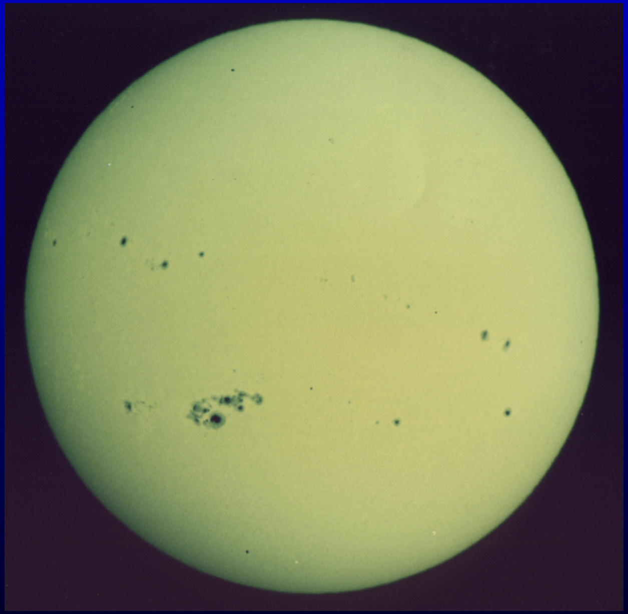
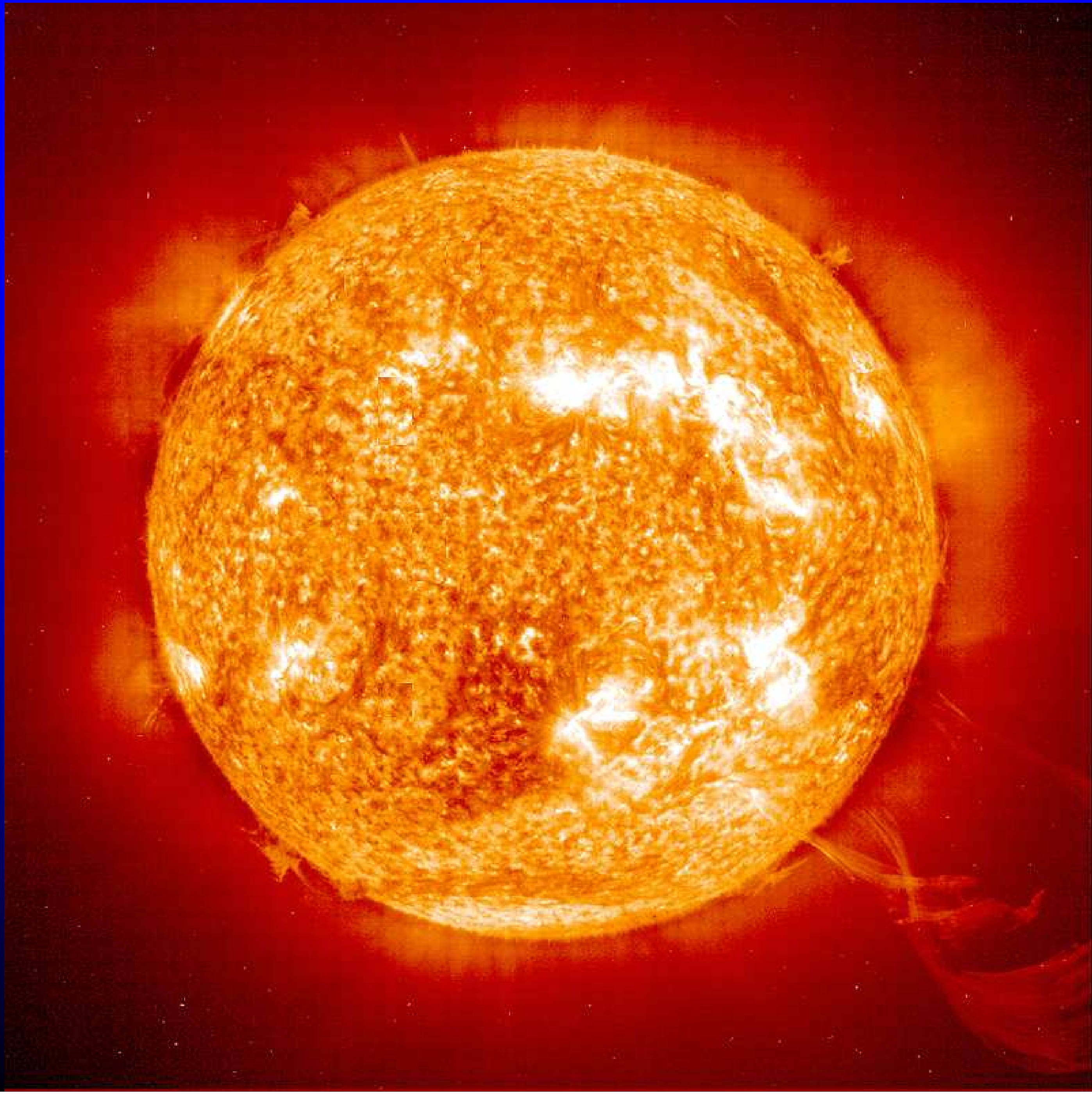
# Our Sun – a typical but above average star





# Relative Abundances of the Stellar Types

| Type | Colour | Proportion |
| --- | --- | --- |
| • 0 | Blue | 0.003% |
| • B | Blue-white | 0.13% |
| • A | White | 0.63% |
| • F | White-yellow | 3.1% |
| • G | Yellow | 8% |
| • K | Orange | 13% |
| • M | Red | 78% |

# Our Sun is a type G2

- The sun is towards the hotter end of the G-type stars; ~3% are hotter and more massive, so ~5% cooler and less massive.
- So ~ (5+13+78)% = ~96% are cooler and less massive.
- Only 4% of stars are hotter and more massive
- Ours is quite an up market star!

# Size of the Sun

The Sun subtends an angular size of ~ 0.5 degrees.

Its mean distance from the Earth is

$1.49 \times 10^{11}$ m

Diameter $= r \times \theta = 1.49 \times 10^{11}$ m $\times 0.5/ 57.3$

$= 1.3 \times 10^{9}$ m

The precise value is 1,391,978 km

# Mass of the Sun

Mass - Derive from orbit of Earth:

$$MmG/r^2 = m\,v^2/r$$ (M = mass Sun, m = mass Earth)

$$M = v^2 r/G$$

But $v = 2\pi r/P$ where P is the period of the Earth's orbit, so substituting,

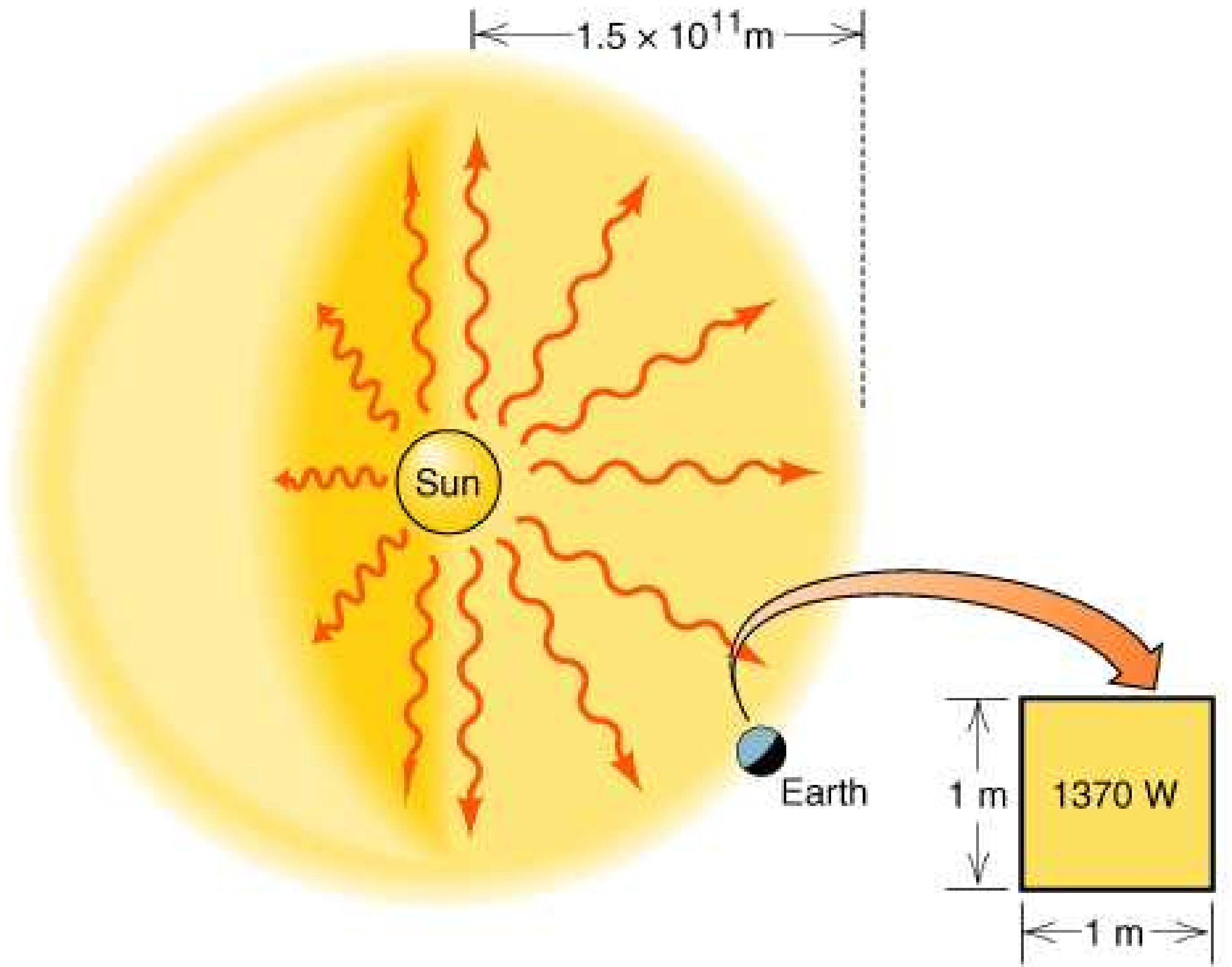
$$M = 4\pi^2 r^3/GP^2$$ Units: kg, seconds, m

$$= 2 \times 10^{30}\ \text{kg}$$

(Try this evaluation!)

# The Solar Constant

How much energy falls per square metre on the “surface” of the Earth at the sub solar point in Watts?


1.5 × 10^11 m
Sun
Earth
1 m
1370 W
1 m

# The Solar Constant

The Solar Constant is the amount of energy that passes through each square metre of space at the average distance of the Earth

It is 1368 watts/sq metre

# Energy Output of the Sun

- Given the Sun is at a distance of 1.5 x $10^{11}$ metres you can calculate the total surface area of a shell at the Earth's average distance and, by multiplying this by the Solar Constant, calculate the total energy output of the Sun.

# Sun's total energy output

- The area of the spherical shell surrounding the Sun at the distance of the Earth is:

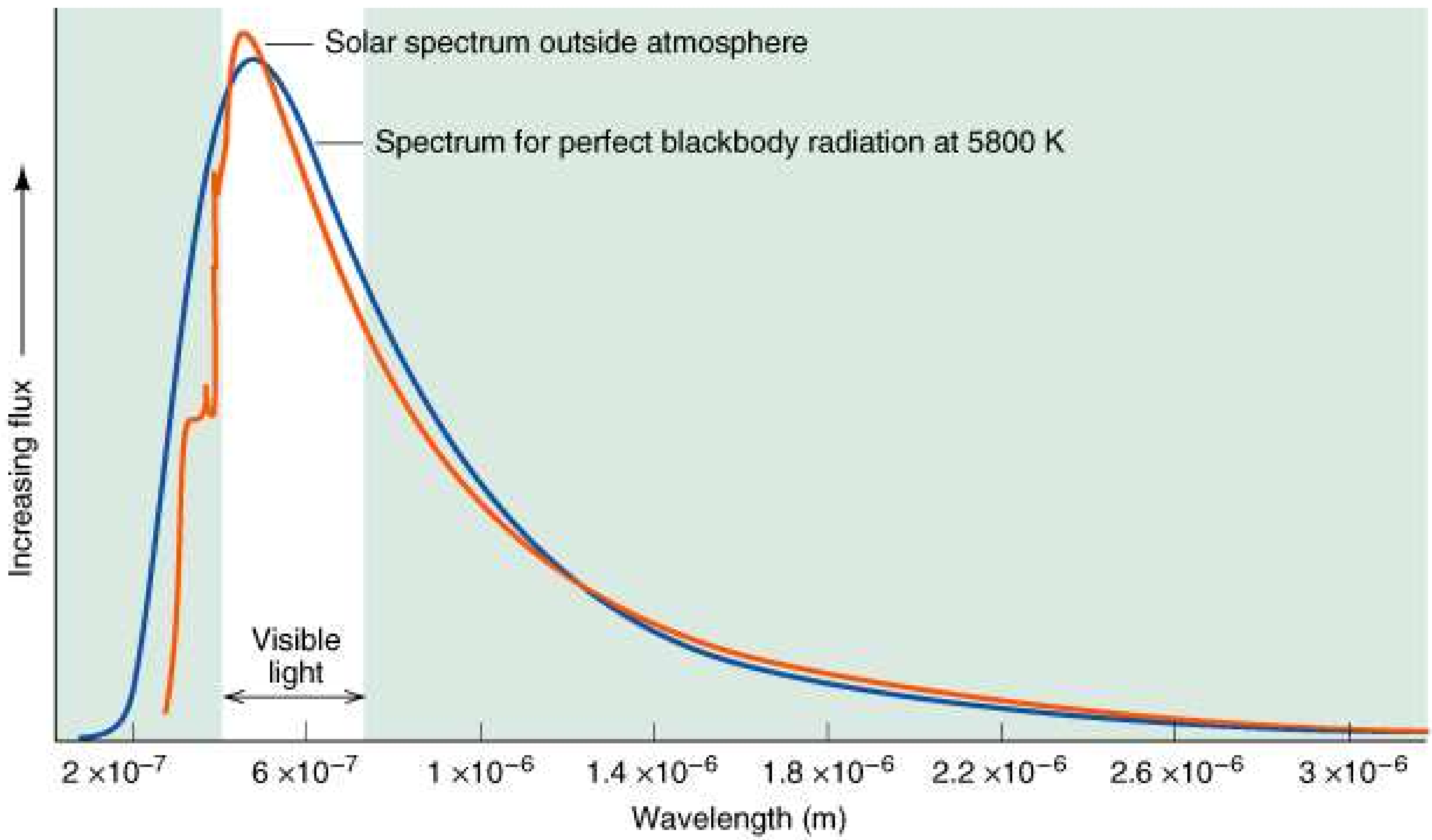
$$A = 4\,\pi\,(1.5 \times 10^{11})^2$$

The Sun's total energy output is thus:

$$1370 \times 4\,\pi\,(1.5 \times 10^{11})^2\ \mathrm{W}$$

$$= 3.86 \times 10^{26}\ \mathrm{W}$$

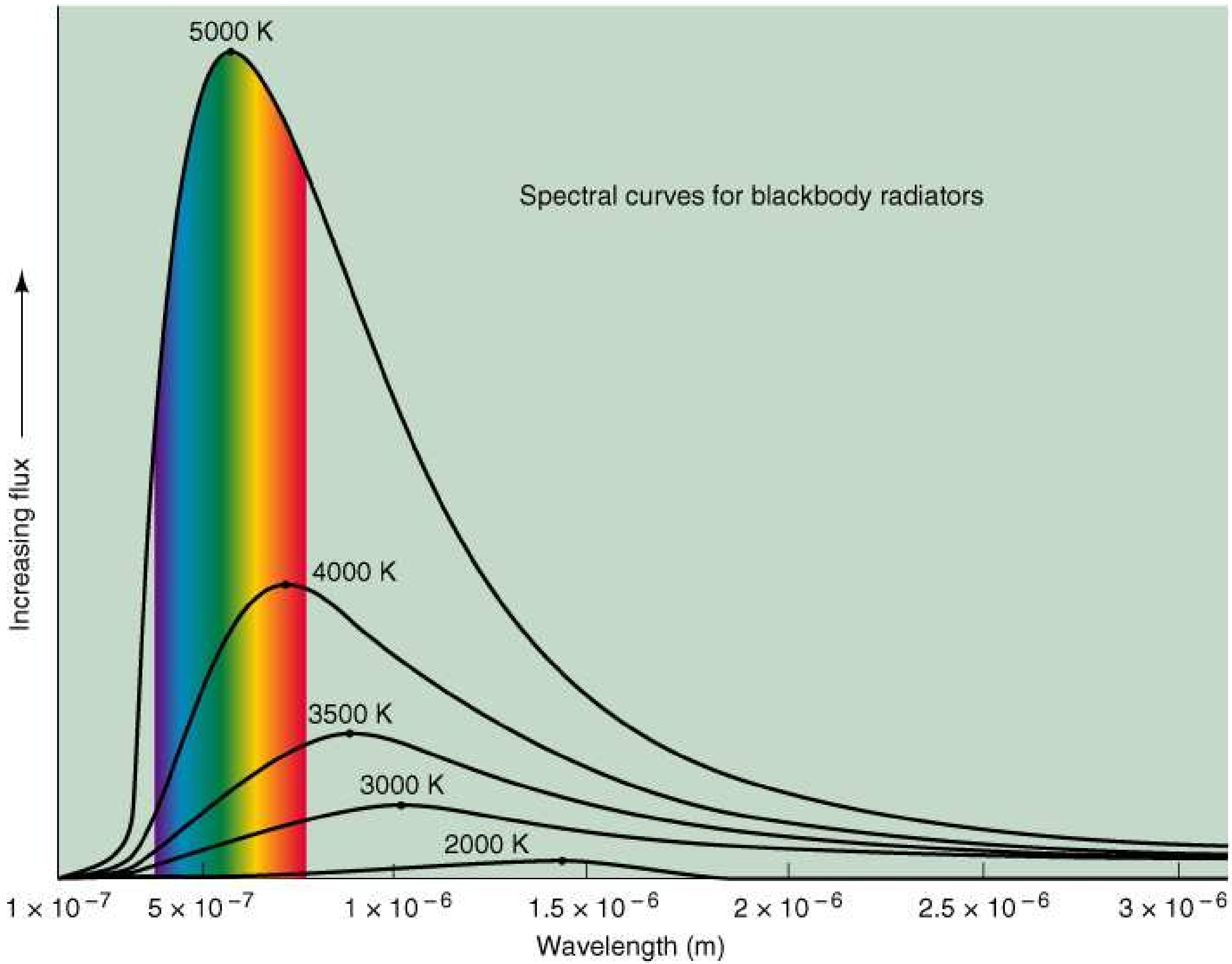
# Energy as a function of wavelength



# Black Body Radiation

A Black Body is a perfect absorber and radiator of energy.

- Think of a spherical shell, matt black inside with a small hole. Any radiation entering that hole will be absorbed inside.
- If the inside of the shell is hot, the hole will radiate energy having spectrum of energy suggested by Max Planck in 1900. Called "Planck's Law". Radiation following this law is called Black Body Radiation and has a Black Body Spectrum.



5000 K
Spectral curves for blackbody radiators
Increasing flux
4000 K
3500 K
3000 K
2000 K
1 × 10^−7
5 × 10^−7
1 × 10^−6
1.5 × 10^−6
2 × 10^−6
2.5 × 10^−6
3 × 10^−6
Wavelength (m)

# Two observations about these curves

1) The peak of the radiation shifts towards shorter wavelengths at higher temperatures. This is encapsulated in Wein's Displacement Law:

   $\lambda_{peak}$ is inversely proportional to the absolute temperature

   $$\lambda_{peak} = k/T \quad \text{where } k = 2.9 \times 10^{-3}$$

   With $\lambda_{peak}$ measured in metres, T in Degrees Kelvin.

   So if the wavelength of the peak energy is known, the temperature can be found.

Example: The surface temperature of the Sun

- The Sun's spectrum peaks at a wavelength of $0.5 \times 10^{-6}$ m

$$T = 2.9 \times 10^{-3} / \lambda_{peak}$$

$$= 2.9 \times 10^{-3} / 0.5 \times 10^{-6}$$

$$= 5800 \text{ K}$$

2) The total energy radiated increases rapidly as the temperature increases. This was encapsulated in Stephan's Law ( Often called the Stephan-Boltzmann Law ) which states that:

The total energy emitted per unit area of a black body radiator is proportional to the fourth power of the absolute temperature.

$$E = \sigma T^4$$

Where $\sigma = 5.7 \times 10^{-8}$

with E in $W/m^2$ and temperature in K

# Surface Temperature from Stephan's Law

NB This is the energy emitted per unit area.

In use you need to multiply by the area!

