

Light travel time
to Earth ≈ 8 minutes

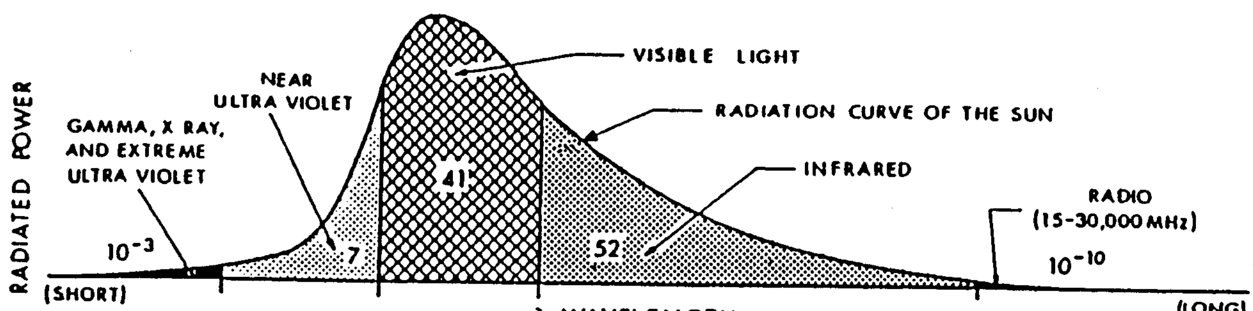
SOLAR REGIONS + NOMENCLATURE





ELECTROMAGNETIC RADIATION

The Sun emits radiation over the entire electromagnetic spectrum [see Figure] . The portions of the spectrum associated with space environment activity are the very short wavelengths (X-rays and extreme ultraviolet) and the longer wavelengths (radio waves). Energy at these wavelengths contribute less than one percent of the sun's total energy output; but during active solar conditions, it is increased radiation at these wavelengths that cause a noticeable impact on the near-earth environment. However, even during the most active solar periods, the sun's total energy output measured outside the earth's atmosphere is nearly constant (to within 0.1%/decade).



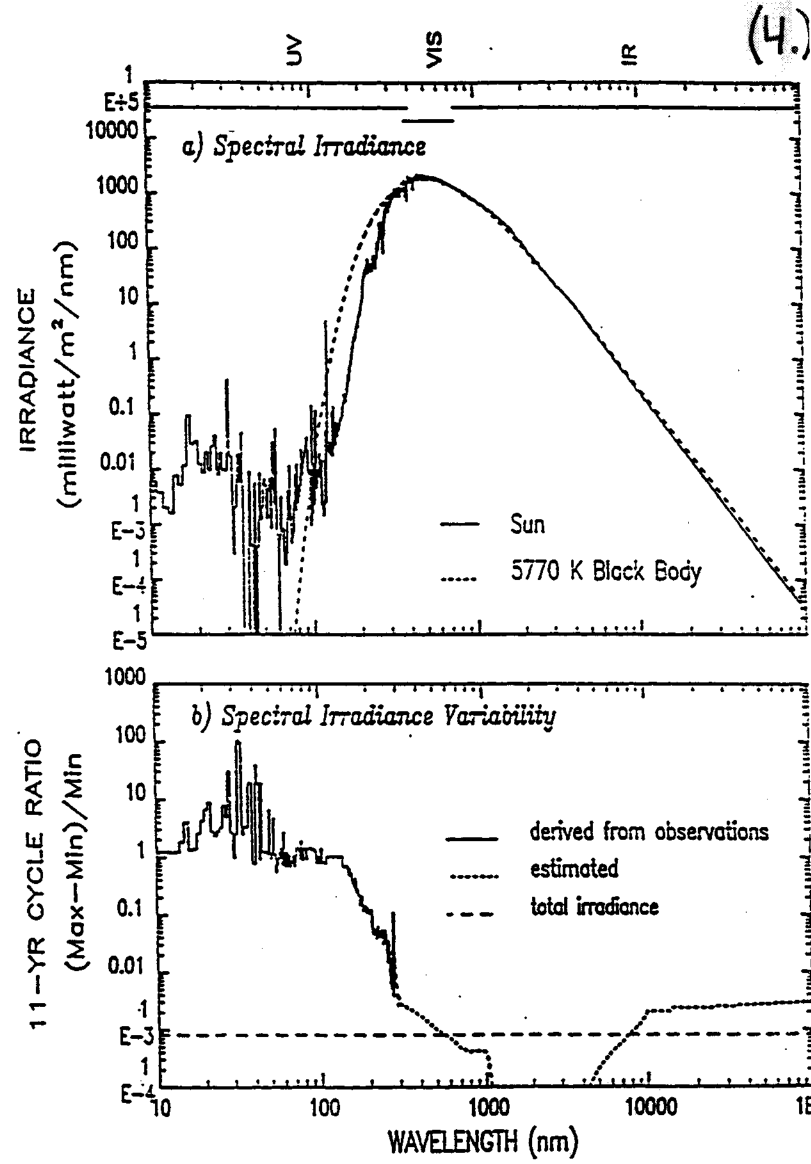
DISTRIBUTION OF RADIATED POWER IN THE SOLAR SPECTRUM
(ABOVE NUMBERS ARE PERCENTAGES OF THE SOLAR CONSTANT)

