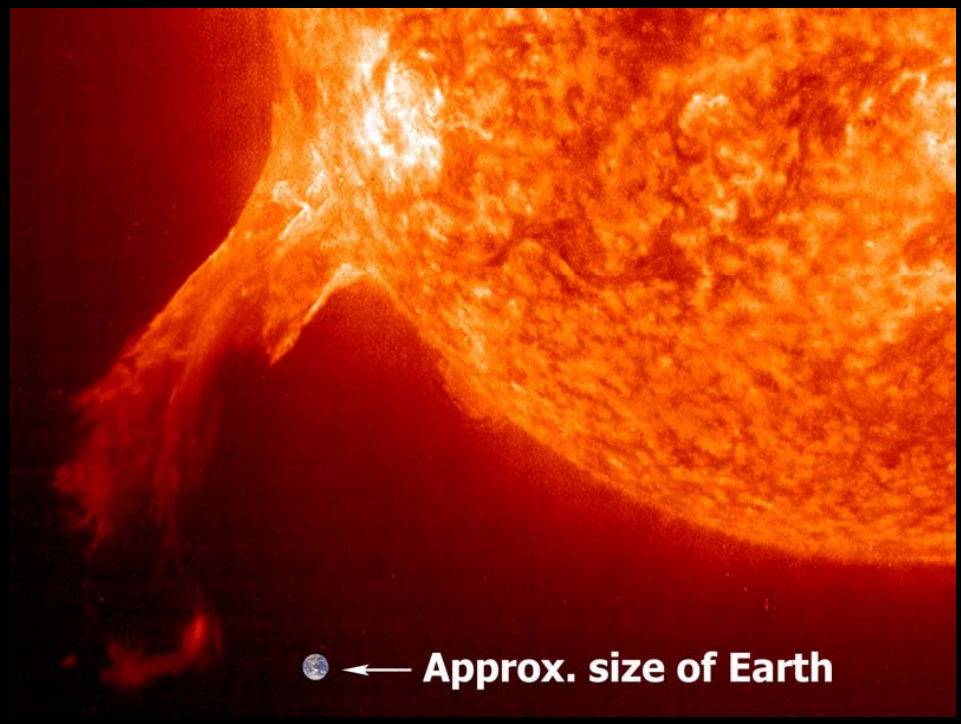
The Sun – Our Star



IST Summer 2008

Sun: General Properties

- The surface temperature of the Sun is 5800K and the its central temperature is 15 million Kelvin.
- The Sun is a G2V class star - an average star in our universe.
- 74% Hydrogen, 24% Helium, 2% Metals

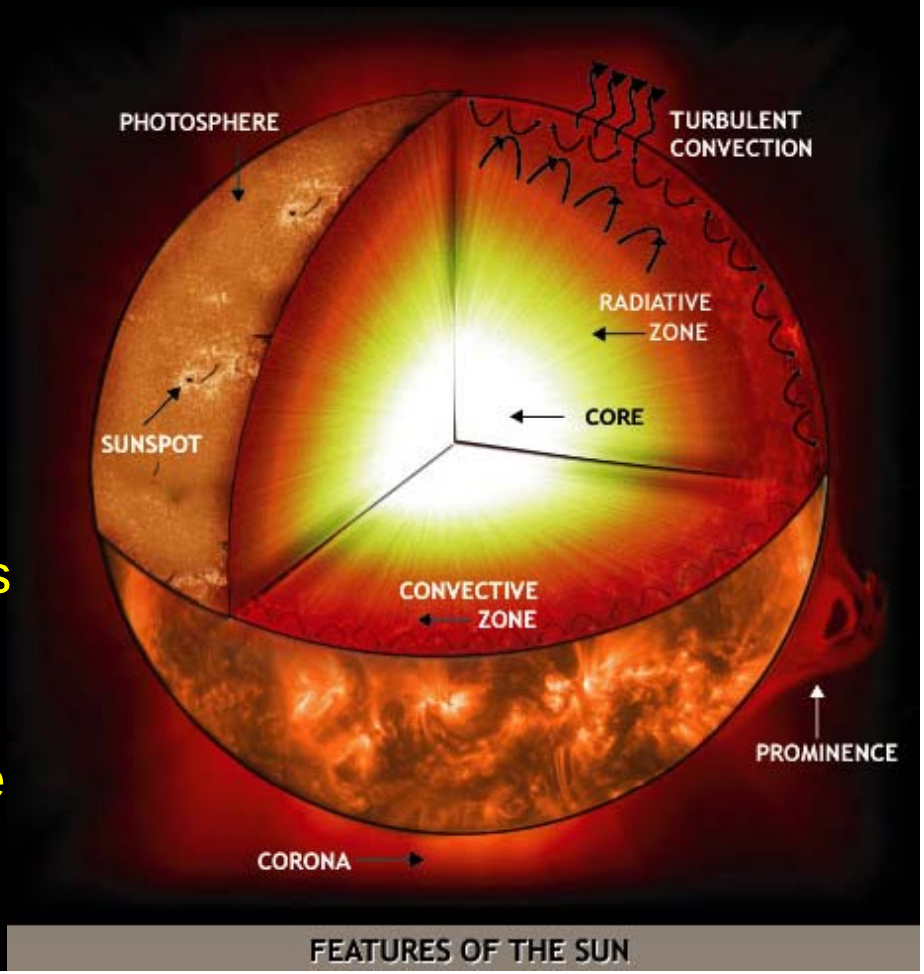
- The Sun is 109 times the radius of the Earth.
- The Sun is 330,000 times the mass of the Earth.

table 18-1 | Sun Data

Distance from the Earth:	Mean: 1 AU = 149,598,000 km
	Maximum: 152,000,000 km
	Minimum: 147,000,000 km
Light travel time to the Earth:	8.32 min
Mean angular diameter:	32 arcmin
Radius:	696,000 km = 109 Earth radii
Mass:	1.9891×10^{30} kg = 3.33×10^5 Earth masses
Composition (by mass):	74% hydrogen, 25% helium,
	1% other elements
Composition (by number of atoms):	92.1% hydrogen, 7.8% helium,
	0.1% other elements
Mean density:	1410 kg/m^3
Mean temperatures:	Surface: 5800 K; Center: 1.55×10^7 K
Luminosity:	3.86×10^{26} W
Distance from center of Galaxy:	8000 pc = 26,000 ly
Orbital period around center of Galaxy:	220 million years
Orbital speed around center of Galaxy:	220 km/s

Sun: Stellar Interior

- Thermonuclear core - the central region of Sun where fusion takes place due to high temperatures and pressures. 200,000 km radius. Site of nuclear reactions
- Radiative zone - a region inside a star where energy is transported outward by the movement of photons. 300,000 km, where solar energy is transported to Surface by radiation
- Convective zone - a layer inside a star where energy is transported outward by means of heat flow through the gasses of the star (convection). 200,000 km below the photosphere, where solar energy is transported by radiation



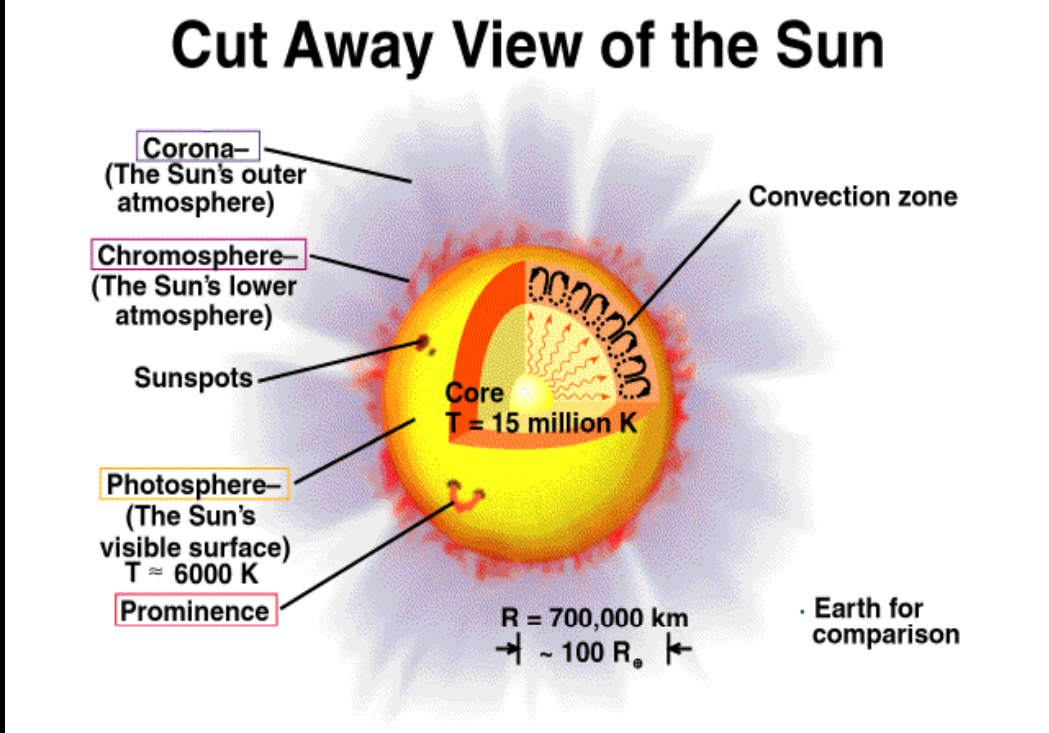
Sun: Atmosphere

- Photosphere - "sphere of light", the visible surface of the Sun. surface that emits radiation (what we see) w=500 km

- Chromosphere - "sphere of color", visible during solar eclipses. sun lower atmosphere (1500 km)

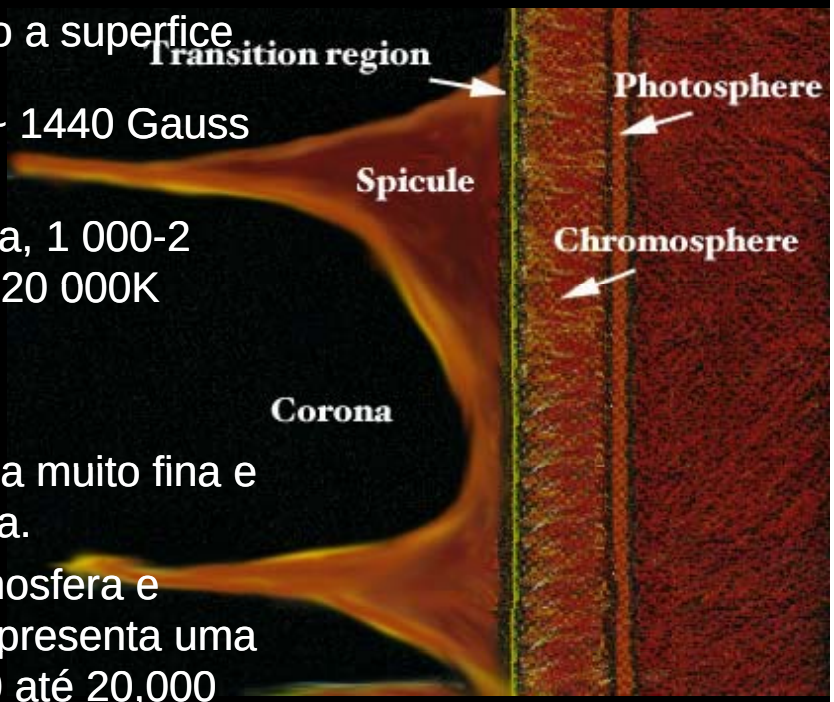
- Corona - the Sun's outermost atmosphere. 10,000km+ tenuous atmosphere -> extend to solar wind

- Solar wind :The outflow of gas constitute by protons and electrons that have escaped the Sun's gravity.



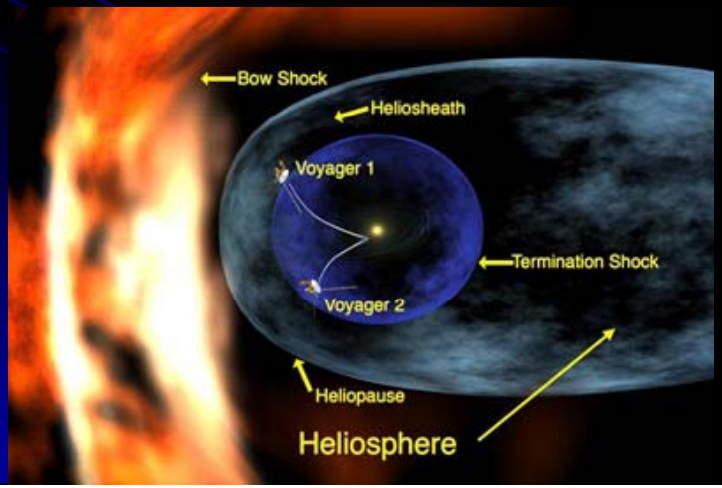
Exterior solar - Atmosfera

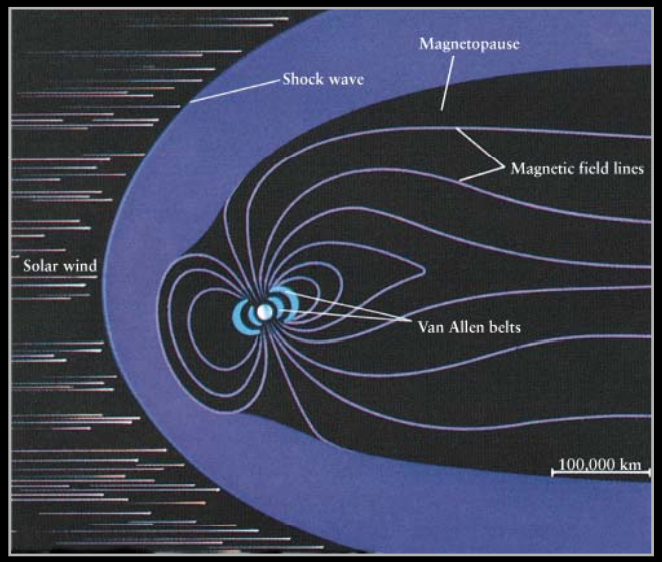
- **fotoesfera**
  - A base da fotoesfera define-se como a superfice visivel do sol.
  - 0 - 10^3 Km acima da superfice, B ~ 1440 Gauss
- **cromosfera**
  - camada irregular acima da fotoesfera, 1 000-2 000Km, temperatura varia de 6 000-20 000K
  - B ~8.4 Gauss
- **região de transição**
  - A região de transição é uma camada muito fina e irregular entre cromosfera e a corona.
  - A energia flui da corona para a cromosfera e durante este processo esta região apresenta uma variacao de temperatura de 100,000 até 20,000 K.
- **corona**
  - região externa do Sol que é visivel durante um eclipse do Sol como uma coroa branca à sua volta.



Solar Wind

- Coronal particles (mostly electrons and protons) are thrown with such velocity that they cannot be held by the Sun's gravity
- The Sun is "evaporing" constantly (ONLY 0.1% of its mass since its formation)
- Interact with objects in the solar system
  - Earth: cause aurorae
  - Comets: produces tails
  - Interacts with edge of solar system: heliopause
- Radiations reach Earth in 8 min, particles in a few days (v= 500 km/s)





Solar Wind: The Earth's Magnetic Field

At Earth:

V = 400 - 700 km/s

T = 50,000-500,000 K*

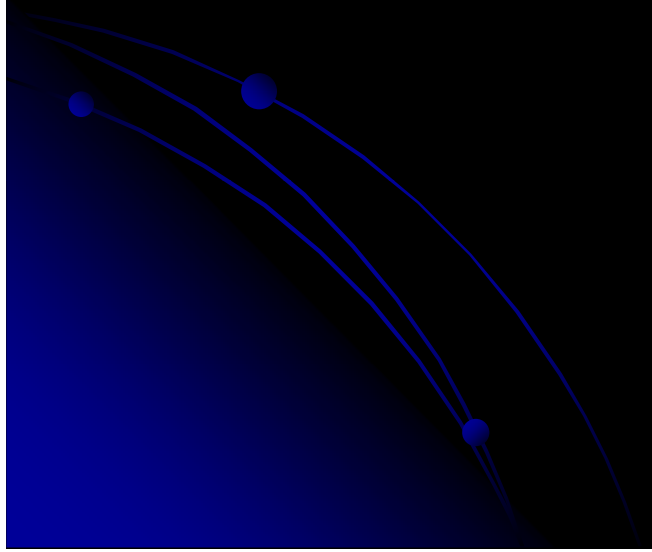
density = 10^3 - 10^4/m3

(Earth @ sea level - ~$2.5 \times 10^{25}/m^3$)

Solar Wind: Auroras are caused by the solar wind.

Sun: Atmosphere

Solar Observations



Solar Atmosphere

Composition:

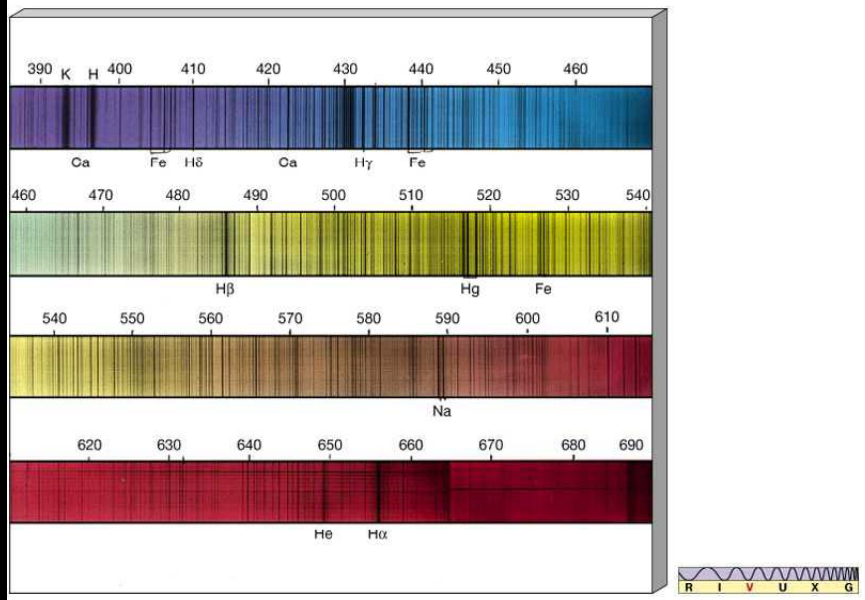
- Analyzing the Fraunhofer absorption lines from the Photosphere and Chromosphere
- 67 different elements in various stages of excitation and ionization

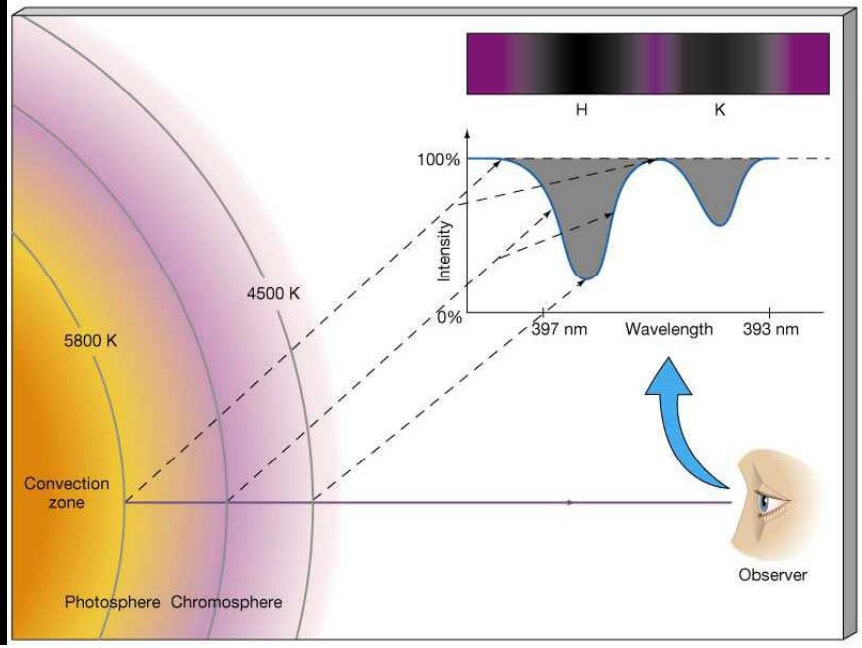
TABLE 15-1

Composition of the Sun

Element	Percent Mass of the Sun	Atomic Number
Hydrogen (H)	76.4	1
Helium (He)	21.8	8
Oxygen (O)	0.8	8
Carbon (C)	0.4	6
Neon (Ne)	0.2	10
Iron (Fe)	0.1	26
Nitrogen (N)	0.1	7
Silicon (Si)	0.08	14
Magnesium (Mg)	0.07	12
Sulfur (S)	0.05	16
Nickel (Ni)	0.01	28

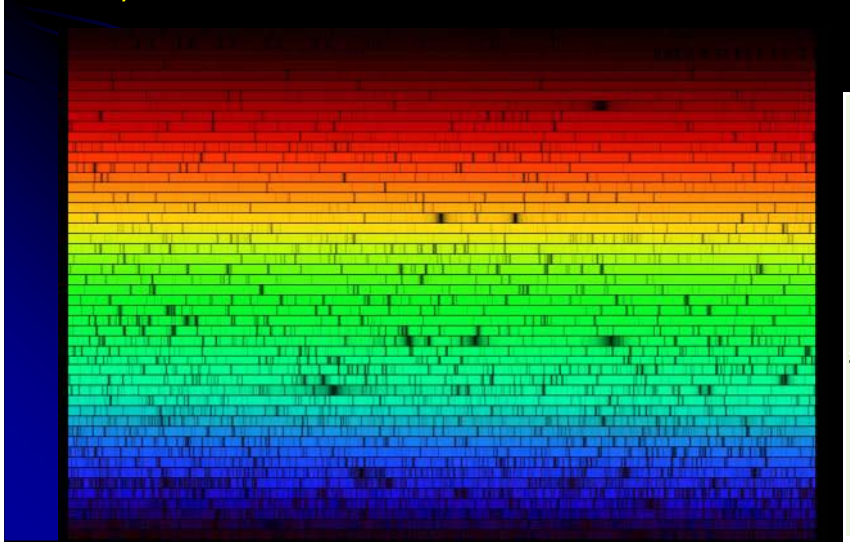
Source: Adapted from Anders and Ebihara (1982).
Note: Based on spectroscopic measurements of the Sun and measurements of meteorites and other samples.

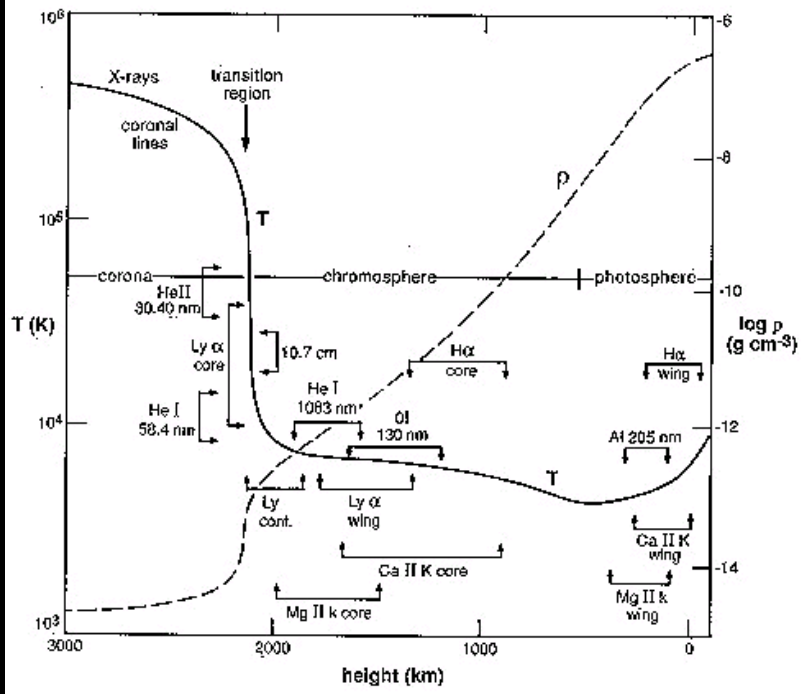




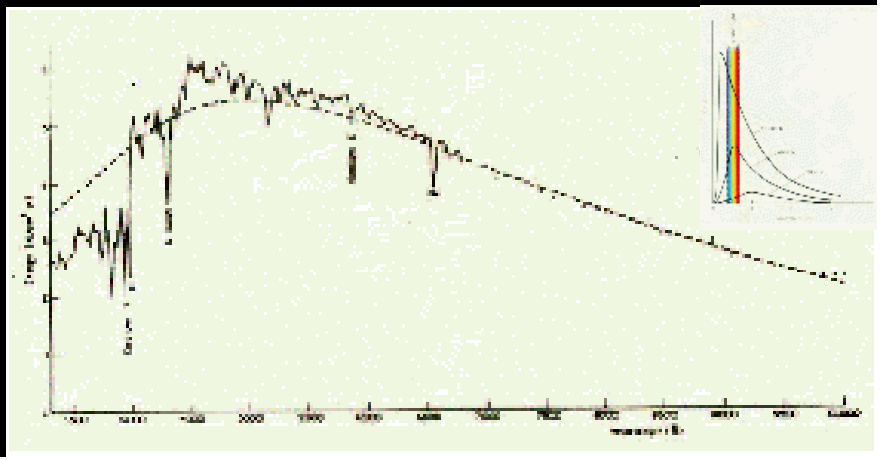
Solar Atmosphere

- **Espectro visivel de alta resolução espectro** (4000 Å -7000 Å); aumenta da esquerda para a direita ;50 imagens espectros (60 Å)
- Riscas Hidrogénio (mais importantes): Balmer H-alfa (6563 Å); Balmer H-beta (4861 Å); Balmer H-gamma (4340 Å)
- No espectro solar foram descobertos 67 elementos.
- Os elementos mais abundantes (em massa) são: Hidrogénio 93 %; Hélio 25 %; Carbono 0.2 %; Azoto 0.09 %;Oxigénio 0.8 %; Neon 0.16 %;Magnésio 0.06 %; Silicio 0.09 %;Enxofre 0.05 %; Ferro 0.14 %





Temperatura e densidade em função da altura na atmosfera para um Sol calmo. Encontra-se indicado a altura a qual as várias riscas espectrais e contínuos são formados.