$E = \sigma A T^4$

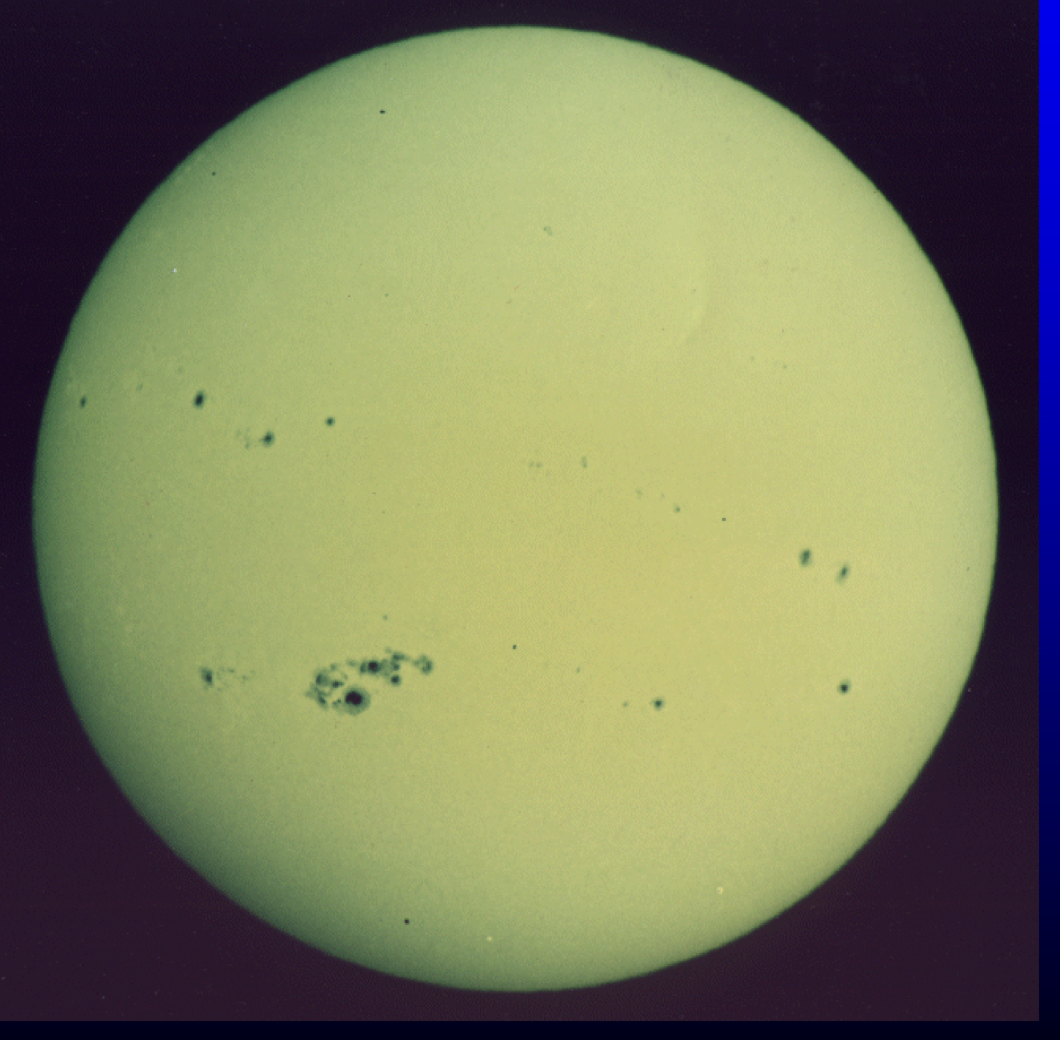
$= 5.7 \times 10^{-8} \times (4\pi \times (6.95 \times 10^8)^2) \times T^4$

$T = (3.86 \times 10^{26} / 3.44 \times 10^{11})^{1/4}$

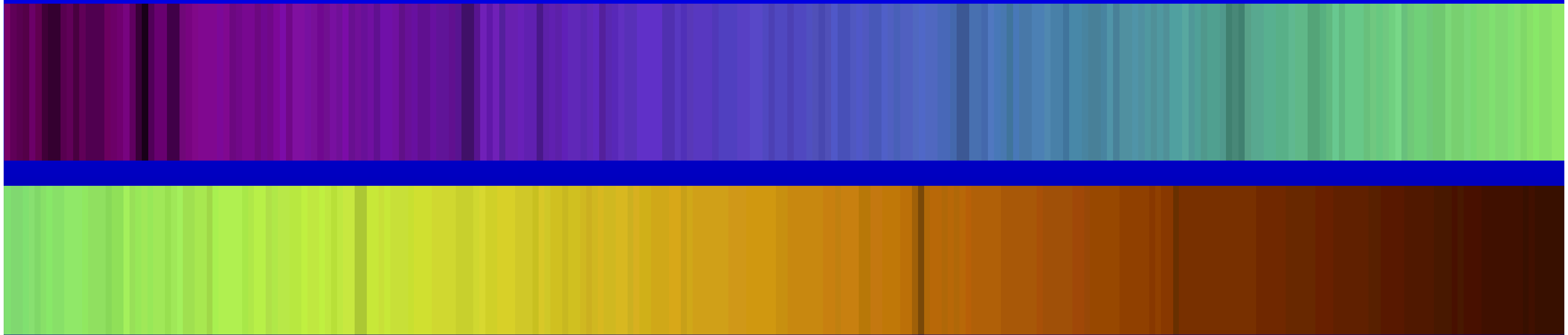
$= 5787$ K

(the two values agree quite well)

# Photosphere with Sunspots



# Fraunhofer Lines

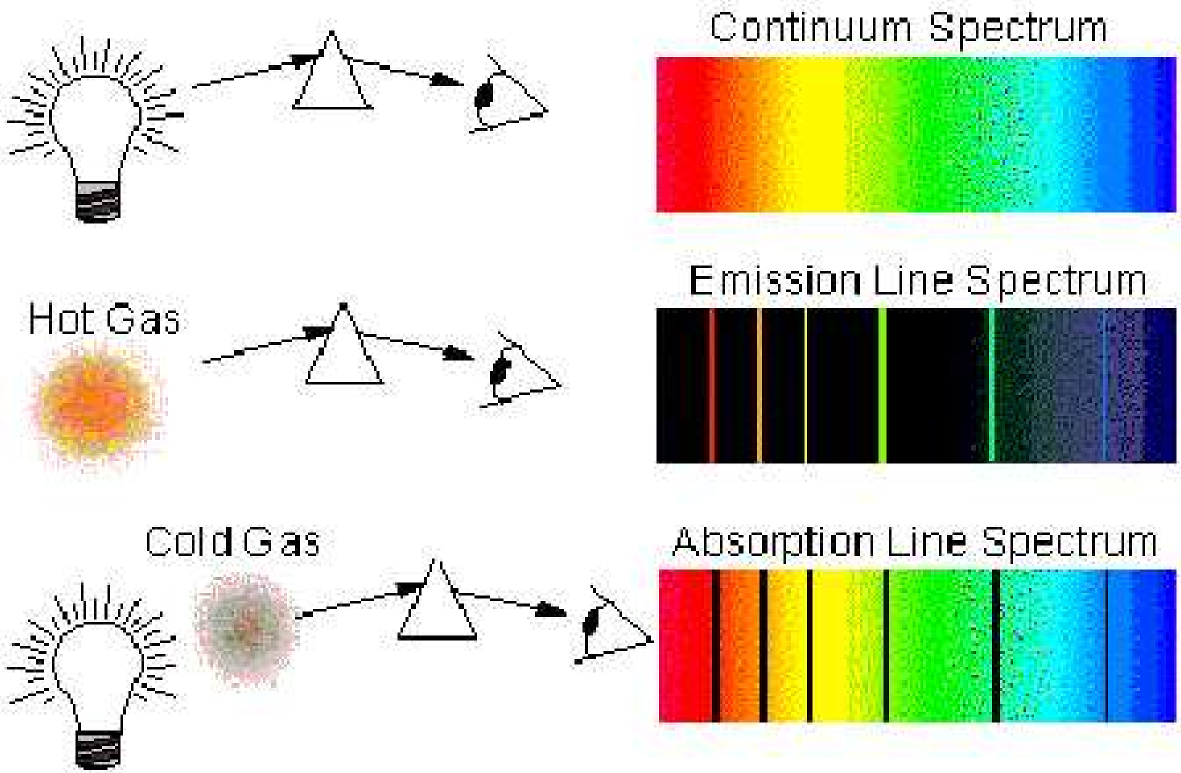


- Joseph Fraunhofer observed the solar spectrum in 1814 and found some 600 dark lines.
- In 1864, Sir William Huggins matched some of these dark lines to the emission spectra of terrestrial substances, demonstrating that stars are made of the same materials of everyday material rather than exotic substances.

# Helium

- A set of lines were found in the Sun's spectrum that had no earthly equivalent.
- It was surmised (correctly) that the Sun's atmosphere contained (a lot of) an element that had not yet been discovered on Earth.
- It was named Helium from "Helios" - the Sun.

(In Greek mythology the Sun was personified as **Hêlios)**



Continuum Spectrum
Hot Gas
Emission Line Spectrum
Cold Gas
Absorption Line Spectrum

# Why don’t the atoms re-radiate the energy so eliminating the darkbands?

- Before the atoms which have been put into their upper energy levels have a chance to re-emit a photon, they may interact with another atom and the “potential” energy relating to the electron being in an upper energy level becomes additional kinetic energy of the atoms – the gas warms up.
- This is called “collisional de-excitation”

# Composition of the Sun

| | by mass | by number of atoms |
|---|---|---|
| Hydrogen | 71% | 91.2% |
| Helium | 27.1% | 8.7% |
| Oxygen | 0.97% | 0.078% |
| Carbon | 0.4% | 0.043% |

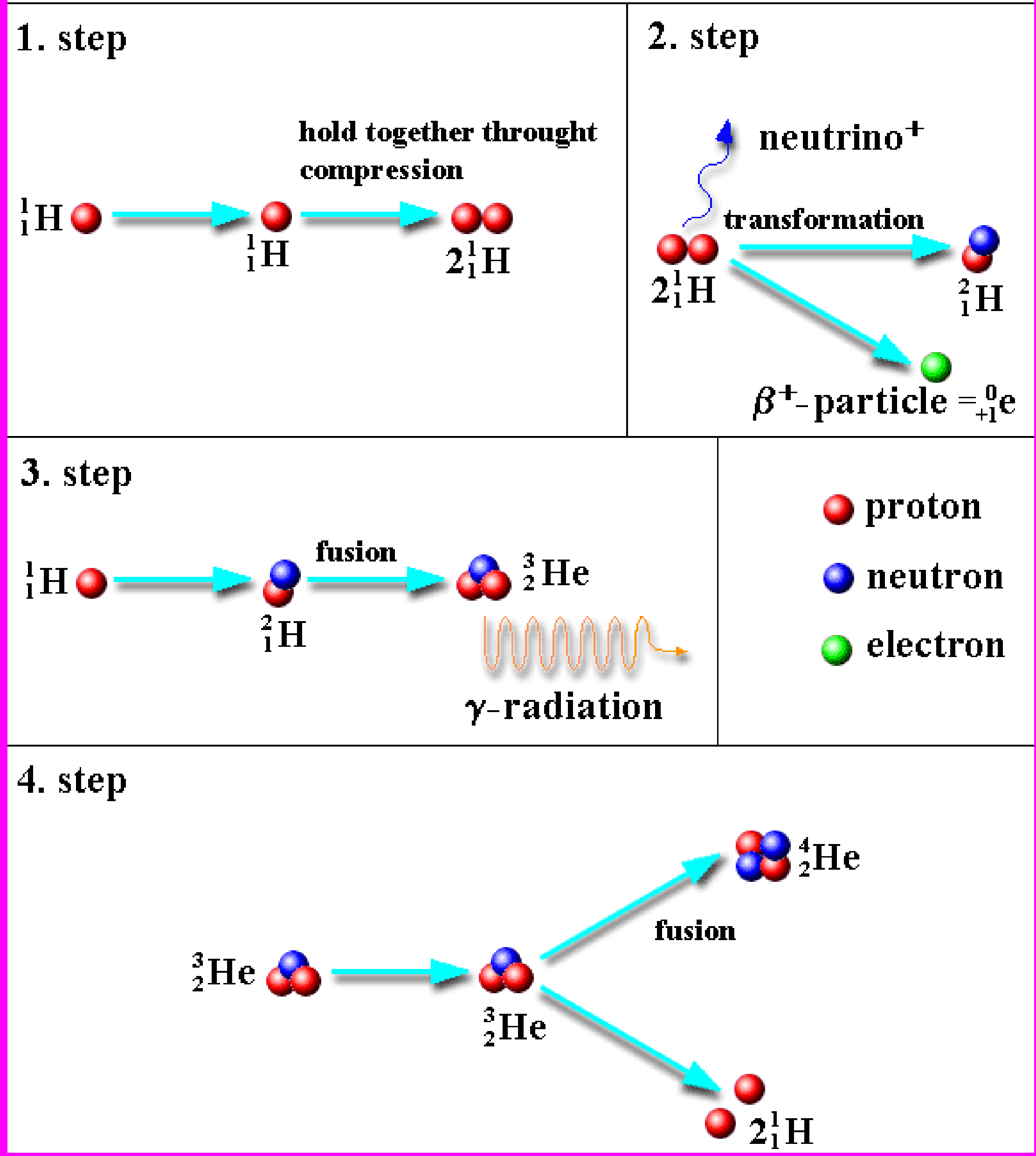
The small remainder comprises all the other elements detected in the Sun’s spectrum

# Nuclear Fusion in the Core

In our Sun, most energy is produced
by the Proton-Proton Cycle

ppI

# proton proton cycle
## (in the burning zone of the sun)



# Step 1

- Two protons fuse to form a deuteron comprising a proton and a neutron.

  In the reaction a neutrino and a positron are produced.

$$^{1}H_{1} + {}^{1}H_{1} = {}^{2}H_{1} + e^{+} + \nu$$

  – (the positron carries away the positive charge from one of the protons)

# Step 2

- A further proton reacts with the deuteron to form a helium-3 (tritium) nucleus comprising 2 protons and 1 neutron.

  A gamma ray photon is emitted.

$$^{2}H_{1} + {}^{1}H_{1} = {}^{3}He_{2} + \gamma$$

# Step 3

- Two helium-3 nuclei react to give a helium nucleus – an alpha particle – comprising 2 protons and 2 neutrons.

$$^{3}He_{2} + {}^{3}He_{2} = {}^{4}He_{2} + {}^{1}H_{1} + {}^{1}H_{1}$$

- Two protons are emitted.

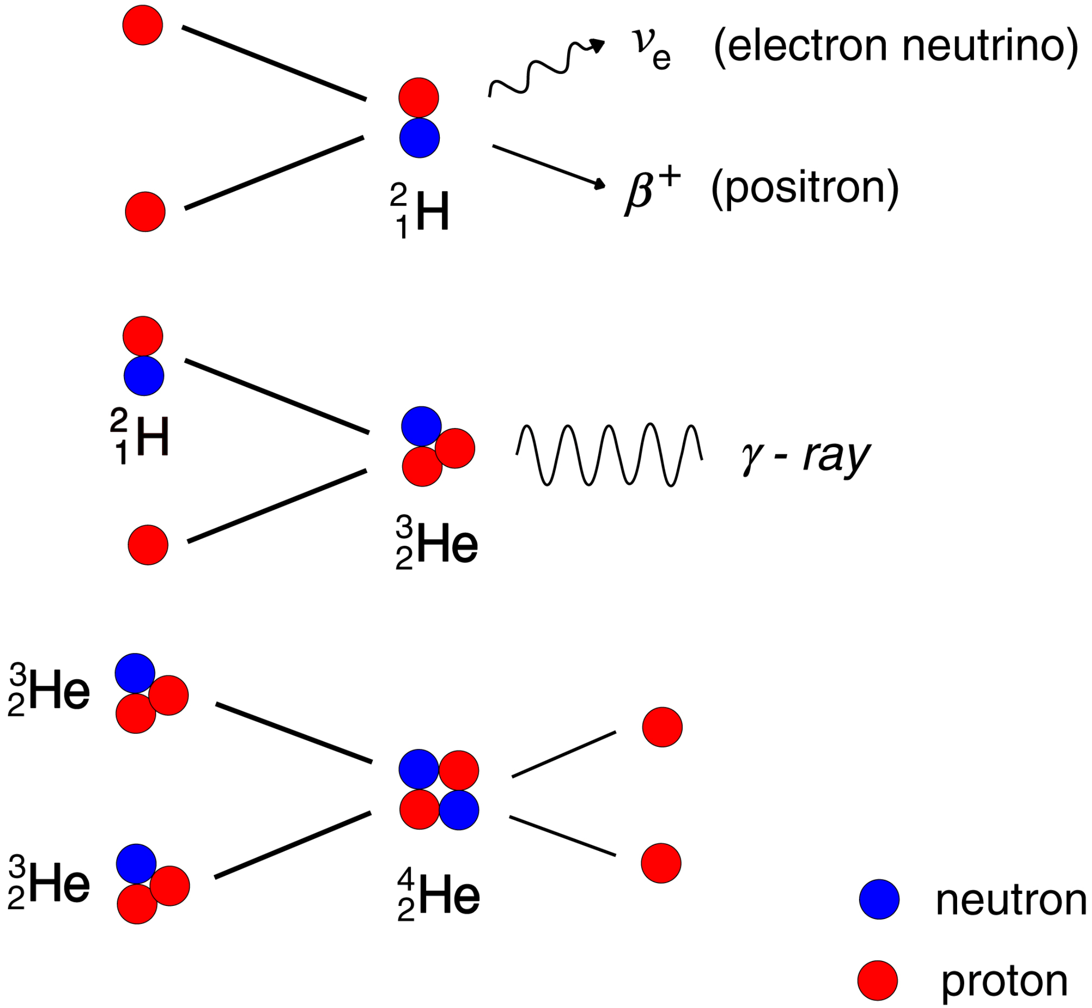
# The Net Reaction

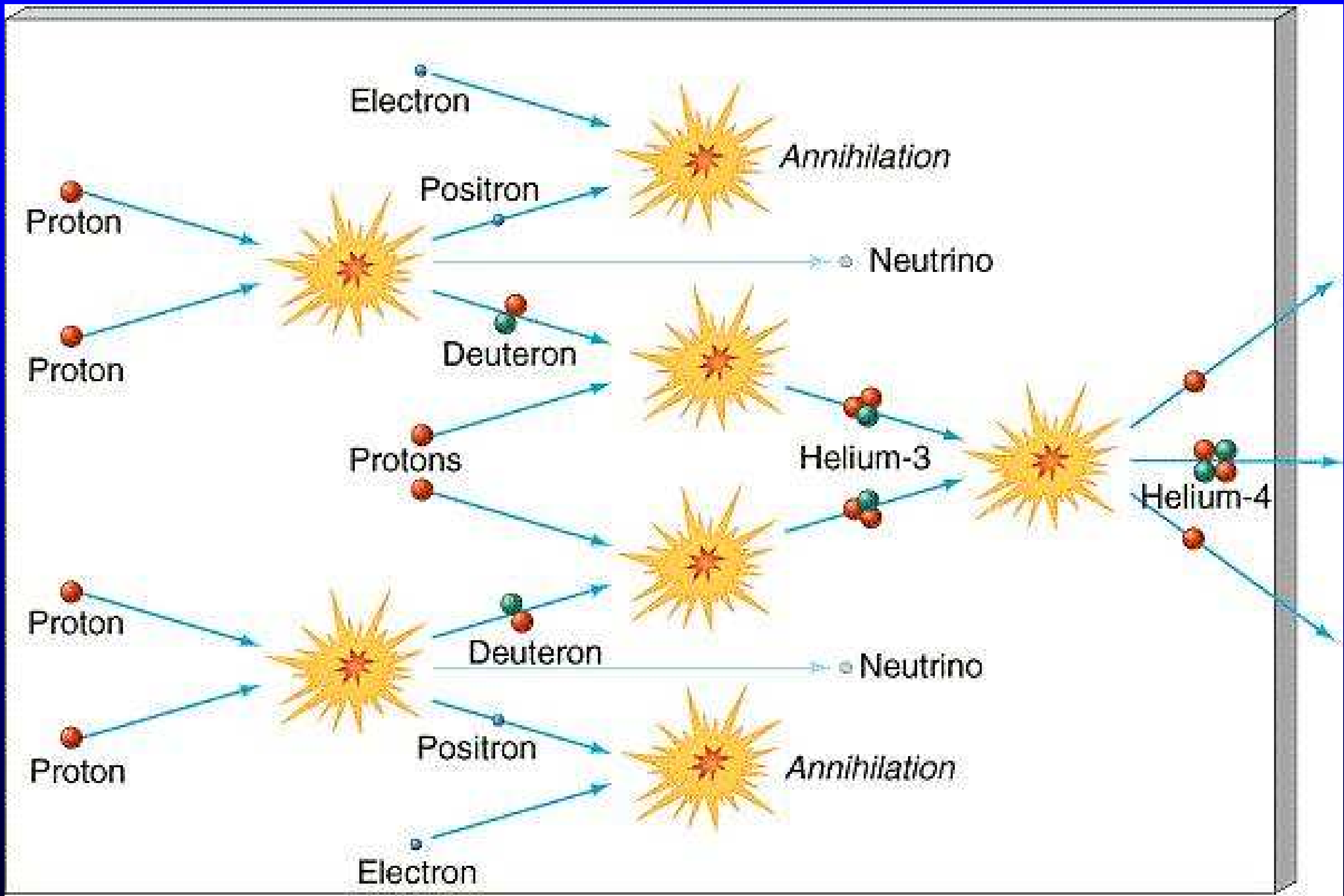
- 4 protons give 1 alpha particle + 2 positrons + 2 gamma ray photons + 2 neutrinos.

$$4\ {}^{1}H_{1} = {}^{4}He_{2} + 2\ e^{+} + 2\ \gamma + 2\ \nu$$

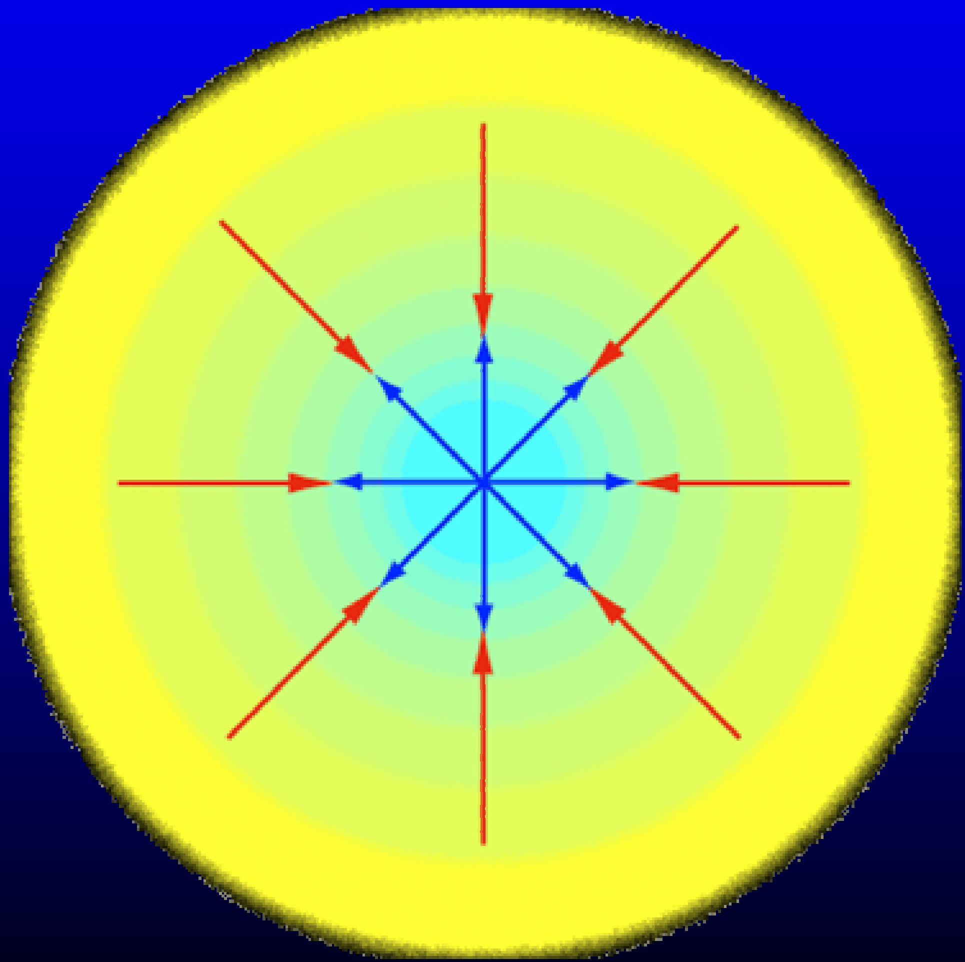
- The 2 positrons will later annihilate 2 electrons to give 4 further gamma ray photons.
- NOTE: About 2% of the energy released in the nuclear reaction is carried away by neutrinos

# Proton-proton Cycle



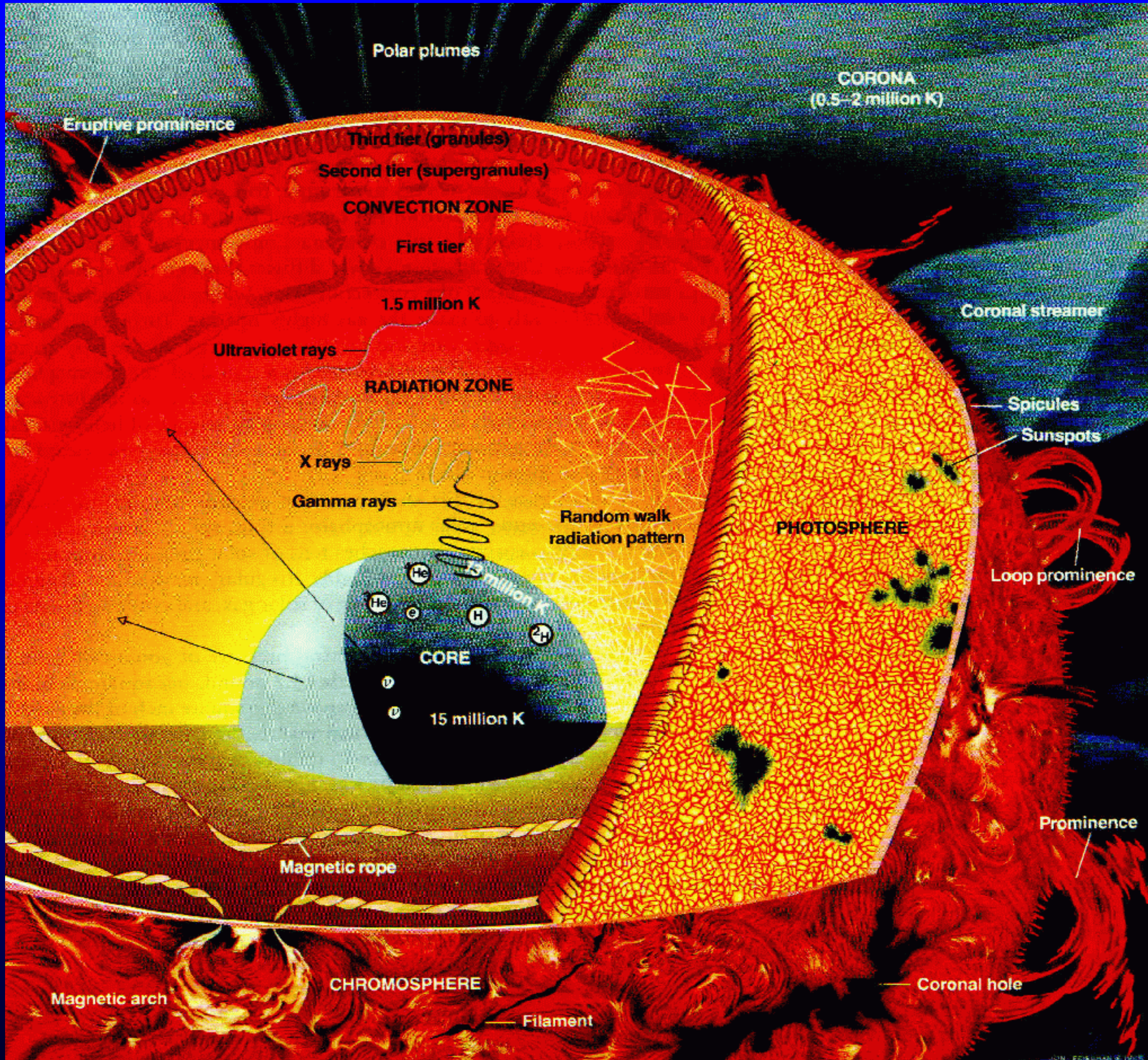

Electron
Annihilation
Positron
Proton
Neutrino
Proton
Deuteron
Protons
Helium-3
Helium-4
Proton
Deuteron
Neutrino
Proton
Positron
Annihilation
Electron