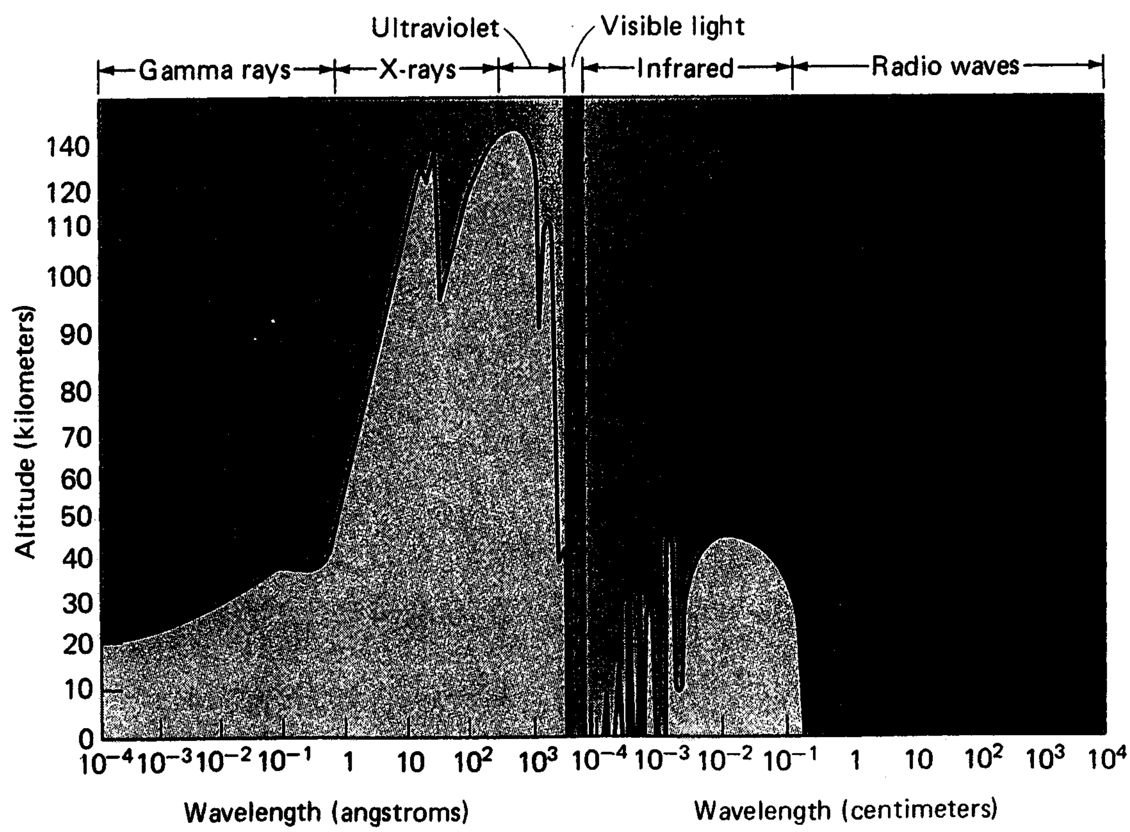
Solar Photon SPECTRUM

--- λ < Visible important for Aeronomy

--- Δλ Variability greatest at shorter λ

--- Earth's atmosphere limits photon penetration by λ due to altitude distribution of Neutral Gas.

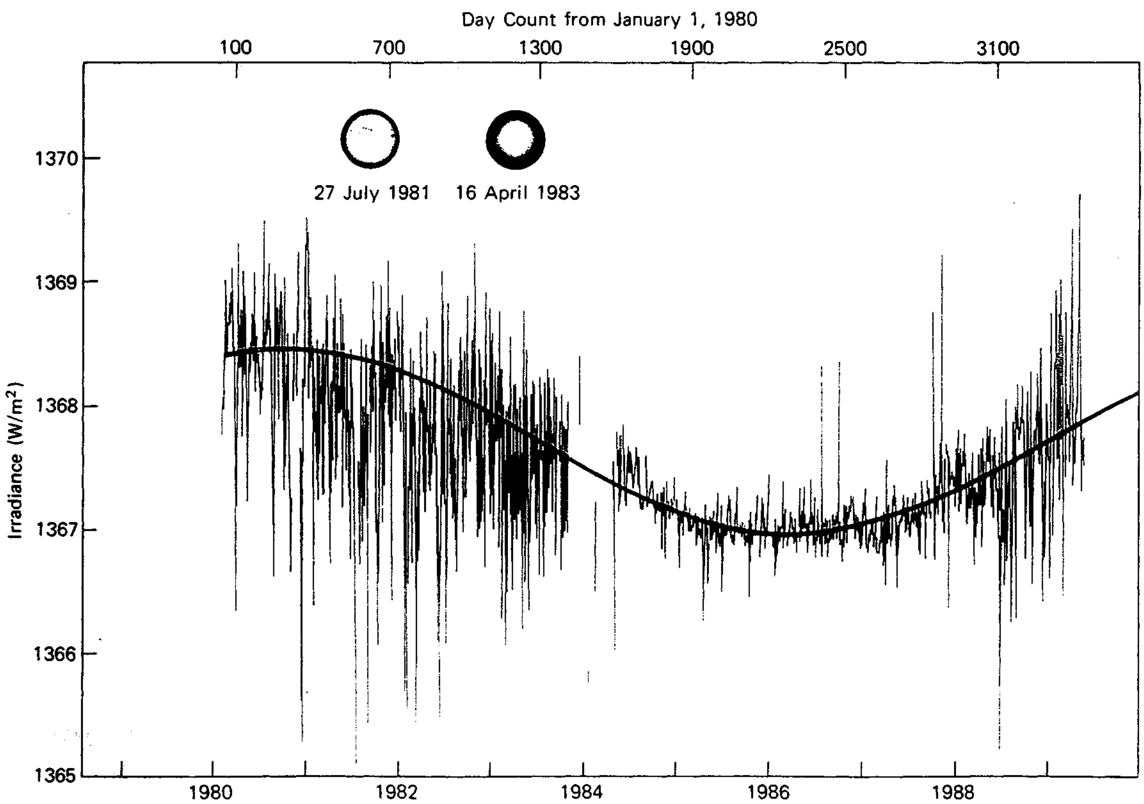




Observations of Solar UV/EUV/X-RAYS a spacebased activity: Yohokoh, SOHO, UARS

The Changing Sun: Yohokoh-SXT, 1991 - 1995

SOLAR ↑MAX   SOLAR ↑MIN



Plasma + Magnetic Fields escaping from Sun ≡ SOLAR WIND [from Schunk + Nagy, 2000]

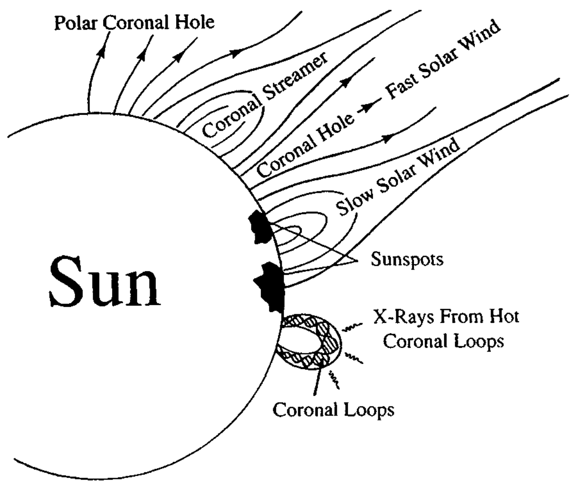


Figure 2.2 Schematic diagram of the magnetic field topology in the solar corona and the associated coronal features. The solid curves with arrows are the magnetic field lines.[2]

Table 2.1. *Solar spectral regions.*

Radio	$\lambda > 1$ mm
Far Infrared	$10\,\mu m < \lambda < 1$ mm
Infrared	$0.75\,\mu m < \lambda < 10\,\mu m$
Visible	$0.3\,\mu m < \lambda < 0.75\,\mu m$
Ultraviolet (UV)	$1200\,Å < \lambda < 3000\,Å$
Extreme ultraviolet (EUV)	$100\,Å < \lambda < 1200\,Å$
Soft x-rays	$1\,Å < \lambda < 100\,Å$
Hard x-rays	$\lambda < 1\,Å$

Note: $Å = 10^{-10}$ m.