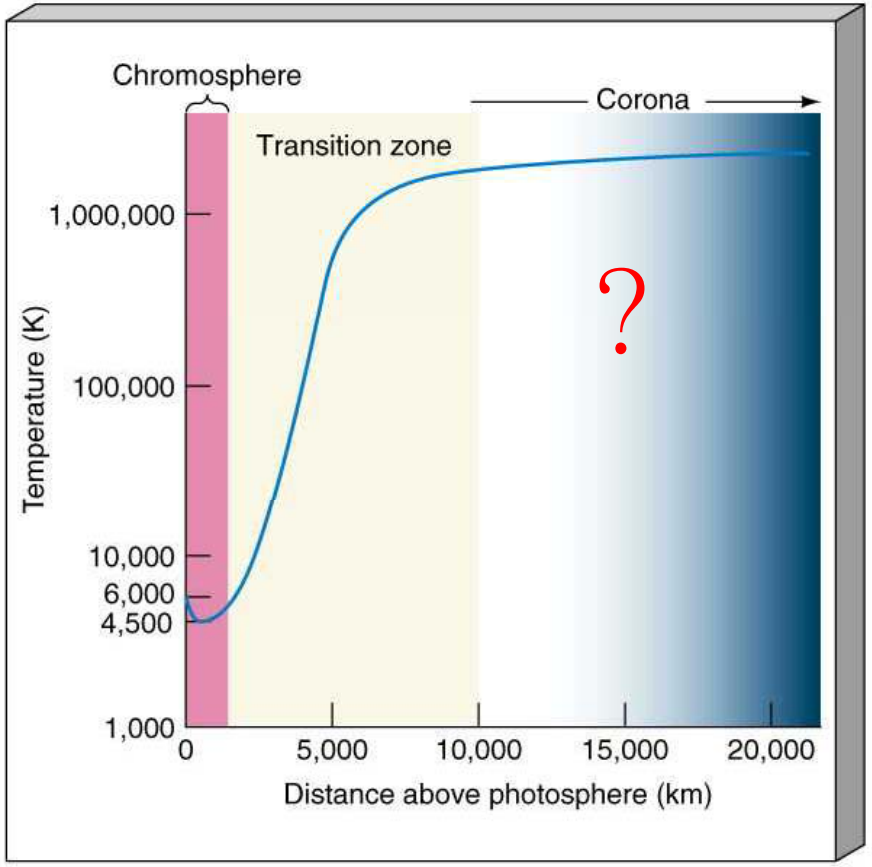


Solar atmospheric temperature

In the Transition zone and Corona

High temperature (3 millions of K) -> atoms are extremely ionized

Transition zone:
1500 -1000 km upper part of the atmosphere where T rises dramatically



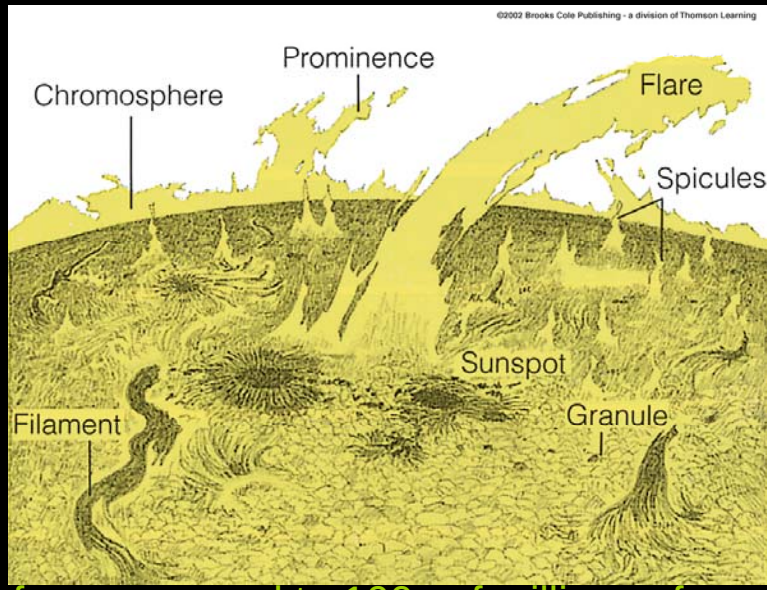
Sun: Surface Features

Plages - heated by rising magnetic field - compresses gas

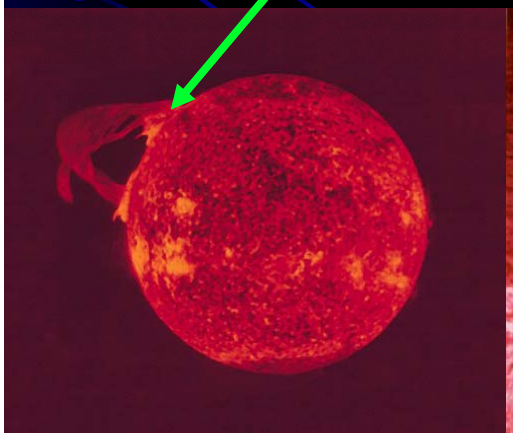
$$\left|\vec{B}\right| \approx 1500 \text{ G}$$

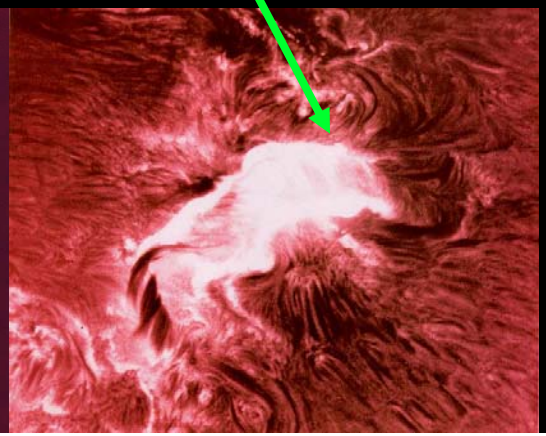
Filaments - cool streamers of gas above photosphere

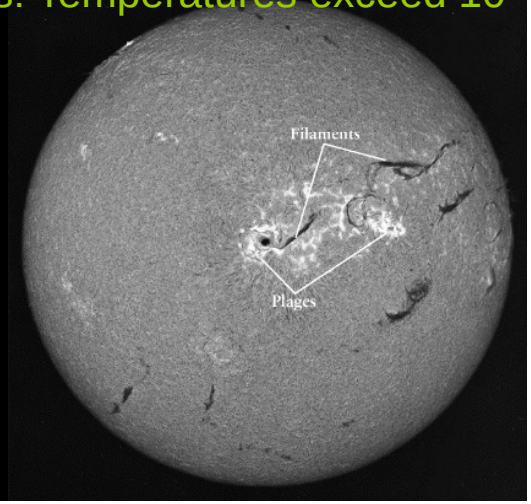
Prominences - filaments seen from the side



Flares - sudden release of energy equal to 100s of millions of megatons - radio through gamma rays! Temperatures exceed 10 *million* K

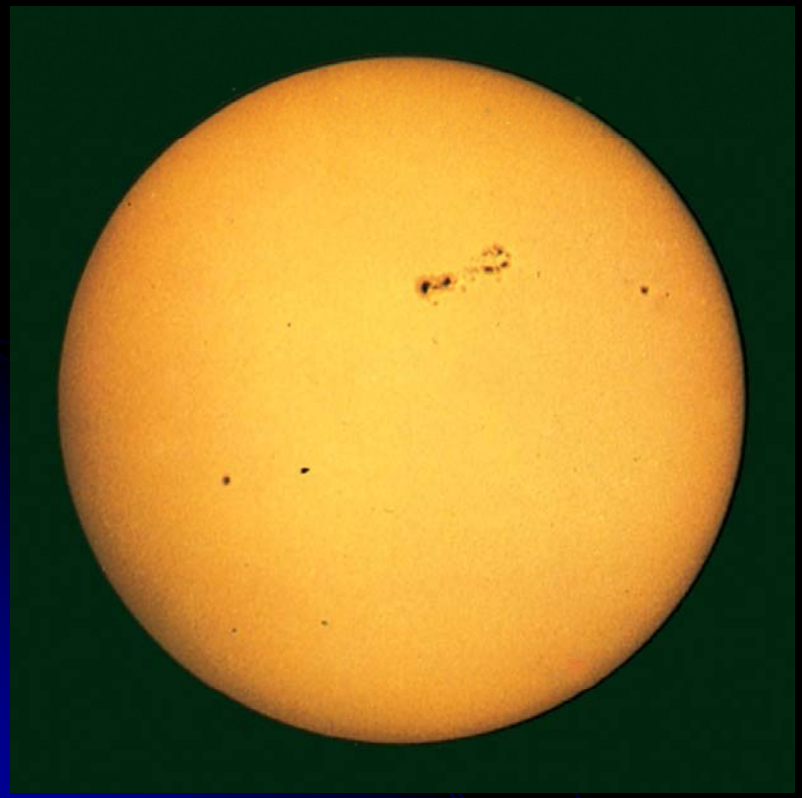






Sun Atmosphere: Photosphere

The photosphere is the lowest of three main layers in the Sun's atmosphere

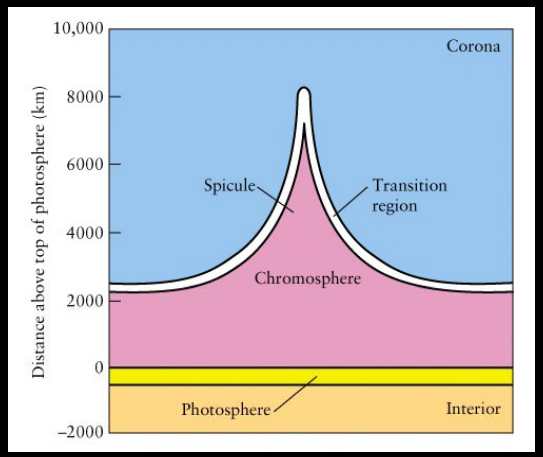


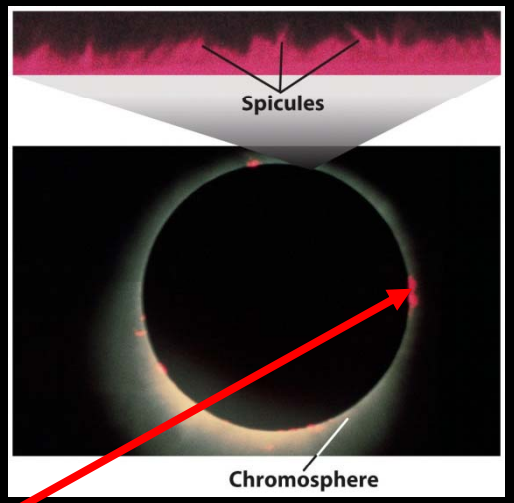
Photosphere

- The Sun's atmosphere has three main layers: the photosphere, the chromosphere, and the corona
- Everything below the solar atmosphere is called the solar interior
- The visible surface of the Sun, the photosphere, is the lowest layer in the solar atmosphere
- B~ 1440 Gauss

Sun Atmosphere: Chromosphere

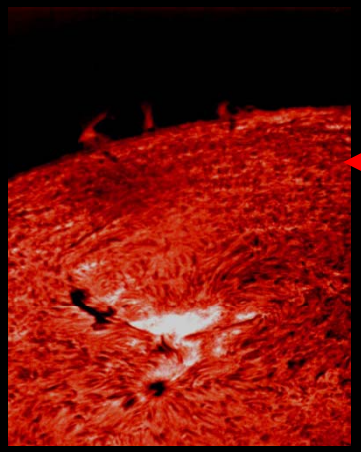
Chromosphere - “sphere of color” - T drops to ~ 4300 K





When seen edge-on we see the

656.3 nm Balmer line Hα



Special Hα filter used to image whole Sun

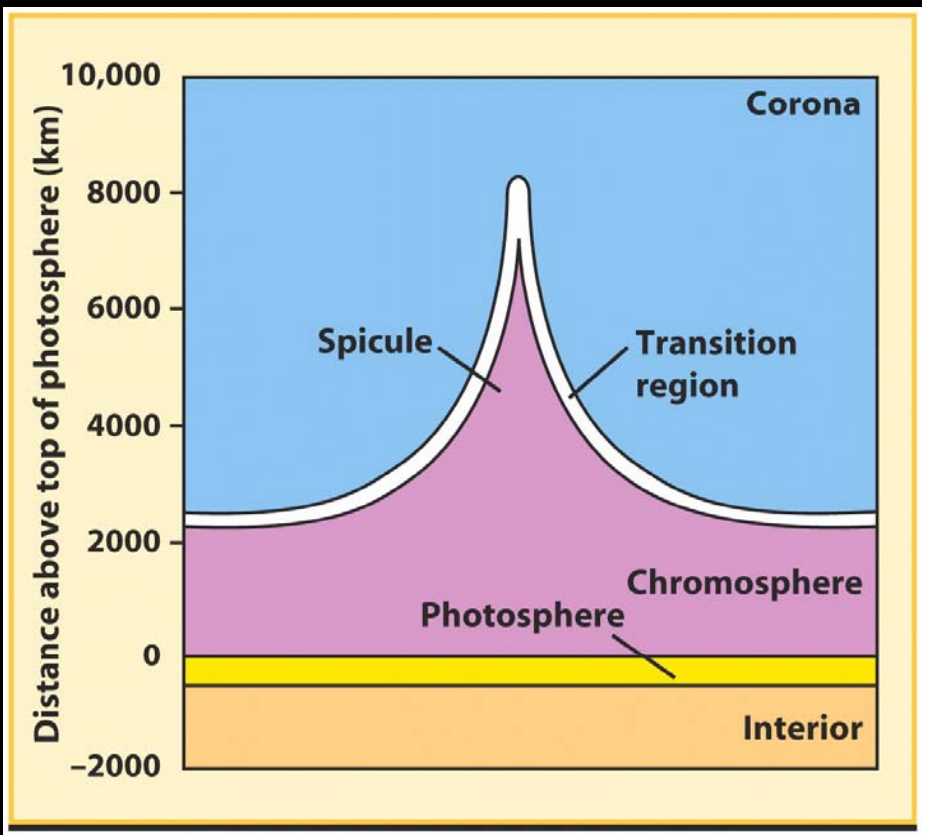
This is where Helium was discovered

(Helios - Greek god of the Sun)

Sun Atmosphere: Chromosphere

The chromosphere is characterized by spikes of rising gas

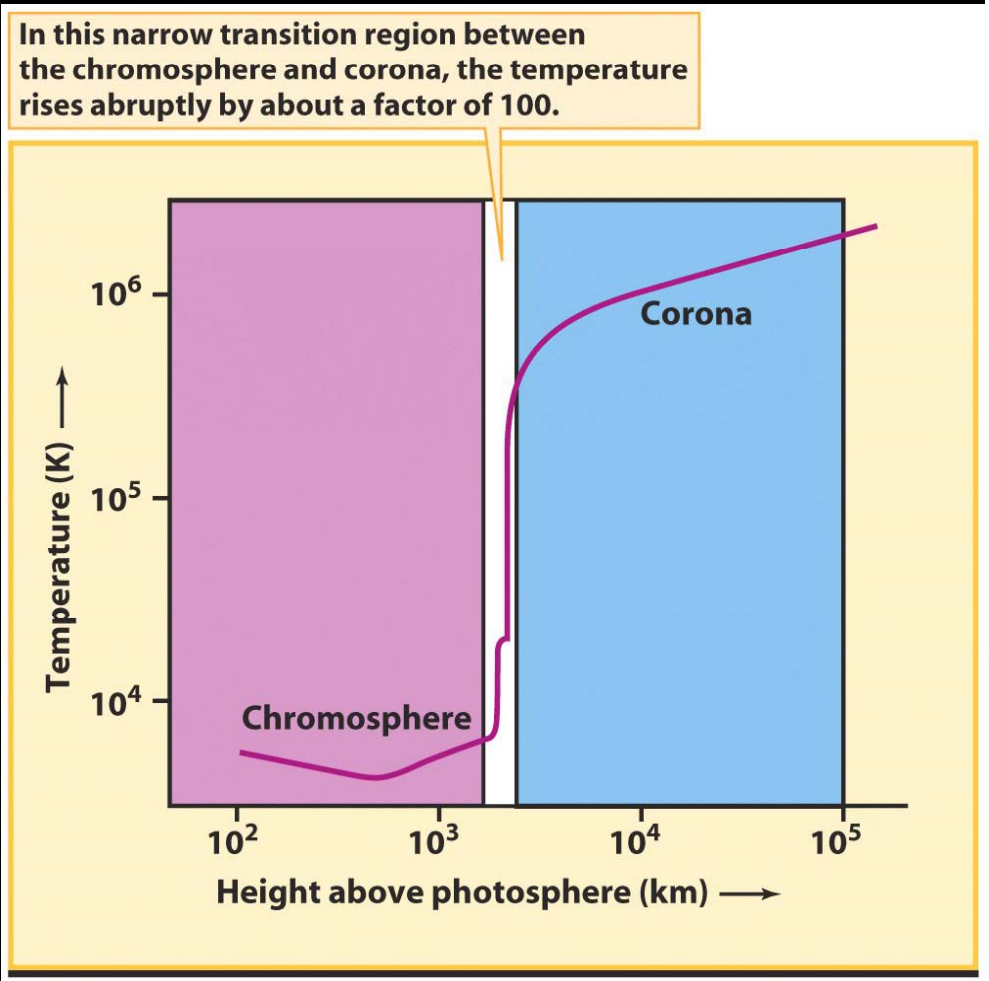
- Above the photosphere is a layer of less dense but higher temperature gases called the chromosphere
- Spicules extend upward from the photosphere into the chromosphere along the boundaries of supergranules



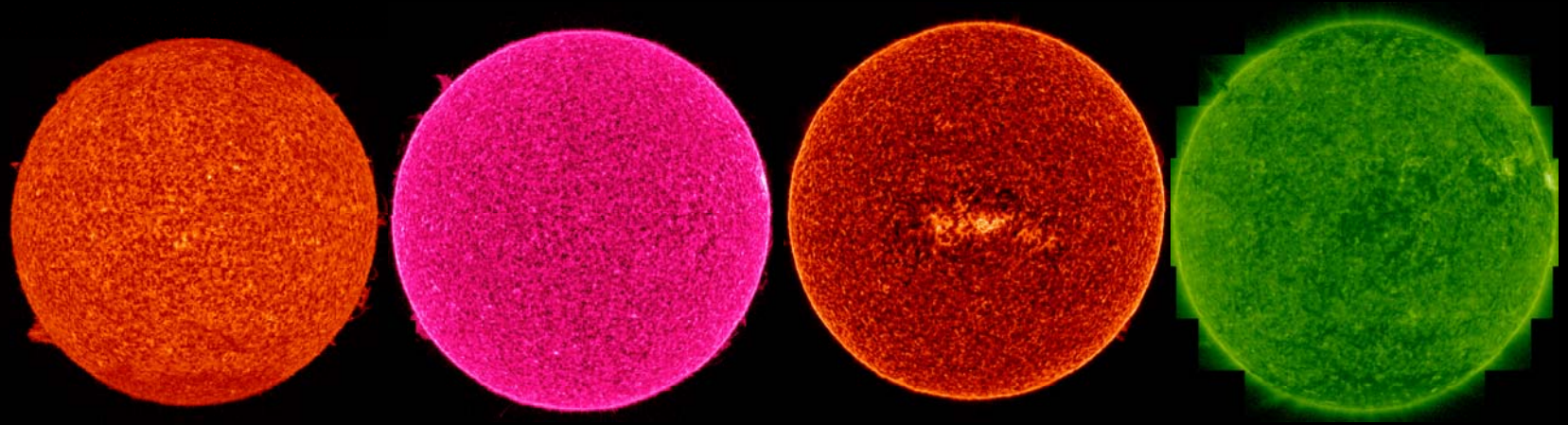
Sun Atmosphere: Transition Region

- The outermost layer of the solar atmosphere, the corona, is made of very high-temperature gases at extremely low density
- The solar corona blends into the solar wind at great distances from the Sun

Temperature Distribution



Sun Atmosphere: Transition Region



He I (T ” 2 10^4 K) C IV (T ” 10^5 K) S VI (T ” 2 10^5 K, 20/05/96) Ne VIII (T ” 6 10^5 K)

Sun Atmosphere: Corona

Corona - T rises to ~ 500,000 - 1,000,000 K !!

The corona ejects mass into space to form the solar wind

Highly ionized atoms, such as Fe^{+13} (also called Fe XIV)*

Light scattered by ions & electrons (inner) & dust grains (outer)

Heated by complex magnetic/particle activity

*NOTE: spectroscopists use a special notation:

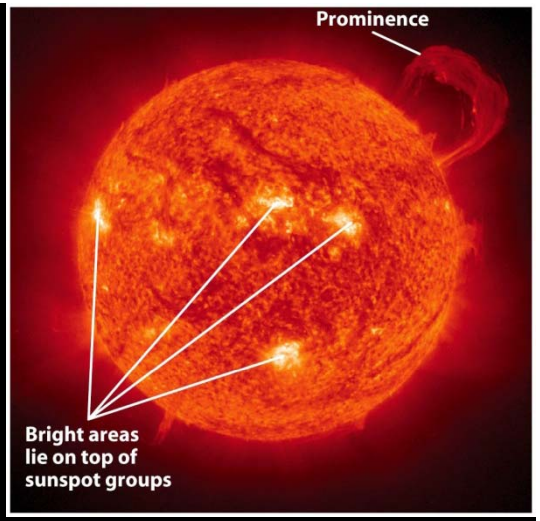
$C^{0} \Rightarrow$ C I

$C^{+1} \Rightarrow$ C II

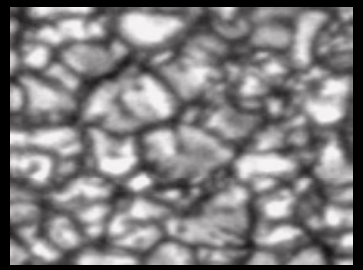
$C^{+2} \Rightarrow$ C III

C^{+3} is C IV

Surface Features



- Sunspot - a temporary cool region in the solar photosphere created by magnetic fields.
- Prominence - a flamelike protrusion seen near the limb of the Sun and extending into the solar corona.
- Granules - convection features about 1000 kilometers in diameter seen constantly in the solar photosphere.
- Coronal Mass Ejections, Coronal Holes



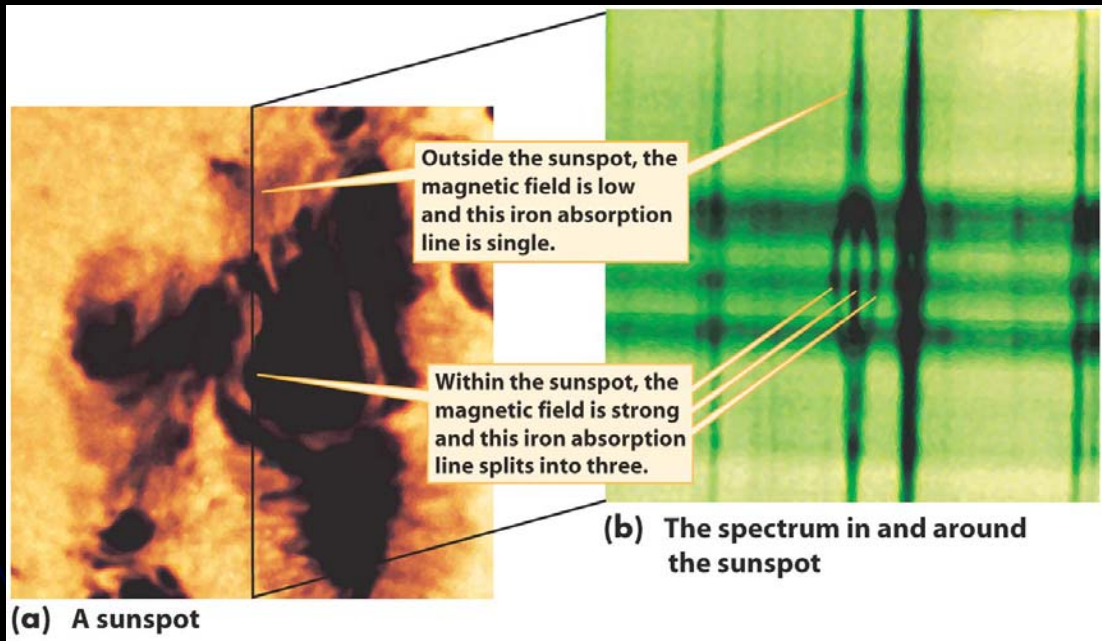
- How do we know that sunspots are caused by intense magnetic fields?
- Answer:
  - Zeeman Effect - the splitting of some of the spectral lines of a hydrogen gas into two or more components.