# Gravitational collapse is opposed by radiation pressure

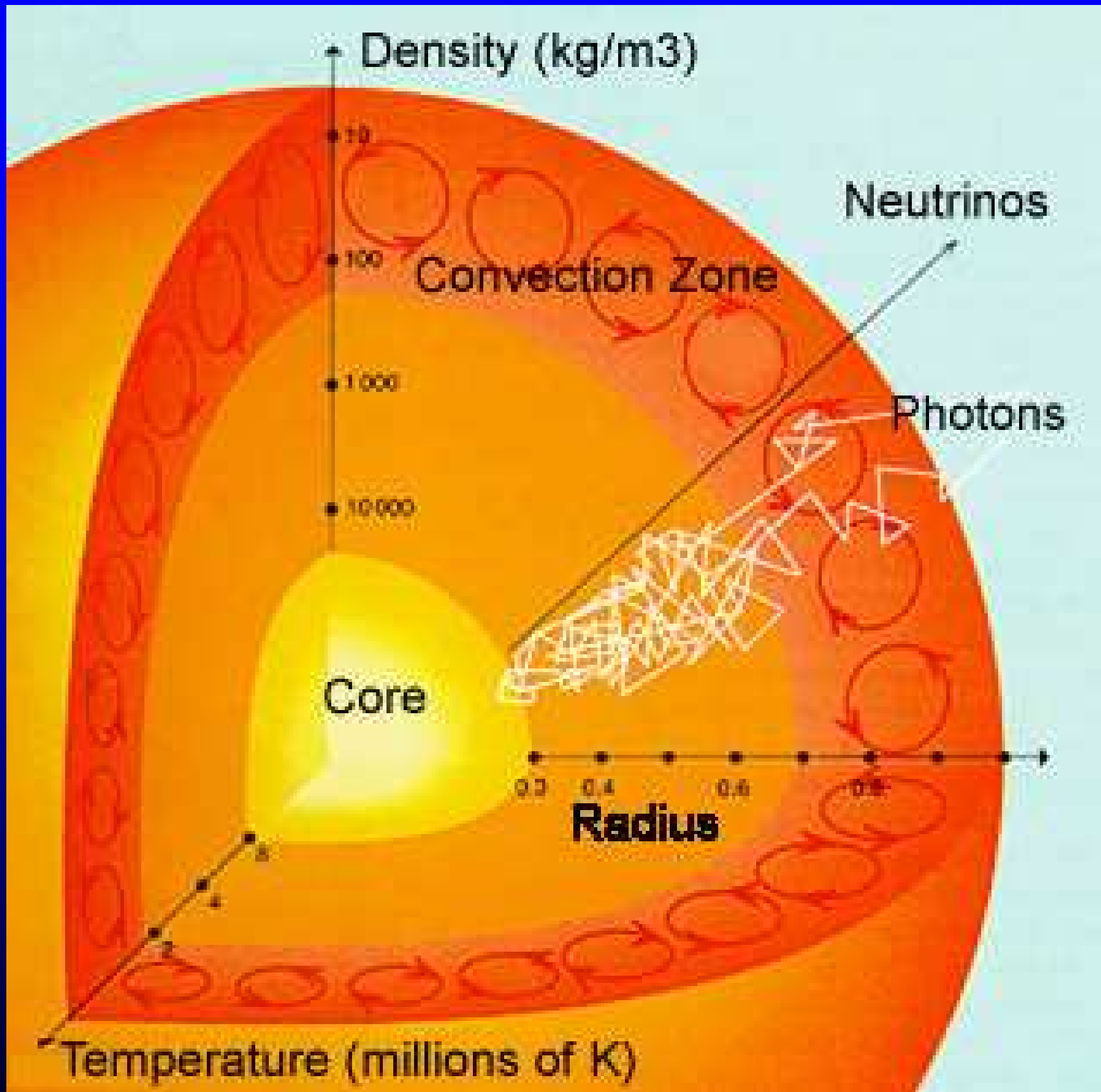


# Transfer of Energy to surface

- Energy is transferred from the core through the inner 2/3 of the Sun by radiative transfer in what is called the radiation zone
  - Photons carry out a "random walk" taking about 60,000 years to traverse this region.
- In the outer 1/3, energy transfer is by convection
  - Large inner convection cells and smaller outer convection cells:
    - Supergranules and granules

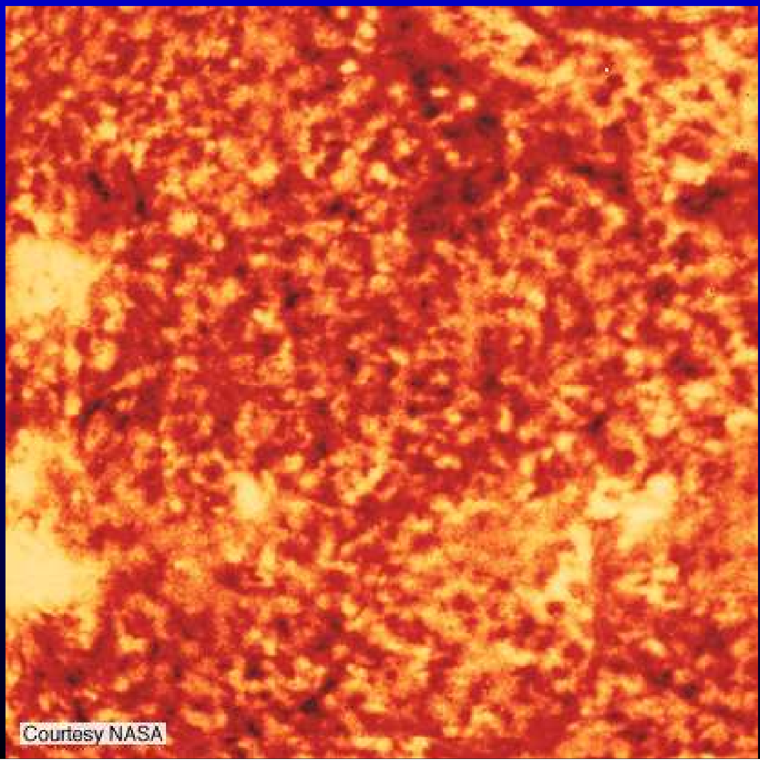


Polar plumes
CORONA
(0.5–2 million K)
Eruptive prominence
Third tier (granules)
Second tier (supergranules)
CONVECTION ZONE
First tier
1.5 million K
Coronal streamer
Ultraviolet rays
RADIATION ZONE
Spicules
Sunspots
X rays
Gamma rays
Random walk
radiation pattern
PHOTOSPHERE
Loop prominence
15 million K
He
He
e
H
CORE
15 million K
Prominence
Magnetic rope
CHROMOSPHERE
Coronal hole
Magnetic arch
Filament


Density (kg/m3)
Neutrinos
Convection Zone
Photons
Core
Radius
Temperature (millions of K)

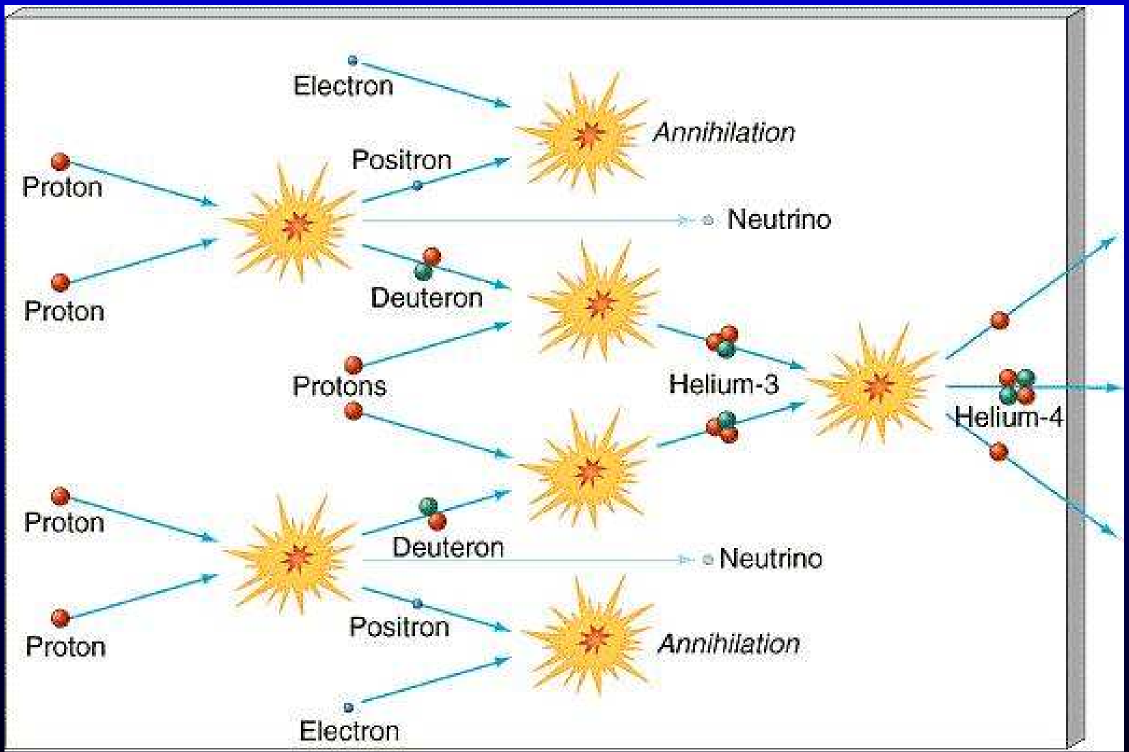
# Solar Granulations

- Caused by the convection currents that bring the Sun's heat to the surface.



# $10^{38}$ neutrinos produced per second!

$$4\ {}^{1}H_{1} = {}^{4}He_{2} + 2\ e^{+} + 2\ \gamma + 2\ \nu$$



# How many neutrinos produced?

- Calculate how many pp1 cycles happen per second.

- What mass is converted per second?
- Energy output is $3.8 \times 10^{26}$ Watts
- $E = m c^2$
- So Mass loss = $3.8 \times 10^{26} / (3 \times 10^{8})^2$ kg /sec
  = $4.4 \times 10^{9}$ kg/sec

(This is only 2 parts in $10^{-21}$ per year of Sun's total mass)

One proton-proton cycle transforms 4.57 x $10^{-29}$ kg*

So ~ $10^{38}$ ppI cycles per second so ~ 2 x$10^{38}$ neutrinos.

* 1 x mass alpha particle – 4 x mass proton

$$= (4 \times 1.6726\ 10^{-27}\ \text{kg} - 6.64465598 \times 10^{-27}\ \text{kg})$$

$$= 4.574\ 10^{-29}\ \text{kg}$$

(This is 0.7% of the mass of the protons)

# Solar Neutrino Problem

- Can detect a neutrino by its reaction with an isotope of chlorine ($^{37}Cl$) to give a radioactive isotope of Argon.
- After exposing a tank full of Carbon Tetra-chloride for a month, the few (~ 5) argon atoms can be detected.
- Not enough neutrinos detected at Earth.
- Only about 1/3 of expected number detected
  - Is Sun’s nuclear reactor slowing down?

# Some numbers

- Neutrino flux at Earth is $6.6 \times 10^{14}$ $m^{-2}$ $s^{-1}$
- The probability that 1 neutrino will react with a $^{37}Cl$ nucleus is $6.1 \times 10^{-36}$ per second
- 24% of Chlorine atoms are $^{37}Cl$.
- 610 tons of Carbon Tetrachloride contain

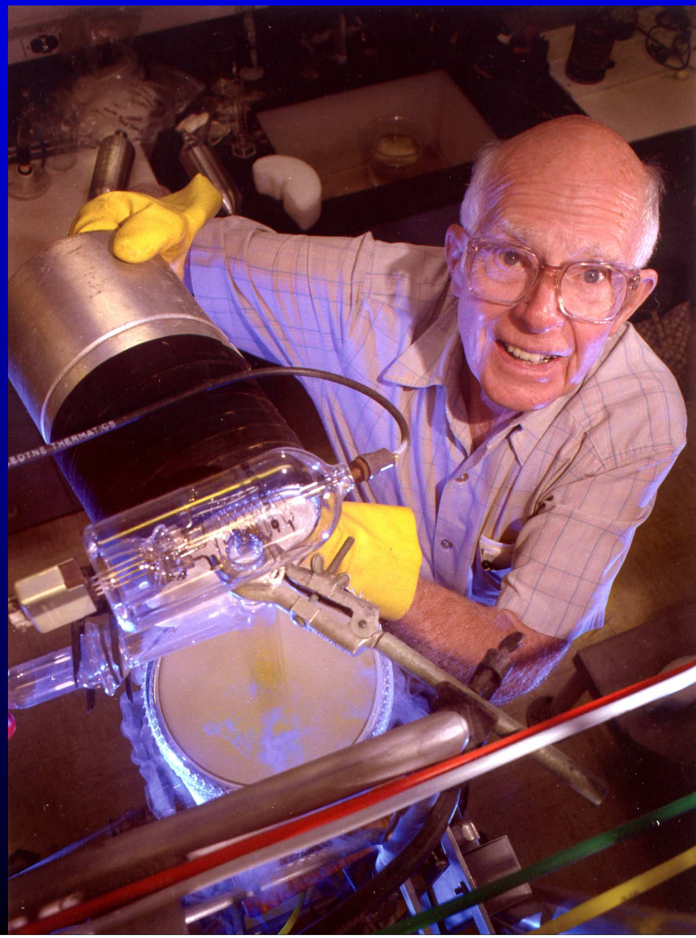
  $2 \times 10^{30}$ $^{37}Cl$ atoms

  So 1 capture to produce $^{37}Ar$ will occur, on average, every 6 days.