Table 2.2. *Energy and mass loss from the Sun.*[7]

Radiated power	3.8×10^{26} watts
Solar wind power	4.1×10^{20} watts
CME power	7.0×10^{18} watts
Mass loss (radiation)	4.2×10^{9} kg s^{-1}
Mass loss (particles)	1.3×10^{9} kg s^{-1}

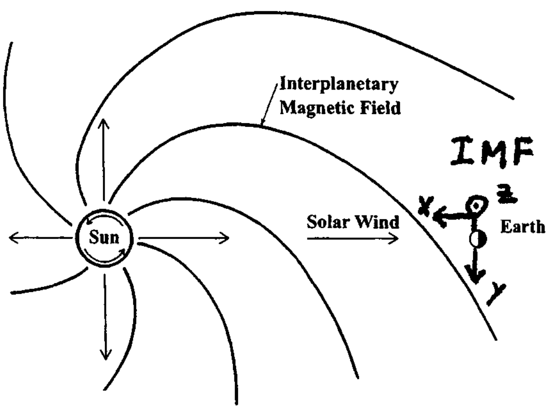
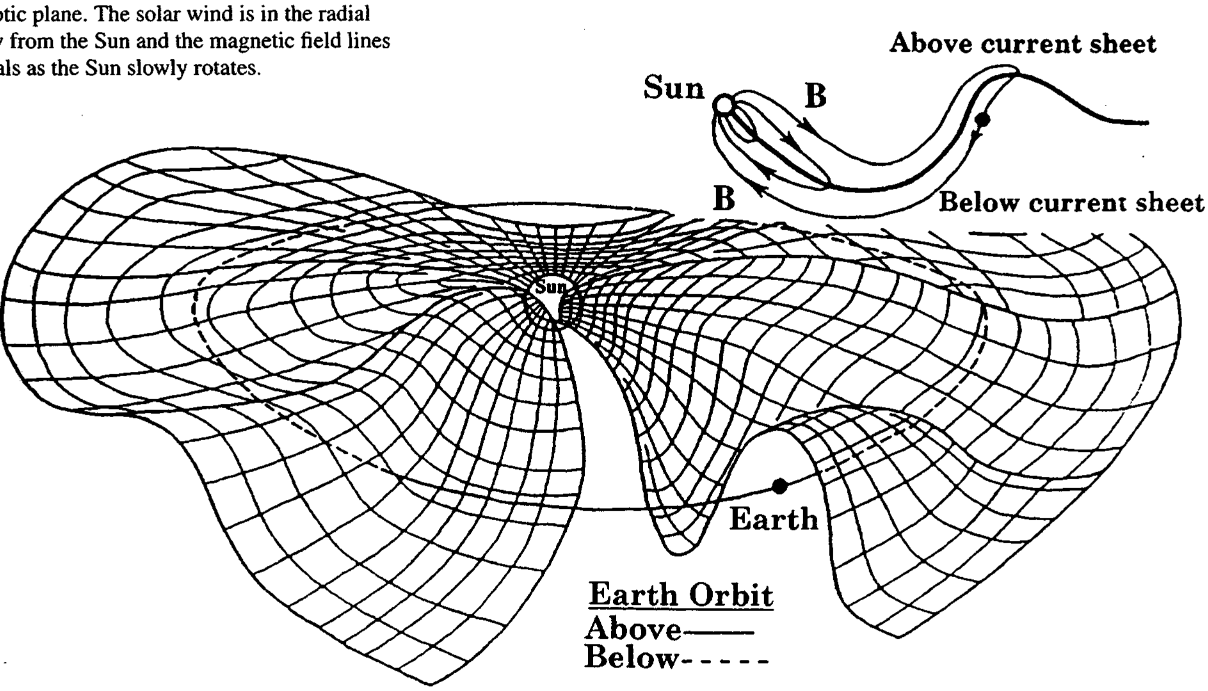


Figure 2.6 Schematic diagram of the Sun–Earth system in the Sun's ecliptic plane. The solar wind is in the radial direction away from the Sun and the magnetic field lines bend into spirals as the Sun slowly rotates.

Table 2.3. *Solar wind parameters near the Earth.*[10]

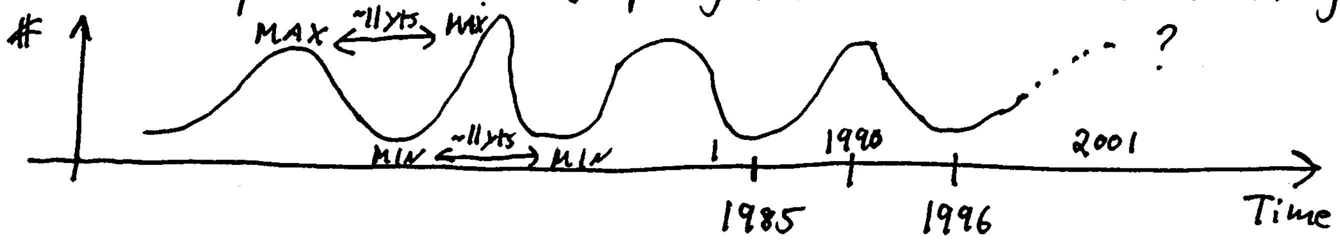
Parameter	Average	Low-Speed	High-Speed
n(cm^{-3})	8.7	11.9	3.9
u(km s^{-1})	468	327	702
nu(cm^{-2} s^{-1})	3.8×10^8	3.9×10^8	2.7×10^8
T_p(K)	1.2×10^5	0.34×10^5	2.3×10^5
T_e(K)	1.4×10^5	1.3×10^5	1.0×10^5
$(1/2 m_p u^2) nu$(erg cm^{-2} s^{-1})	0.70	0.35	1.13
β	2.17	1.88	1.24
V_A(km s^{-1})	44	38	66
V_S(km s^{-1})	63	44	81



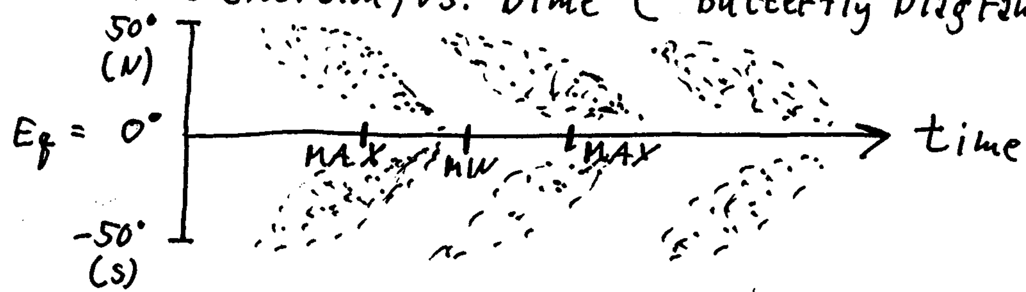
The Sunspot Cycle

- OBSERVATIONS → Ancient Asian records
  → Galileo (1609)
  → "Maunder Minimum" (1645-1715) -- Missing/Few spots.
- CHARACTERISTICS → Dark → Lower Temperature
  → Strong $\vec{B}$ -- reason for low Temperature
  → Variability -- clues about Sun's magnetic field
- THE SOLAR CYCLE: sunspots (and many characteristics) vary with an approximate ~11 year period (# of spots, locations of spots, $\vec{B}$ in spots, non-visible light, # of flares)

--- # Sunspots vs. time (a proxy for all forms of solar activity).