Sun Atmosphere: Sun's Magnetic Fields

- Spectral lines get split in strong magnetic fields (Zeeman Effect)
- How far they are split is proportional to the strength of the magnetic field
- → Magnetic field 1000 times stronger in sunspots than the sun's average magnetic field

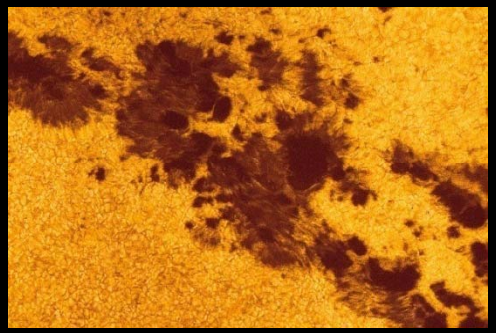
Zeeman Effect

Sunspots and Magnetic Fields



Sun Atmosphere: Photosphere - Sunspots

The Active Sun: Sunspots are low-temperature regions in the photosphere

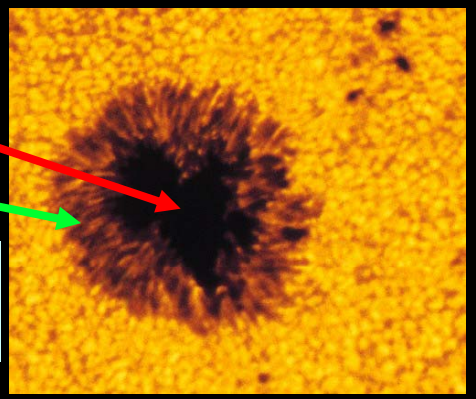


Sunspots:

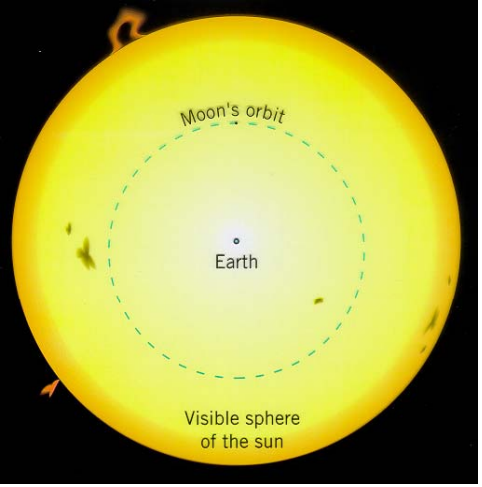
- Appear in groups
- T~4000-4500 K, diameter 23 000 Km
- Darker than surrounding photosphere (WHY?)
- Large magnetic fields inhibit convection

umbra

penumbra

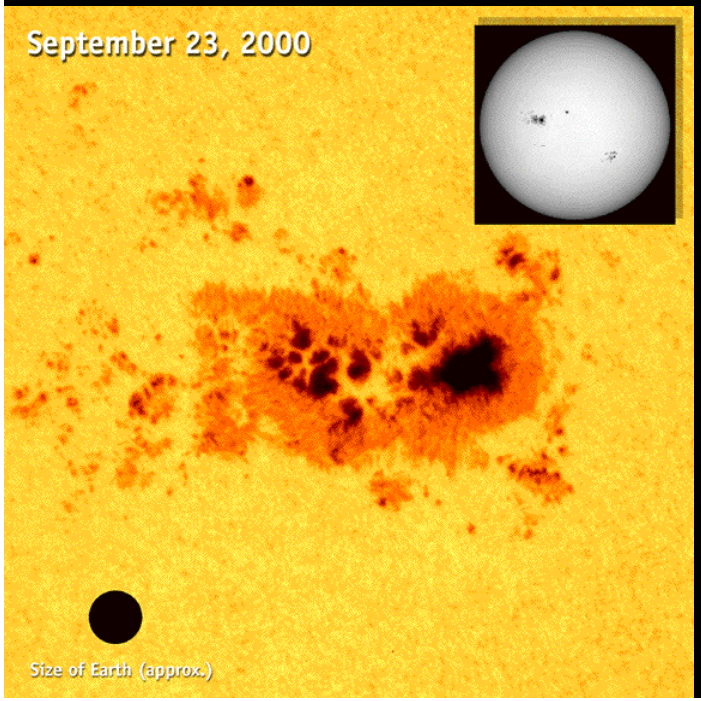


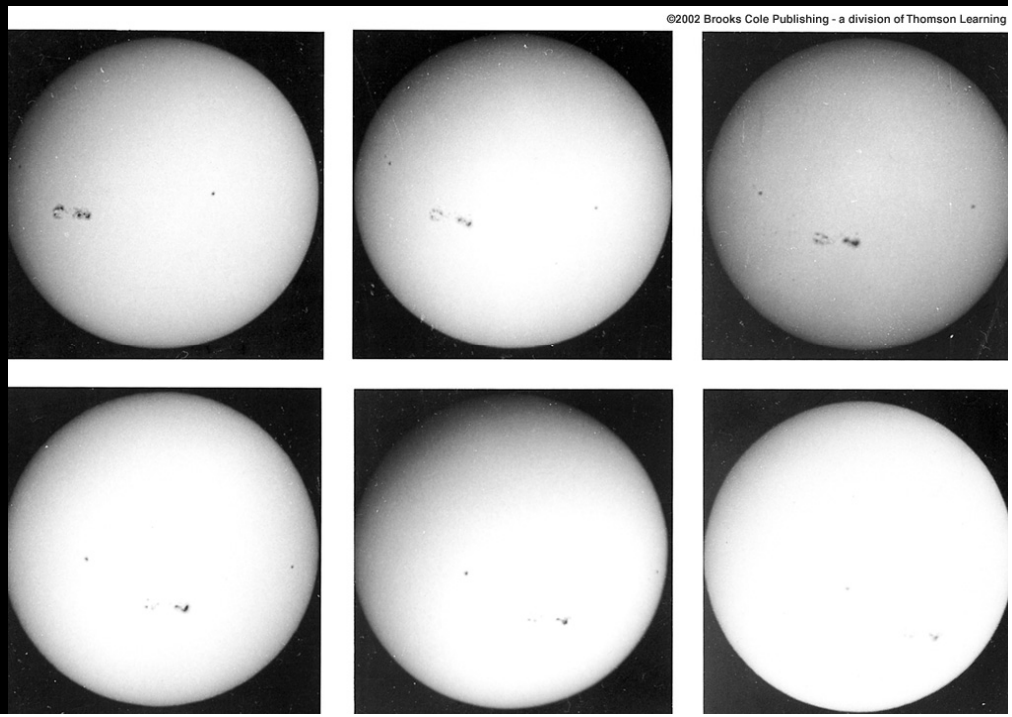
$$\left|\vec{B}\right| \approx 2000\,\mathrm{G} - - 3000\,\mathrm{G}$$



Sun Atmosphere: Photosphere - Sunspots

The sun in 21 – 26 August 1971
Not steady (size and shape changed)

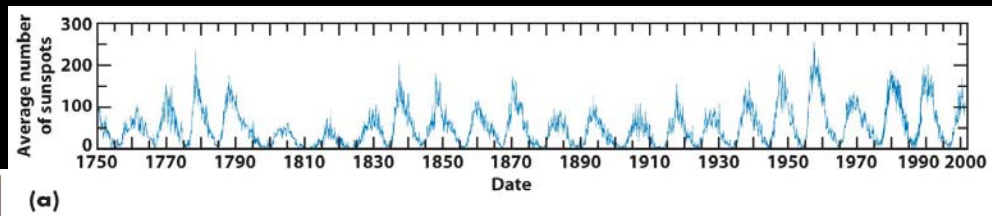




Sun Atmosphere: Photosphere - Sunspots

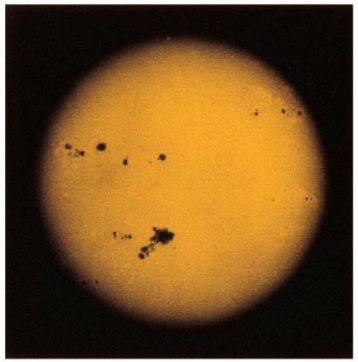
- The Sun's surface features vary in an 11-year cycle
- The average number of sunspots increases and decreases in a regular cycle of approximately 11 years

Sunspot Cycle

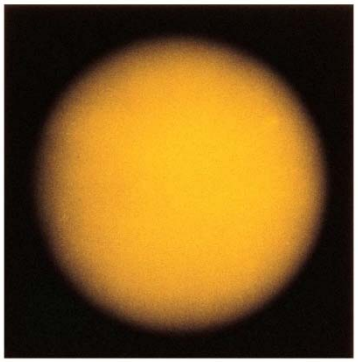


(a)

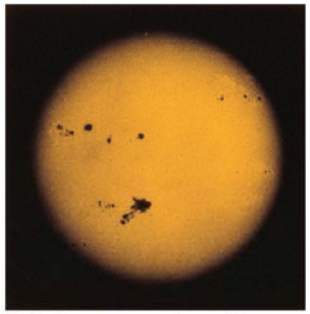
Sunspot Maximum and Minimum



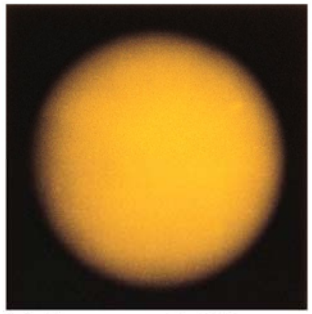
Near sunspot maximum



Near sunspot minimum



(b) Near sunspot maximum



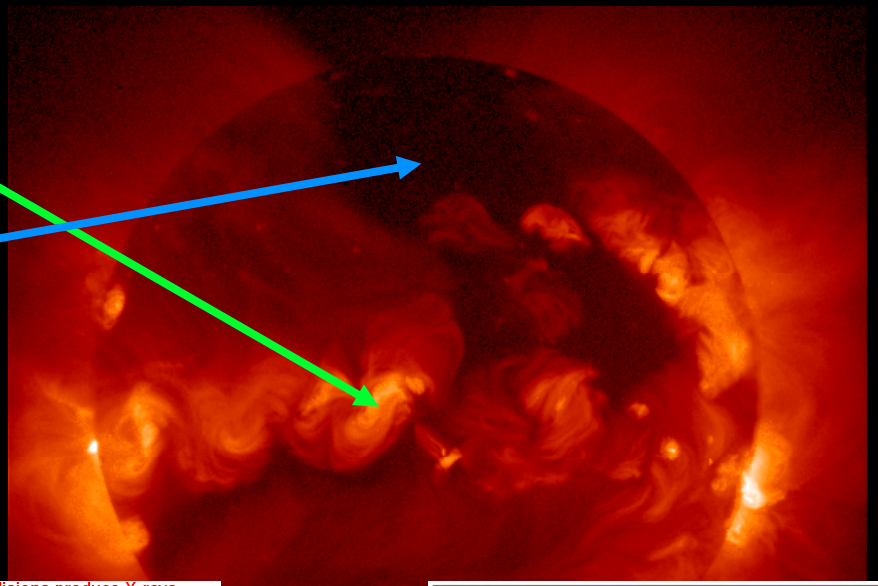
(c) Near sunspot minimum

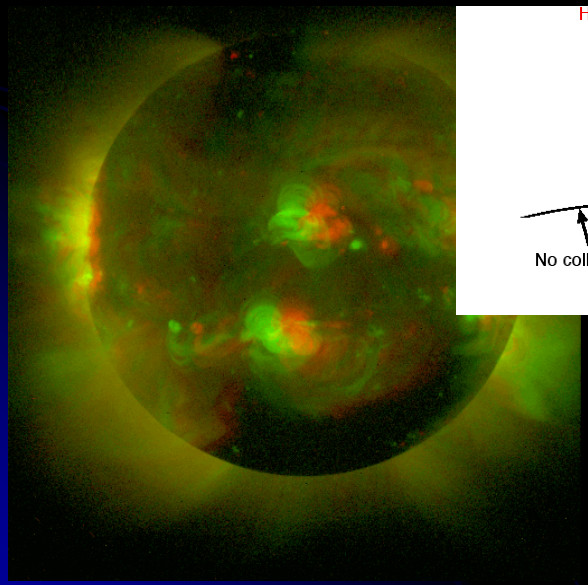
Sun Atmosphere: Corona – Coronal Mass Ejections

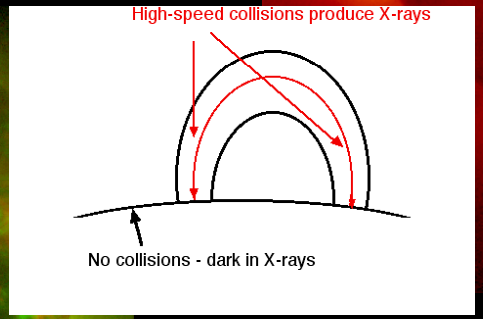
Magnetic field loops trap hot gas, area bright in X-rays

Open fields - gas flows & area is dark in X-rays - *coronal holes*

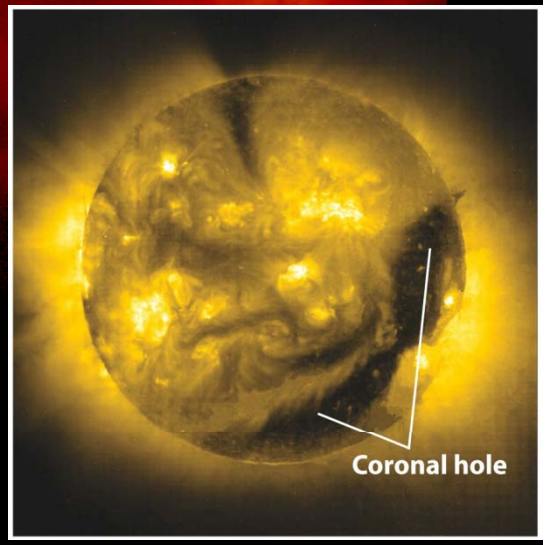
Activity in the corona includes coronal mass ejections and coronal holes







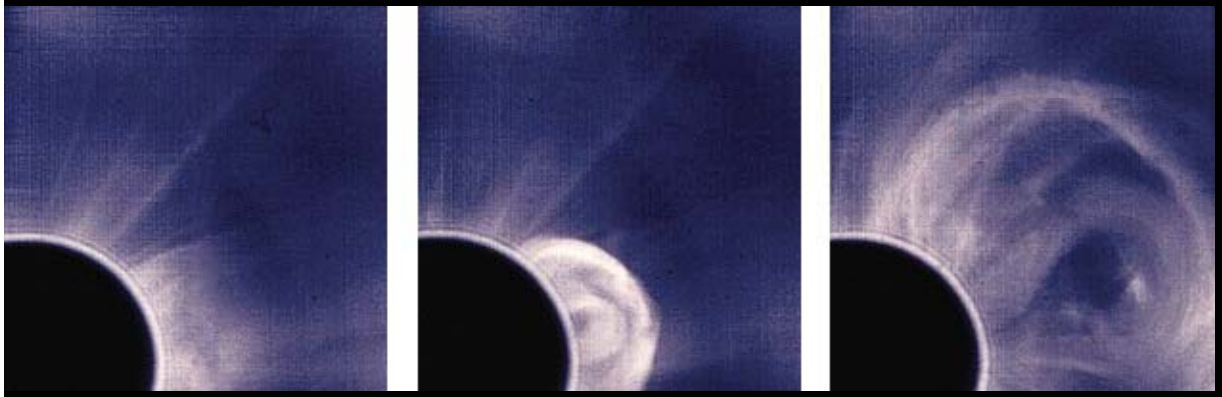
Look at this with 3D glasses (red-green) - from Yohkoh spacecraft



The Ultraviolet Corona

Sun Atmosphere: Corona – Coronal Mass Ejections

Coronal Mass Ejections

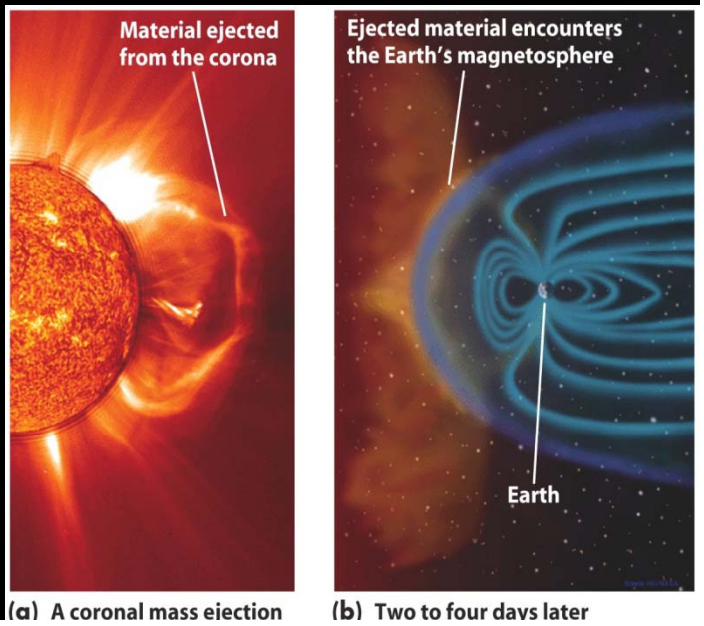


Coronal Mass Ejection

Expel trillions of tons at hundreds of km/s!

Potential damage to:

- satellites & astronauts
- power grids
- radio communication



Other activity about the Sun

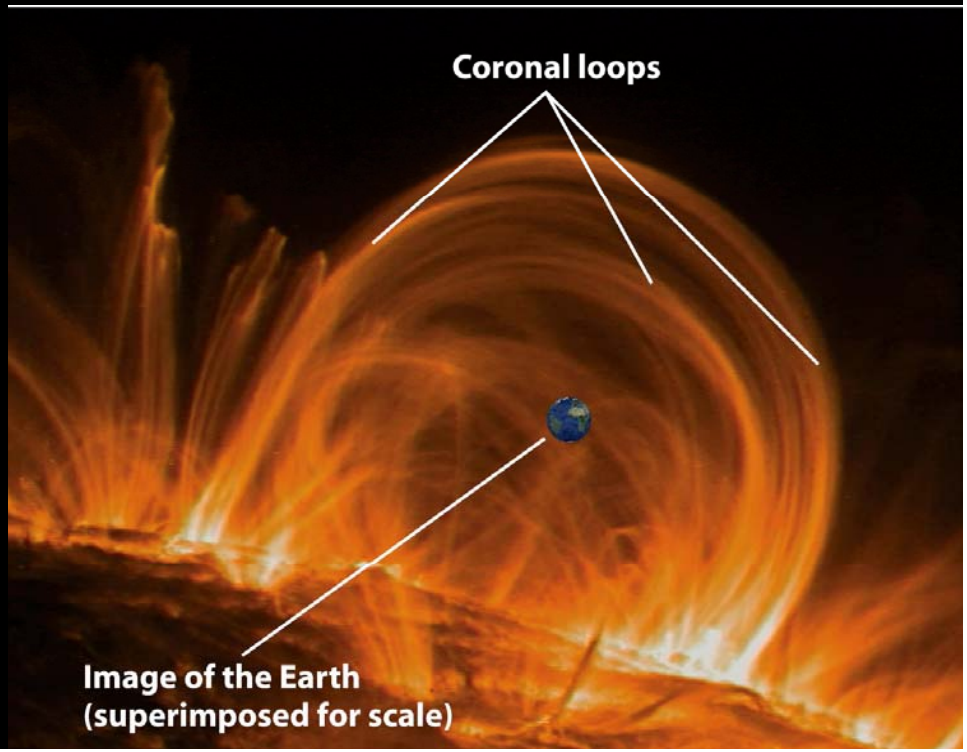
- Prominences
  - Loops of ionized gas (plasma) bent by magnetic fields
  - May last up to three months
- Flares - much violent than prominences
  - Eruptions on the lasting 5 to 10 min
  - Includes coronal mass ejections (500 to 1000 km/s)
  - Can disrupt communications and electricity
  - Cause more aurorae and can disable satellites
- All these phenomenon happen in active regions on the Sun, which vary in position.
- We don’t understand the details for the formations of these structures

Sun Atmosphere: Sun's Magnetic Fields

The Sun's magnetic field also produces other forms of solar activity

- **Solar Flares:** A solar flare is a brief eruption of hot, ionized gases from a sunspot group
- **Coronal Mass Ejection:** A coronal mass ejection is a much larger eruption that involves immense amounts of gas from the corona

Magnetic Arches in the Corona



Convective Regimes

- Granulation/mesogranulation/supergranulation in >0.97 R, radiative transfer, ionization
- Global convection in >0.7 R

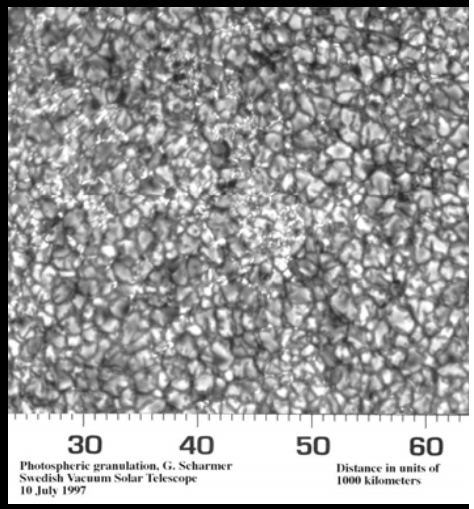
- Granulation 1 Mm 1 km/s velocity doppler measurements
- Mesogranulation 5Mm 60 m/s correlation tracking
- Supergranulation 30 Mm 400 m/s correlation tracking, doppler, local helioseismology
- Giant cells 100 Mm 50 m/s global and local helioseismology

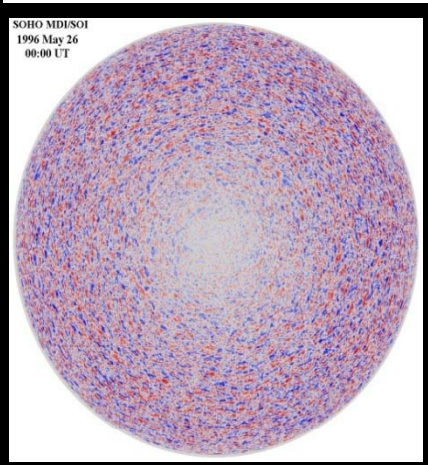
Convection Granulos

- **Granulos:** estruturas celulares pequenas(1-10Mm) que cobrem a inteira superfice do Sol. Estes granulos são a parte visivel das celulas de conveccao(100 Km penetracao), onde o fluido mais quente emergente nas zonas claras, arrefece (variacao de temperatura 100 -200 K) e contrai-se, voltando a imergir nas regiões mais escuras. Este fenomeno tem uma duração de 20 min. A superfice granulada está constantemente a renovar-se por fragmentação e mistura (apresentar filme). O fluido pode atingir velocidades supersónicas da ordem de 7km/s e produzir 'sonic booms', outro ruido acústico. Este processo é responsável pela produção de ondas acusticas no interior do sol. *Nota: Meso-granulos: 10 vezes maior que os granulos. Tempo de vida 20* magnético nos bordos da ordem 100 Gauss.