# Homestake Mine

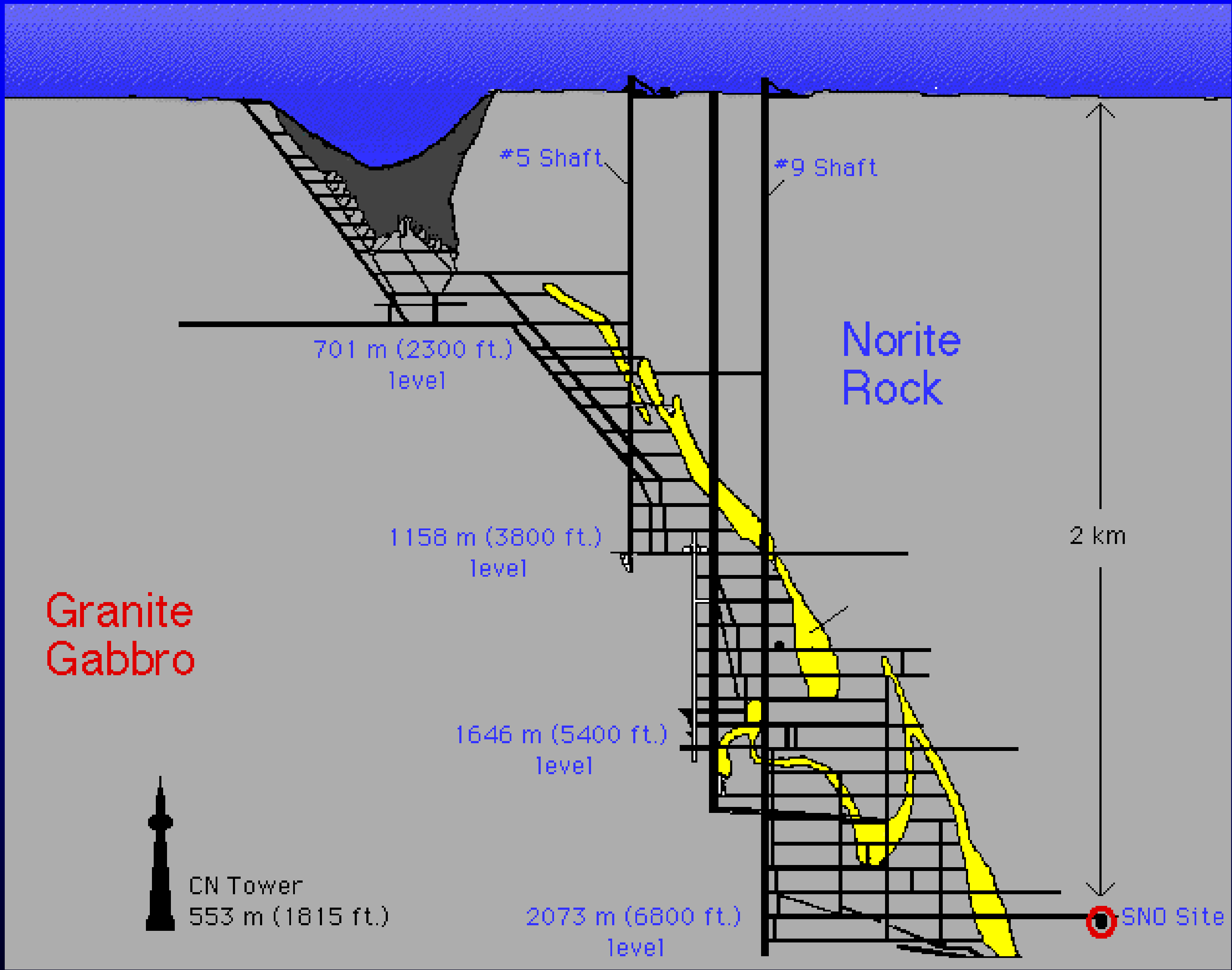

Chlorine neutrino reaction as a path to neutrino detection

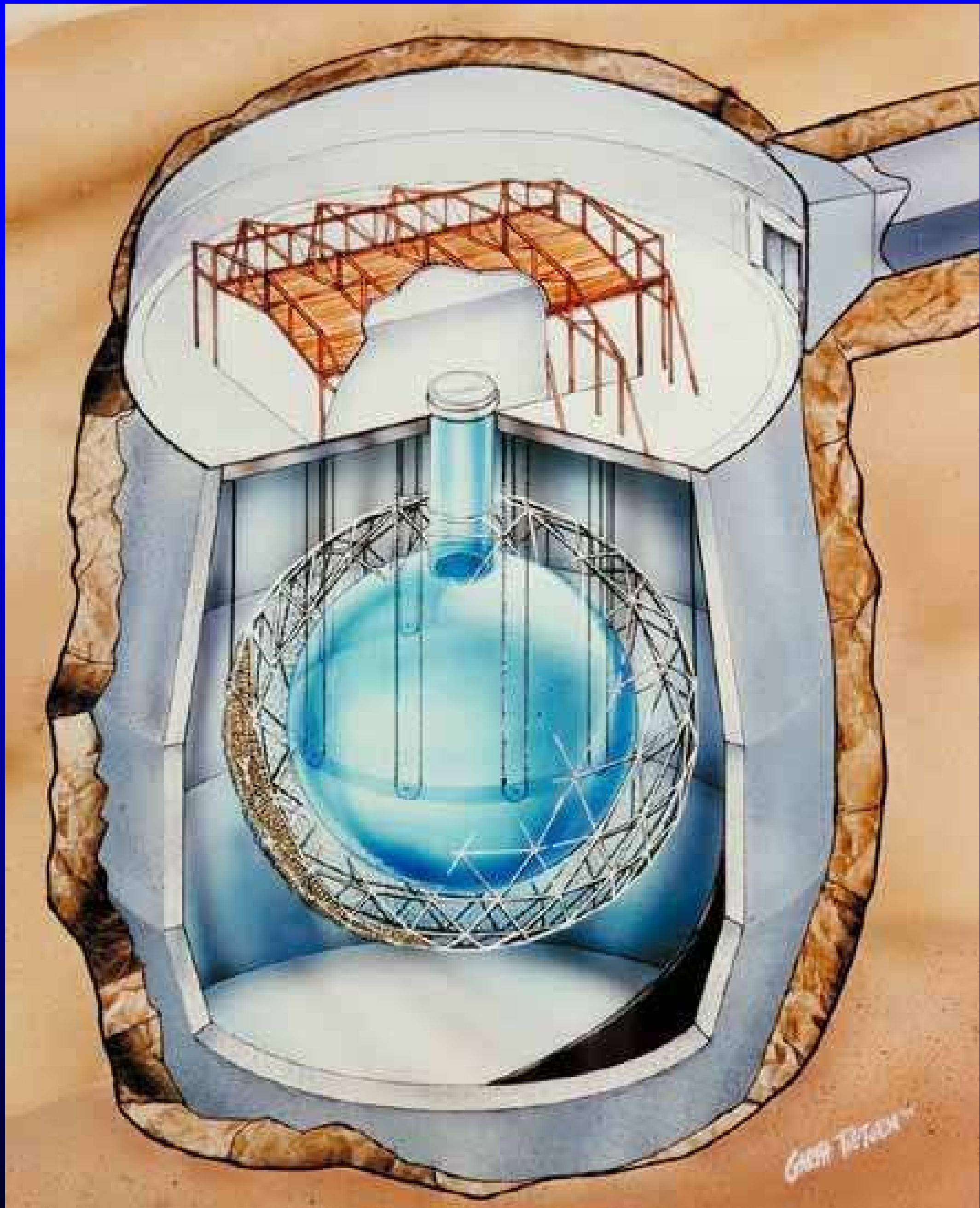
# Ray Davis

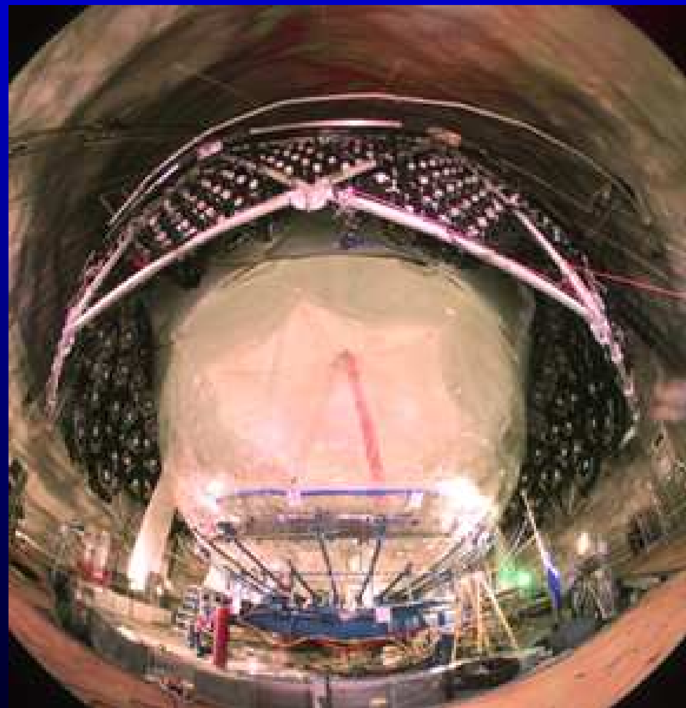


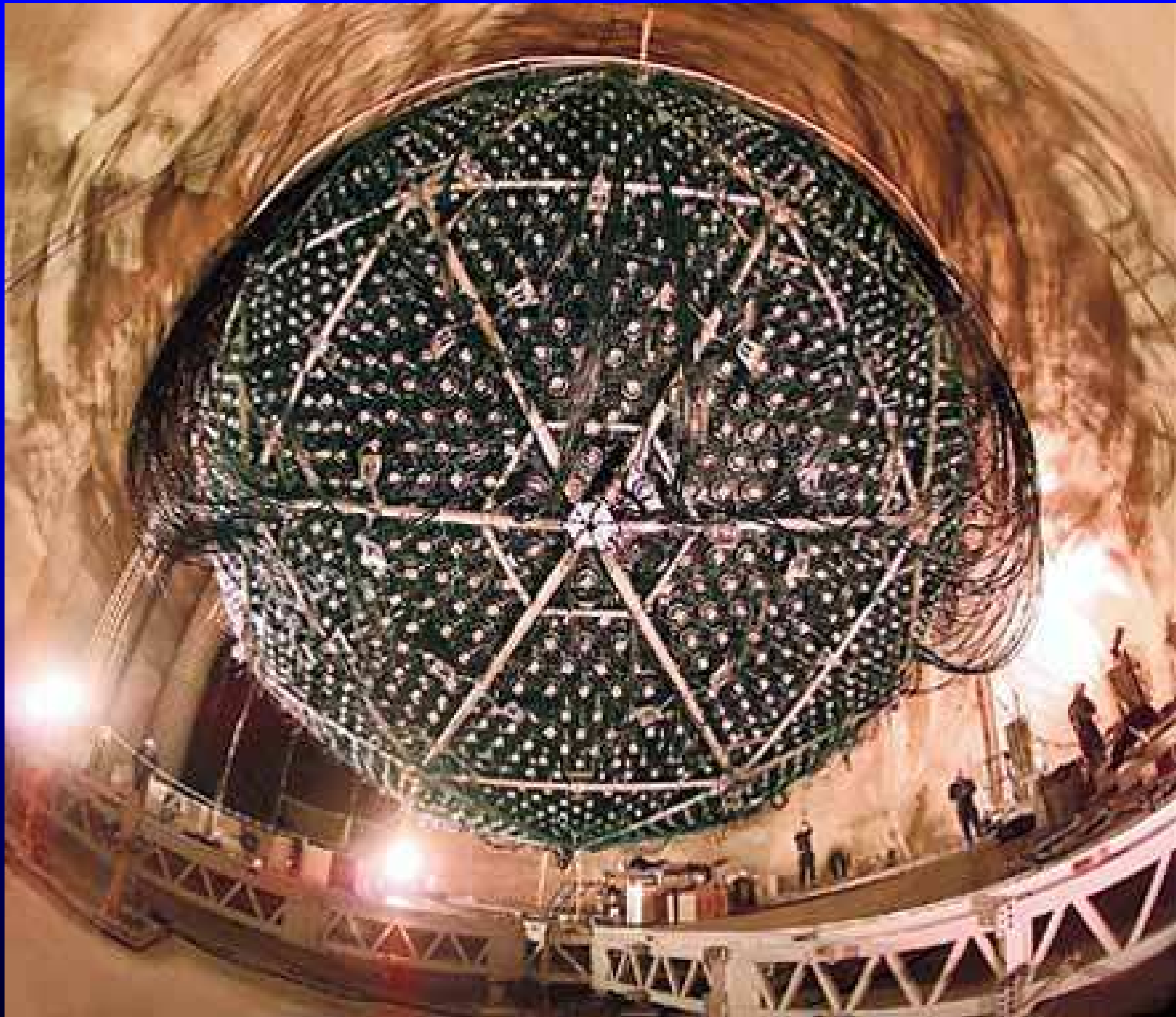
- Ray Davis received the Nobel Prize for Physics for this work when his results were confirmed by the Sudbury Mine Experiment and the solar neutrino problem was solved.

# Sudbury Mine









# The Sudbury Mine Detector

- Contains 1000 tons of HEAVY WATER in a 12m diameter sphere.
- Thus many Deuterons.
- Can detect neutrinos by the reaction:
- Deuteron + neutrino gives 2 protons + electron
- The high speed electron produces Cerenkov radiation which is detected by 9456 photomultiplier tubes.
- A detection rate of ~ 10 per day!

- Confirmed Ray Davis' results.
- But was also able to resolve the problem.
- We need to learn a little more about neutrinos….
- Three types of Neutrino:

  Electron, Muon and Tau

# The significant result

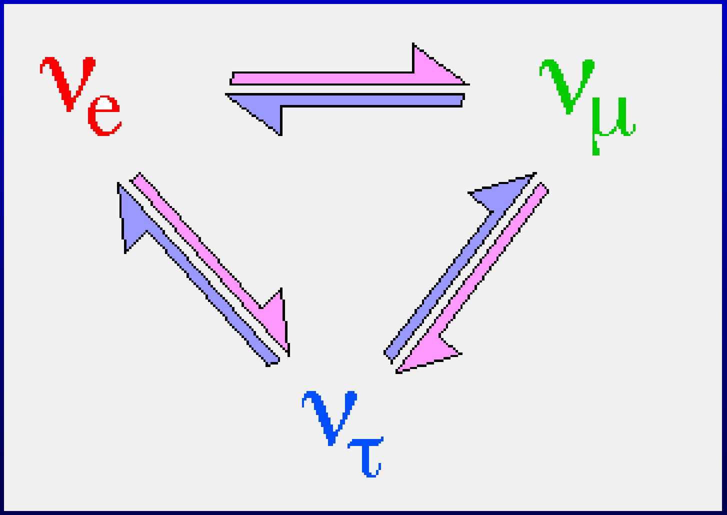
- 2 tonnes of salt were added to the heavy water to make it more sensitive to the Muon and Tau neutrinos
- The *total* number of all types seen arriving from the Sun was equal to the expected number of electron-neutrinos produced in the Sun.

# A solution?

- If Electron-neutrinos could change into Muon or Tau neutrinos, on their journey to the Earth from the Sun then one would get equal numbers of each type.
- The observations would be understood
- BUT a problem: it was thought that neutrinos were massless
- If so, they cannot change type en route from the Sun

# The solution to the problem

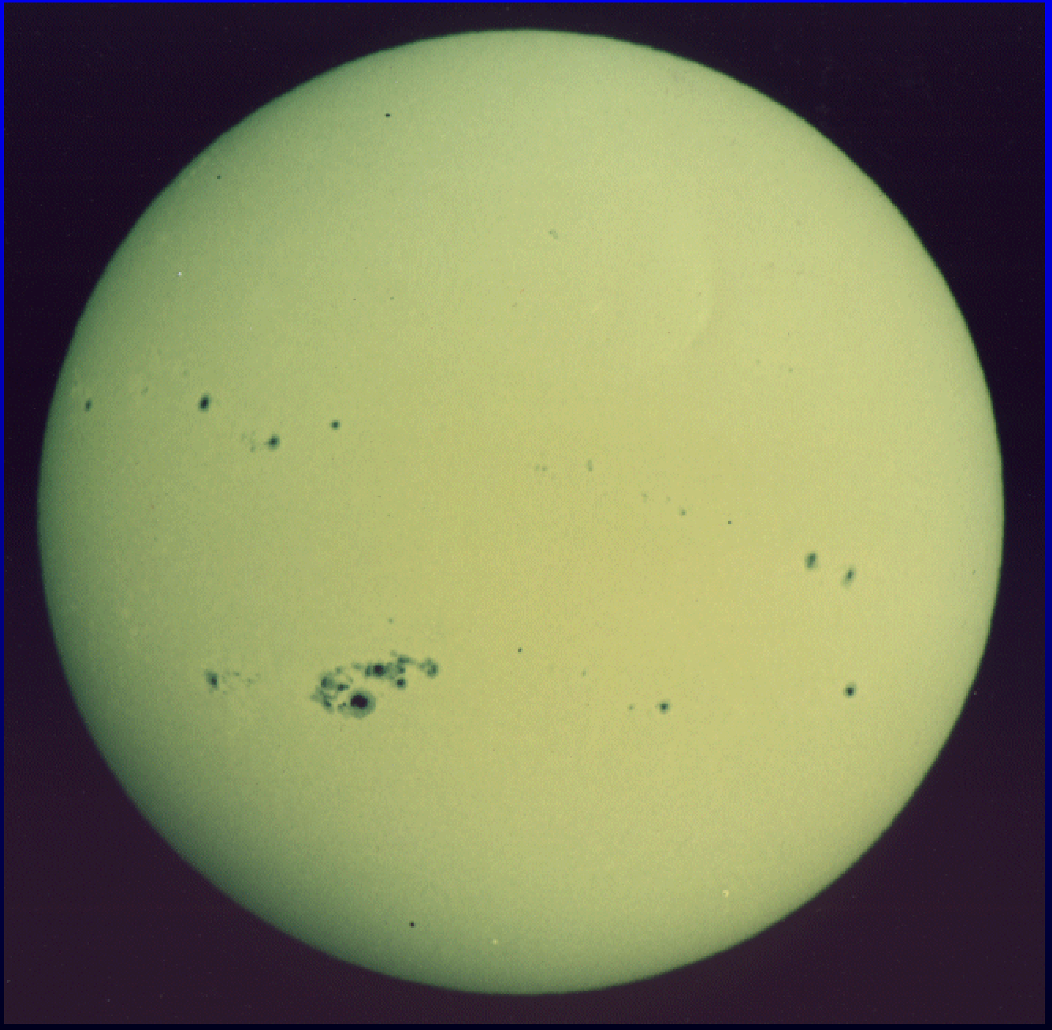
- It appears that neutrinos have a very small mass which allows them to oscillate between three types of neutrino – Electron, Mu and Tau.
- 2/3 of the electron neutrinos produced will become Mu and Tau neutrinos on the way to the Earth so we only see 1/3 !