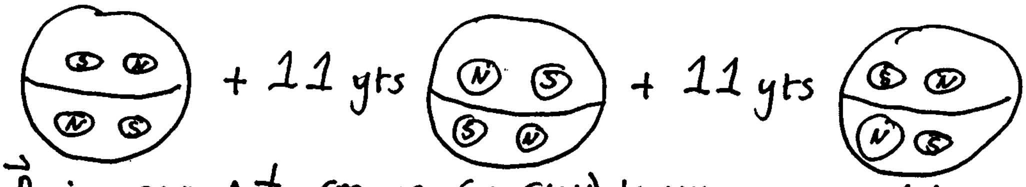
--- # + Latitude (Position) vs. time ("Butterfly Diagram")



[redacted]

[Rotation of sun → ~25 days near equator } "Differential Rotation"
→ ~31 days near poles } → Not solid!

--- Magnetic Polarity Pattern vs. time

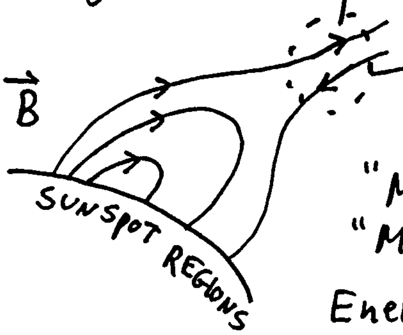


$\vec{B}$ in sunspot groups (+ SUN) reverse every 11 yrs → 22-year full cycle

Source: Twisting $\vec{B}$ due to differential rotation every 11 years [redacted]

The Active Sun: Chromosphere + Corona

- Large Chromospheric Features: Flares.



Region of oppositely directed $\vec{B}$-fields.
Dynamically pushed together + cancel!

"Magnetic Field Merging"
"Magnetic Field Annihilation"

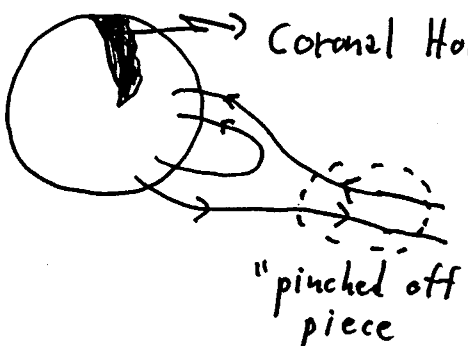
$$\underset{(\text{magnetic})}{\text{Energy}} \quad \frac{B^2}{8\pi} \Longrightarrow \text{Kinetic Energy, } \frac{1}{2}mv^2$$

Material Ejected!

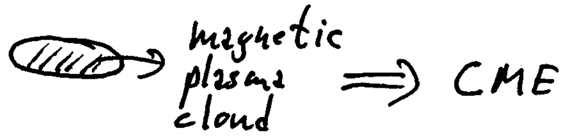
- Even Larger Coronal Features: Coronal Hot Spots
  Coronal Holes
  Coronal Mass Ejections (CME)

--- Hot Corona Problem: Heating of sun's high atmosphere probably due to wave energy from high $\vec{B}$ regions below.

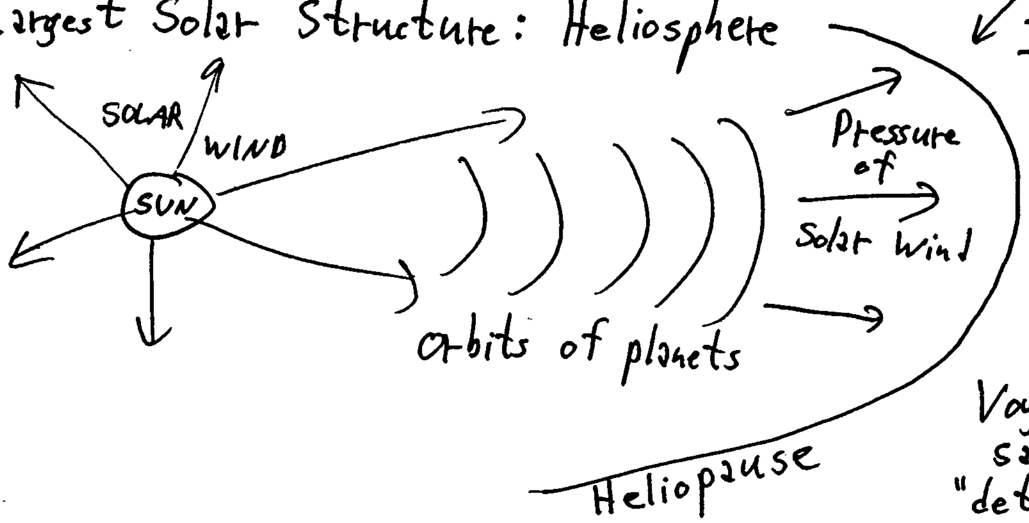
Images of corona in X-rays → Bright (Hot) spots above sunspots.
→ Dark spots → no material to heat (density holes)



Coronal Holes are sources of high speed solar wind (≥500 Km/sec) unconstrained by $\vec{B}$-fields



- Largest Solar Structure: Heliosphere



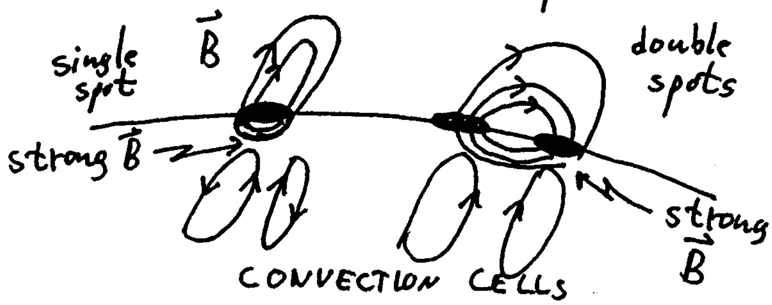
Inter-stellar Wind

Location? Beyond Pluto --- but?