- **Supergranulos:** Estruturas similares aos granulos mas muito maiores (20-50 mm). Podem ser observados através do efeito Doppler. Tempo de vida 1 a 2 dias, velocidades 0.5 Km/s. O movimento do fluido nestes granulos transporta tubos de campos magnéticos para os bordos dos supergranulos onde é produzida a *rede cromosferica*. Campo magnético nos bordos da ordem 100 Gauss.

Granulos



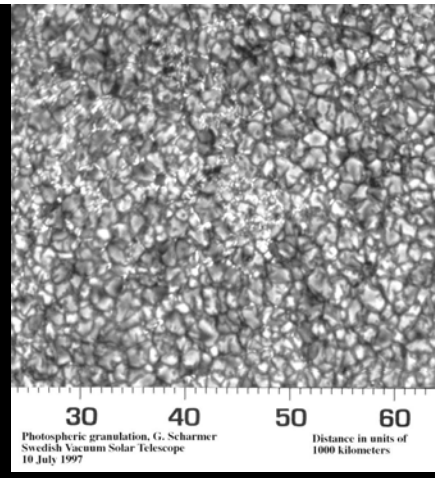


Supergranulos

Sun Atmosphere: Photosphere

Convection in the photosphere produces granules

Granules - convection features about 1000 kilometers in diameter seen constantly in the solar photosphere.



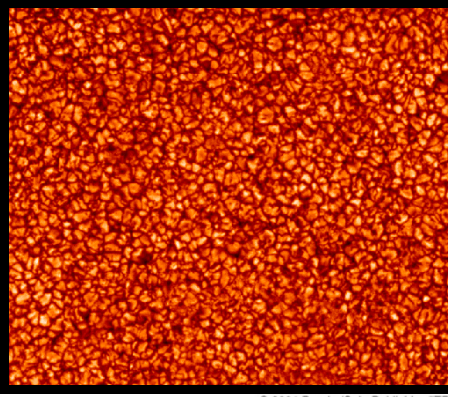
Granulation: convection cell structure on the surface

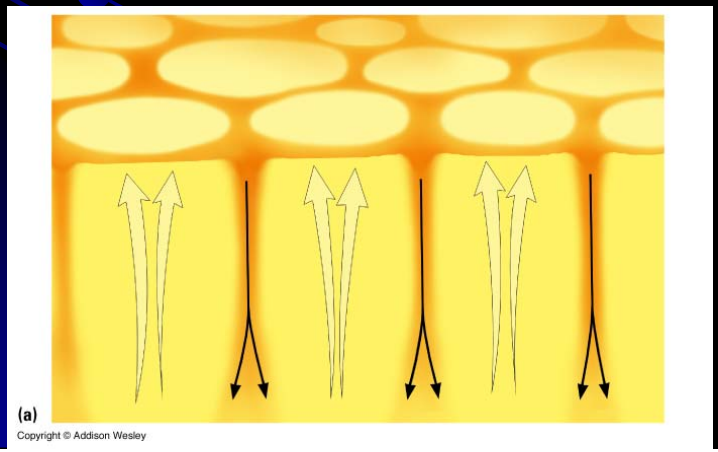
Size =1000 km, life time=10min

Bright granules go upward

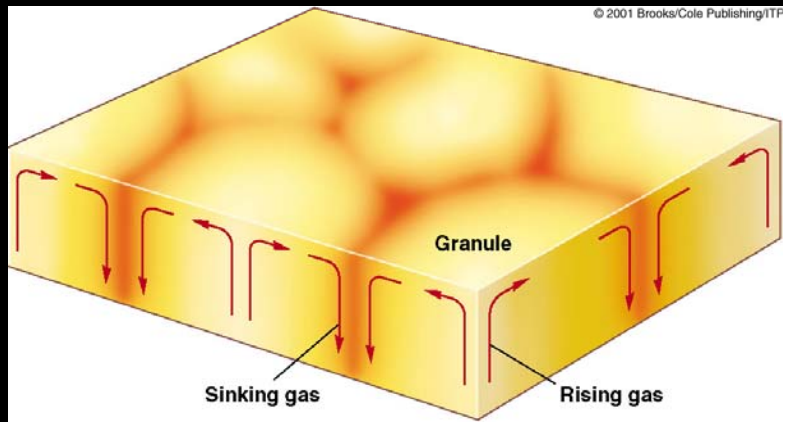
Dark granules sink

Temperature difference is 500 K



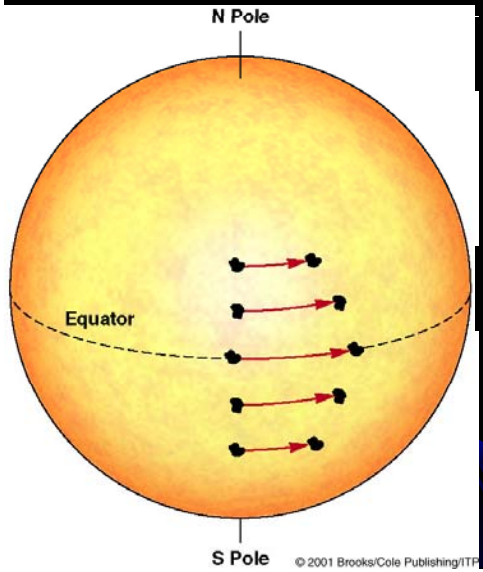


Granules



Sun Atmosphere: Sun's Differential Rotation

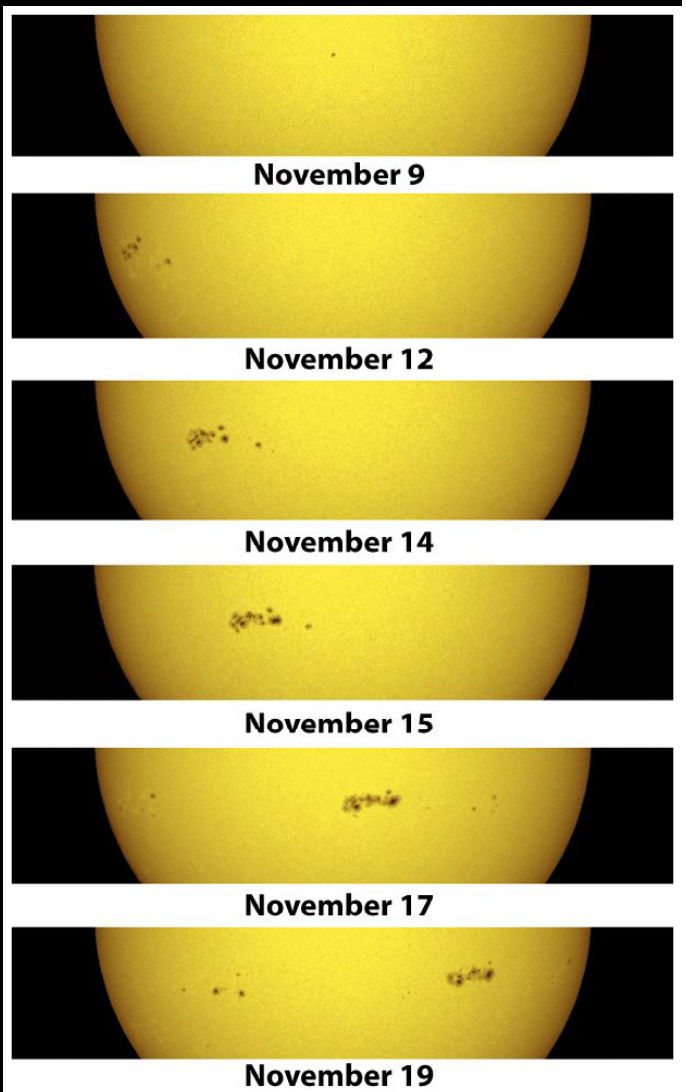
- Rotation rate P= 25 days at equator, P=31 days at high latitude (differential rotation rate)
- T= effective temperature = 5800 K (distribution of radiation followed a Black body curve)



P_{pole}=36 days

$P_{equator}$=25 days

The Sun's Rotation with Sunspots

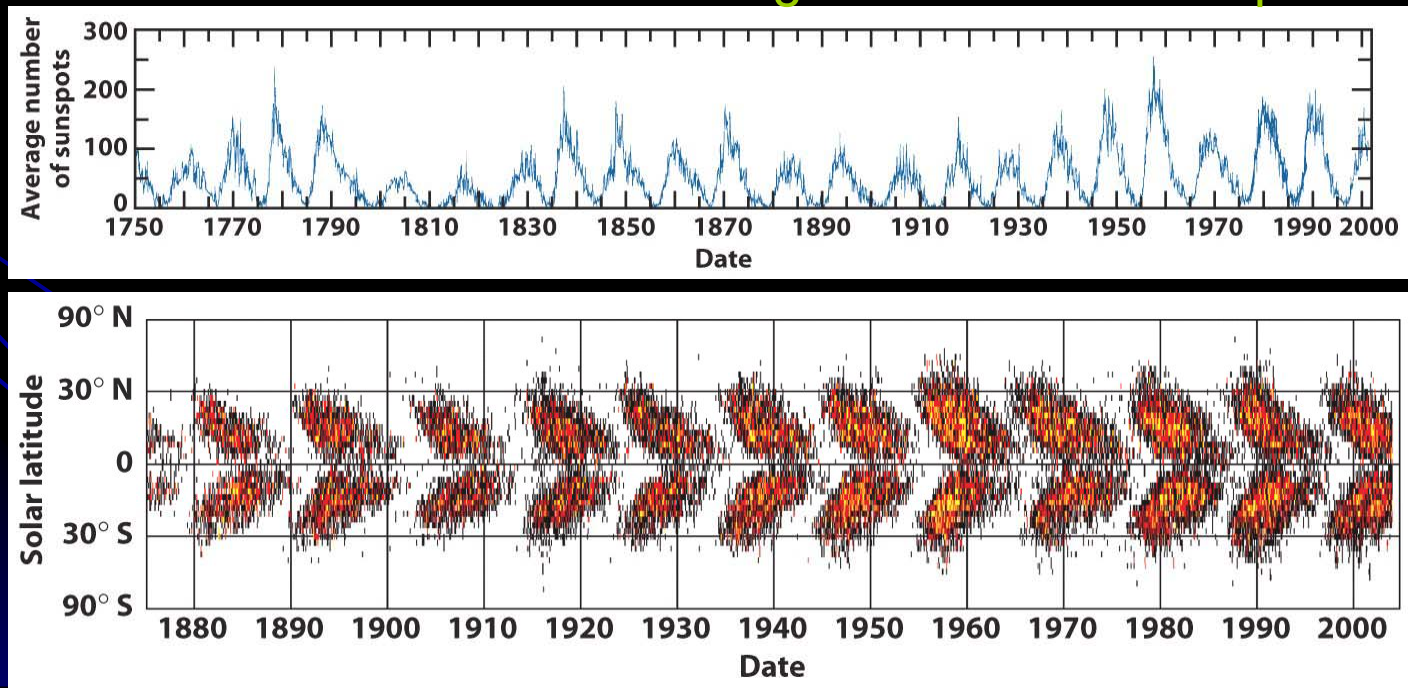


Sun Atmosphere: Sunspots Solar Cycle

Related to a 22-year cycle in which the surface magnetic field increases, decreases, and then increases again with the opposite polarity

- The average number of sunspots increases and decreases in a regular cycle of approximately 11 years, with reversed magnetic polarities from one 11-year cycle to the next
- Two such cycles make up the 22-year solar cycle
- Maundar's Butterfly Diagram shows a pattern when we plot the latitude of each sunspot as a function of time.

Variations in the Average Latitude of Sunspots



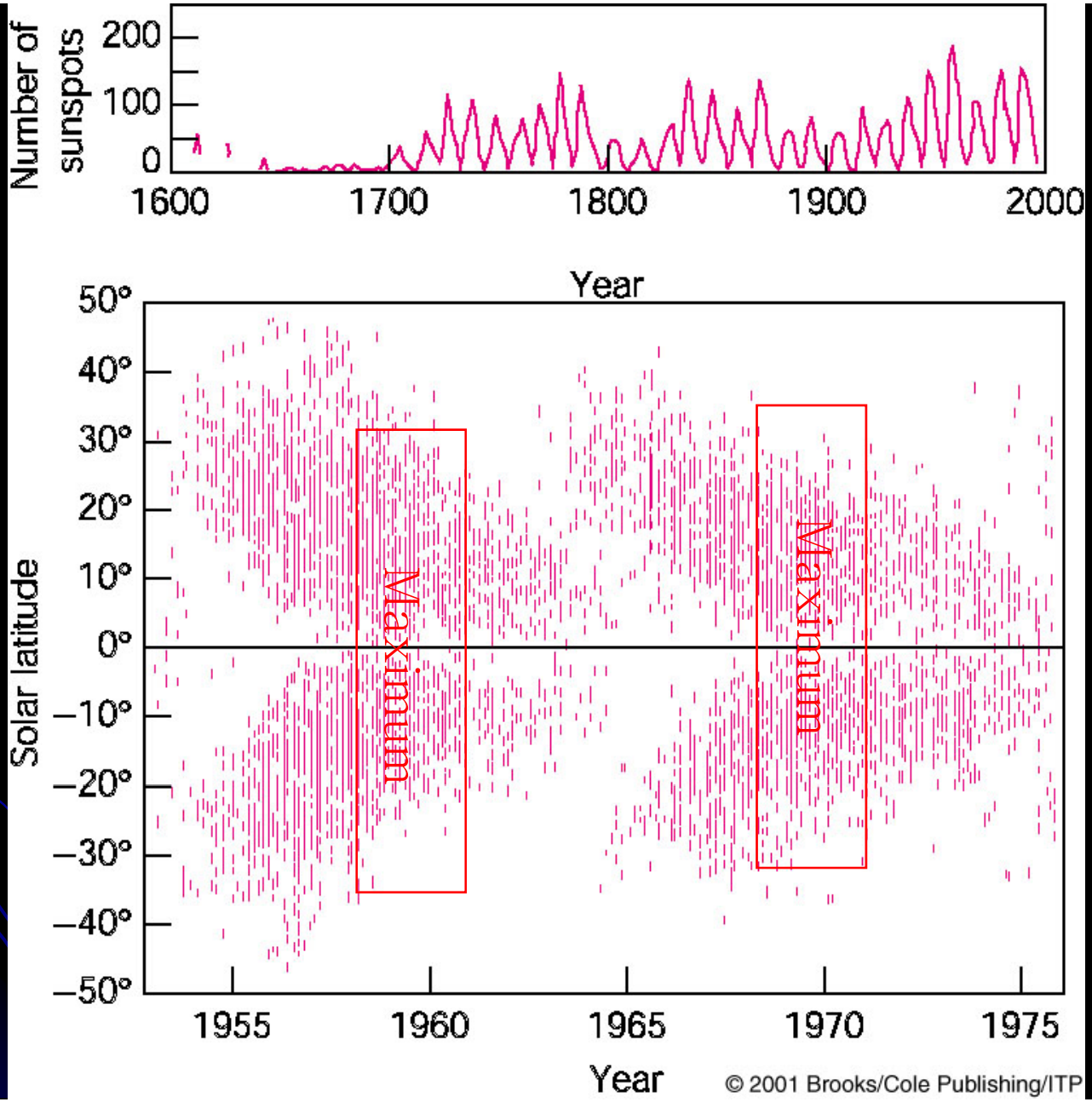
Maunder Minimum

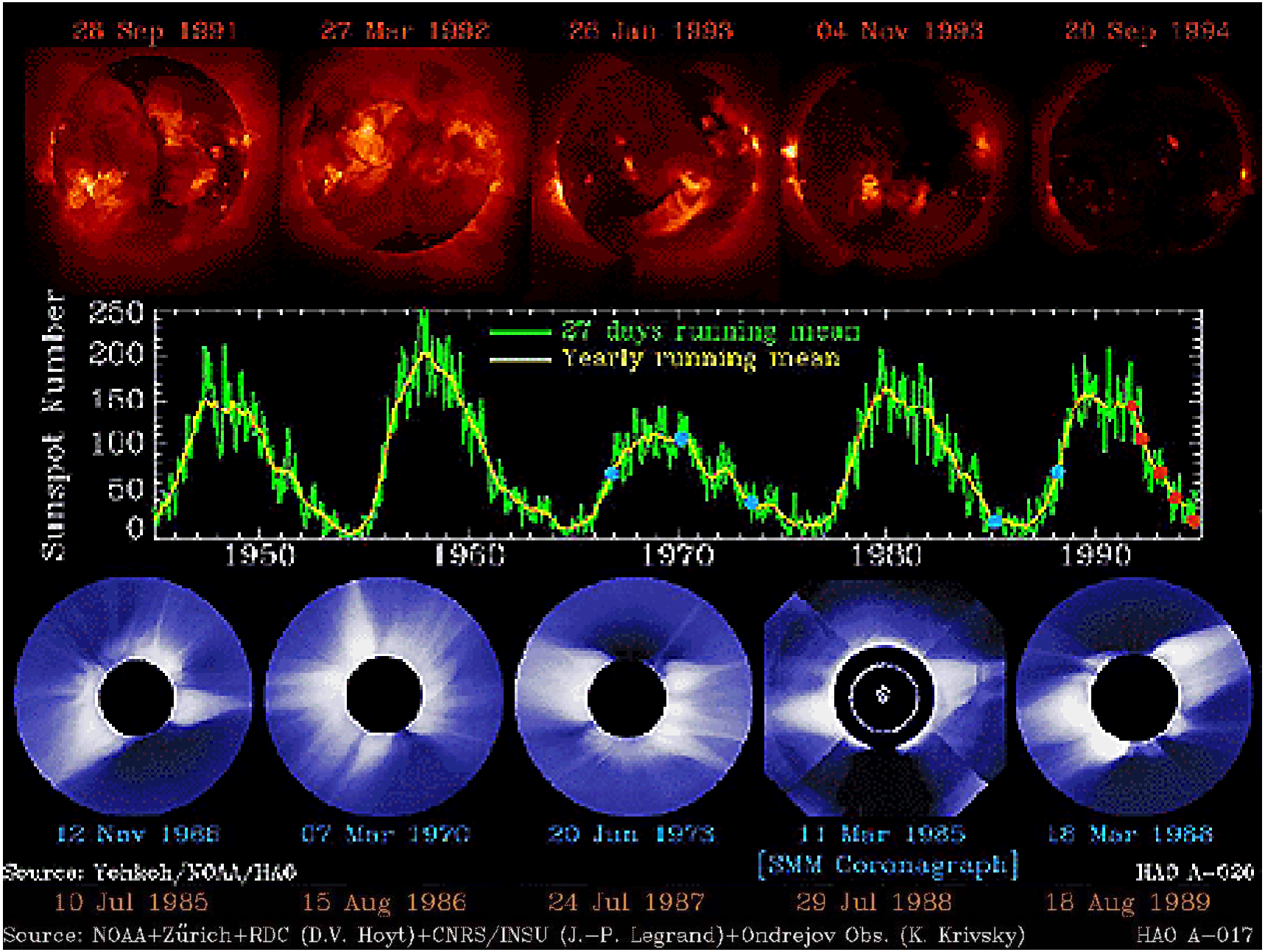
(1645-1715)

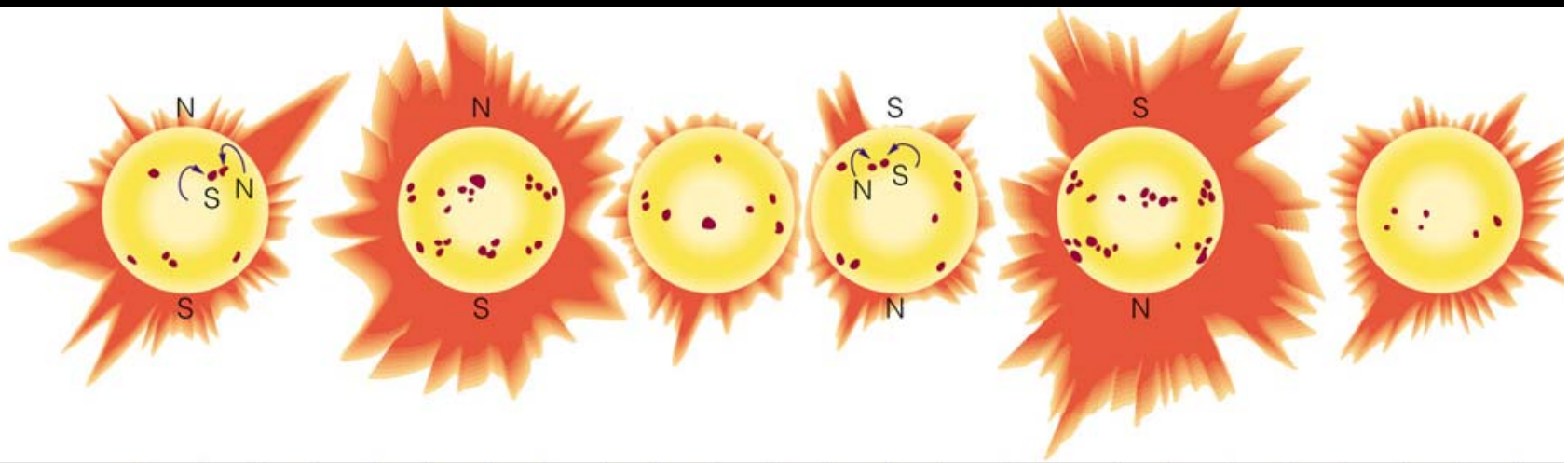
&

“Little Ice Age”

Maunder Butterfly diagram




28 Sep 1991
27 Mar 1992
26 Jun 1993
04 Nov 1993
20 Sep 1994
Sunspot Number
250
200
150
100
50
0
27 days running mean
Yearly running mean
1950
1960
1970
1980
1990
12 Nov 1968
07 Mar 1970
20 Jun 1973
11 Mar 1985
[SMM Coronagraph]
18 Mar 1986
Source: Tohkoh/NOAA/HAO
HAO A-030
10 Jul 1985
15 Aug 1986
24 Jul 1987
29 Jul 1988
18 Aug 1989
Source: NOAA+Zürich+RDC (D.V. Hoyt)+CNRS/INSU (J.-P. Legrand)+Ondrejov Obs. (K. Krivsky)
HAO A-017



Years	0	2	4	6	8	10	12	14	16	18	20	22
Sunspot number	Minimum		Maximum			Minimum			Maximum			Minimum
Sunspot latitude	High		Medium		Low	High			Medium		Low	High
Flares, storms, prominences	Minimum		Maximum			Minimum			Maximum			Minimum

Sun: Atmosphere

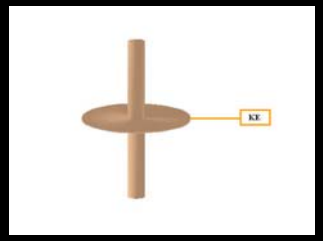
Solar Magnetic Field: Solar Dynamo Model

What is a dynamo?