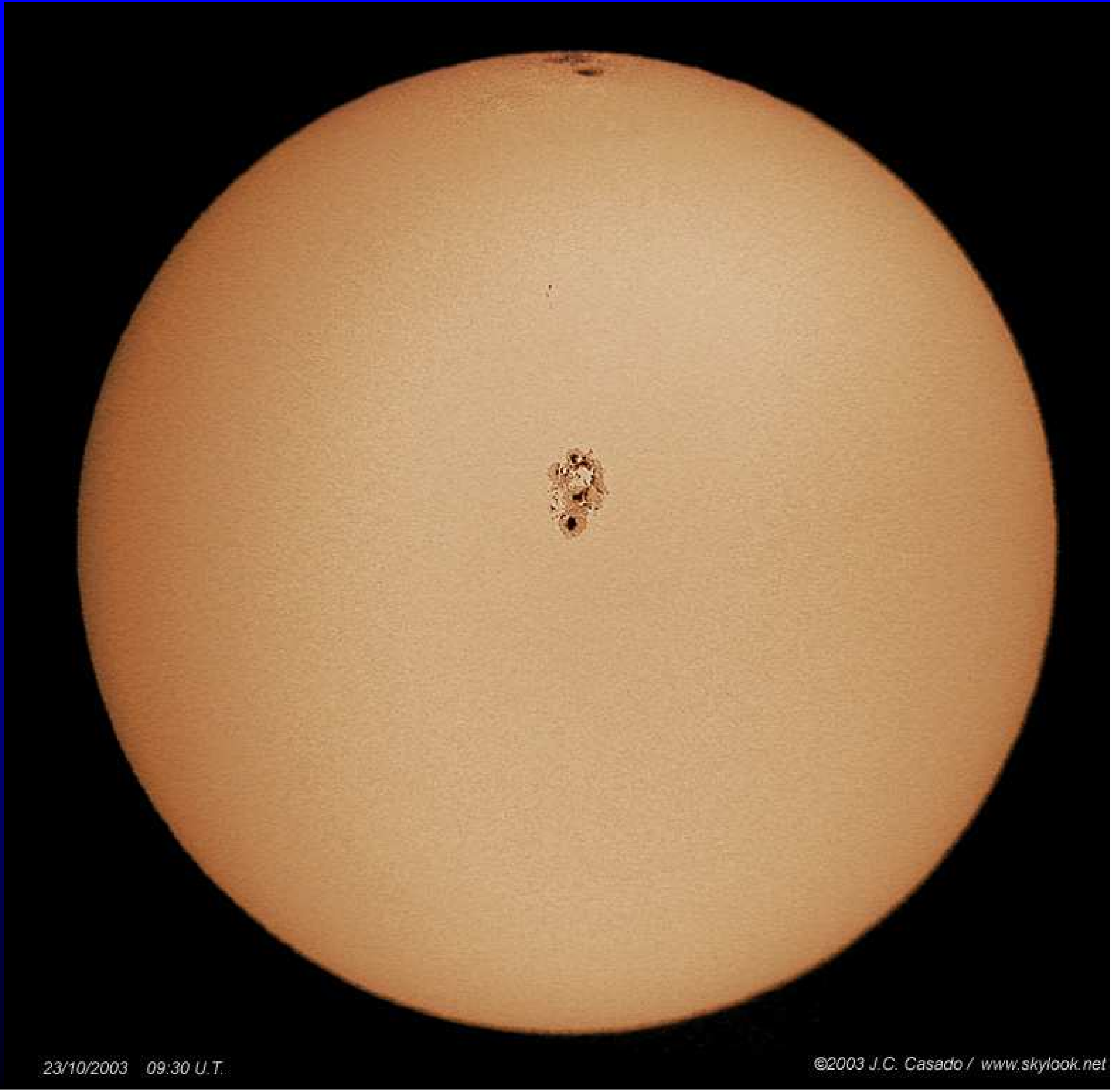
# The Sun's Atmosphere

The light comes from a 450 km thick layer called the photosphere

# Photosphere with Sunspots

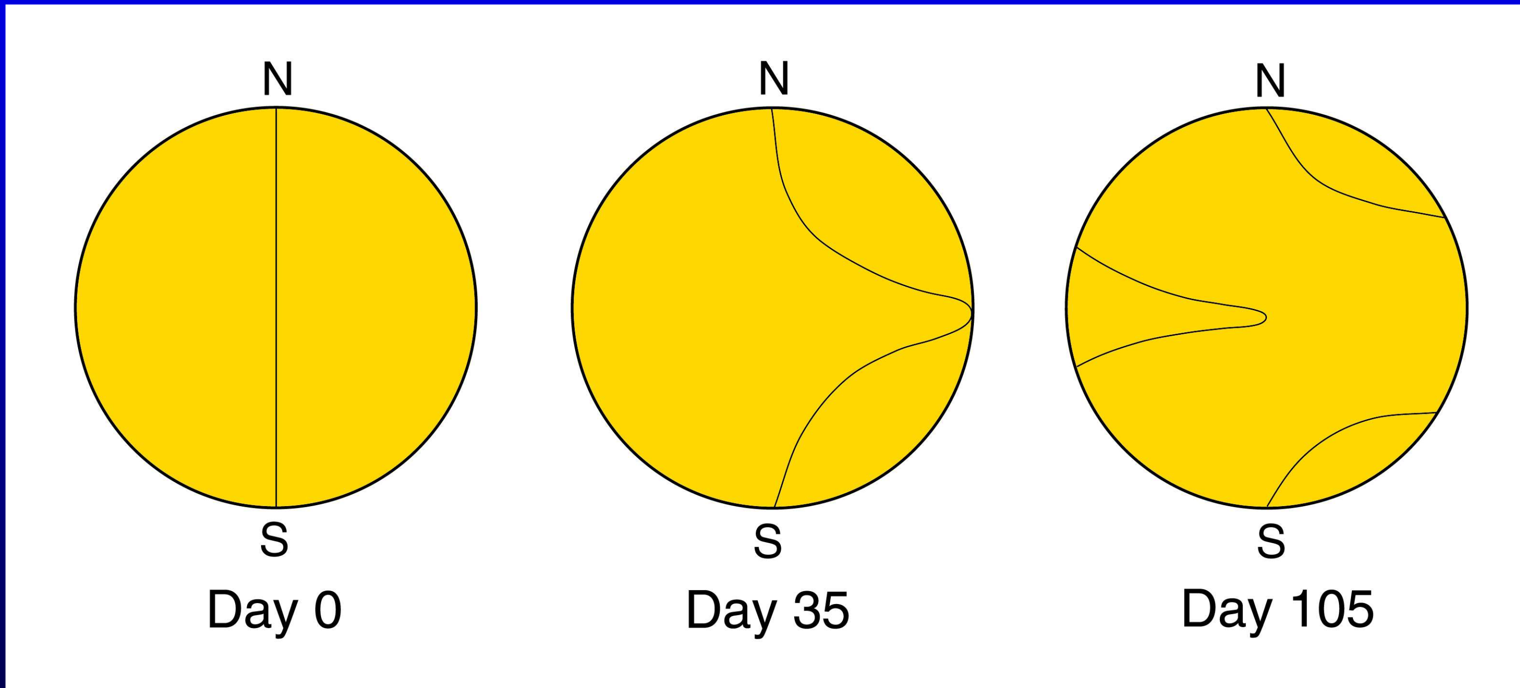


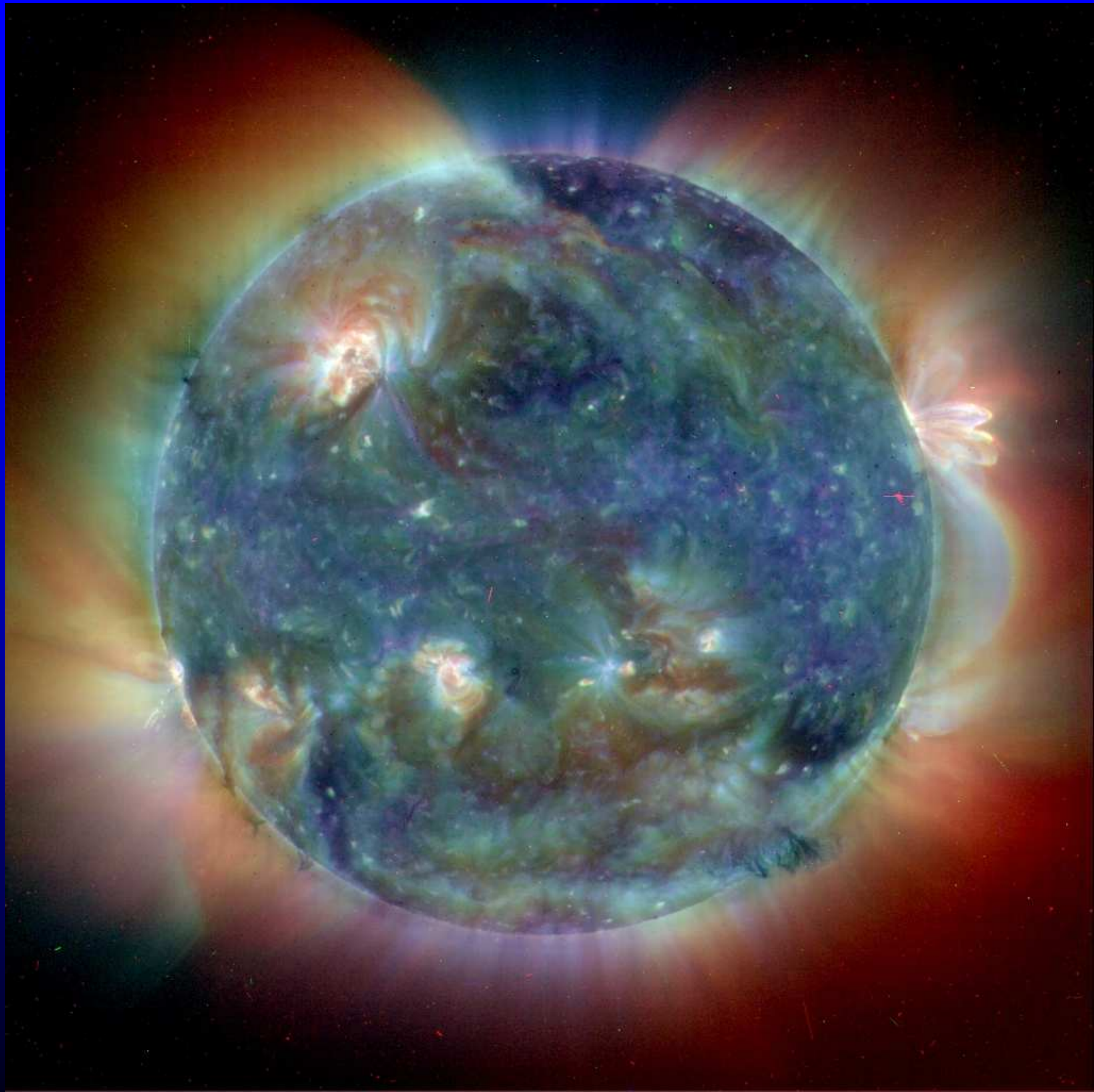
# Oct 23 2003

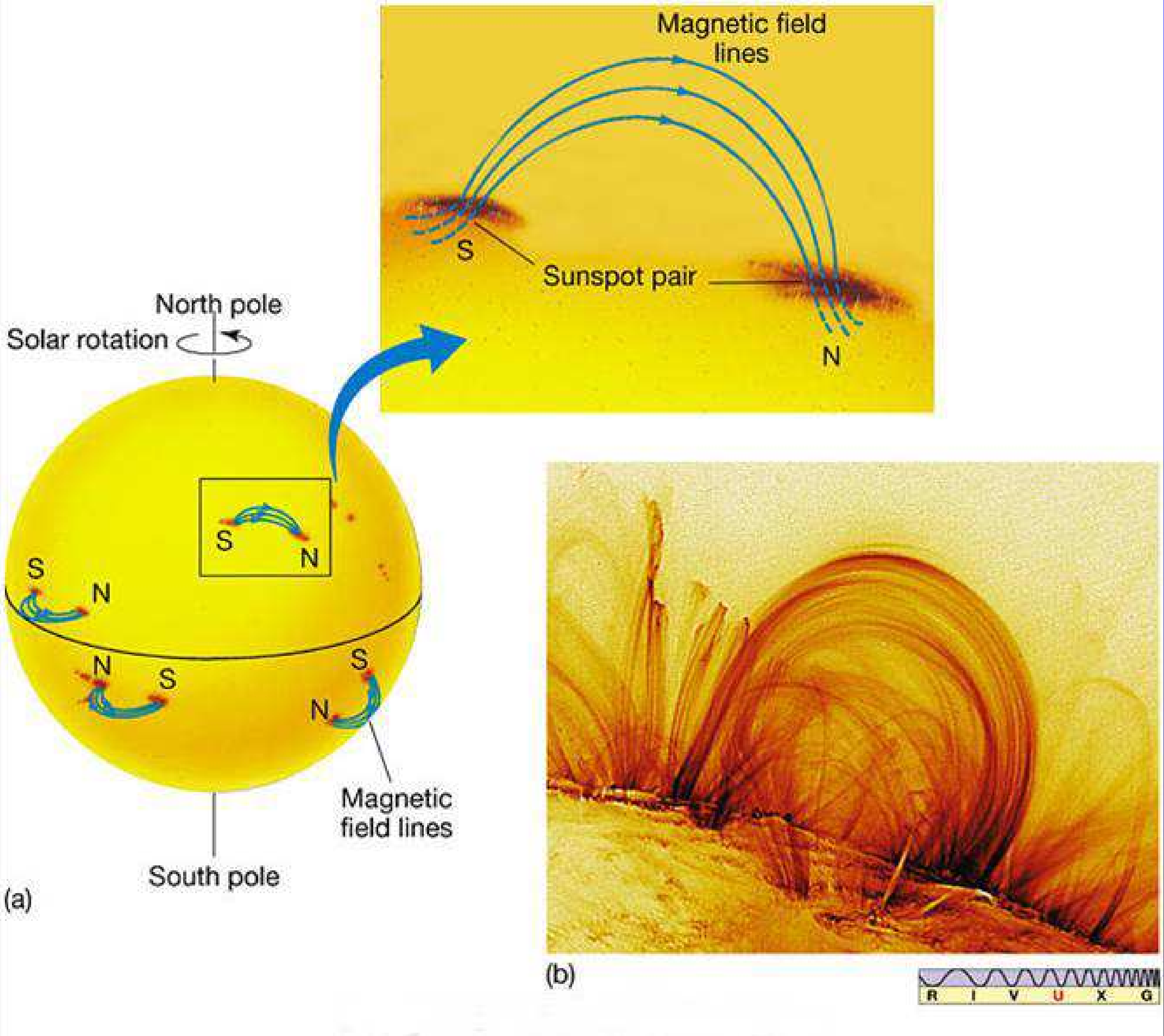


# The Sun Spot Cycle

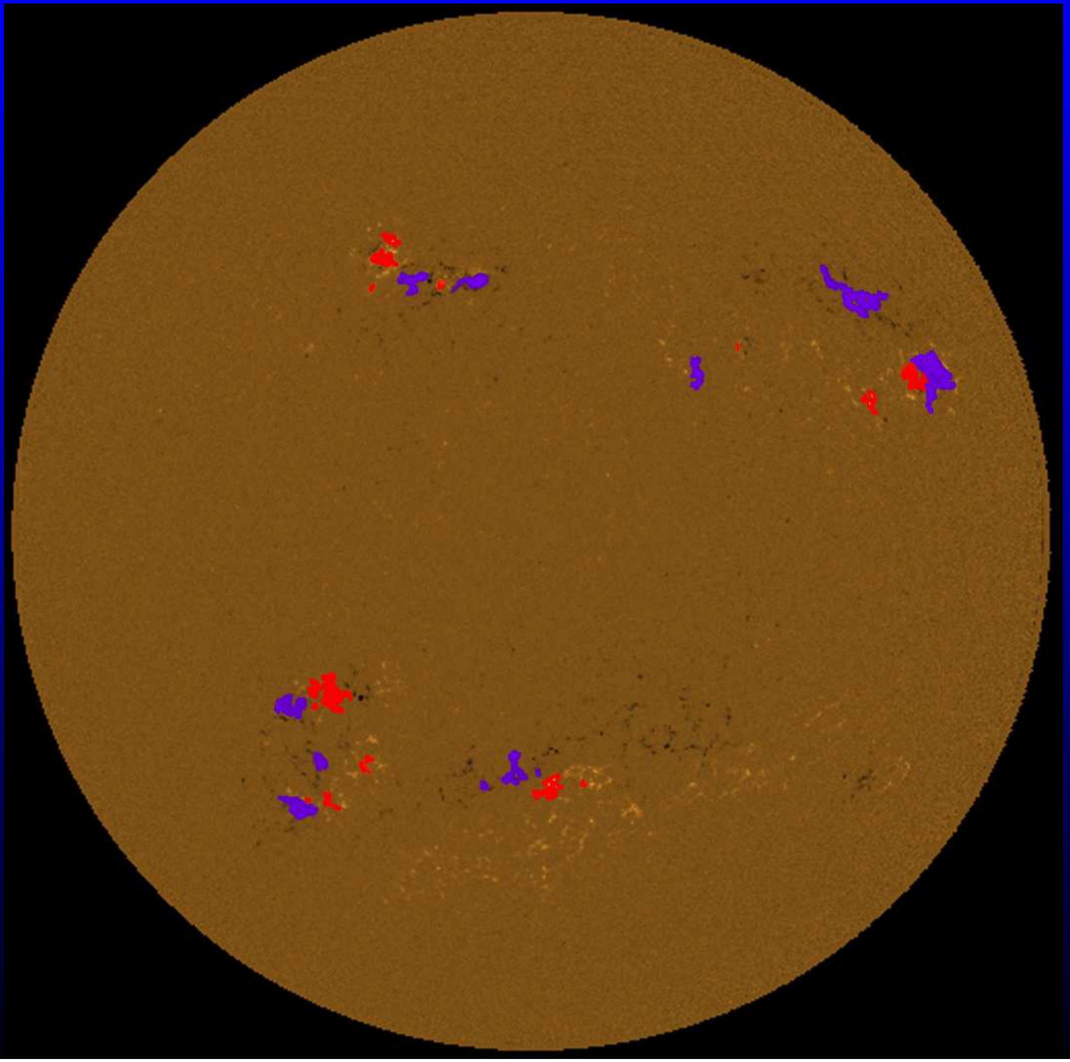
- Imagine that the Sun has a well ordered magnetic field with field lines passing through the surface material.
- The equator of the Sun rotates in around 26 days, but nearer the poles it rises to ~36 days.
- This causes the magnetic field to be wound up – like an elastic band.
- Eventually it “bubbles” outwards and bursts through the photosphere.
- One gets pairs of sunspots where the field line first break out and then re-enter the Sun.

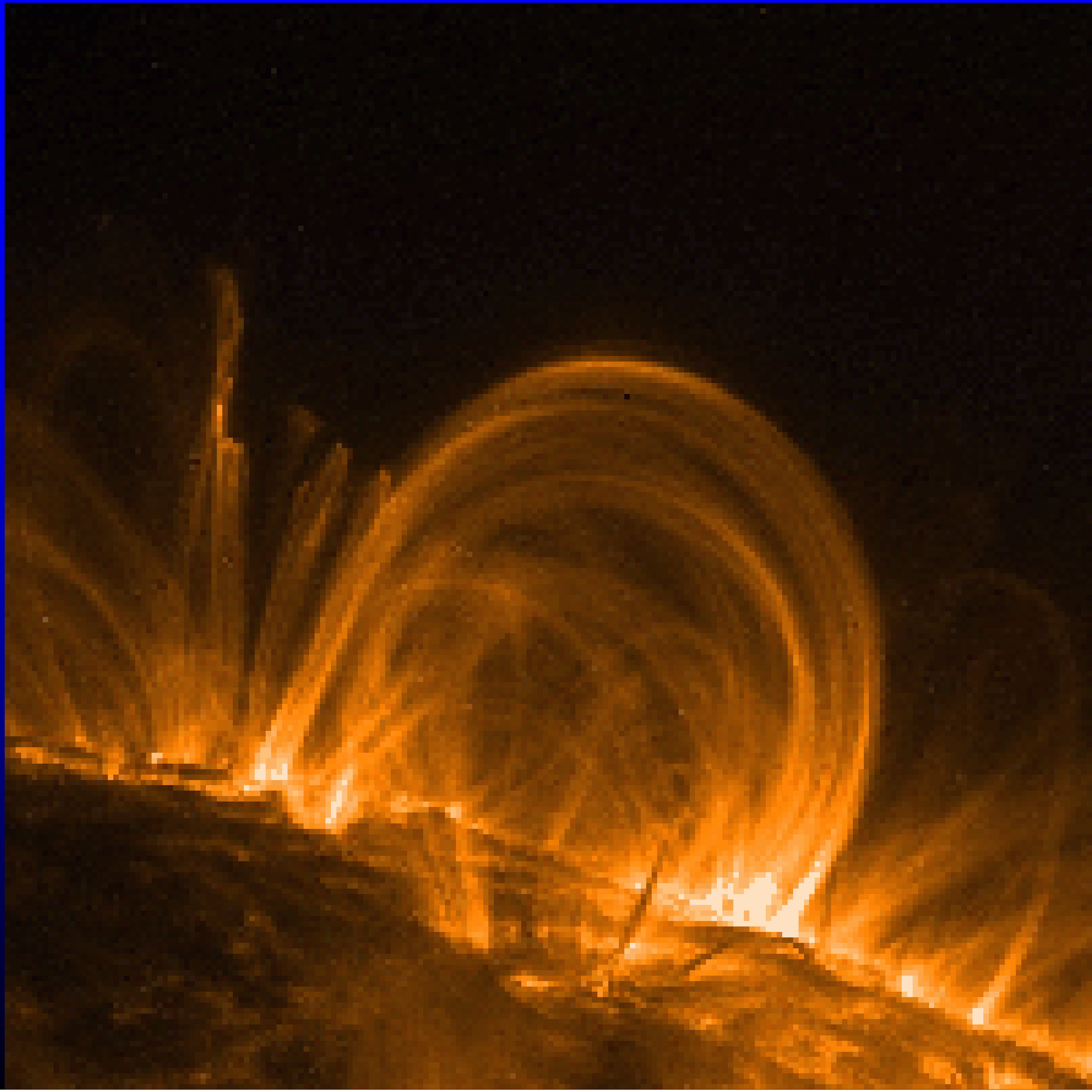

N
S
Day 0
N
S
Day 35
N
S
Day 105



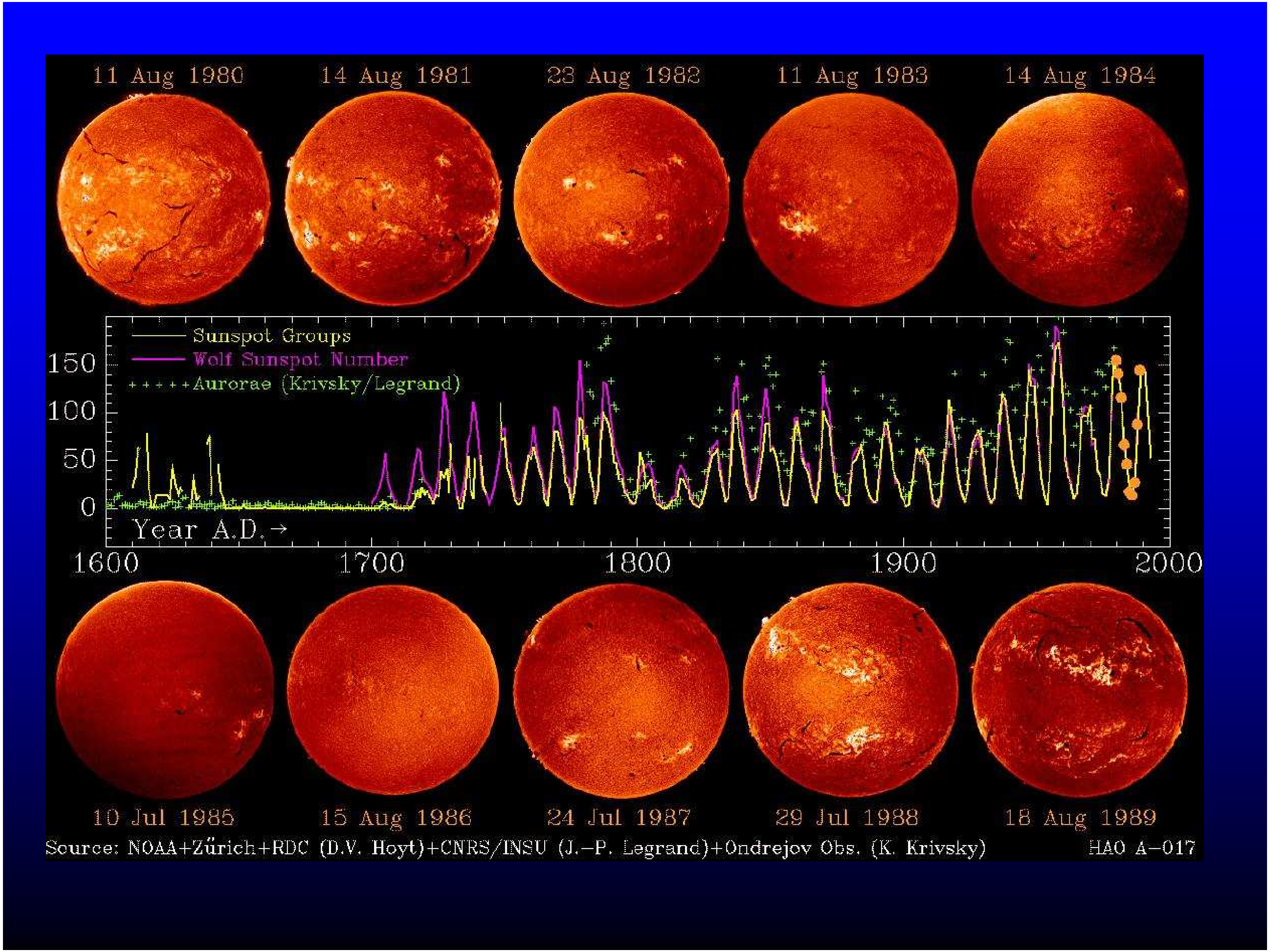

Magnetic field lines
S
Sunspot pair
N
North pole
Solar rotation
S
N
S
N
N
S
S
N
Magnetic field lines
South pole
(a)
(b)
R I V U X G

# Pairs of spots have opposite polarity
# In opposite sense in lower hemisphere

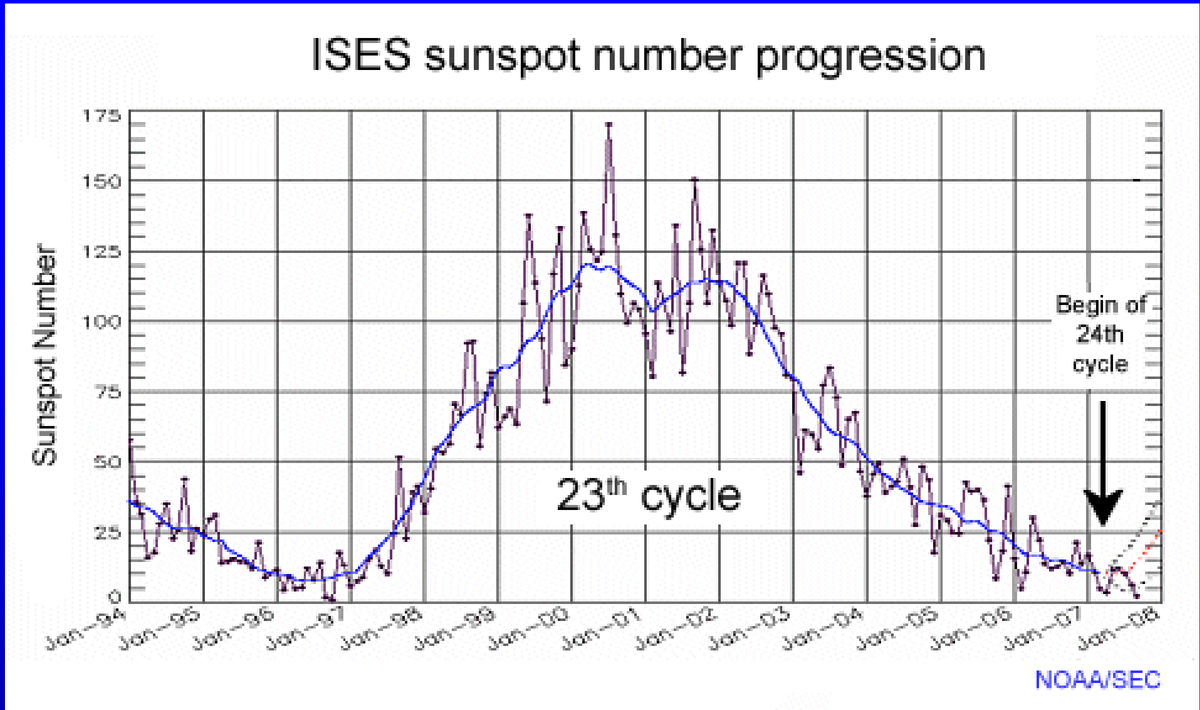




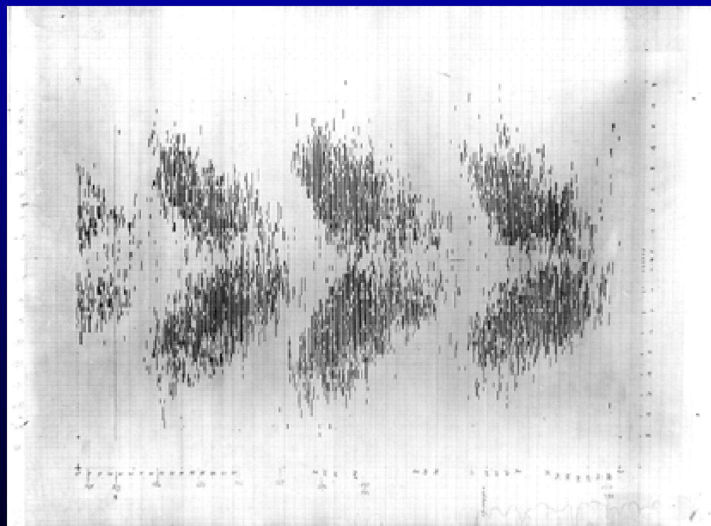
- The magnetic field finally begins to break up and the number of sunspots reduces to SOLAR MINIMA.
- The magnetic field then builds up again – but with opposite polarity – and the number of sunspots increases to SOLAR MAXIMA.
- The period between solar maximums is ~ 11 yrs – the Sunspot Cycle - though the sequence only exactly repeats every 22 yrs due to to field polarity change.  (Currently nearer 21 years per cycle)



11 Aug 1980
14 Aug 1981
23 Aug 1982
11 Aug 1983
14 Aug 1984
Sunspot Groups
Wolf Sunspot Number
+++++Aurorae (Krivsky/Legrand)
150
100
50
0
Year A.D.→
1600
1700
1800
1900
2000
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

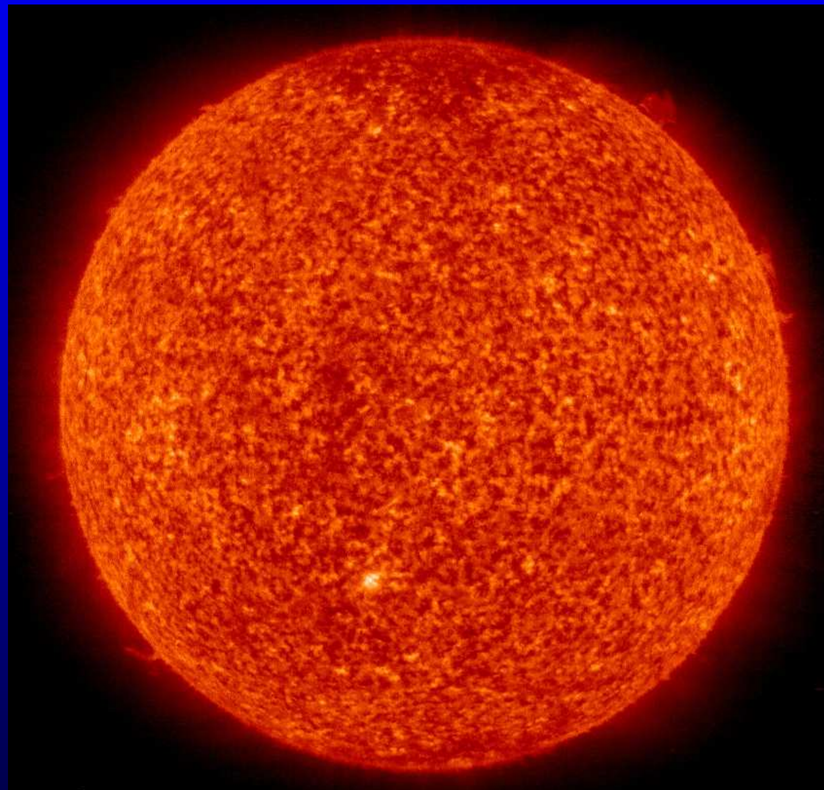



- Towards solar maximum the sunspots migrate towards the equator – giving rise to the butterfly diagram



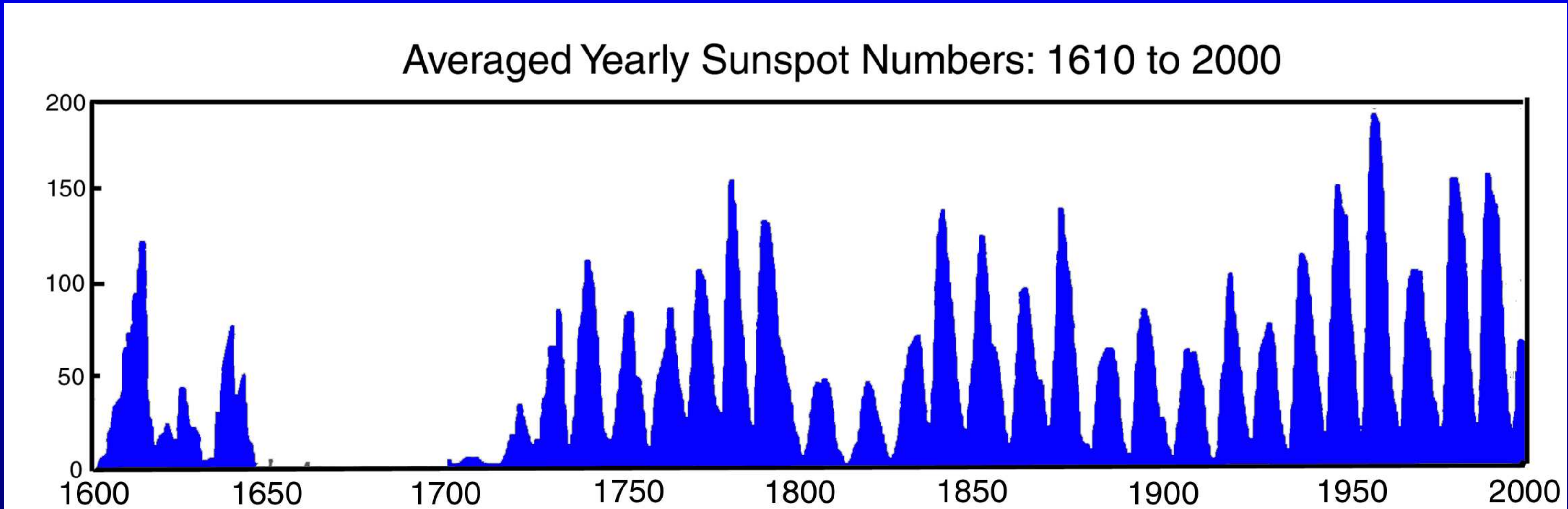
# October 6th 2008


Visible



Hα

# Maunder Minimum

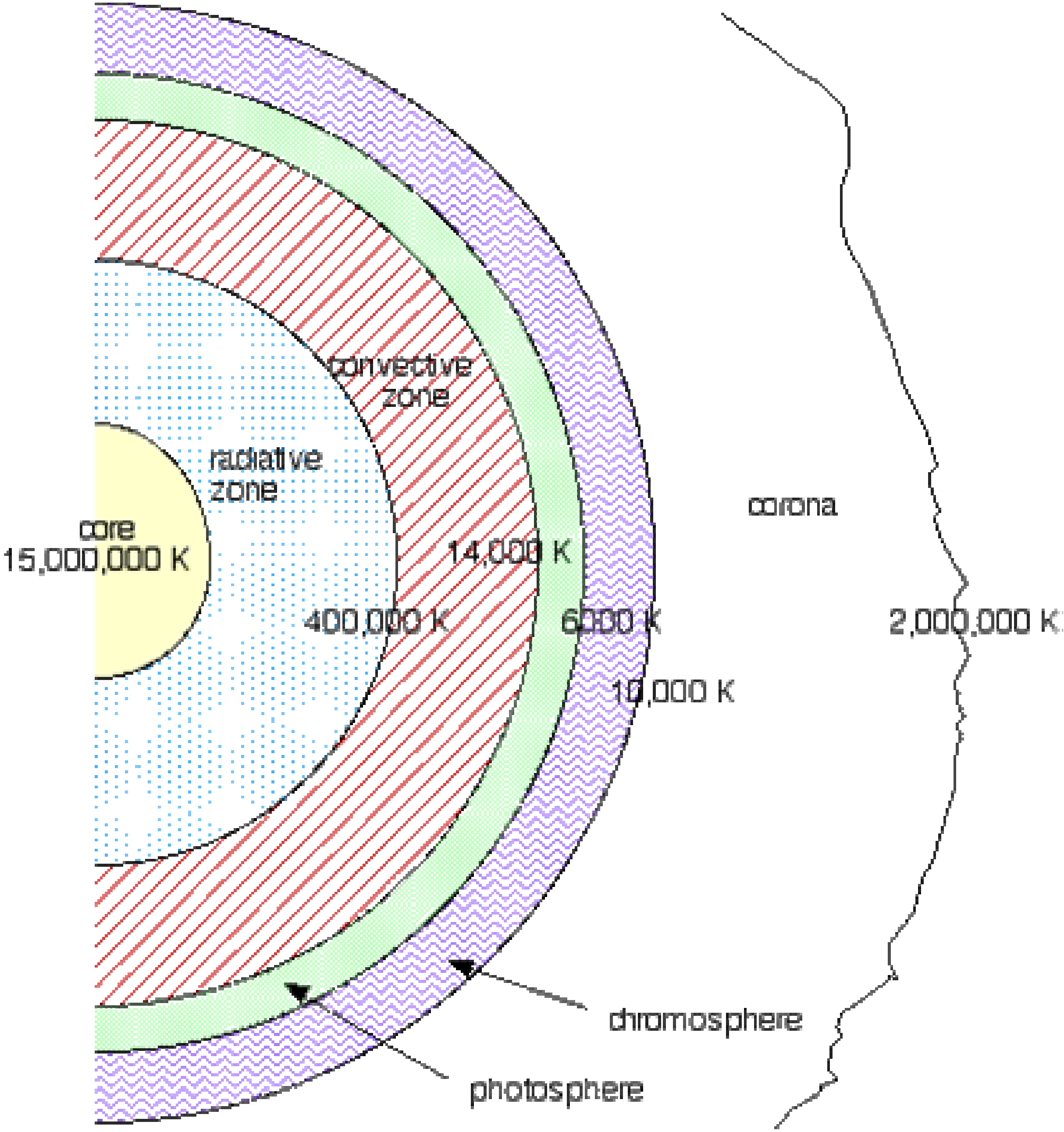


# Sunspots

- Regions where the Sun's magnetic field  breaks through the surface.
- This prevents heat flow, so these regions are ~ 1000K less than the average photospheric temperature – hence look dark.
- The magnetic field lines can rupture releasing vast amounts of energy which can propel clouds of charged particles out into space – solar flares.
- Sometimes these can interact with the Earth, disrupting power grids and communications.