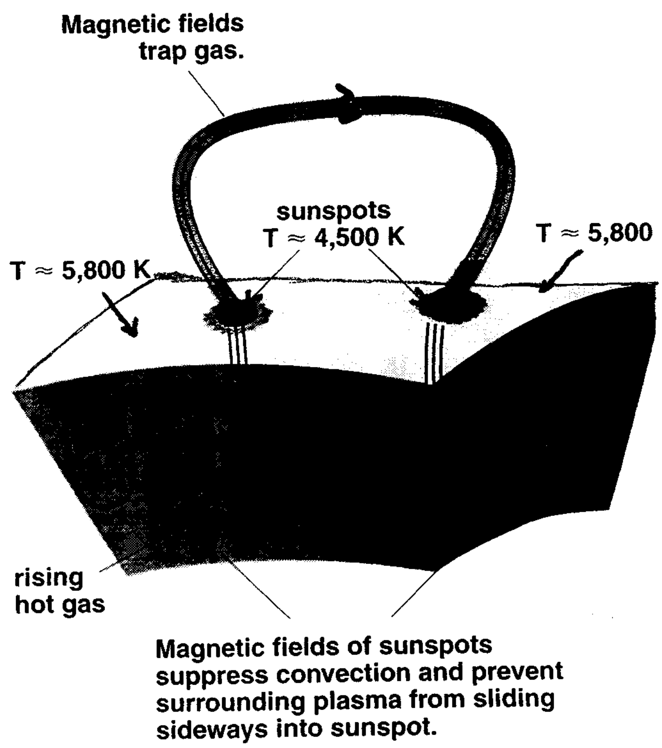
Voyager + Pioneer satellites to "detect" it.

The Active Sun: Photosphere

- Large surface features: Sunspots
  - --- From Spectroscopy → Dark = cool gas; → strong $\vec{B}$-field in sunspot region
  - --- Plasma and $\vec{B}$ → charged particles can move easily $\parallel \vec{B}$, but not $\perp \vec{B}$.



The strong $\vec{B}$ hinders flow of hot material to photosphere.



(10.)

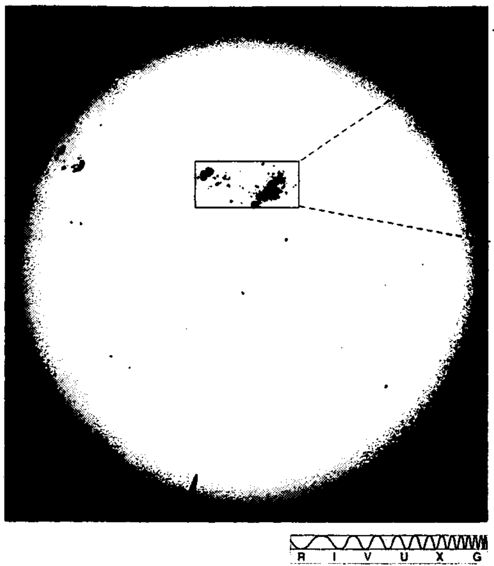


Figure 9.14 **Sunspots** This photograph of the Sun, taken during a period of maximum solar activity, shows several groups of sunspots. The largest spots in this image are more than 20,000 km across, nearly twice the diameter of Earth. Typical sunspots are only about half this size. *(Palomar Observatory)*

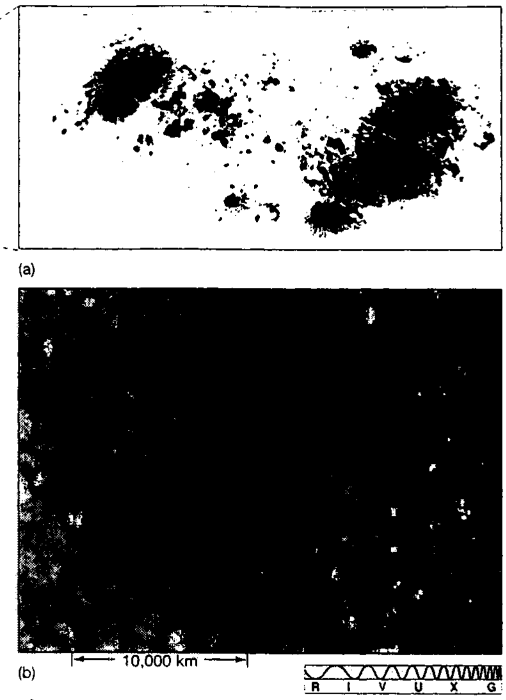


Figure 9.15 **Sunspots, Up Close** (a) The largest pair of sunspots in Figure 9.14. Each spot consists of a cool, dark inner region called the umbra surrounded by a warmer, less dark region called the penumbra. The spots appear dark because they are slightly cooler than the surrounding photosphere. (b) A high-resolution, true-color image of a single sunspot shows details of its structure as well as the surface granularity surrounding it. This spot is about the size of Earth. *(Palomar Observatory)*

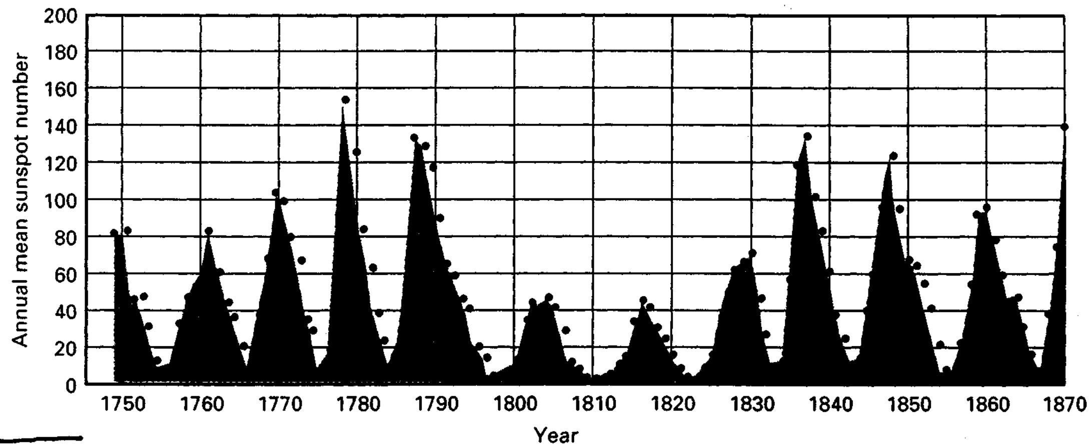
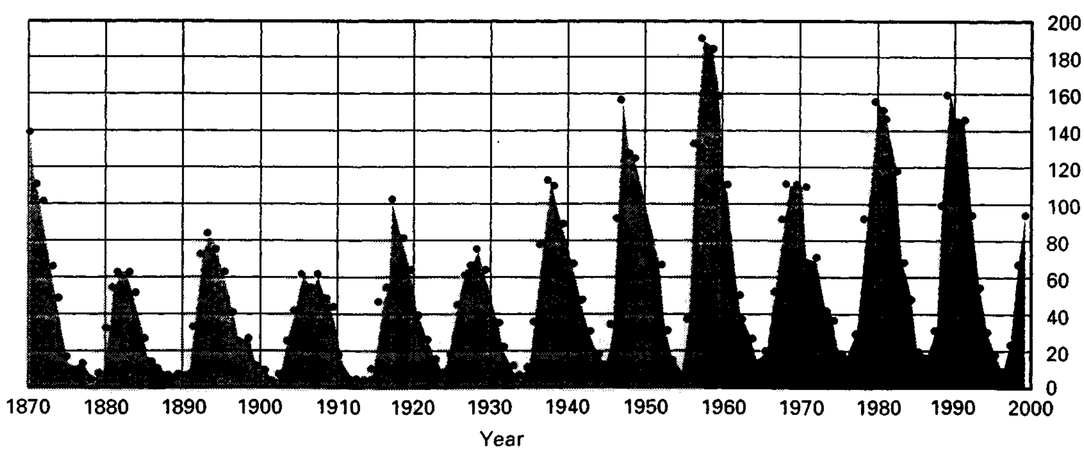