Homopolar-disc Dynamo Generator

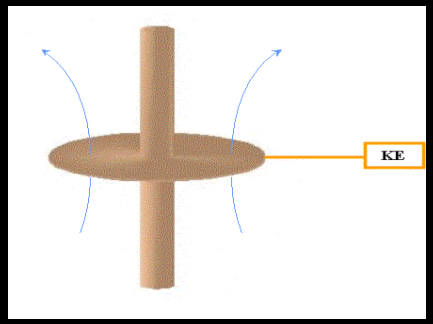
A copper disc that can rotate about its axis

Supply kinetic energy to rotate the disc

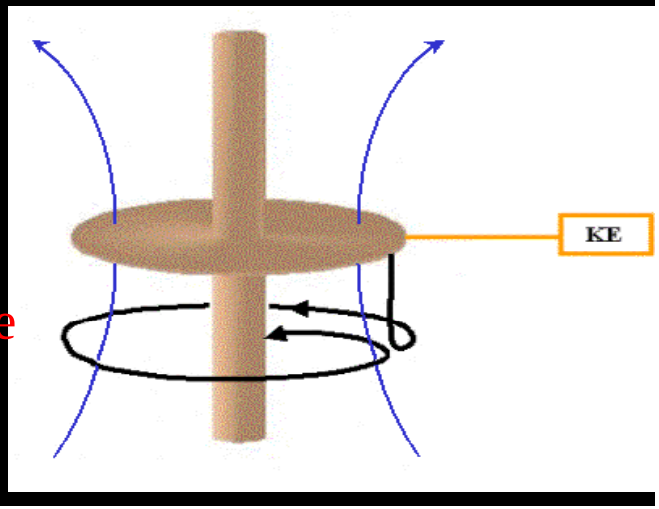


A dynamo is a process by which the magnetic field in an electrically conducting fluid is maintained against Ohmic dissipation

Introduce magnetic fields; an electromotive force between the axis and the rim will be generated



Connect a wire twisted in the same sense as the sense of rotation; magnetic fields will grow



Observational Constraints Solar Dynamo Theory

Structure & Velocities

- Differential rotation with latitude, depth, time
- Meridional circulation with latitude, depth, time
- Convection zone depth
- Existence of solar tachocline
- Other motions from helioseismic interferences *(synoptic maps)*

Magnetic Properties

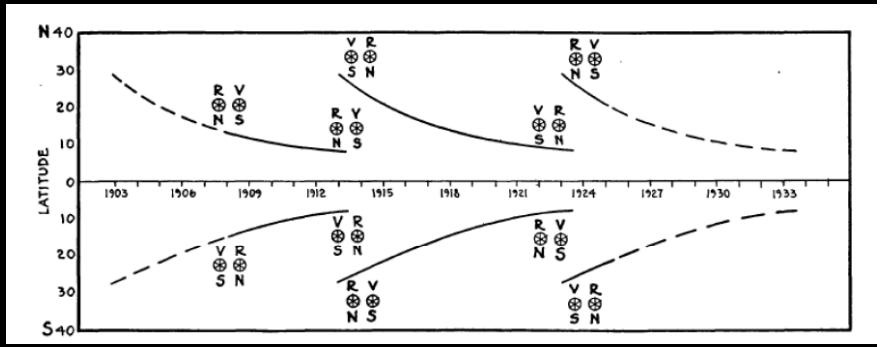
- Butterfly diagram for spots
- Hales polarity laws
- Field reversals
- Phase relation in cycle between toroidal & poloidal fields
- Field symmetry about equator
- Field "handedness" (*current helicity, magnetic helicity)*
- Solar cycle envelope
- Cycle period – cycle amplitude relation
- Active longitudes
- Sunspot group tilts *(Joy's Law)*, asymmetries between leaders & followers
- Others???

Solar Dynamo

The behavior of the Sun's magnetic field shows trends which provide crucial information on how this field is generated and evolves. Successful models for the solar dynamo must explain several observations:

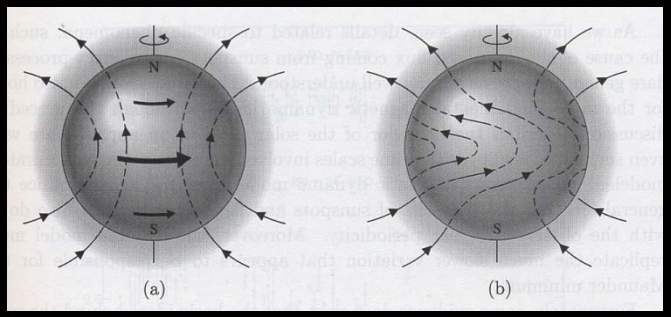
1. Sun follows a cycle with mean period of 11 years (8-15 year range)
2. Sunspots emerge at progressively lower latitudes as cycle proceeds (Spörer's Law)

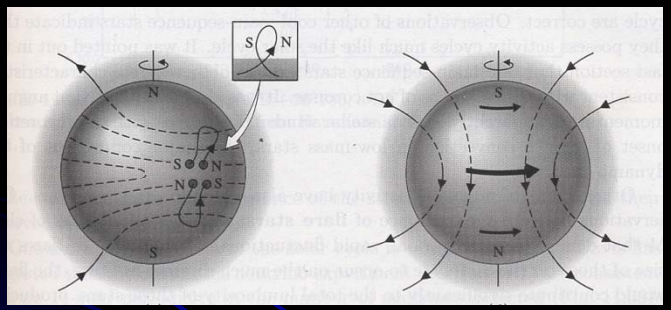
3. Sunspots appear in bipolar regions. The leading spots (relative to solar rotation) have opposite polarities in the N and S hemispheres and the order of these polarities switches from cycle to cycle (Hale Polarity Law)

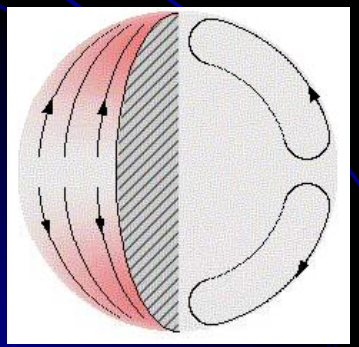


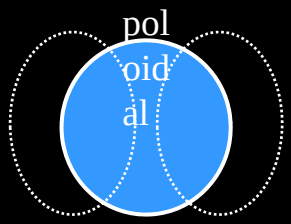
4. Leading sunspots are located closed to equator than following spots (Joy's law) - magnetic field of sunspot groups tilted towards equator.
5. Polar magnetic fields reverse near time of solar maximum.
6. Maunder minima behavior.

Solar dynamo processes

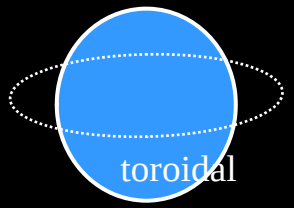








Ω-effect: Differential rotation creates toroidal field from poloidal field



α-effect: Helical turbulence twists rising flux tubes, which can tear, reconnect, and create **reversed** poloidal field

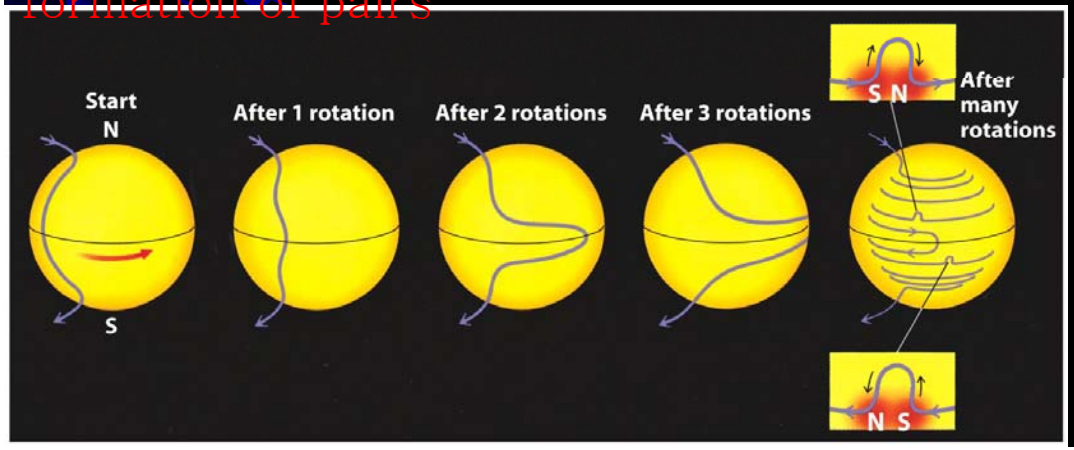
Meridional circulation: surface flow carries reverse poloidal field poleward; equatorward flow near tachocline is inferred

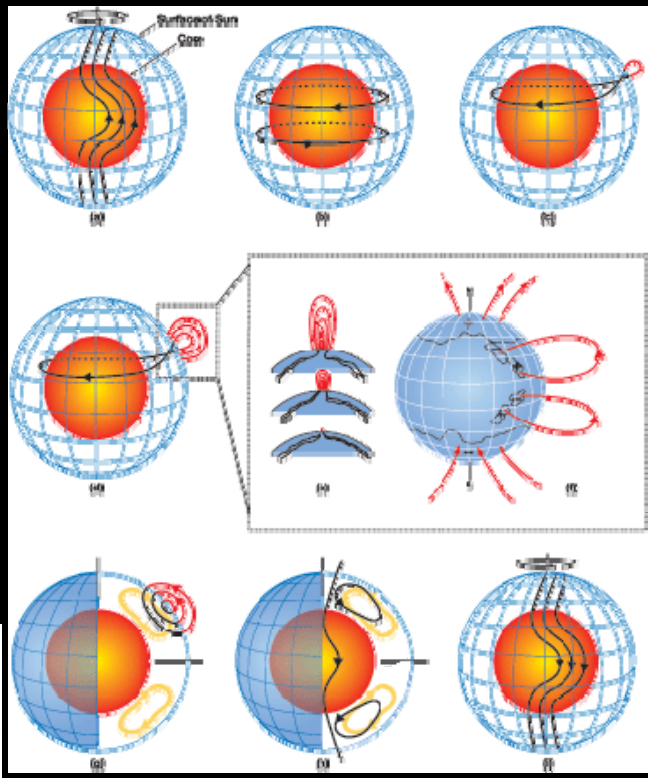
Schematic Summary of Predictive Flux-Transport Dynamo Model

Shearing of poloidal fields by differential rotation to produce new toroidal fields, followed by eruption of sunspots.

Spot-decay and spreading to produce new surface global poloidal fields.

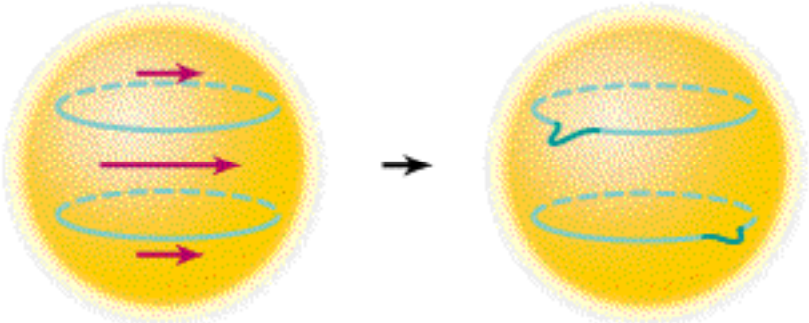
Sun differential rotation bends Magnetic lines; Magnetic gas upwelled toward the surface-> Magnetic strength increases, formation of pairs





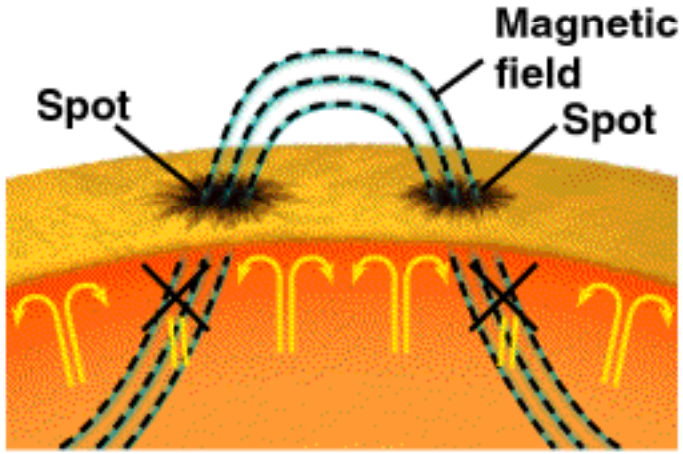
Transport of poloidal fields by meridional circulation (conveyor belt) toward the pole and down to the bottom, followed by regeneration of new toroidal fields of opposite sign.

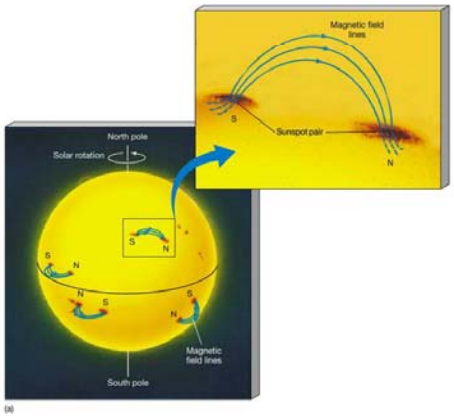
Winding of Sun's magnetic field

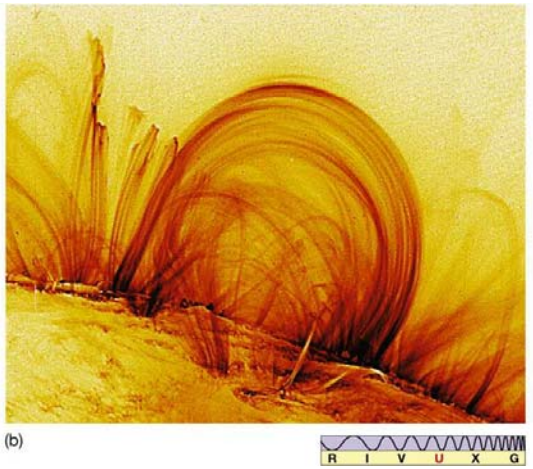


Subsurface magnetic field now in coils

Coils develop kinks that break through surface



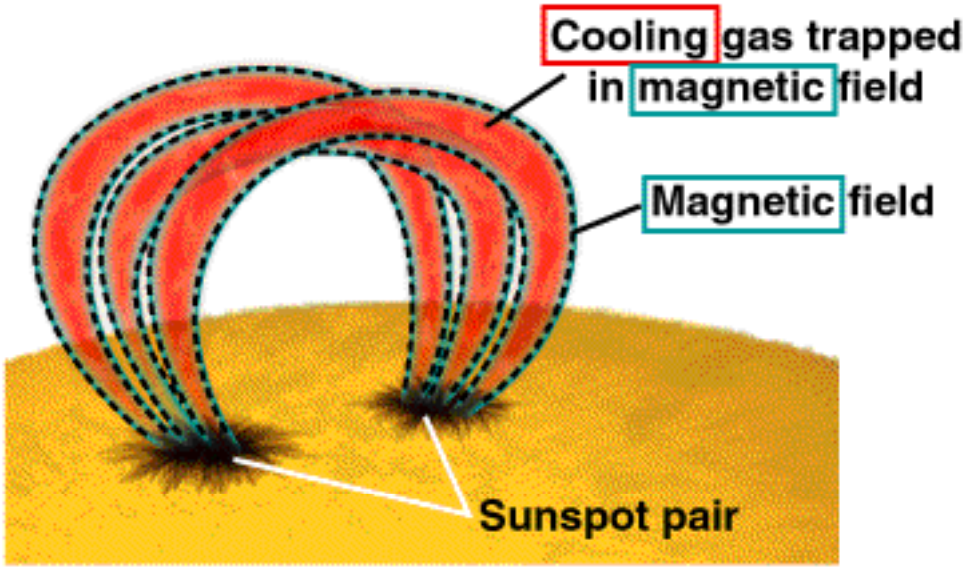


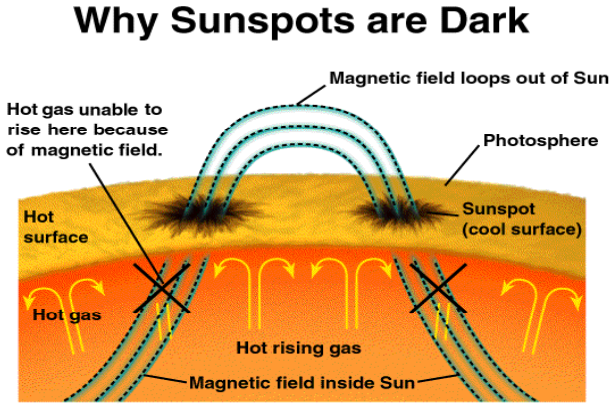


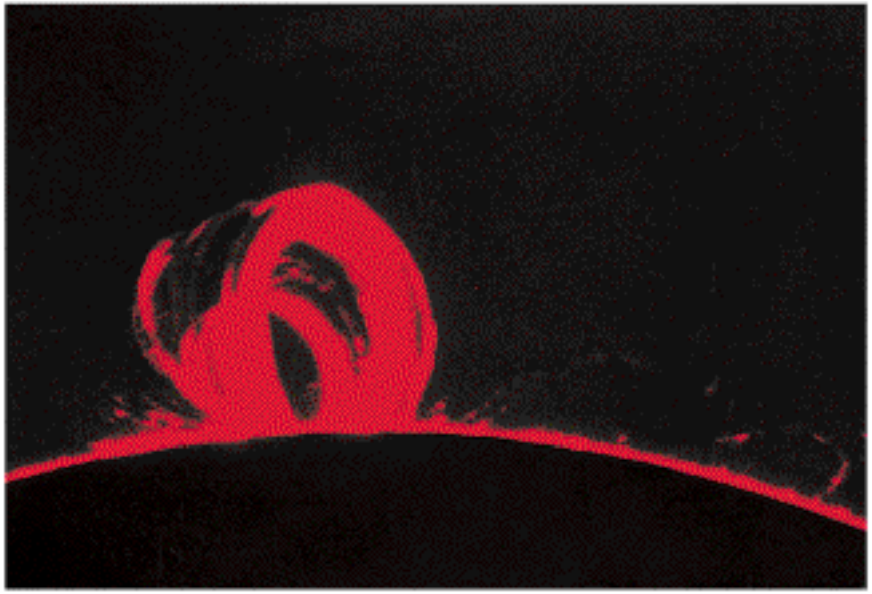
Solar Prominences

Sunspot pairs

Same configuration on both hemispheres







Magnetic Solar Cycle

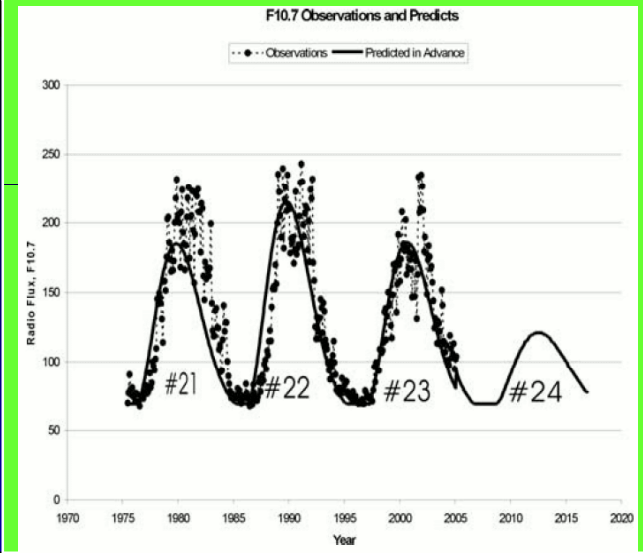
- The rotation rate varies from once every 25 days to once every 30 days.
- This differential rotation twists the magnetic field lines.
- This causes the number of sunspots to vary over an 11 year period.

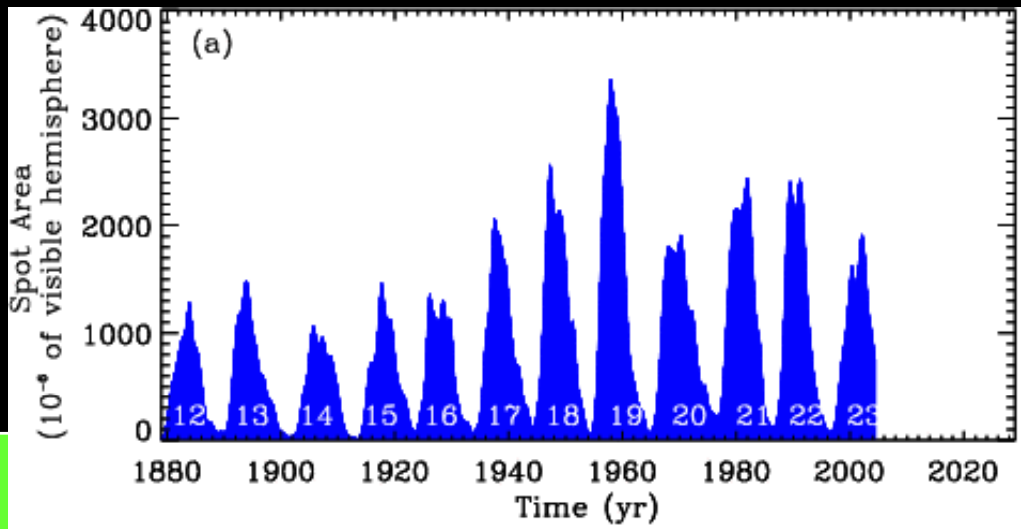
- The 11 (22) year sunspot cycle
  - Number and location of sunspots changes with time
    - Reaches maximum every 11 years (last was in 2001)
    - Tend to drift from higher latitude to equator
  - Cycle not consistently 11 years and may not come to same maximum
- Magnetic fields
  - Reverse after 11 year cycle
  - Effect seen in sunspot pairs
- Activity goes up around sunspot maximum

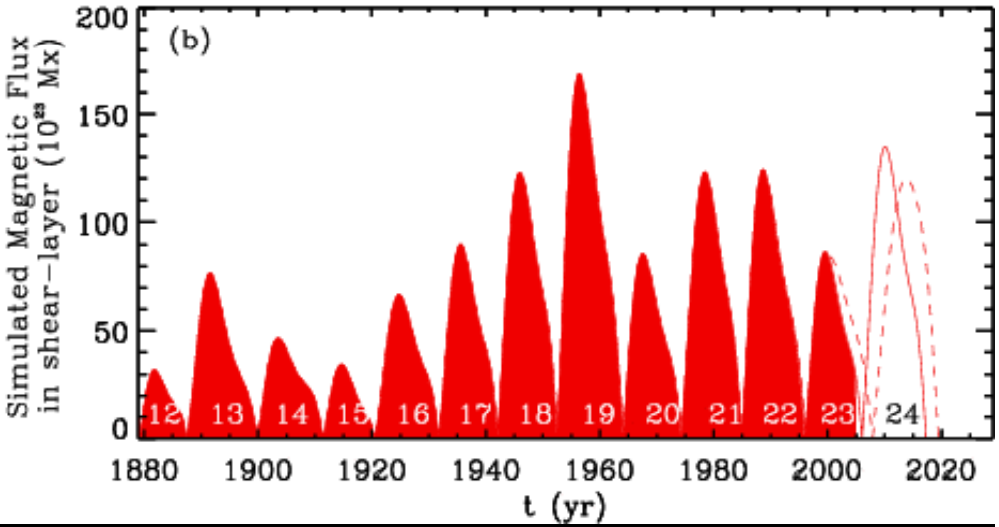
Simulating relative peaks of cycles 12 through

- Reproduced the sequence of peaks of cycles 16 through 23
  - Predict cycle 24 will be 30-50% bigger than cycle 23

Cycle 24 prediction using (Schatten 2005)







(Dikpati, de Toma & Gilman, 2006, GRL)

Sun: Solar Interior

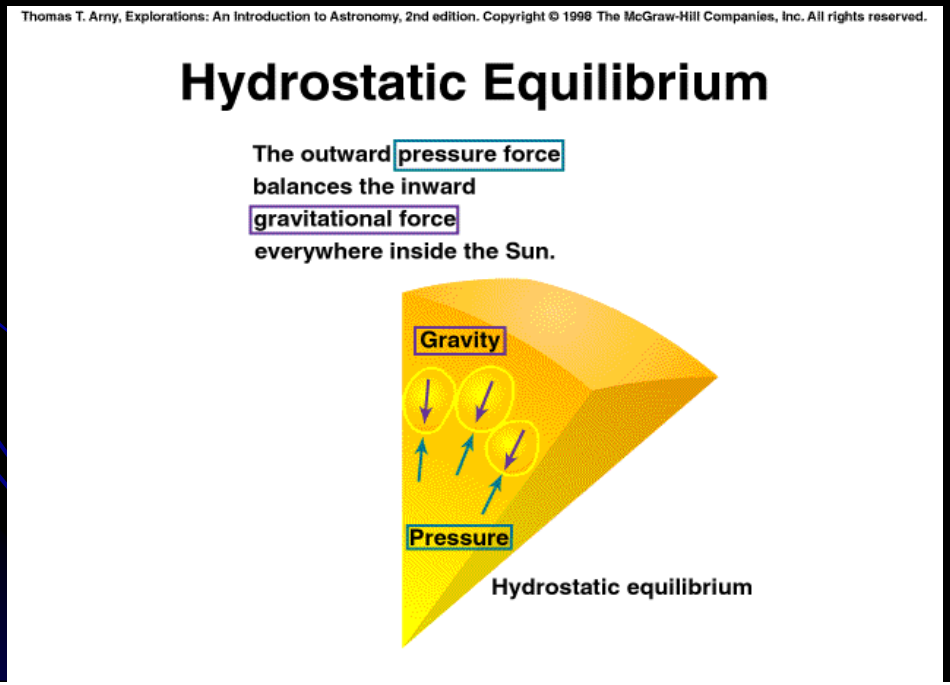
Stellar Physics

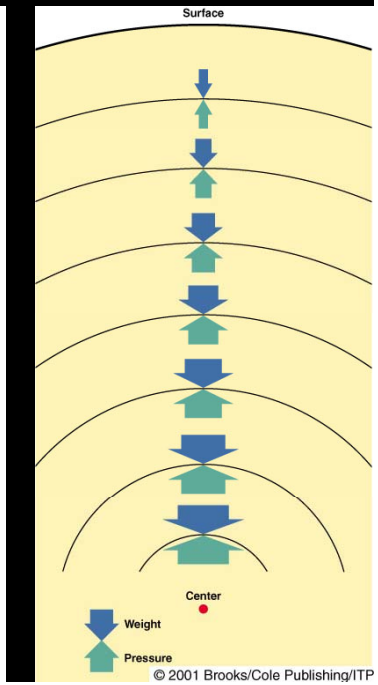
Hydrostatic Equilibrium

- What is the force the holds the sun together?
  - **Gravity (inward)**
- What is the force that keeps the sun from collapsing?
  - **Pressure force (outward)**