# The Sun’s Atmosphere

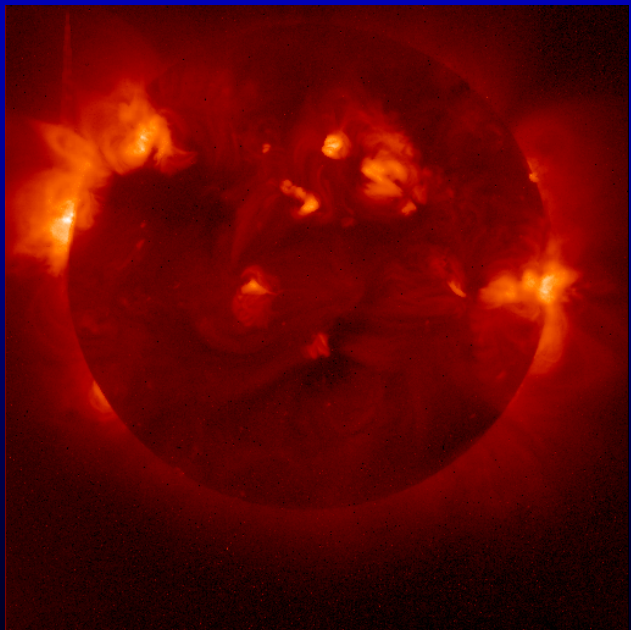
- We see the surface – The Photosphere – at a temperature of  5800K.
- Above it lies the Chromosphere – about 2000  km thick and at a temperature first dropping from 6000K to 4000K and then rising to 10000K.
- Above this lies the Corona stretching out for many thousands of km starting where there is an abrupt rise in temperature to ~50000K then increasing up to ~ 1 million K.
- We do not fully understand how such high temperatures arise ( energy transport by magnetic fields?)

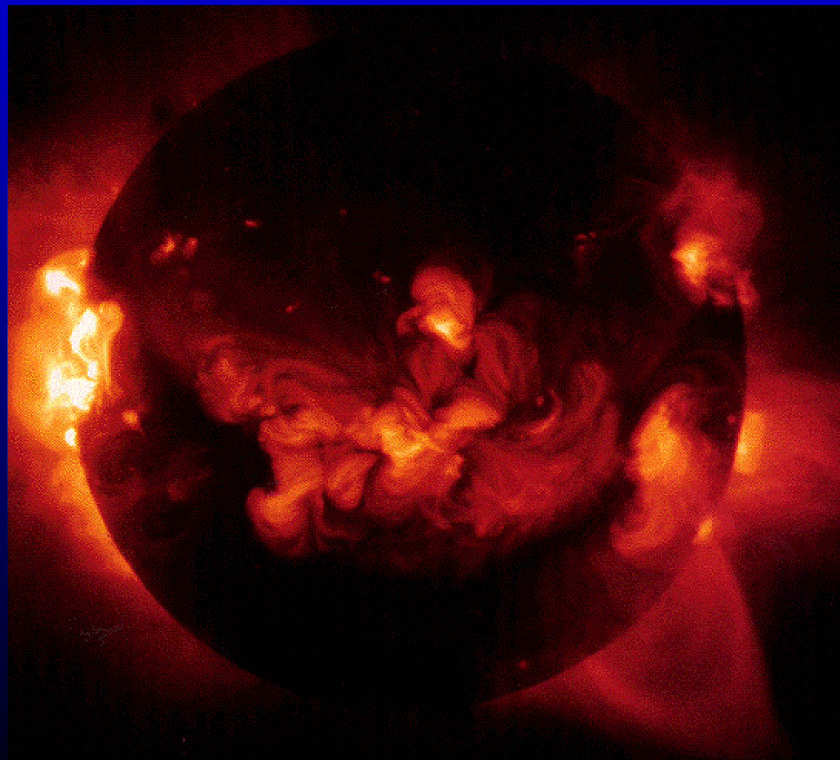


convective zone
radiative zone
core
15,000,000 K
14,000 K
400,000 K
6000 K
10,000 K
corona
2,000,000 K
chromosphere
photosphere

# The Corona

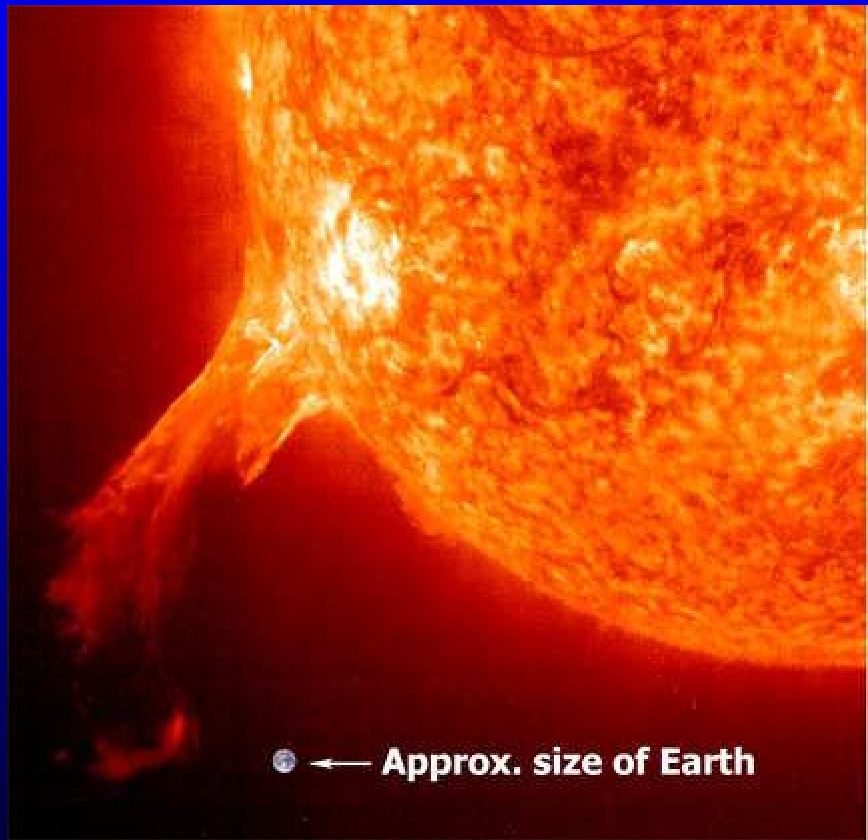
- At temperatures of 1 million K or more, X-ray photons are emitted so we can observe the Sun in X-rays.