Figure 9-18 The 11-year sunspot cycle is but one manifestation of the solar-activity cycle.

← MAUNDER MINIMUM



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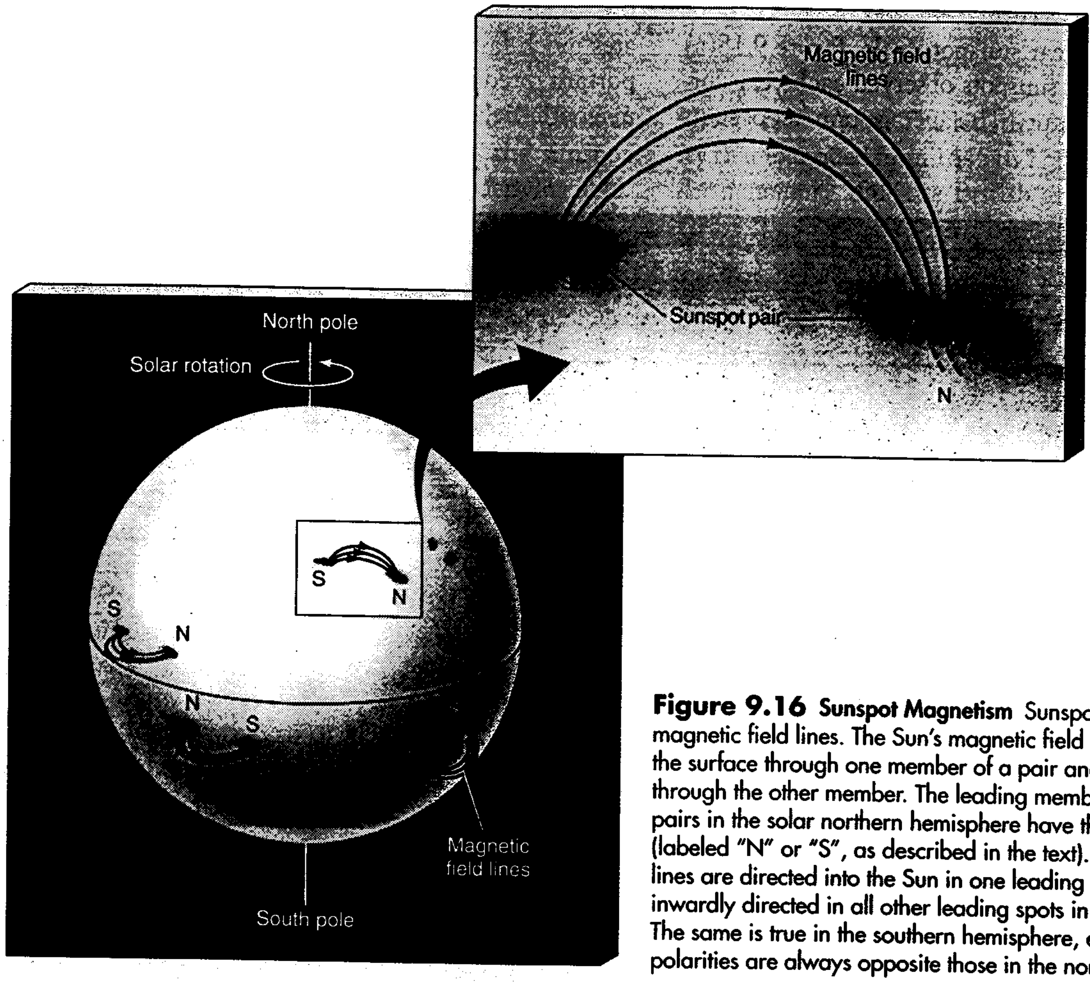


Figure 9.16 Sunspot Magnetism Sunspot pairs are linked by magnetic field lines. The Sun's magnetic field lines emerge from the surface through one member of a pair and reenter the Sun through the other member. The leading members of all sunspot pairs in the solar northern hemisphere have the same polarity (labeled "N" or "S", as described in the text). If the magnetic field lines are directed into the Sun in one leading spot, they are inwardly directed in all other leading spots in that hemisphere. The same is true in the southern hemisphere, except that the polarities are always opposite those in the north.