Hydrostatic Equilibrium:

The local balance between pressure and gravity





Energy Transport

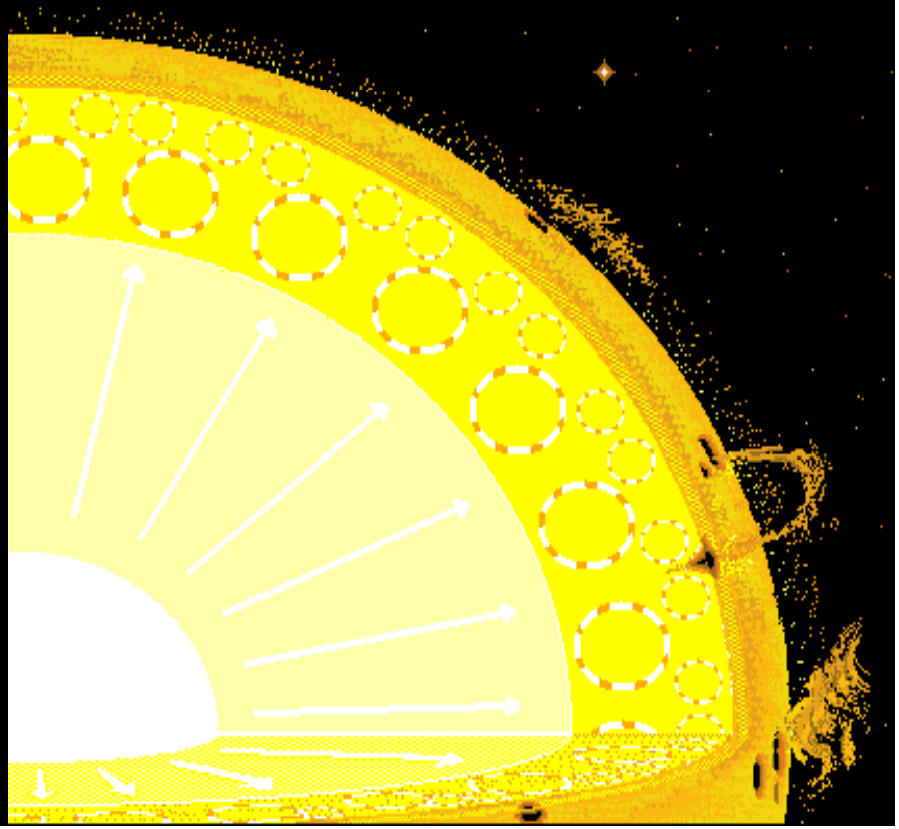
Core: extremely hot plasma, gas completely ionized, no electronic transitions -> transparent to photons

Radiation zone: T dropped, more electrons bounded to atoms -> opaque to photons. They are absorbed by the material

Convection zone: gradient of temperature, hot material rises upward, cold material sinks. Energy is transported by **physical motion** of the gas

Photosphere: low density cannot sustained convection process, gas

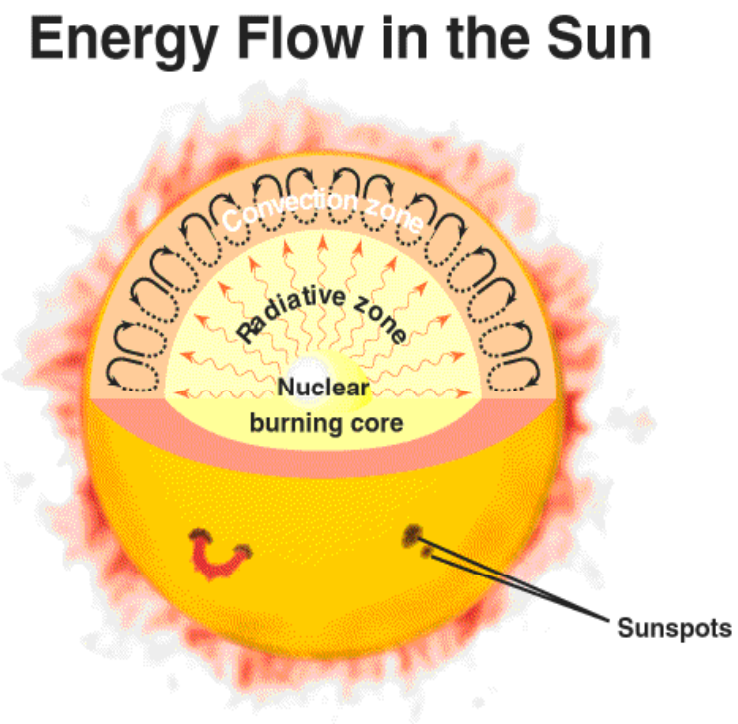
- Photons: So many interactions occur, that it literally takes hundreds of thousands of years for a typical photon to travel from the center of Sun to the surface.



Energy Transport

- Before reaching the atmosphere, photons generated in the core of the Sun, travel through the main body called it interior.
- They travel a zigzag path on their way out, as they are scattered back and forth by particles (mostly electrons).

- So many interactions occur, that it literally takes hundreds of thousands of years for a typical photon to travel from the center of Sun to the surface.



Nuclear Fusion

- If protons get close enough to each other they will *fuse* into other and create another atom (but this rarely happens!)
- Problem: the two protons have like charges and resist being near each other (electromagnetic force)
- However, if the protons get really close the *strong nuclear* force dominates and the protons fuse.

Converting mass into energy

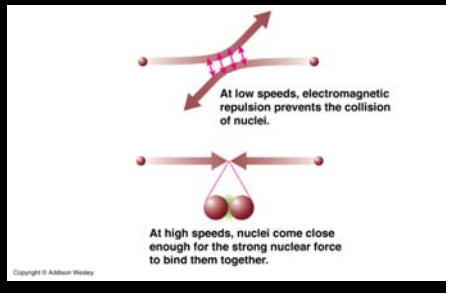
- When light atoms fuse they create an atom which is less massive than the parent atoms: the missing mass (*m*) gets converted to energy (*E*)
- The energy is determined by

$$E = mc^2$$

Where *c* is the speed of light (3.00 x 10^8 m/s).

What makes the Sun shine?

- Thermonuclear fusion at the Sun's core is the source of the Sun's energy.

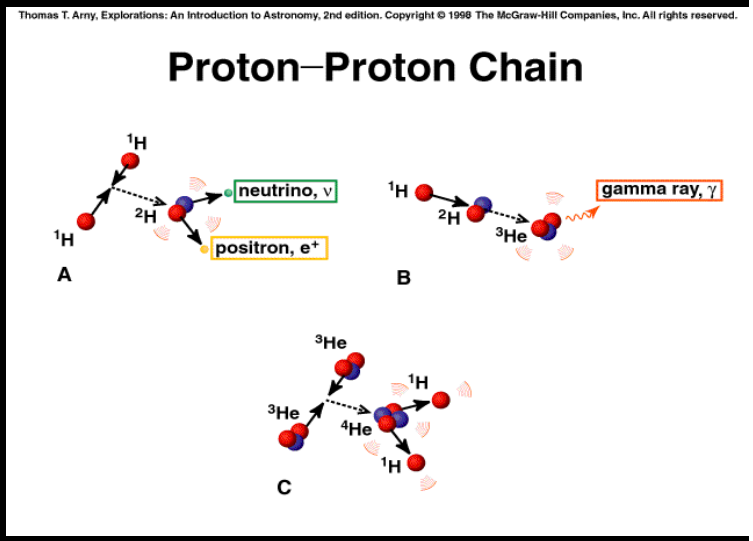


4×1 hydrogen = 6.693×10^{-27} kg

\- 1 helium = 6.645×10^{-27} kg

Mass lost = 0.048×10^{-27} kg

The extra mass is converted to pure energy. i.e. light.



For one hydrogen-to-helium fusion event, $E = 4.3 \times 10^{-12}$ Joules

This is a tiny number by itself is insignificant, but when multiplied by the vast number of hydrogen atoms undergoing fusion in the Sun, the total energy is equivalent to exploding 100 billion-megaton H-bombs per second! Our sunshine has a violent birth.

Proton-Proton Cycle (98%)

- The Sun's core fuses hydrogen into helium:

$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$ e^{+} = positron ν = neutrino (2 times)

$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$ γ = gamma-ray photon (2 times)

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\ {}^{1}H$

NET RESULT: $4\ {}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu + 2\gamma$

- Only 0.71% of Mass is converted into energy, yet …. for every 1 kg of Hydrogen fused, 0.9929 kg of Helium are produced and 6.4×10^{14} J of energy is released!

- Nevertheless, to get the luminosity of the Sun, 600 million tons of hydrogen must be fused into helium *each second.*
  - high speeds (from the high temperatures) of the atoms in the center of the Sun are mandatory

The Carbon-Nitrogen-Oxygen (CNO) Cycle (2%)

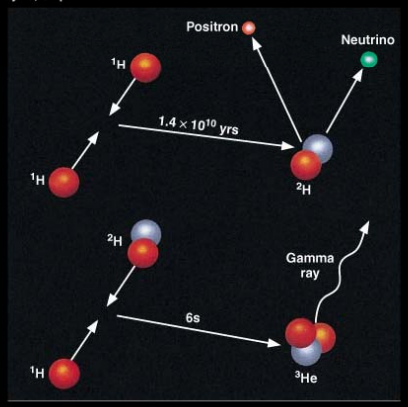
- Alternative way of producing energy: net result is the same:

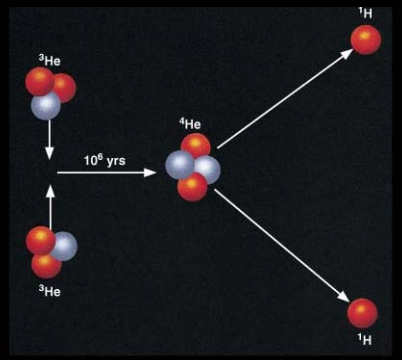
  $4\ {}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu + 3\gamma$

- However, Carbon-12 is used as a catalyst
- Much more efficient in stars with a mass greater than 1.1 solar masses (this process needs higher Temperatures)

Proton-proton chain in detail……

Fraknoi/Morrison/Wolff, Voyages Through the Universe, 2/e
Figure 15.4 P-P Cycle, Steps 1 and 2





$$(A)\quad {}^1H + {}^1H \Rightarrow {}^2H + e^+ + \nu_e$$
$$e^+ + e^- \Rightarrow \gamma$$
$$(B)\quad {}^2H + {}^1H \Rightarrow {}^3He + \gamma$$
$$(C)\quad {}^3He + {}^3He \Rightarrow {}^4He + 2\,{}^1H$$

PPI

(91% of time)

$$(D)\quad {}^3He + {}^4He \Rightarrow {}^7Be + \gamma$$
$$(E)\quad {}^7Be + e^- \Rightarrow {}^7Li + \nu_e$$
$$(F)\quad {}^7Li + {}^1H \Rightarrow {}^8Be^* + \gamma$$
$$(G)\quad {}^8Be^* \Rightarrow 2\,{}^4He \qquad (^* \Rightarrow \text{excited state})$$

PPII

(8% of time)

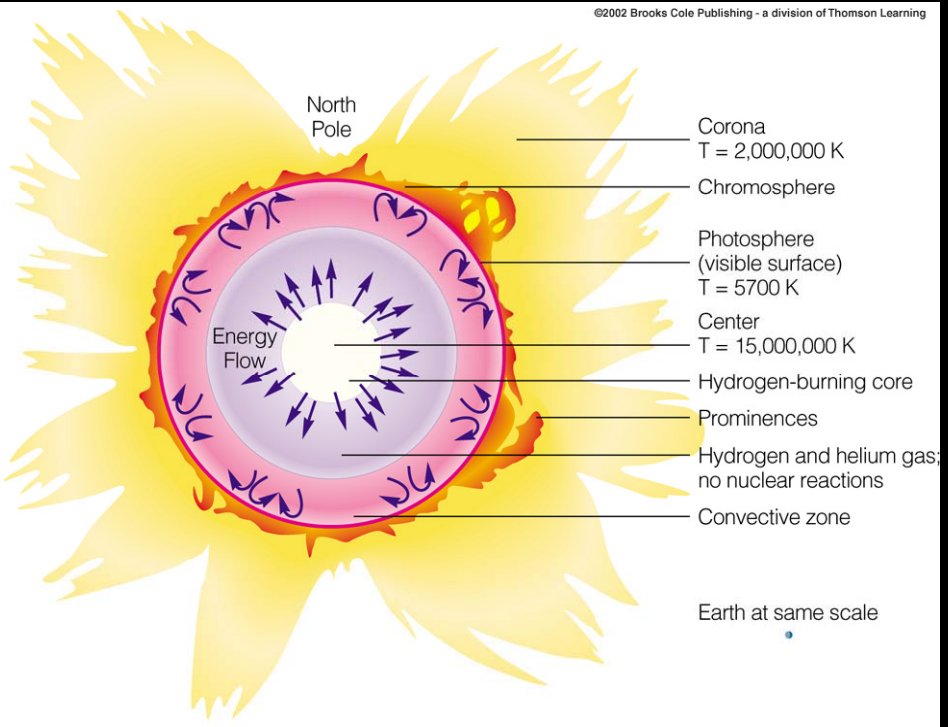
$$(H)\quad {}^7Be + {}^1H \Rightarrow {}^8B + \gamma$$
$$(I)\quad {}^8B \Rightarrow {}^8Be^* + e^+ + \nu_e$$
$$(J)\quad {}^8Be^* \Rightarrow 2\,{}^4He$$

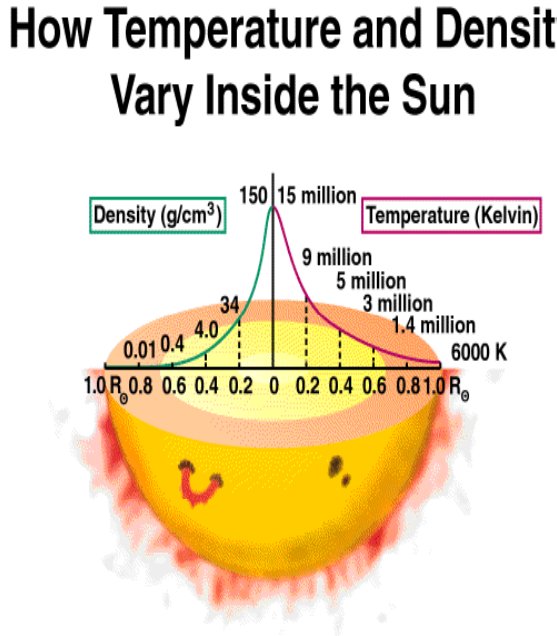
PPIII

(1% of time)

FIGURE: PPI
Protons in Red
Neutrons in Blue

Solar Model





Sun: Solar Interior

Solar Standard Model

SOLAR INTERIOR MODELS

Mathematical descriptions of what the Sun should be like inside

Hydrostatic Equilibrium - balance of gravity & pressure

Thermal Equilibrium - balance of heat energy everywhere

Energy Transport (how does it get from the core to the surface?

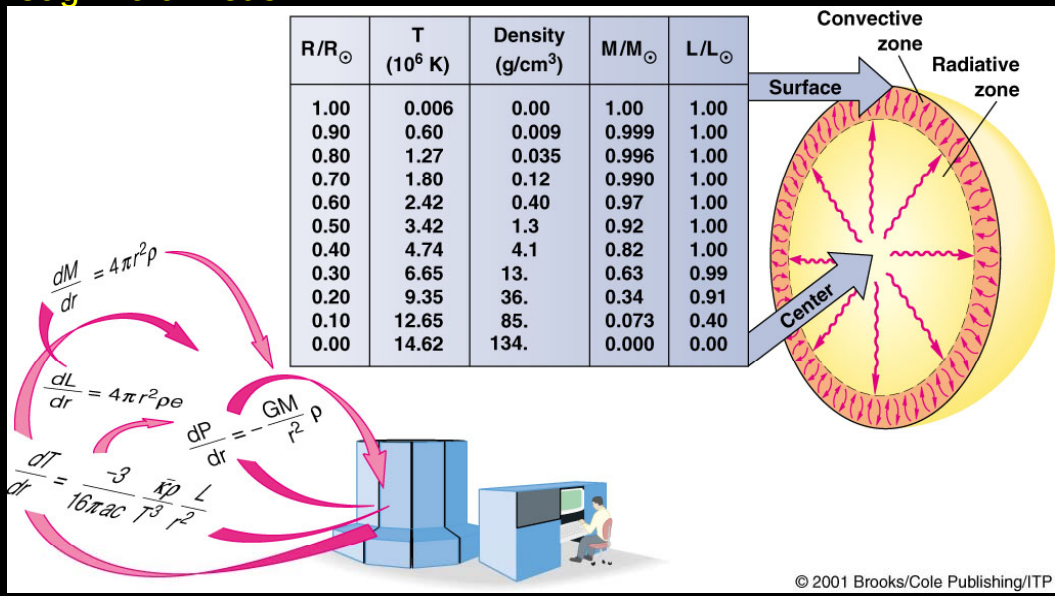
- •conduction - direct transfer through physical contact
- •convection - transfer of energy through fluid motion
- •radiation - transfer via photons

Equation of State - relates pressure, density, temperature

Opacity - how photon transfer are affected by the gas

Energy Generation - energy production vs. temperature, density, etc.

$R/R_\odot$	T (10^6 K)	Density (g/cm^3)	$M/M_\odot$	$L/L_\odot$
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.27	0.035	0.996	1.00
0.70	1.80	0.12	0.990	1.00
0.60	2.42	0.40	0.97	1.00
0.50	3.42	1.3	0.92	1.00
0.40	4.74	4.1	0.82	1.00
0.30	6.65	13.	0.63	0.99
0.20	9.35	36.	0.34	0.91
0.10	12.65	85.	0.073	0.40
0.00	14.62	134.	0.000	0.00



"Boundary Conditions" - L, M, R, etc. to look like a *real* star!

Results: T_c~15x10^6K, P_c~3x10^{11} Atm, density ρ_c~160 g/cm^3 !!

SOLAR INTERIOR MODELS

Mathematical descriptions of what the Sun should be like inside

Basic Facts:

Mass $M_\odot = 2 \times 10^{30}$ kg = 300,000$M_\oplus$

Radius $R_\odot = 7 \times 10^{8}$ m = 7×10^{5} km = 111$R_\oplus$

Mean Density = Mass/Volume = $M/((4/3)\pi R^3) = 1400$ kg/m^3 = 1.4 g/cm^3

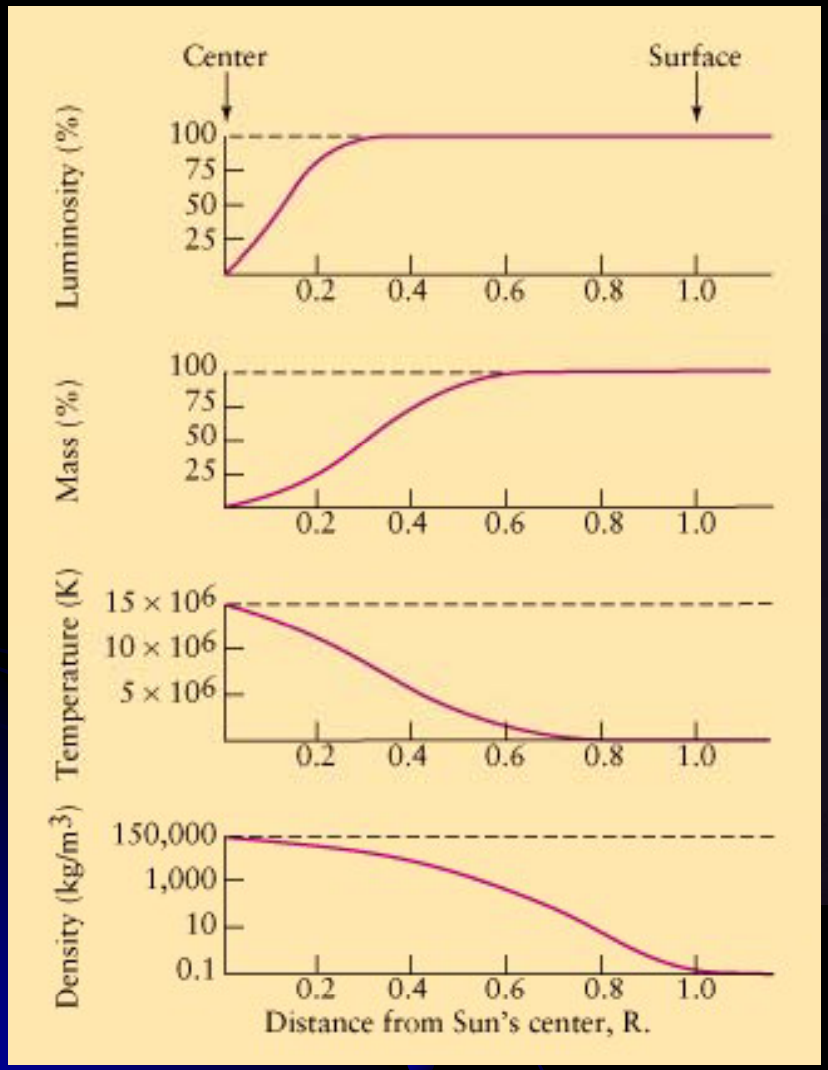
Distance = 1.5×10^{11} m = 1.5×10^{8} km = 8.3 light-minutes

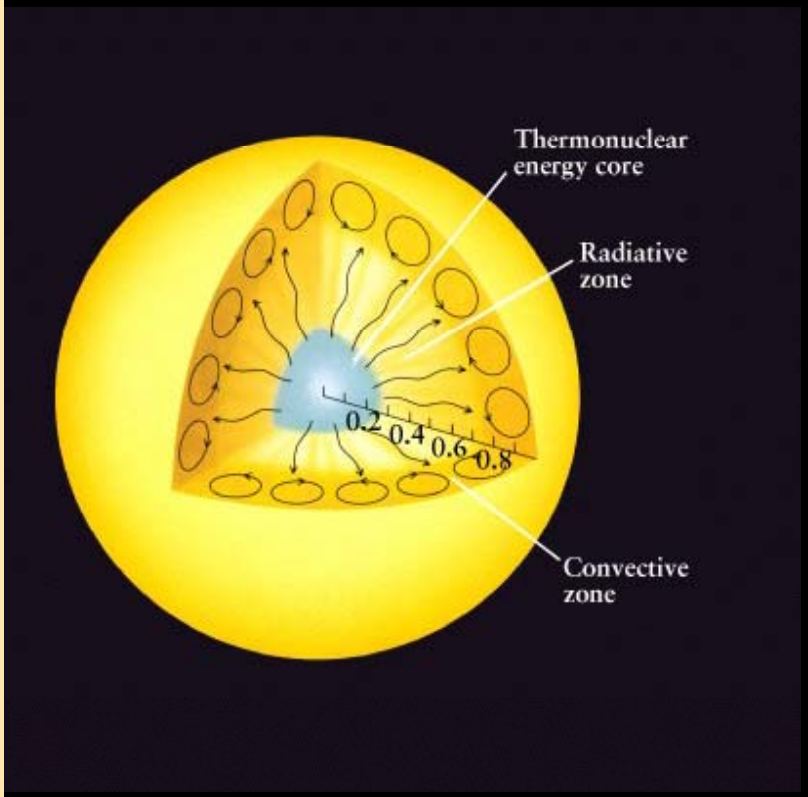
Luminosity $L_\odot = 3.9 \times 10^{26}$ W (Solar Constant = 1350 W/m^2)

Mean Surface Temperature = $T_{effective} = 5780$ K

Composition	By Mass	By Number
H	~68%	~90%
He	~31%	~10%
“Heavies”	~1%	~1%

The Standard Solar Model (SSM)