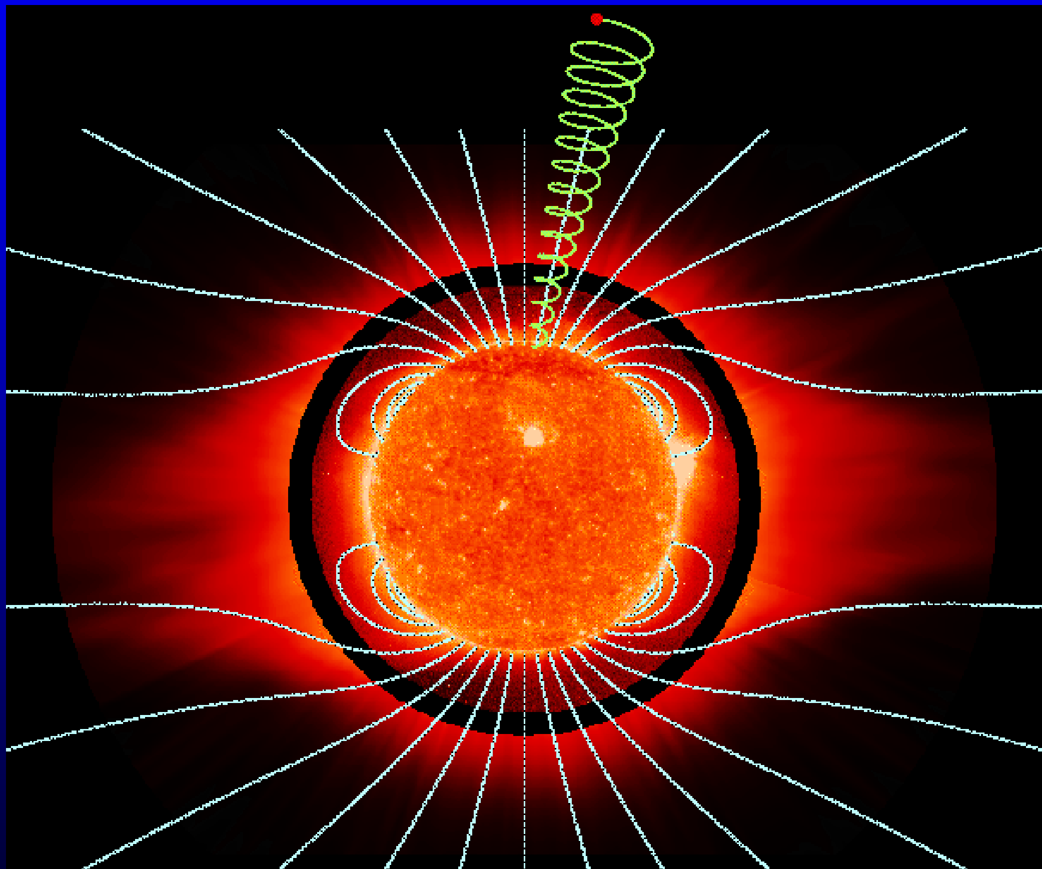


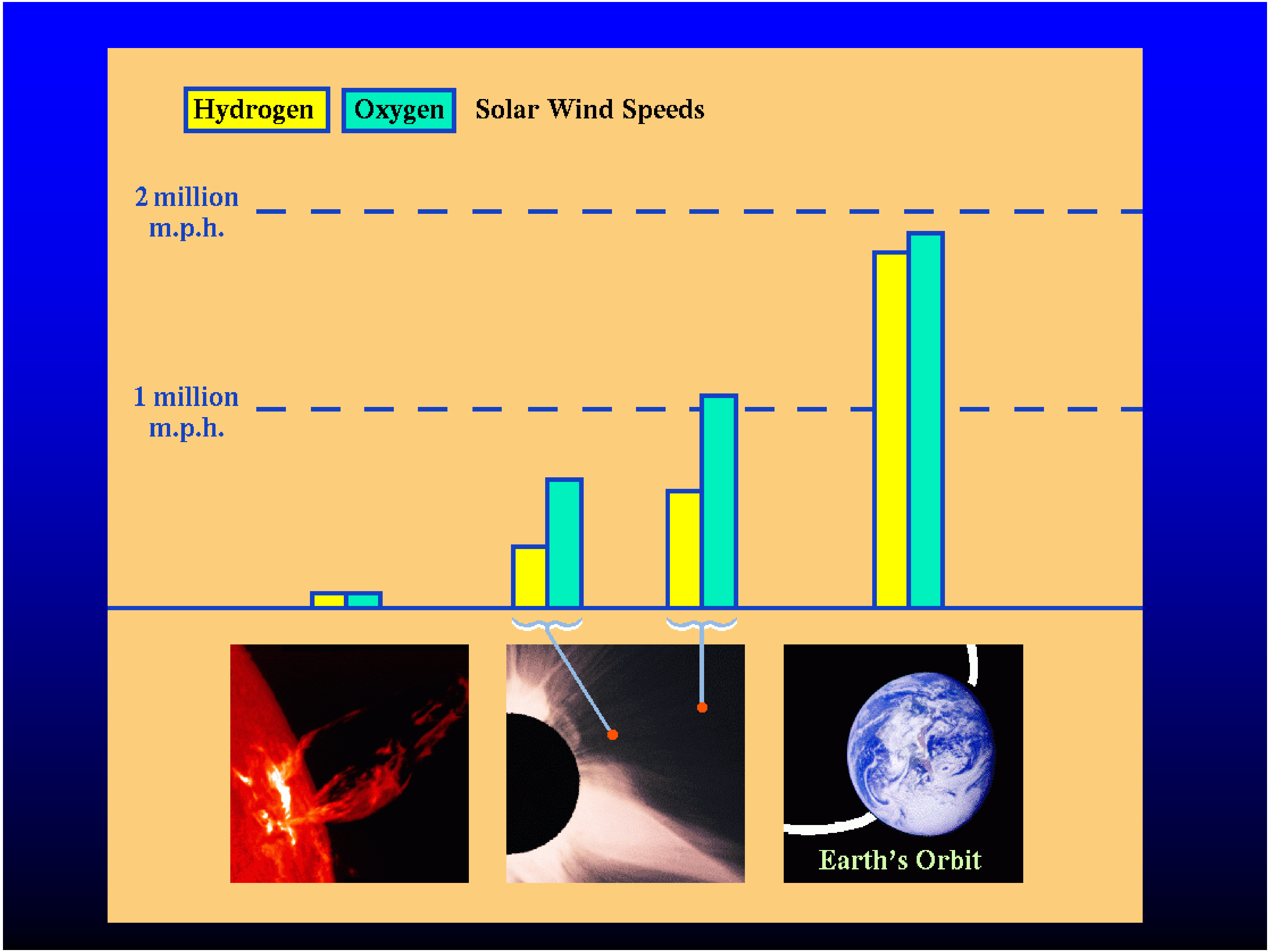
# A Prominence

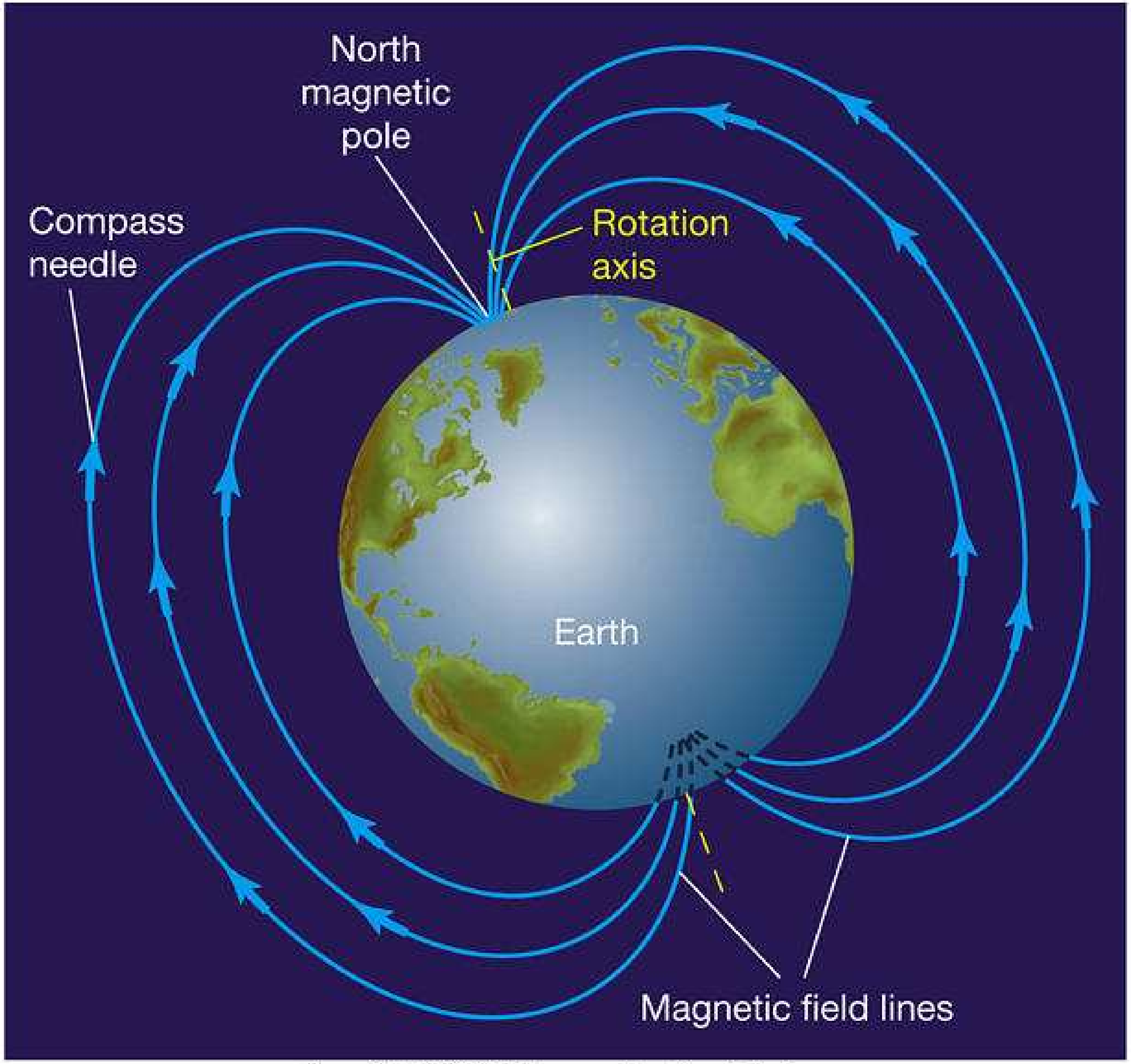
# A Solar Flare

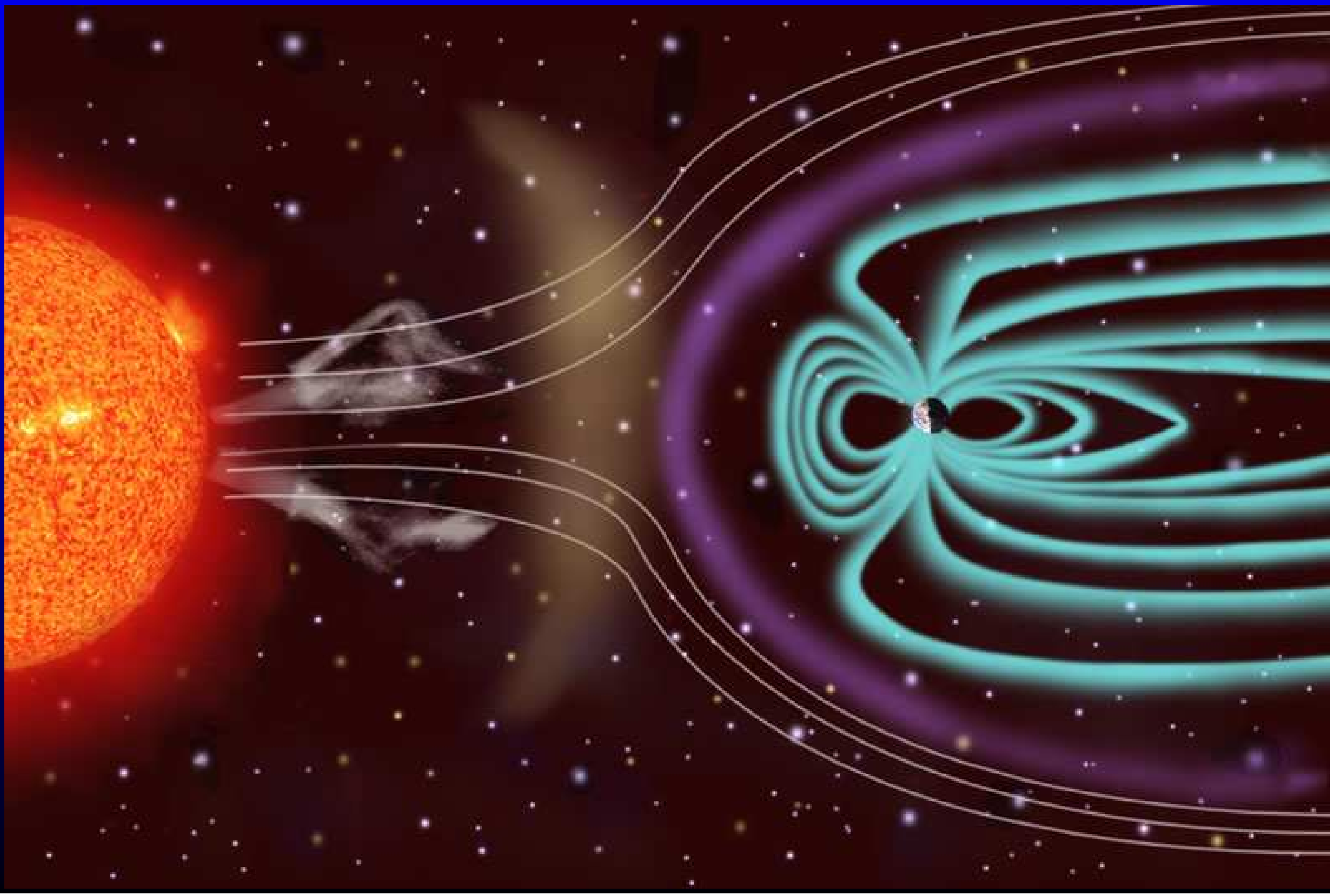


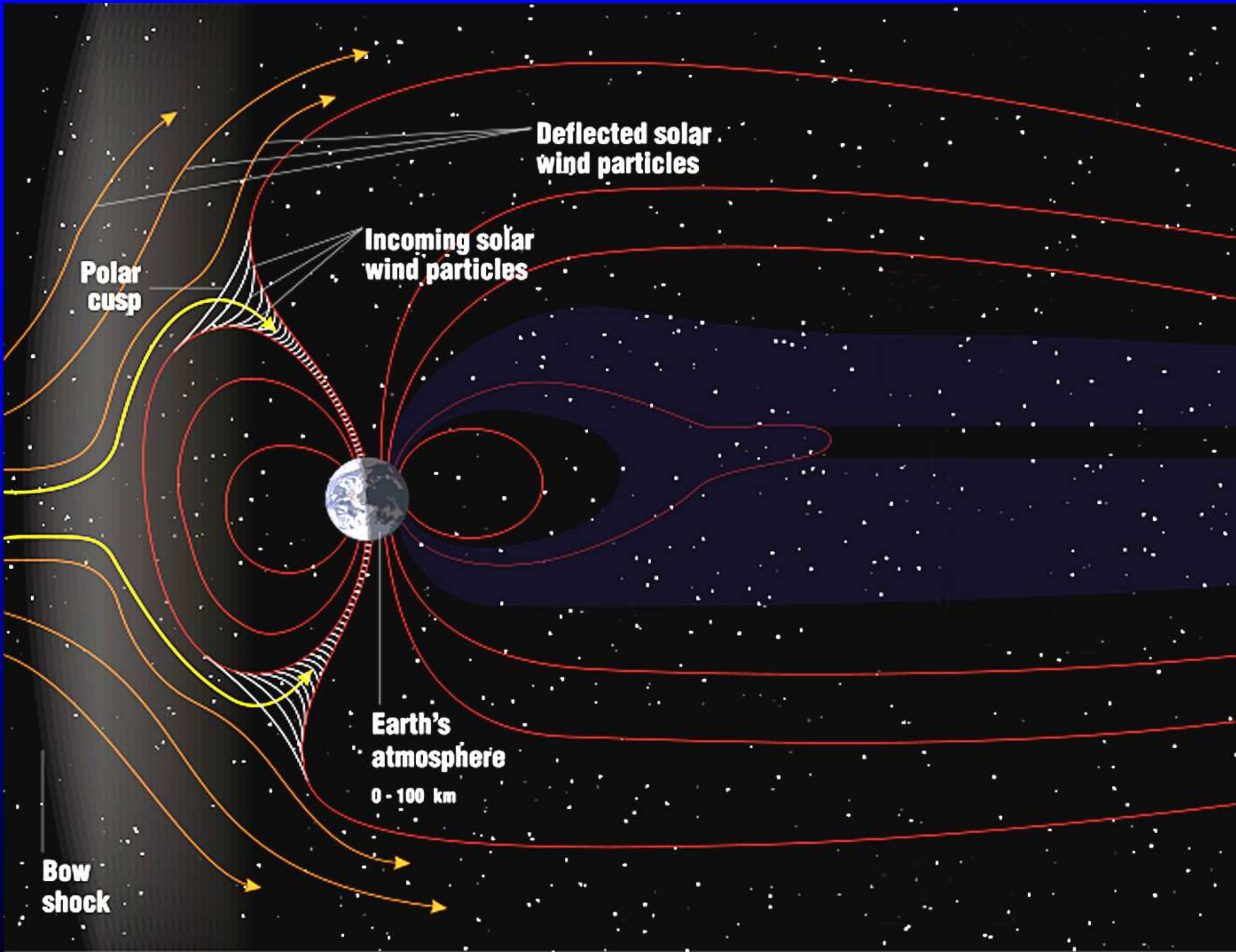
# The Solar Wind



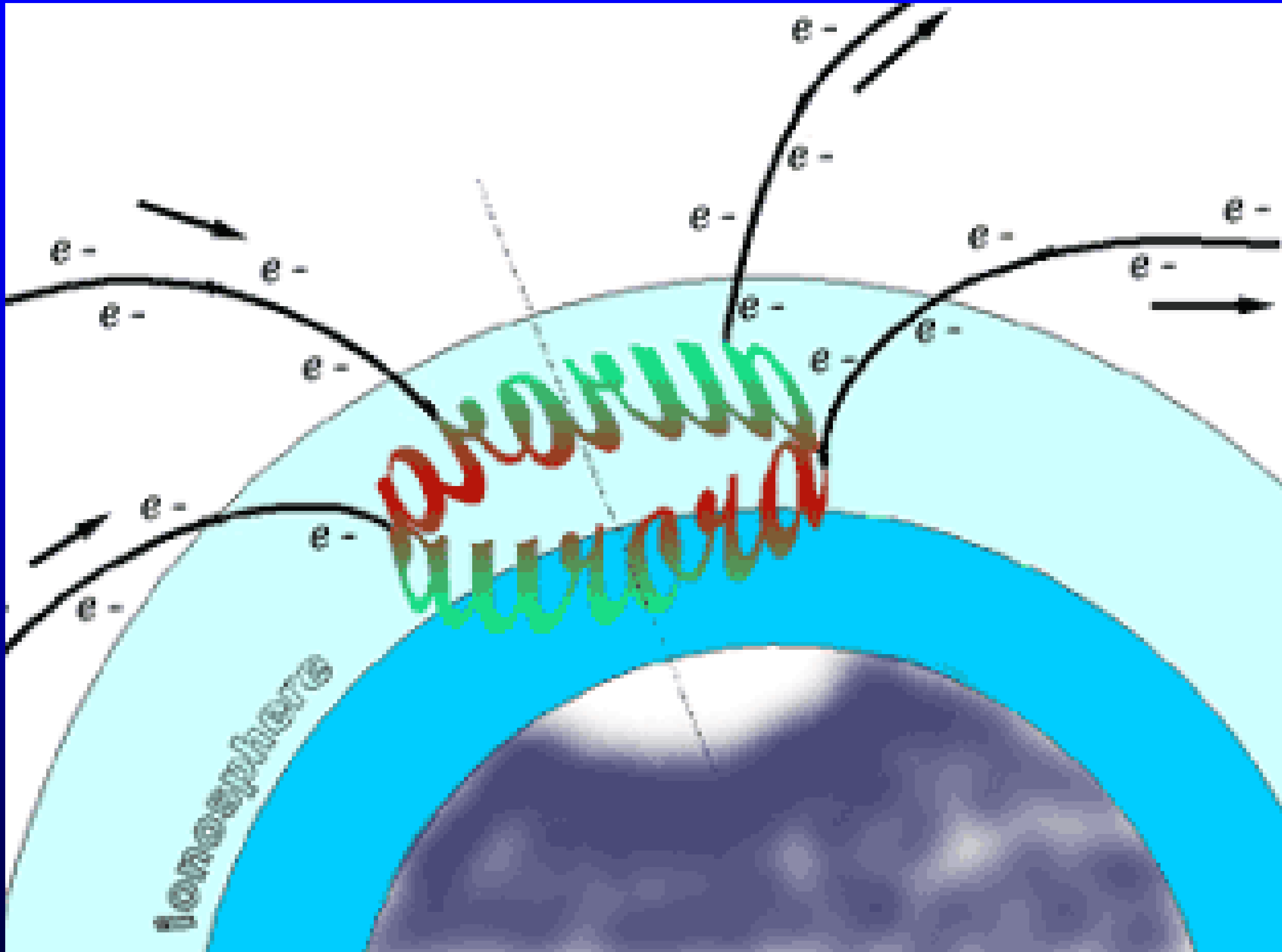

Hydrogen
Oxygen
Solar Wind Speeds
2 million m.p.h.
1 million m.p.h.
Earth's Orbit

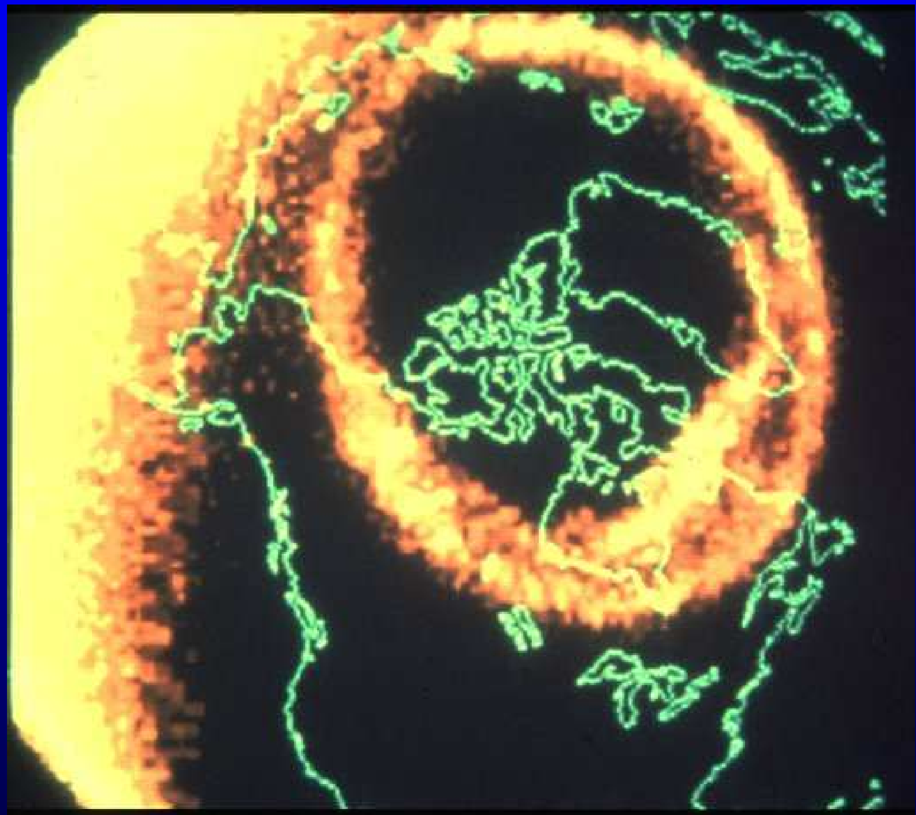

North magnetic pole
Compass needle
Rotation axis
Earth
Magnetic field lines

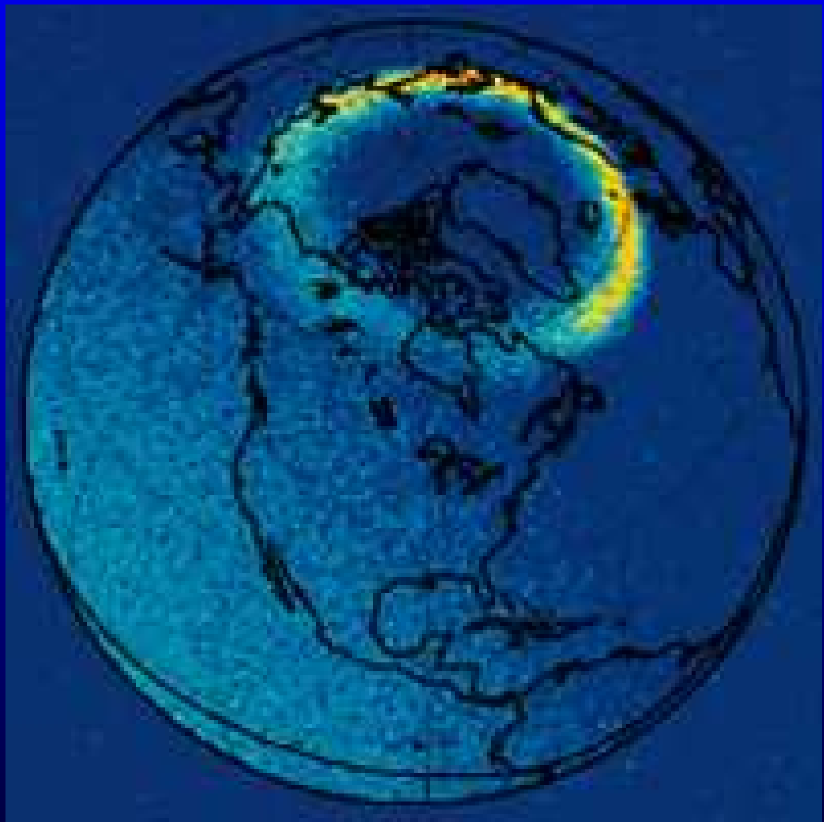


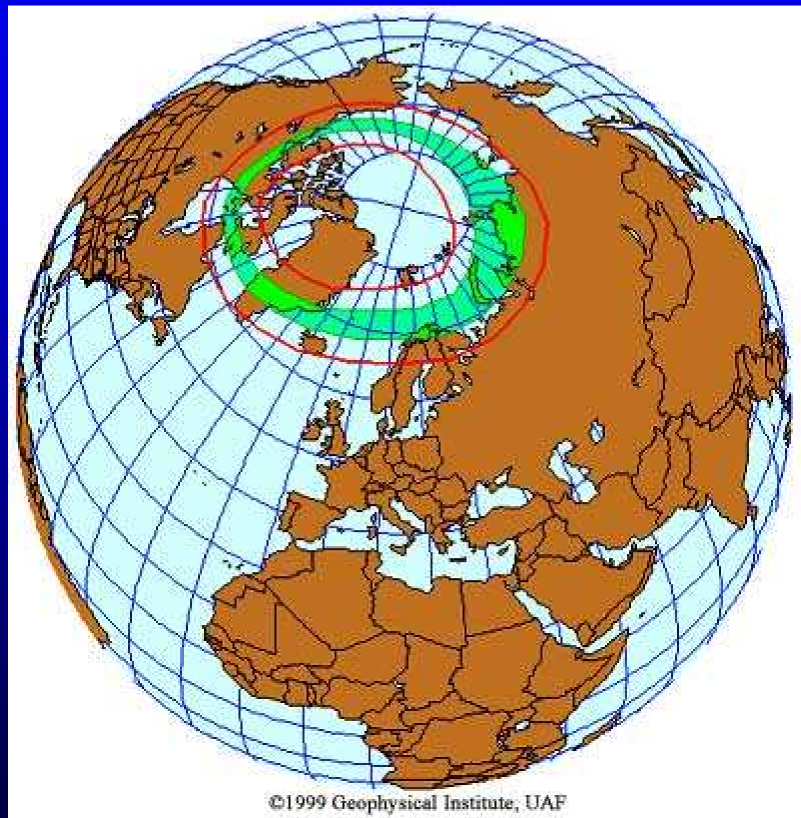


Deflected solar wind particles
Incoming solar wind particles
Polar cusp
Earth's atmosphere
0 - 100 km
Bow shock

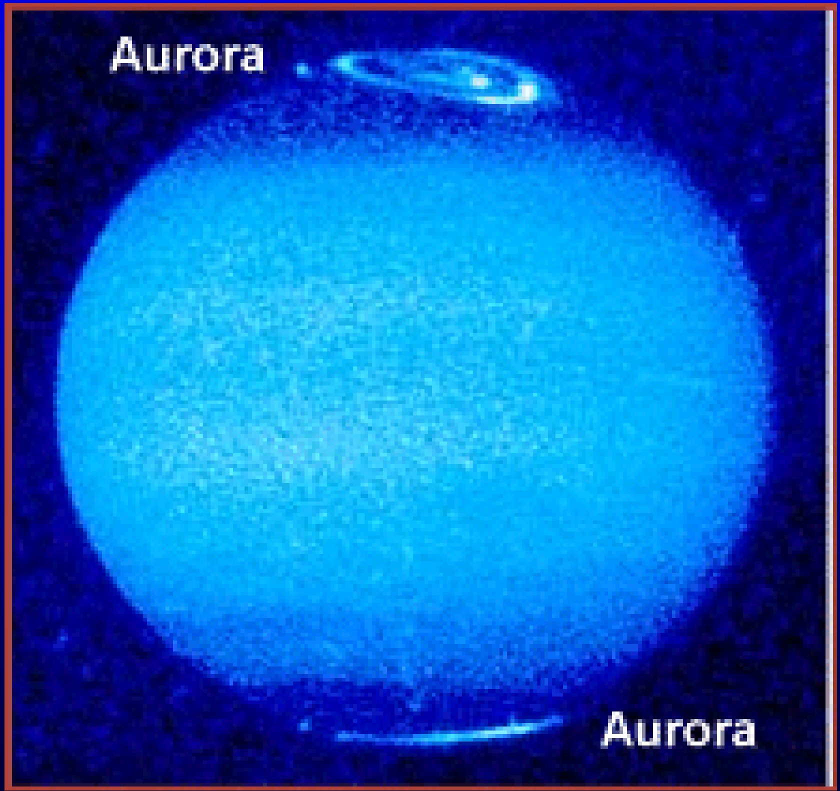

aurora
ionosphere
e -






©1999 Geophysical Institute, UAF

# Jupiter and Saturn

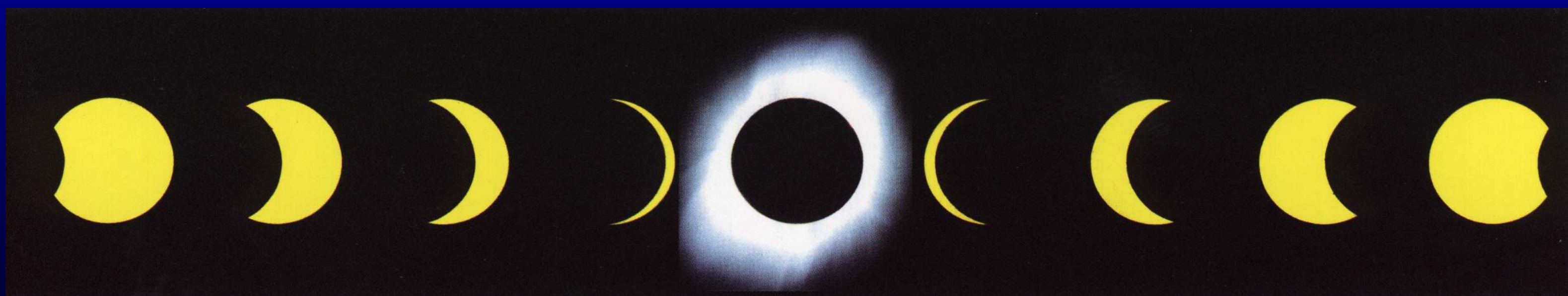




Big Dipper
Polaris
Cassiopeia

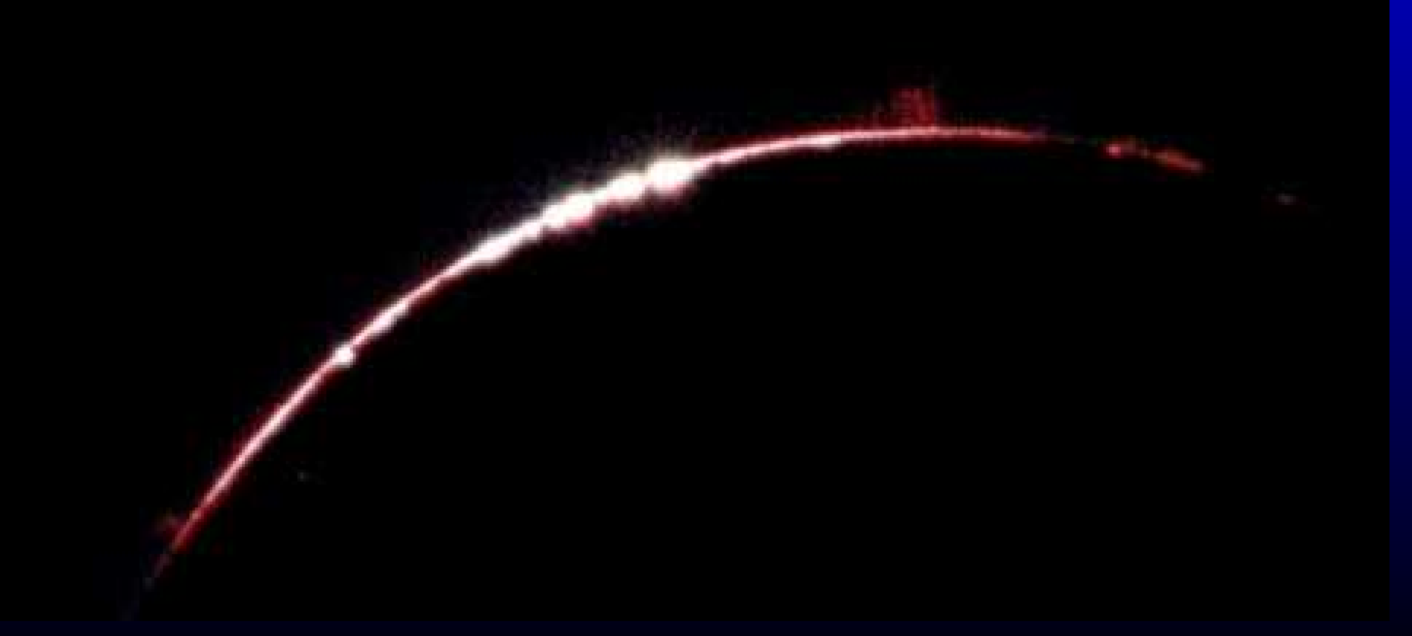
# Solar Eclipses

The Eclipse of August 11th 1999.



# Baily’s Beads

- The sun is almost covered.  The final fine sliver of sun reveals Baily’s beads.  These are points of bright sunlight glimmering between the mountain peaks on the lunar limb.



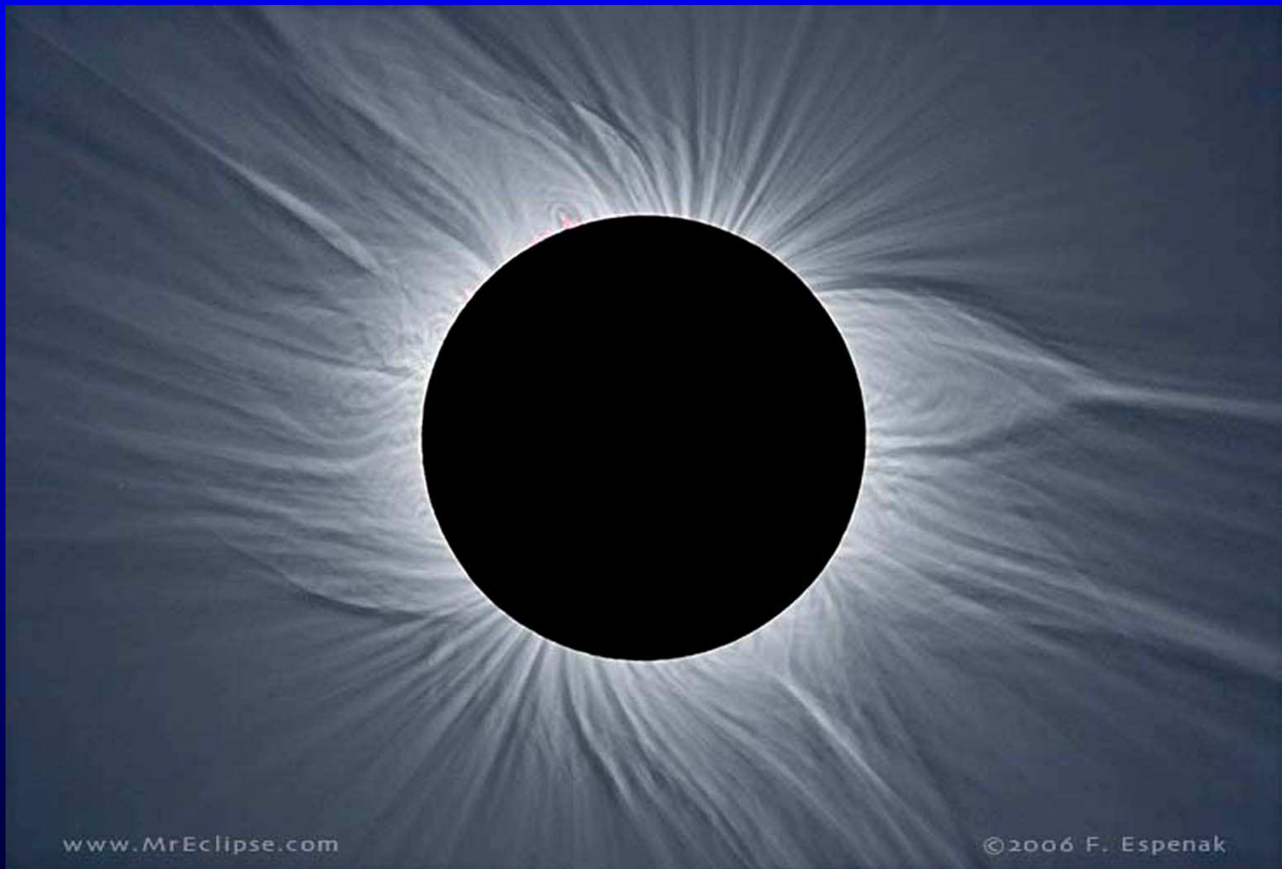
# Second Contact

- The very last burst of sunlight passes the obscuring moon. It is called the **Diamond Ring** and is perhaps the most beautiful sight of all.