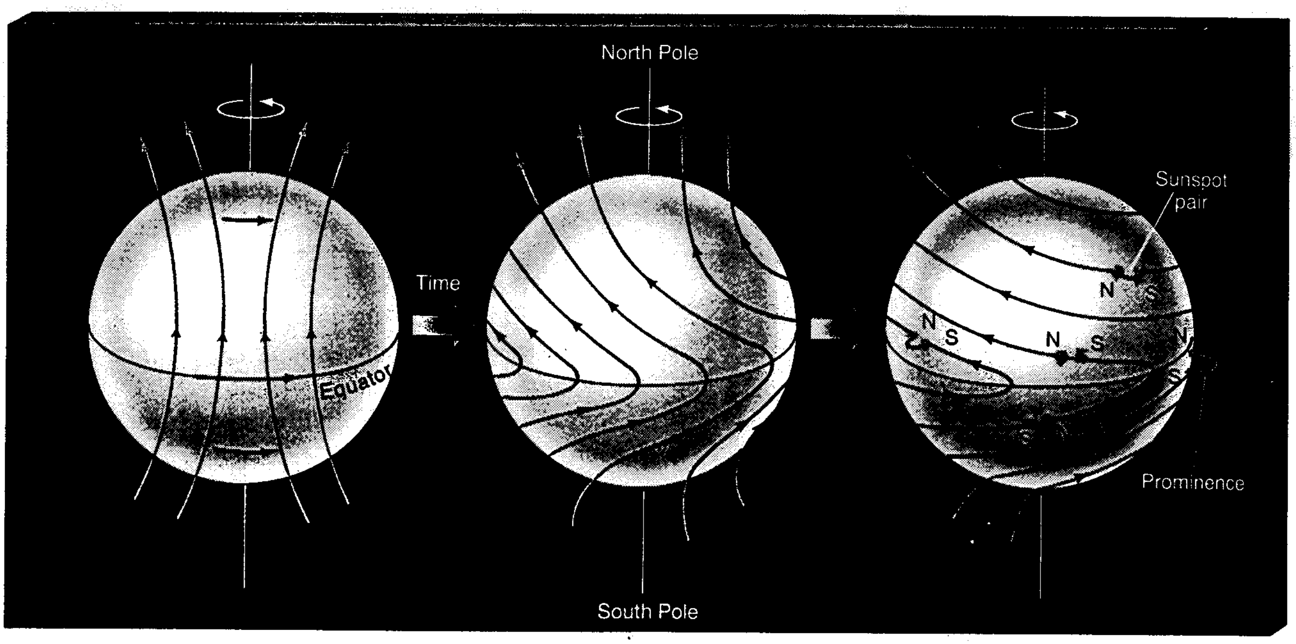


Figure 9.17 Solar Rotation The Sun's differential rotation wraps and distorts the solar magnetic field. Occasionally, the field lines burst out of the surface and loop through the lower atmosphere, thereby creating a sunspot pair. The underlying pattern of the solar field lines explains the observed pattern of sunspot polarities. (If the loop happens to occur near the edge of the Sun and is seen against the blackness of space, we see a phenomenon called a prominence, see Figure 9.20.)

[from Chaisson + McMillan, 2001]

INDICES OF SOLAR ACTIVITY USED IN AERONOMY:

- Ideally, continuous monitoring of the Sun from space at all wavelengths in UV/EUV/X-rays needed. One difficulty is long-term calibration of detectors that degrade with time in space.
- Groundbased "proxies" sought for years to do this:

(1) Zurich ("Wolf") Sunspot Number (R)

(2) 2800 MHz ("Ottawa") Radio Flux ($F_{10.7}$)
→ 10.7 cm

(3) Visible light signatures, e.g., Calcium plage index + others at Sacramento Peak Observatory.

--- By far the most widely used is $F_{10.7}$

It is good for long time scales, i.e., solar cycle.

It is not good for short time scales, i.e., day-to-day.

--- Thus, EUV flux is estimated by "scaling" actual observations (when available) by $F_{10.7}$.

At solar minimum, $F_{10.7} \approx 70$ Units
At solar maximum, $F_{10.7} \gtrsim 200$ Units

∴ "Average" $F_{10.7} \approx 140$ units

EXAMPLE OF EARTH's Exospheric Temperature (T_∞) (13.)
--- to be covered later in course --- vs. $F_{10.7}$.

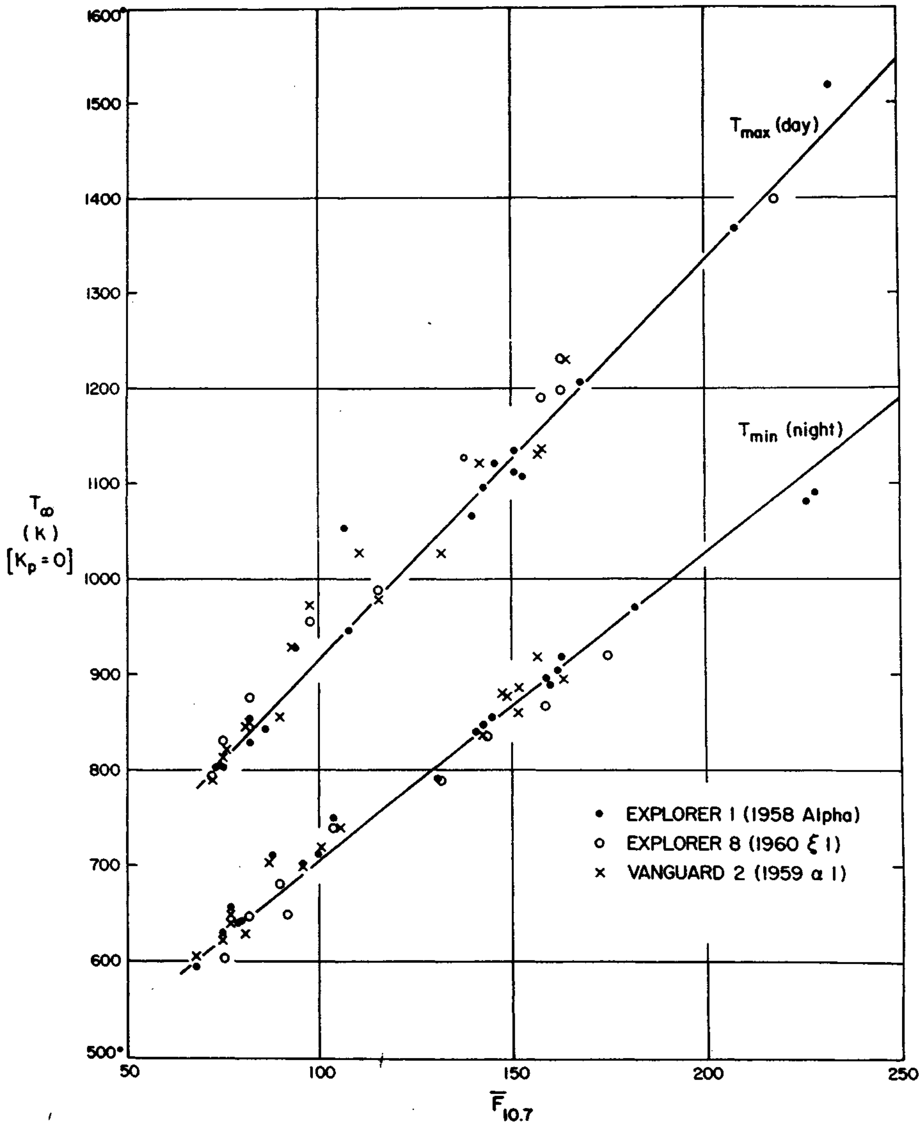
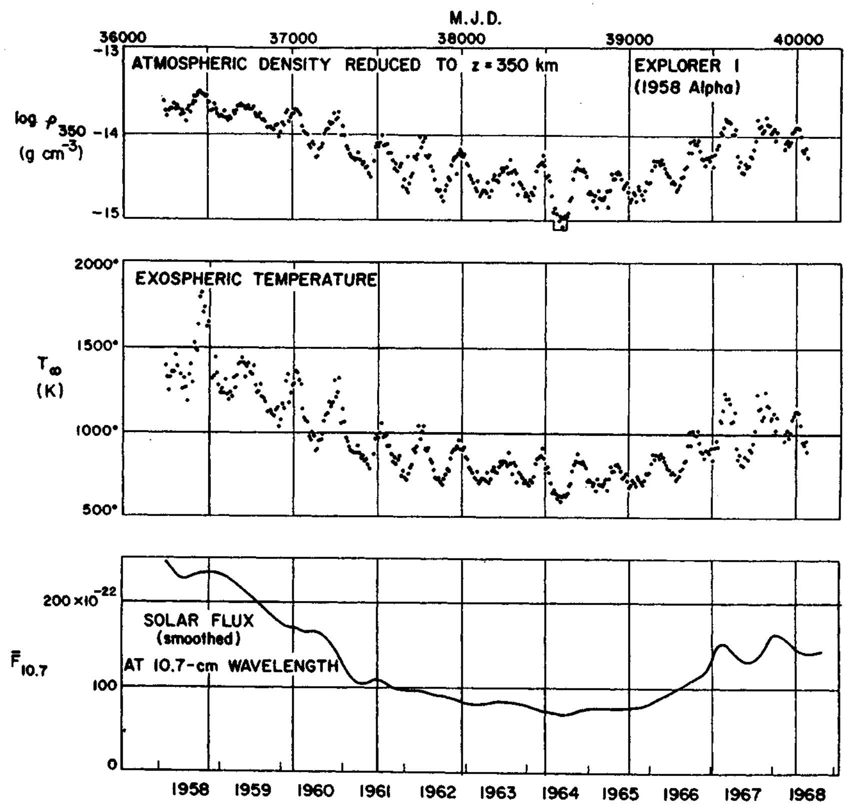