Theoretical Model
Standard Solar Model

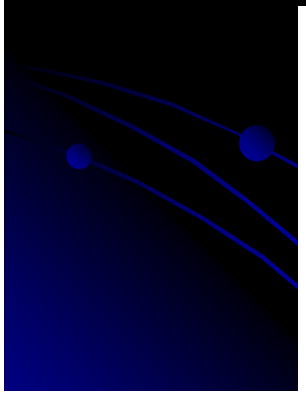
Comparison with Earth and Jupiter

T_{center}(Earth) =6500 K

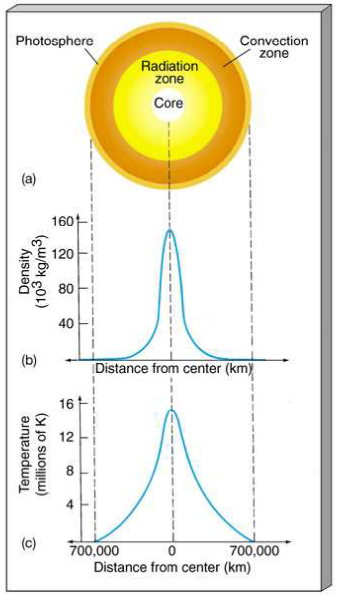
ρ_{center}(Earth)=12,000 kg/m3

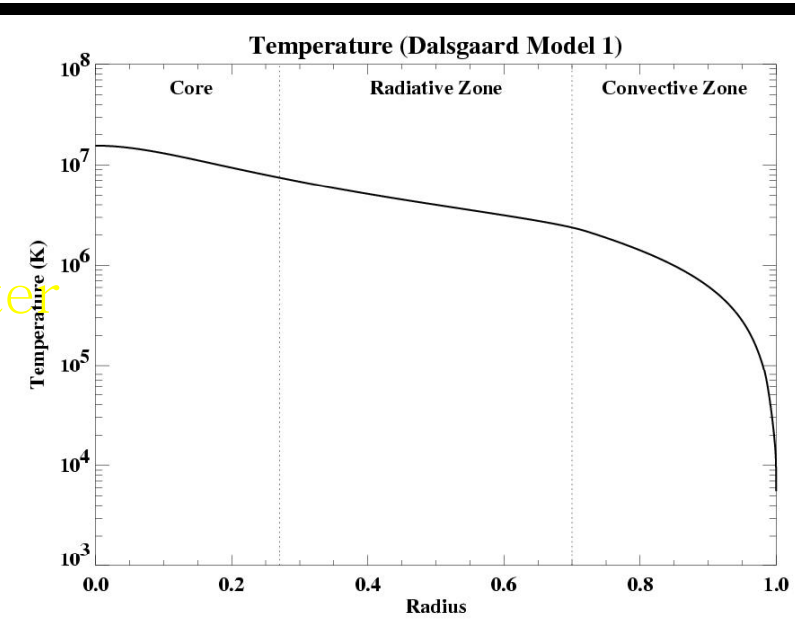
T_{center}(Jupiter) = 25,000 K

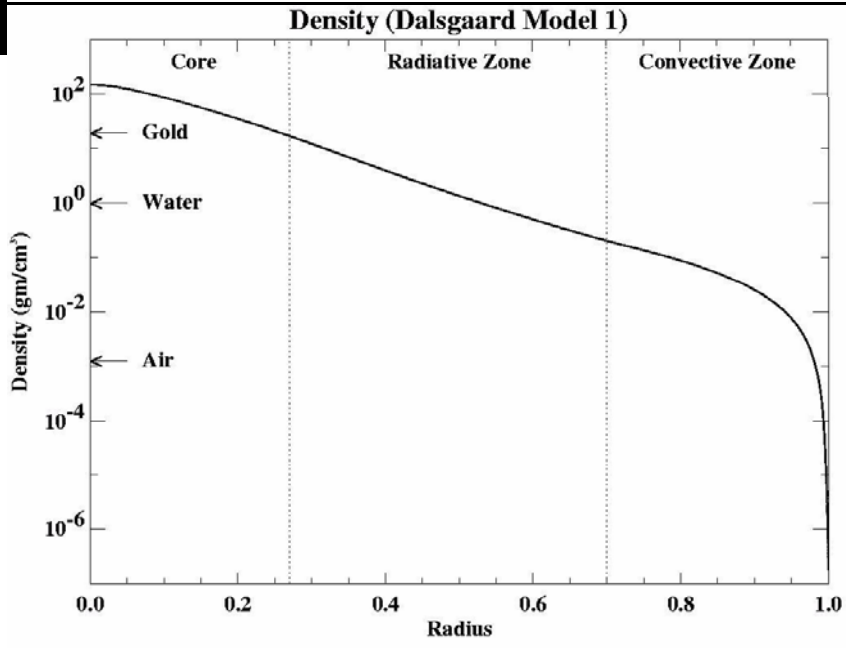
P_{center}(Jupiter) = 25,000 kg/m3



Variation of density (fast and wide range)





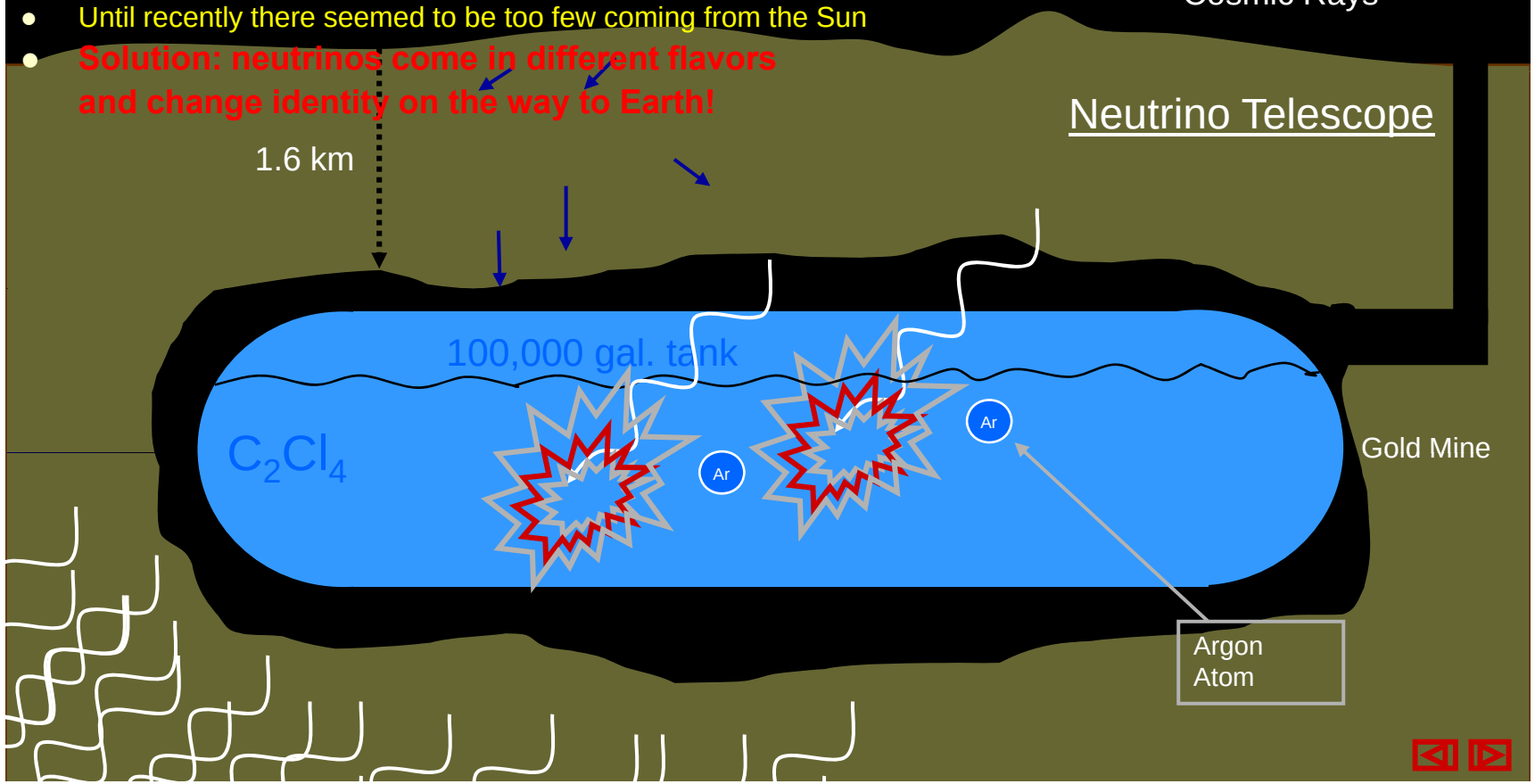


Sun: Solar Interior

Solar Neutrinos

The Solar Neutrino

- **Standard solar model** is the generally accepted theory of solar energy production.
- The model predicts that billions of neutrinos per second flow from the Sun.
- Neutrinos react very little with ordinary matter so detecting them is difficult.
- Neutrino telescopes indicate that only 1/3 of the neutrinos predicted by theory are “seen.”
- Neutrinos are highly non-interacting particles which can be used direct probe into the Sun (if our nuclear fusion idea is right)
- However, they are incredibly hard to detect
- Huge underground detectors are used to look for neutrinos from the Sun
- Until recently there seemed to be too few coming from the Sun
- **Solution: neutrinos come in different flavors and change identity on the way to Earth!**



The Experiments

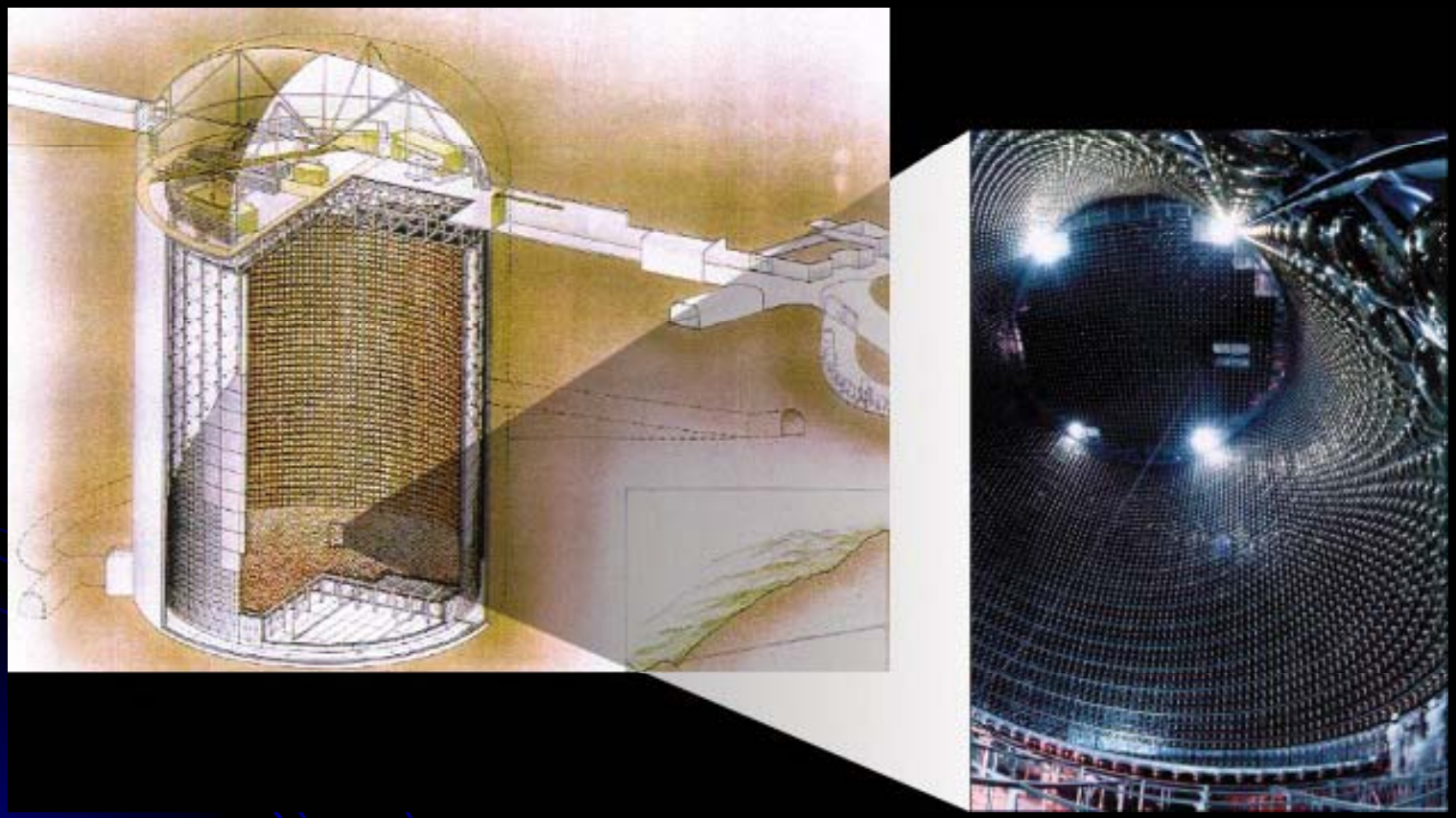
Ray Davis Homestake Mine - looks for ν from pp III
- gets 1/3 predicted value

pp III ***very*** sensitive to T

Experiment only measures 1 "flavor" of ν - the "electron ν"

What if ν's change in flight????

Super-K - gets about 1/2 the predicted amount



Sudbury Neutrino Observatory (SNO) - sensitive to all “flavors” - agrees with SSM!!

Neutrino Oscillations

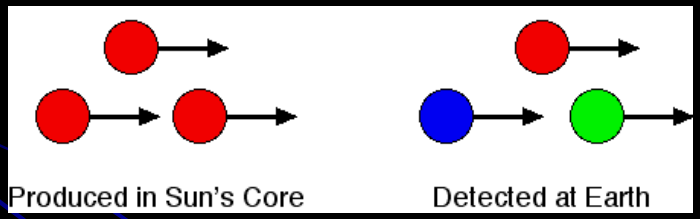
Sun only makes electron ν's

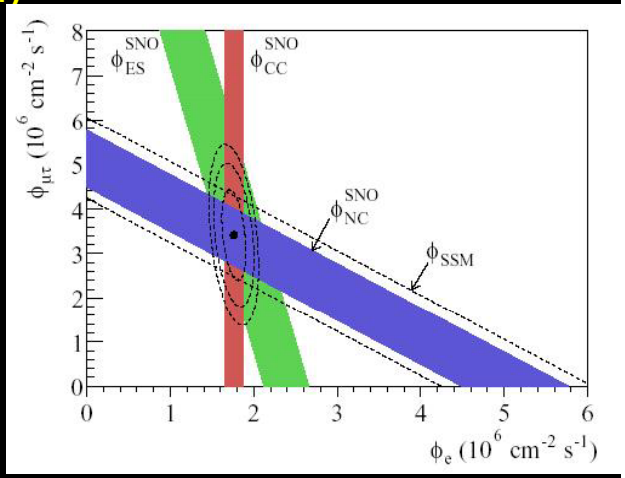
SNO Results show:

We detect ~1/3 of electron ν's predicted by SSM

We detect TOTAL number of ν predicted by SSM

∴2/3 of the electron ν's were converted into other flavors before they reached Earth (so the total number is conserved)





- This deficit is now understood as a consequence of neutrinos oscillating while en route from the solar core.

• Requires revising "standard physics" of subatomic particles - New Physics!

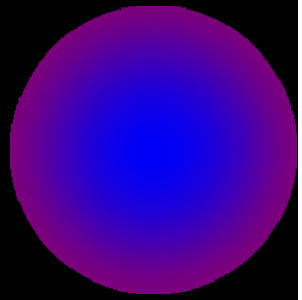
SNO

Sun Interior: Helioseismology

Solar internal ‘Observations’

Helioseismology

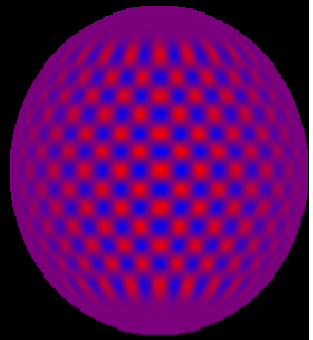
- Estimated by helioseismology <-> vibration of the sun
- Complex analysis, need a 24 h monitoring provided by ground telescopes and SOHO spacecraft observatory.
- The solar interior supports numerous kinds of oscillations, whose motion on the solar surface can be detected.
- Comparison of frequency and observed wave-pattern with solar model predictions constrains the properties of the model as a function of depth below the surface.



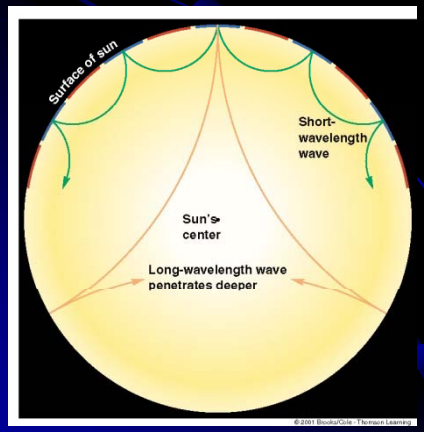
$l = 1, m = 1$

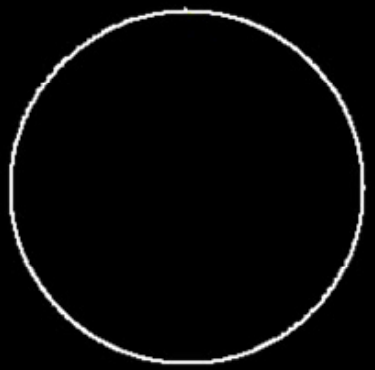
GONG- Global Oscillation Network Group

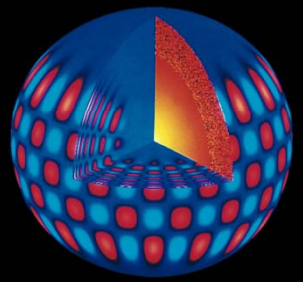
Continuous monitoring of Sun's surface and atmosphere. SOHO (ESA)



$l = 36, m = 24$





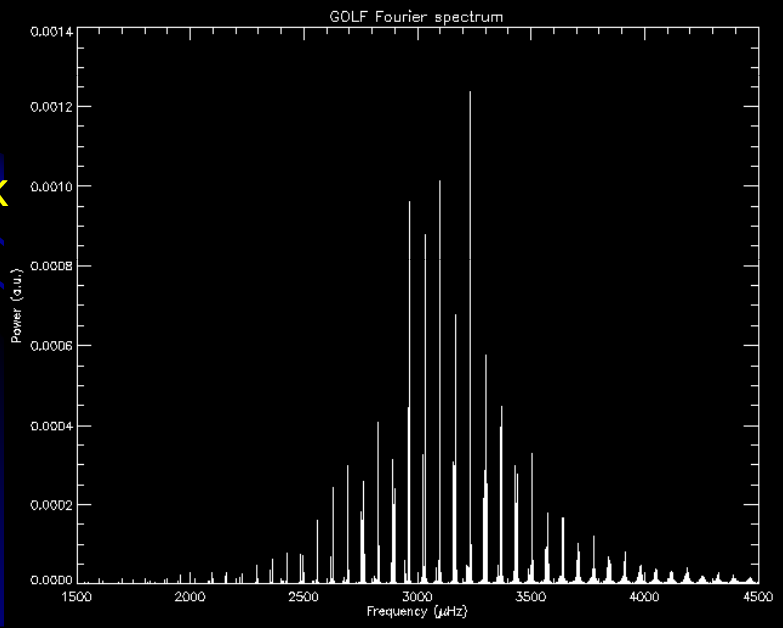


Sun Interior: SOHO Seismology

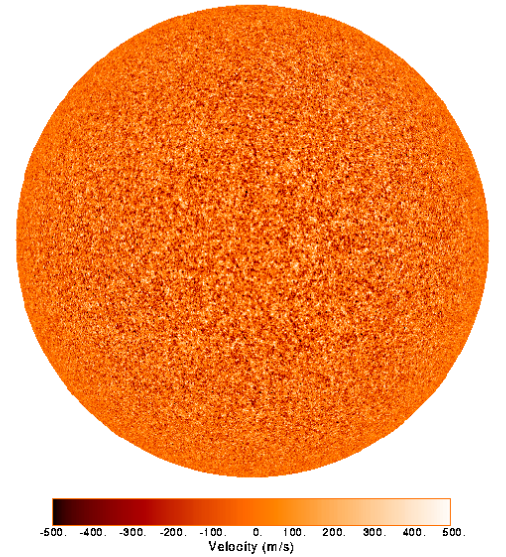
- Wave patterns are observable by measuring Doppler shifts as a function of position on the solar surface.
- Thousands of normal modes have been detected in this way.

From the power spectra the mode frequencies are estimated (peak- bagging): these are then the data for the inversions.