Fig. 5. Global night-time minimum and daytime maximum exospheric temperatures derived, through the use of the present models, from the densities obtained from the drag of three artificial satellites, plotted against the smoothed 10.7-cm solar flux $\bar{F}_{10.7}$. To obtain the data points, all variations except the diurnal variation were suppressed by using the equations associated with the models. The straight line through the minimum temperatures is represented by the equation $T_{min} = 379^\circ + 3.24^\circ\ \bar{F}_{10.7}$ (see Eq. (14)); the one through the maxima, by $T_{max} = 1.30\ T_{min}$.



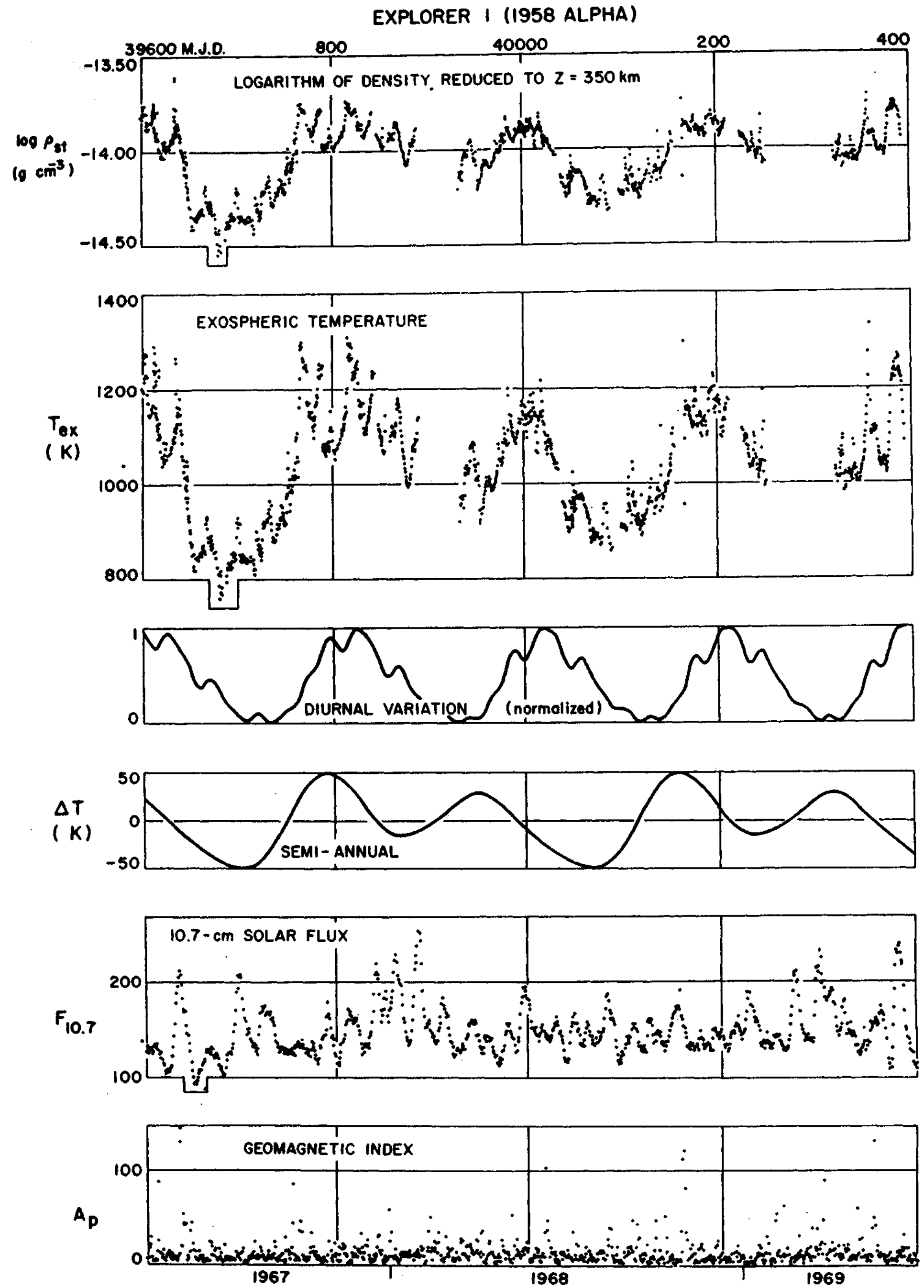


Fig. 6. Ten-day means of the densities obtained from the drag of the Explorer 1 satellite and of the exospheric temperatures derived from them through the use of older models. Since the purpose of this figure is to illustrate the variations of density and temperature with the solar cycle (see bottom curve), it was not deemed necessary to redo the temperature diagram by means of the present models; the difference would be hardly noticeable. MJD is the Modified Julian Day (JD minus 2 400 000. 5).

Fig. 7. Densities obtained from the drag of the Explorer 1 satellite and exospheric temperatures derived from them by use of older models. Since the purpose of this figure is to illustrate the 27-day oscillations and the geomagnetic effect superimposed on the diurnal variation, it was not deemed necessary to redo the temperature diagram by use of the present models; the difference would be hardly noticeable. The schematic diagrams of the diurnal and semi-annual variations are also from older models.