GOLF: Whole-disk power spectrum

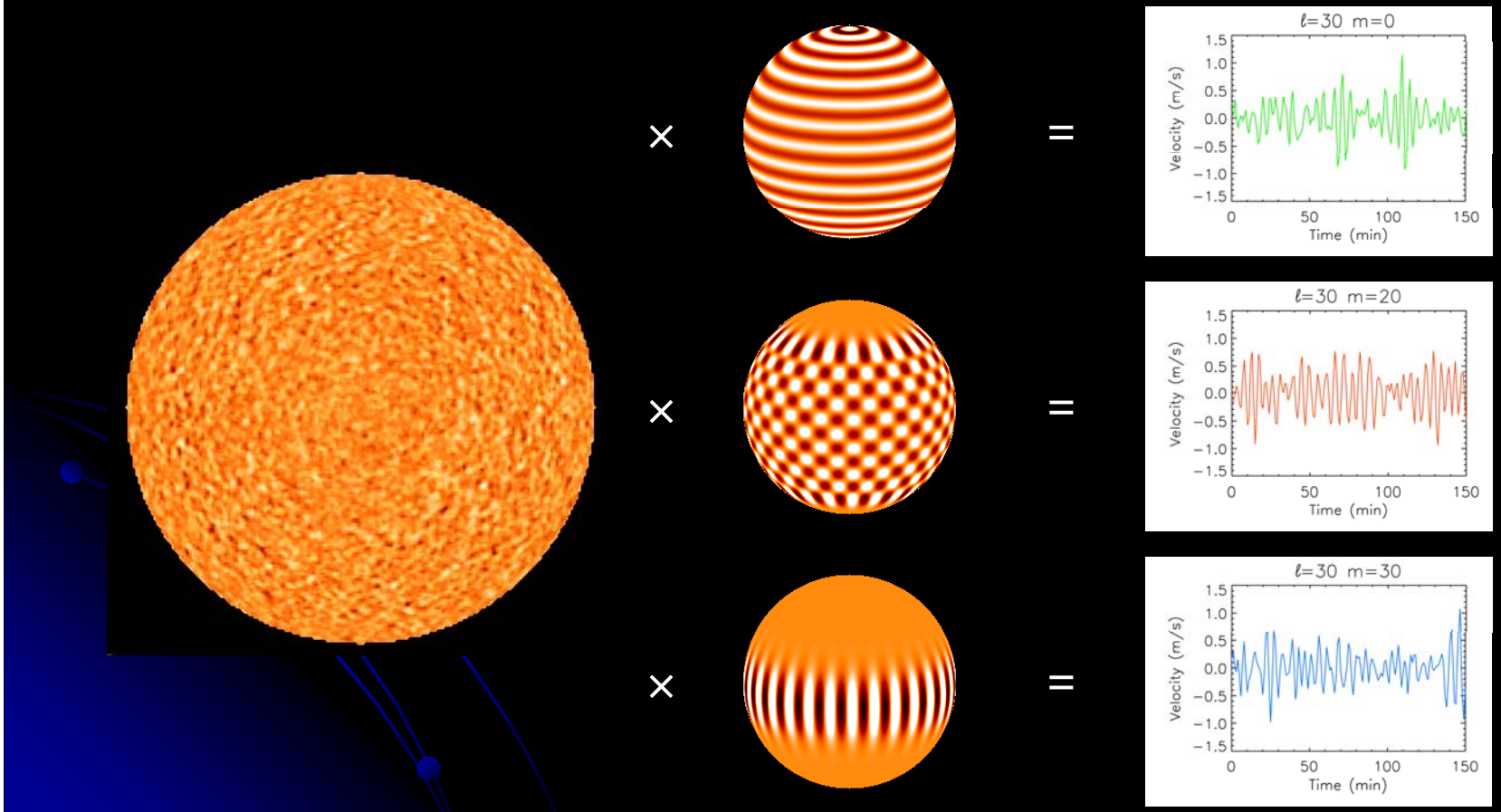


SOI/MDI: Doppler-velocity data

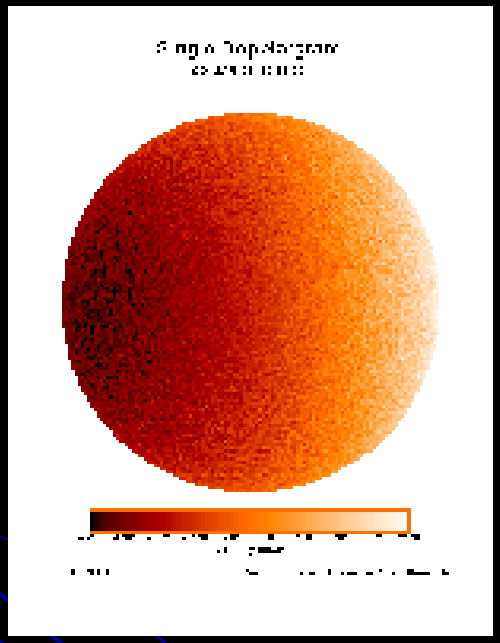


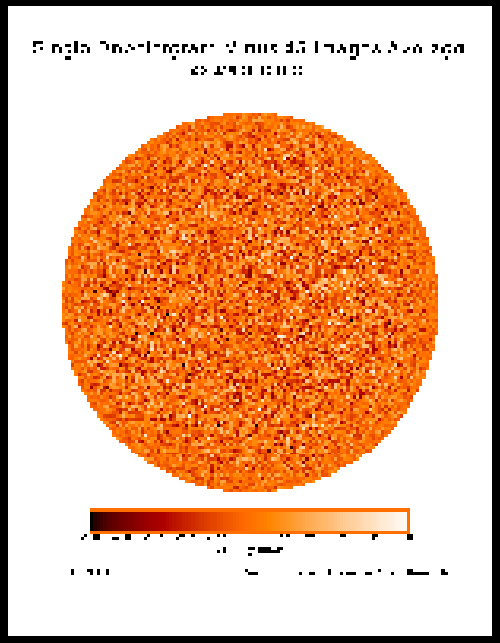
Dopplergram

Disentangling the Modes



Helioseismic Waves Observed



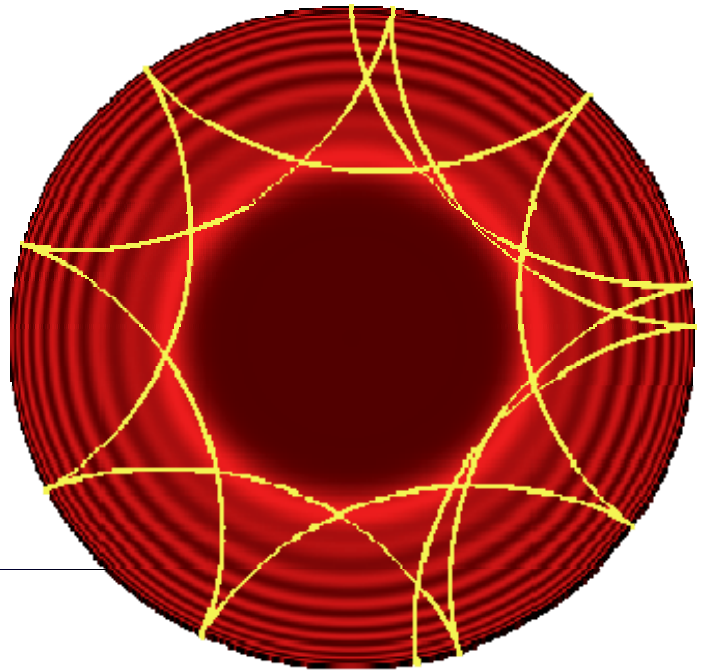


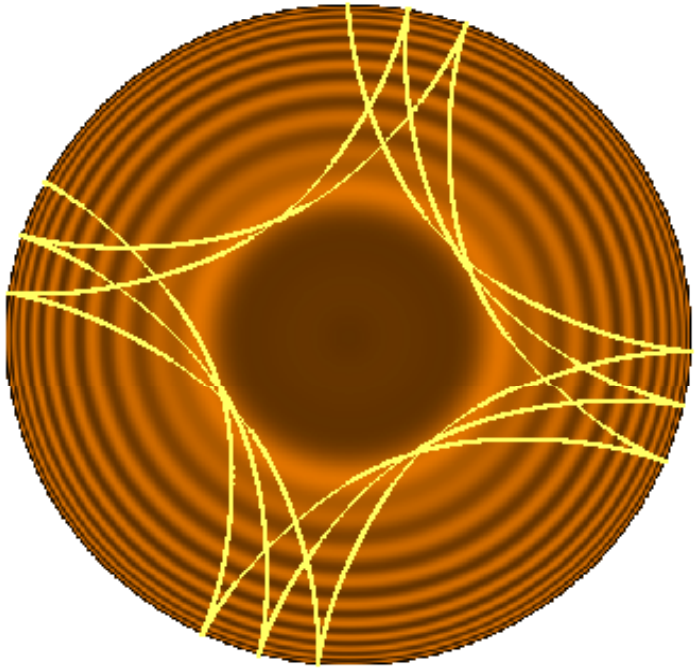
- Wave patterns are observable by measuring Doppler shifts as a function of position on the solar surface.
  - Thousands of normal modes have been detected in this way.

Sun Interior: Helioseismology

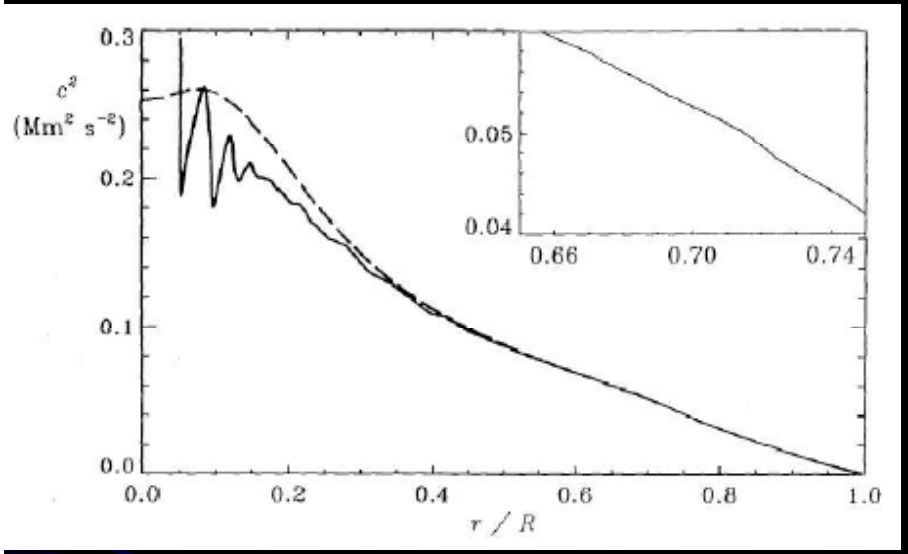
Solar Inversions (Results)

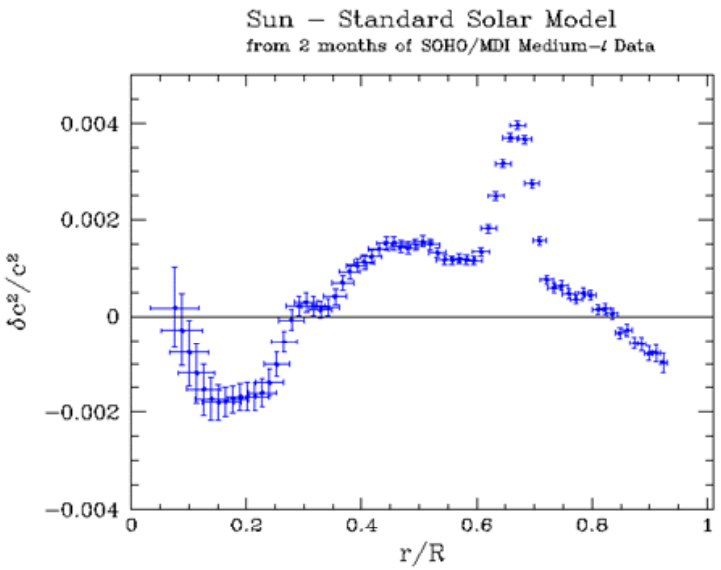
Solar Inversions





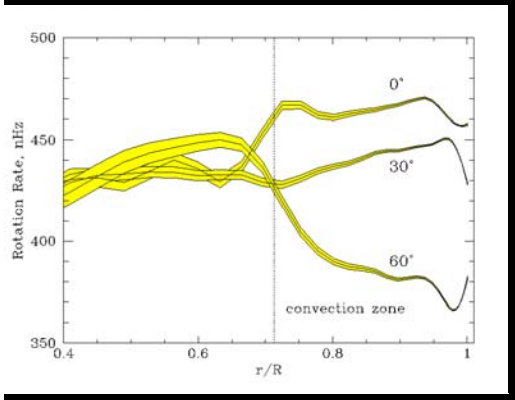
Helioseismology: Sound speed inversion

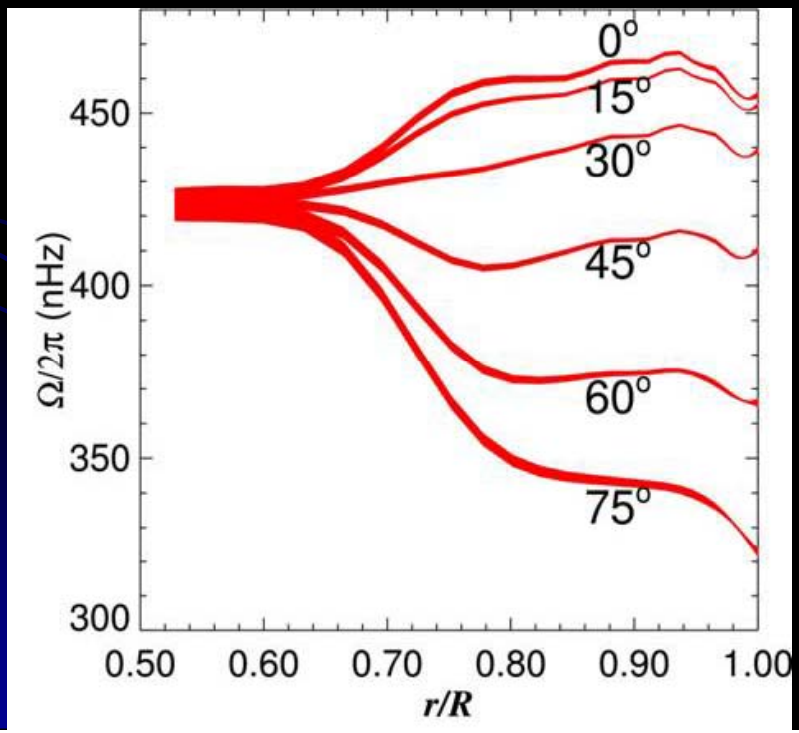


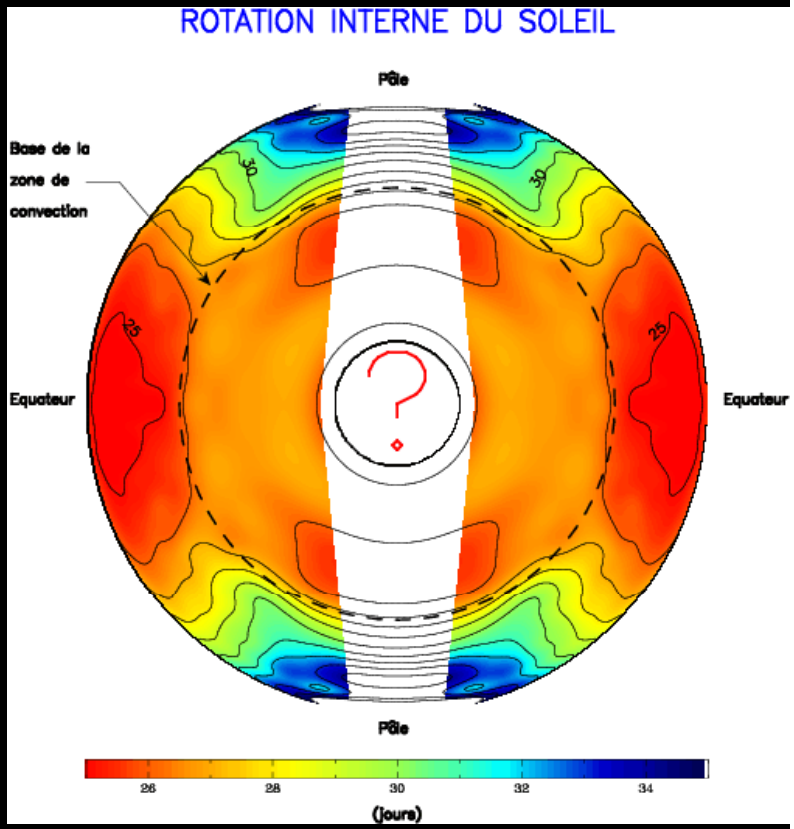


The first result of the asymptotic sound inversion that confirmed the standard solar model. The large discrepancy in the central region is due
inaccuracy of the data and the asymptotic approximation.

Helioseismology: differential rotation

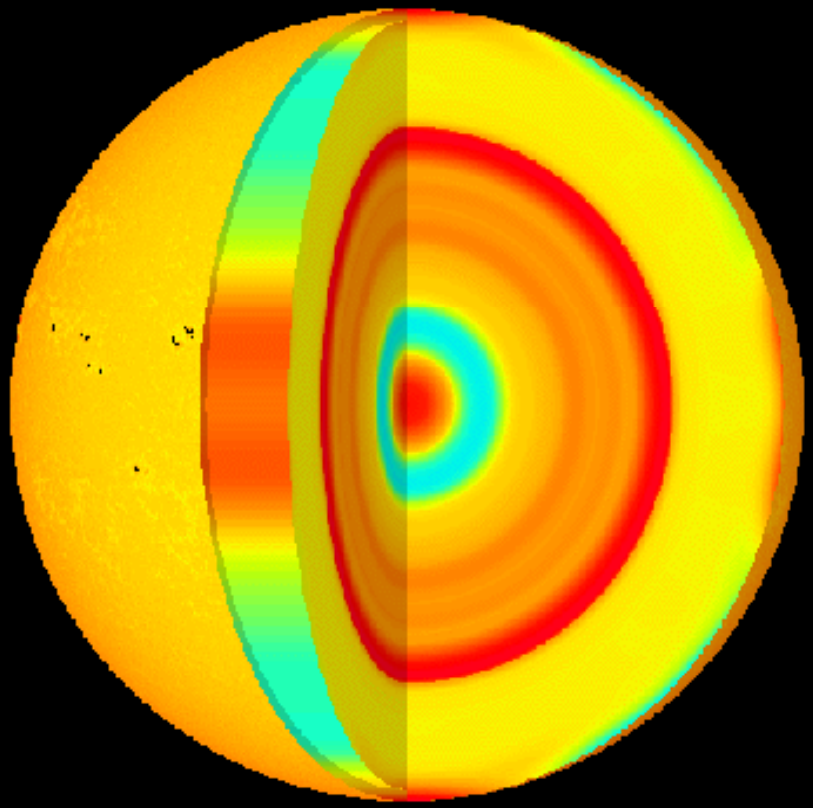


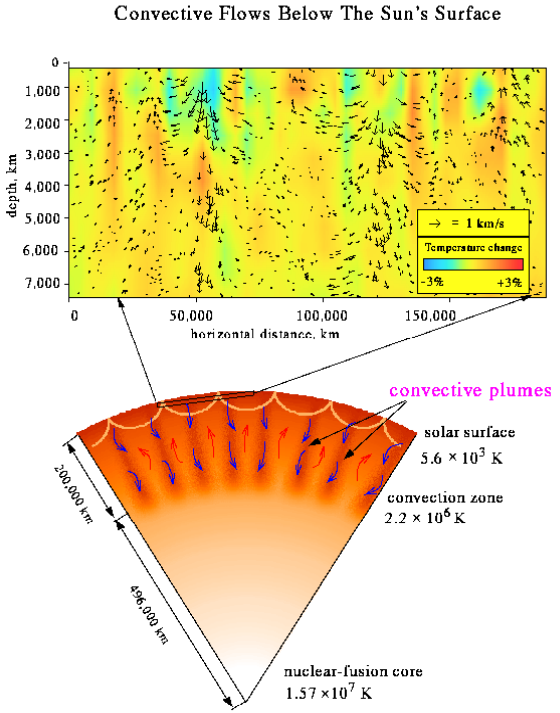




Time-distance

Internal Flows



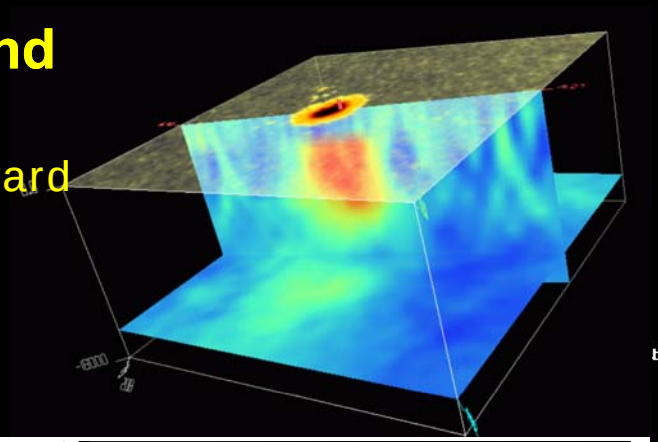


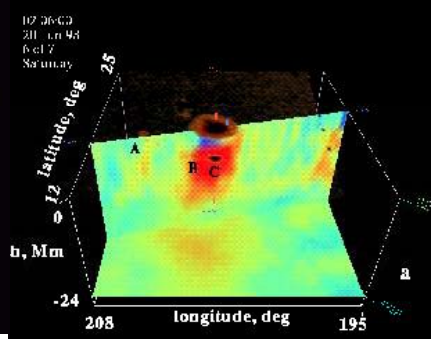
Sub-surface Structures

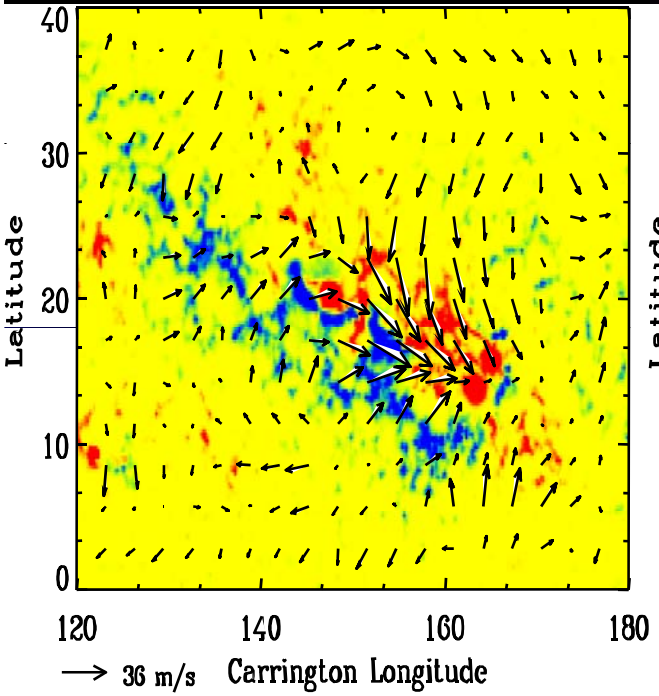
Structure of Sunspot

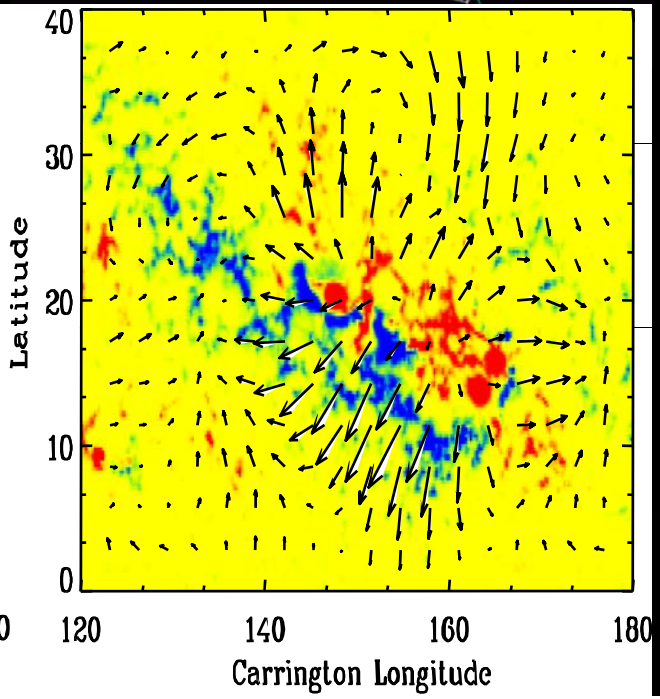
Large-scale flows around active regions:

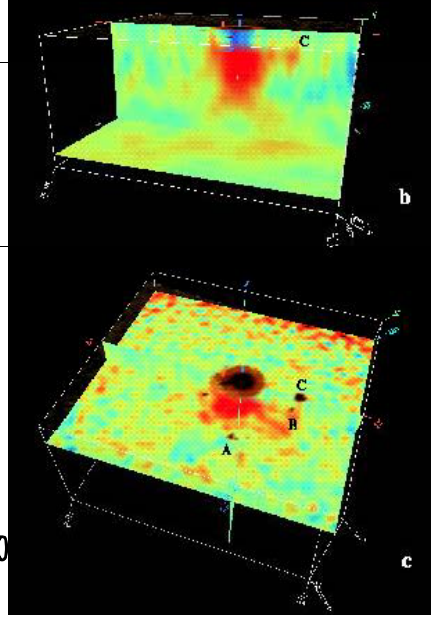
- converging 40 m/s flow toward the neutral line in the upper layers
- diverging flow below 9 Mm



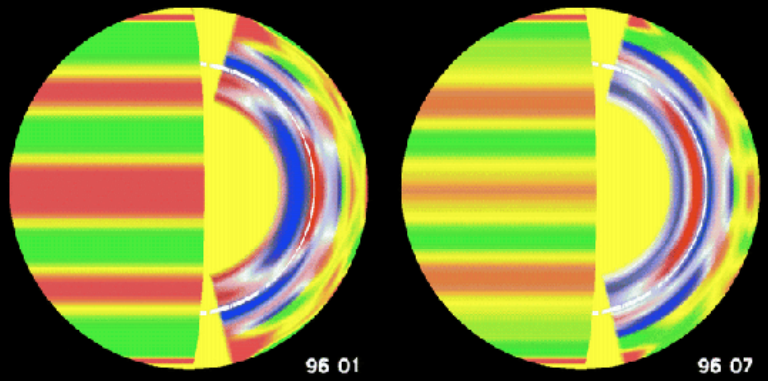




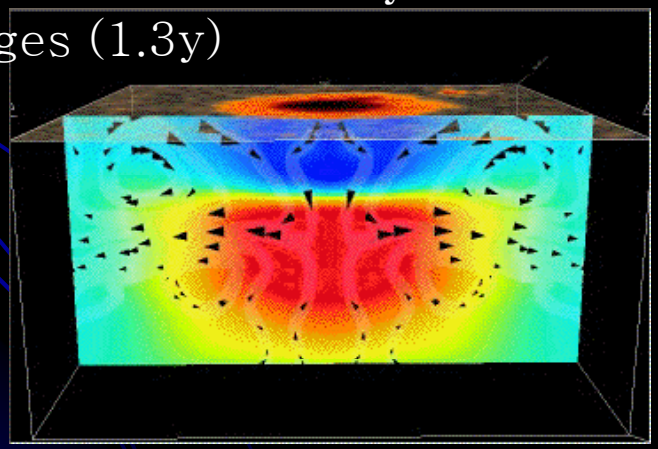




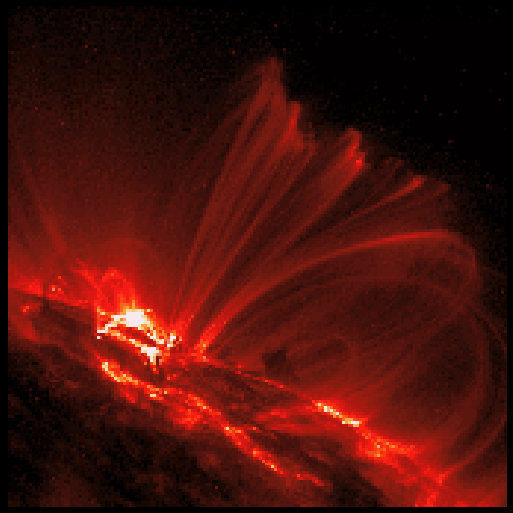
MDI/SOHO reveals the interior and explains surface activity



MDI shows how the dynamo changes (1.3y)



MDI shows how magnetic elements form sunspots



Sunspots are footpoints of emerging magnetic flux t

END