# The Chromosphere

- For just a few seconds following the diamond ring the sun's Chromosphere is visible. This is the tenuous atmosphere above the sun's surface and appears as a thin pink band -due to the excited hydrogen atoms within it.

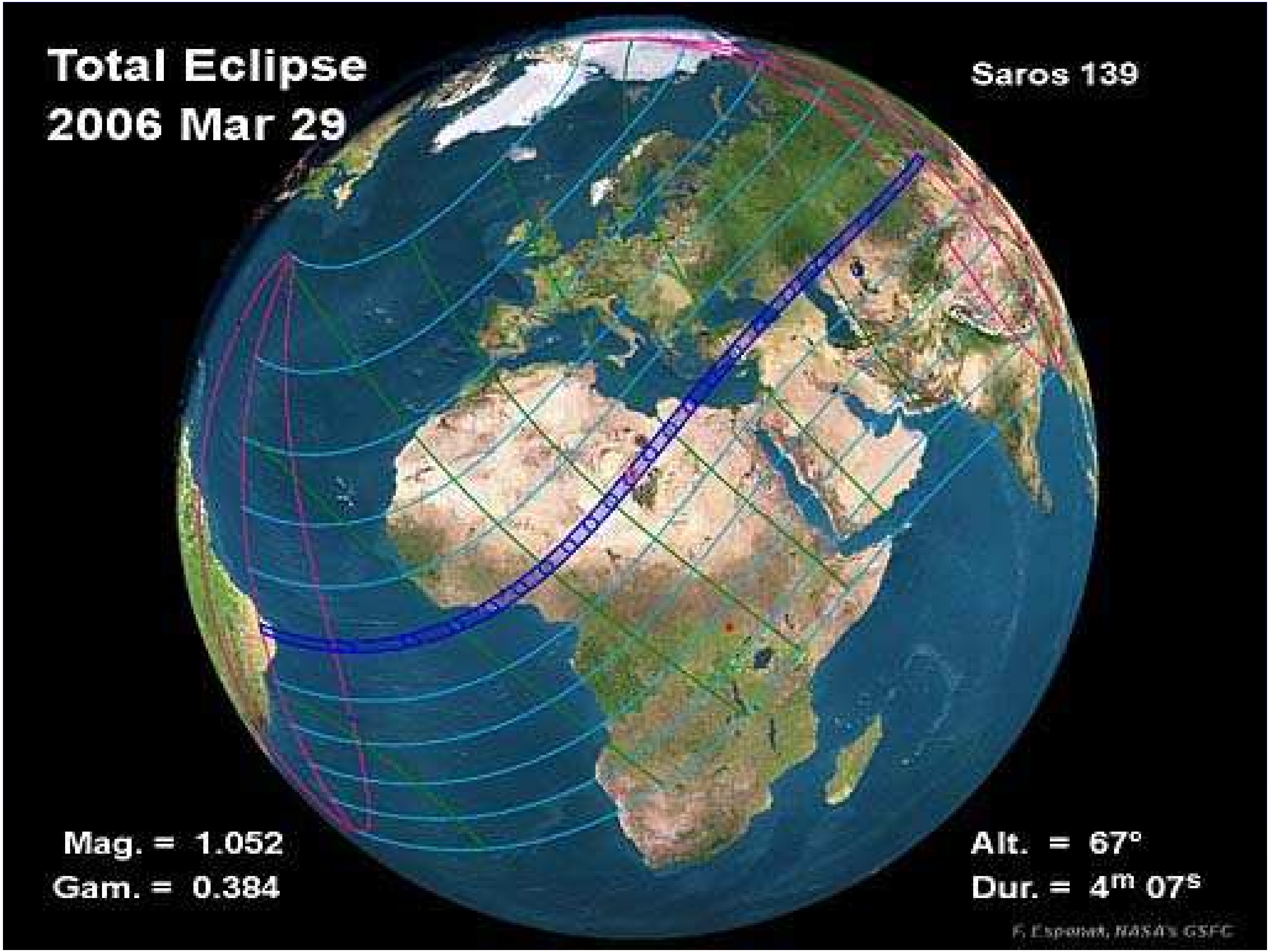
# The Solar Corona


www.MrEclipse.com
©2006 F. Espenak

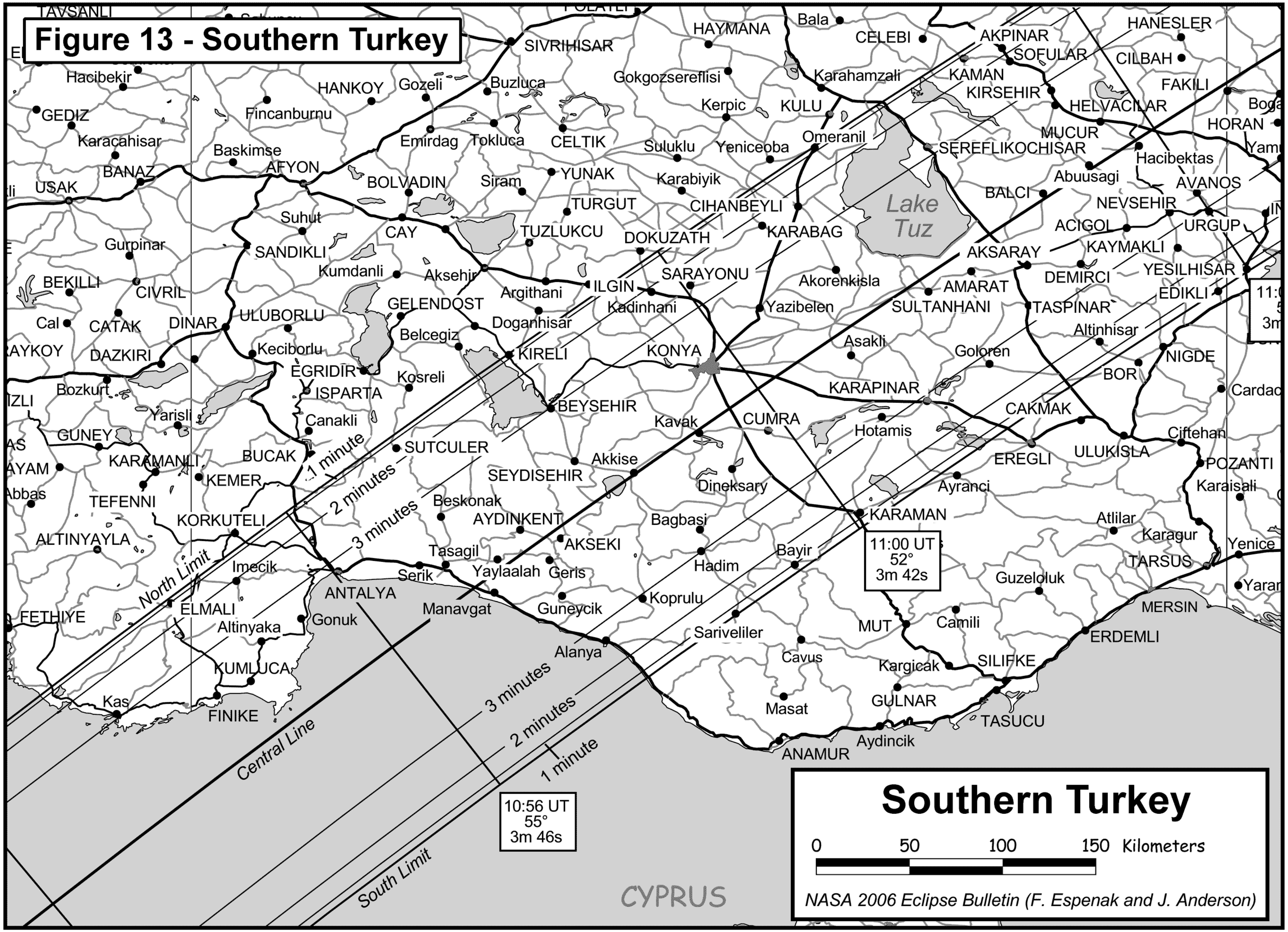
# At Solar Maximum less structure is seen.


July 11, 1991

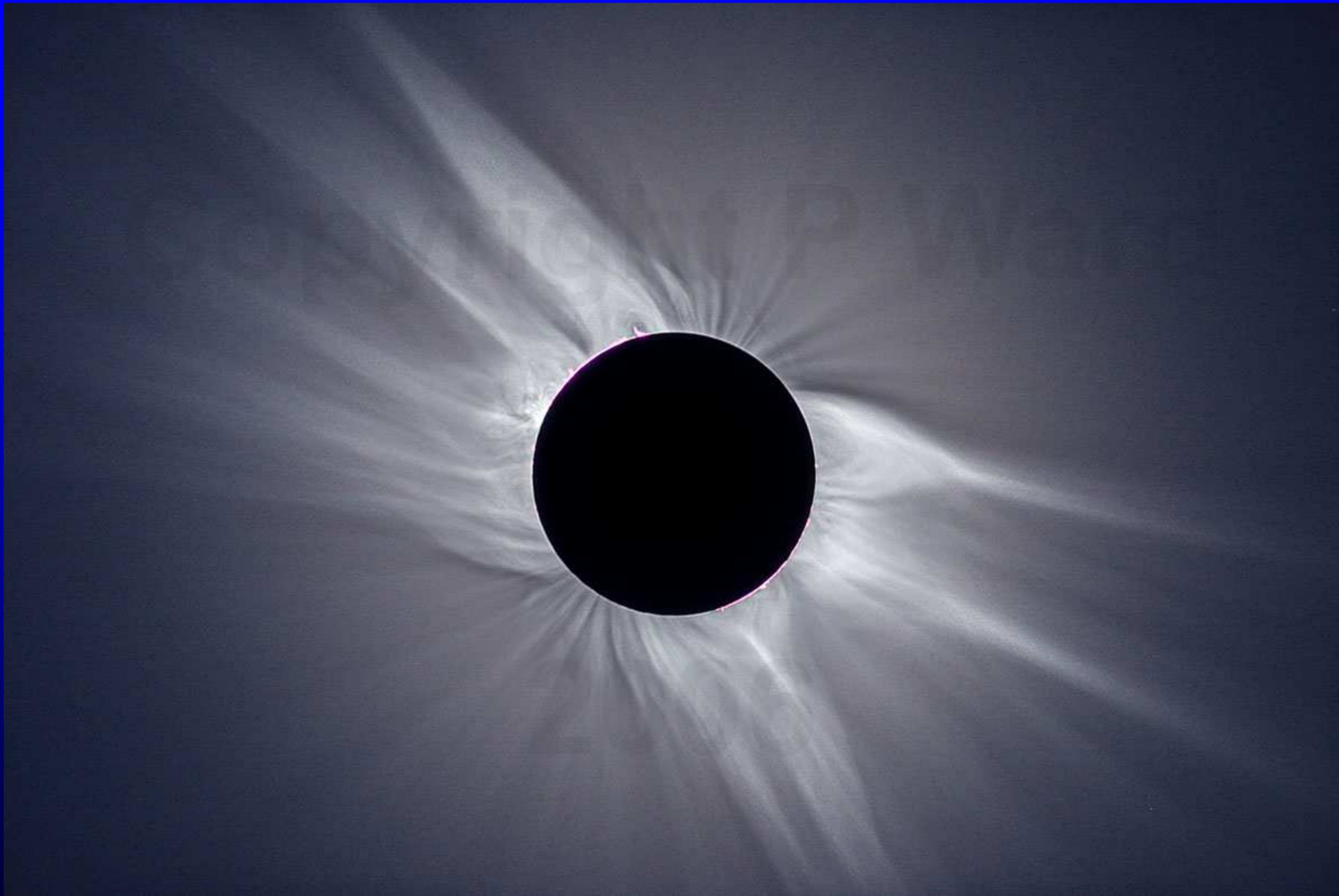

August 11, 1999

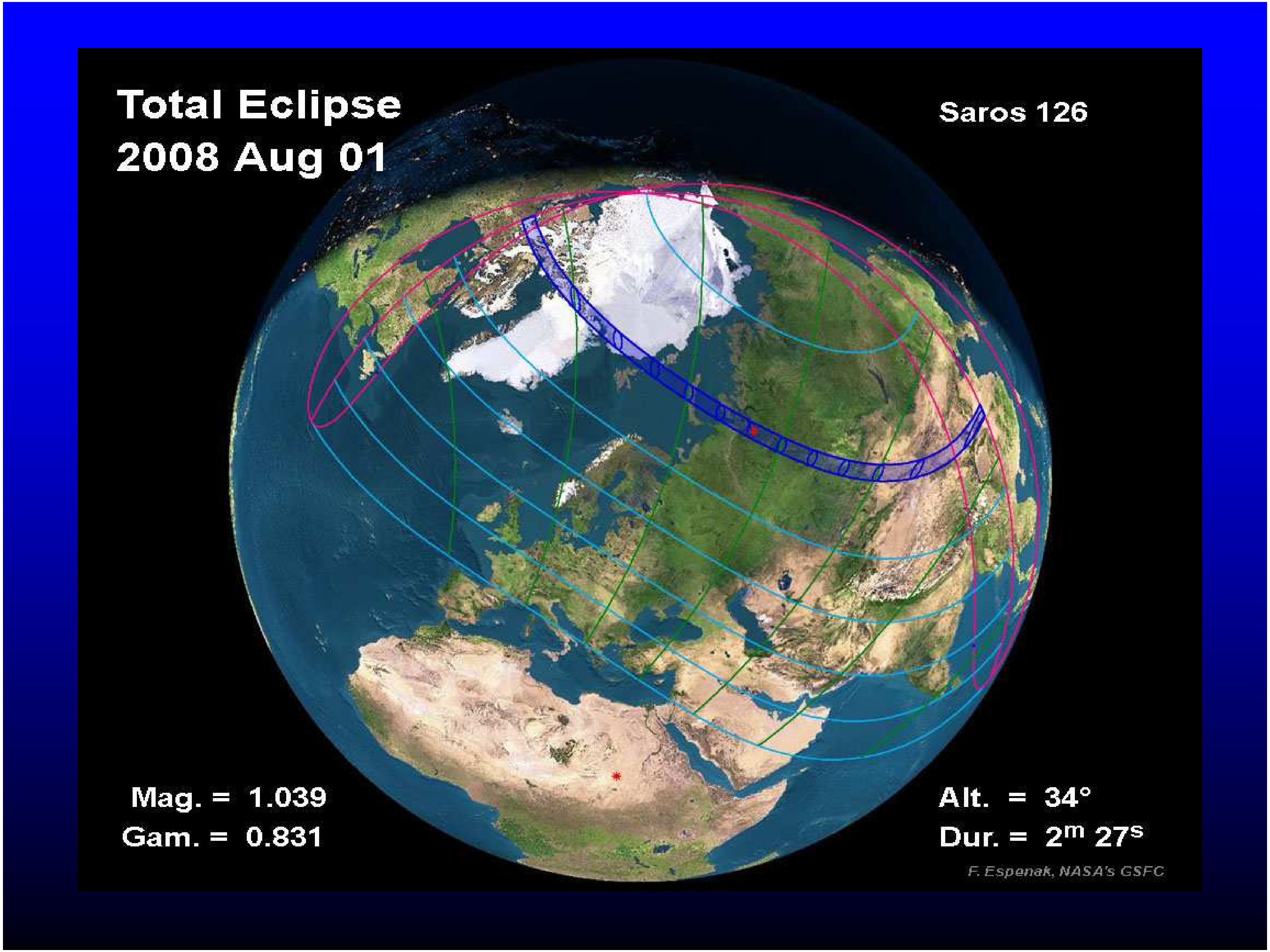

Total Eclipse
2006 Mar 29
Saros 139
Mag. = 1.052
Gam. = 0.384
Alt. = 67°
Dur. = 4m 07s
F. Espenak, NASA's GSFC

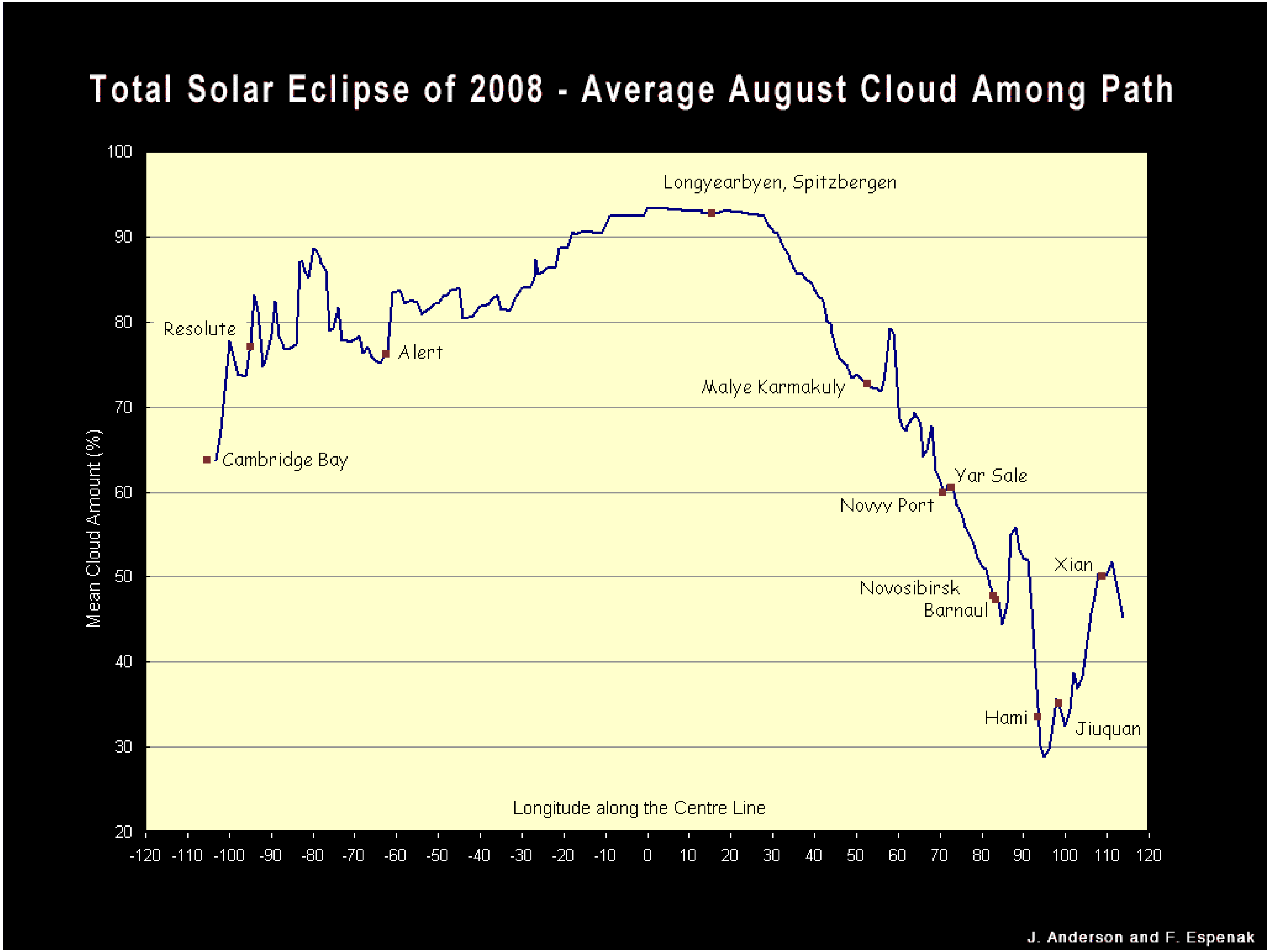
# Figure 13 - Southern Turkey



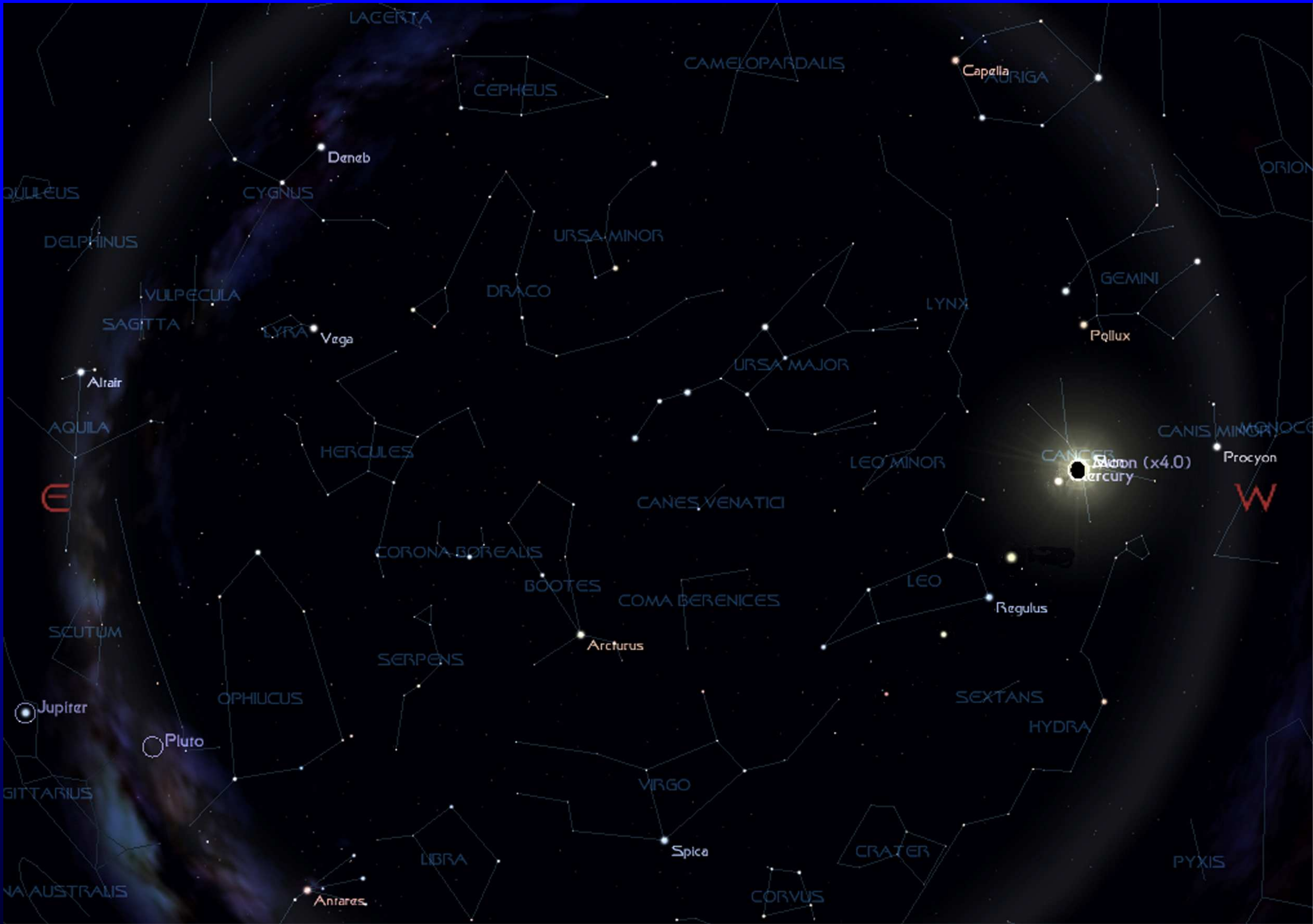
**TOTAL SOLAR ECLIPSE-2006 March 29-UT10:37:28- LIBYAN DESERT** (N 30°57'34.5" E 24°16'50.4")
Takahashi FSQ 106 (f.l. 530mm f/5) - Losmandy G11 - Nikon D2x
100 ISO - 11 photographs (from1/500sec to 2sec) processed with Photoshop
**GIANNI FARDELLI - e-mail:gianni@widepicture.com - http://www.widepicture.com**



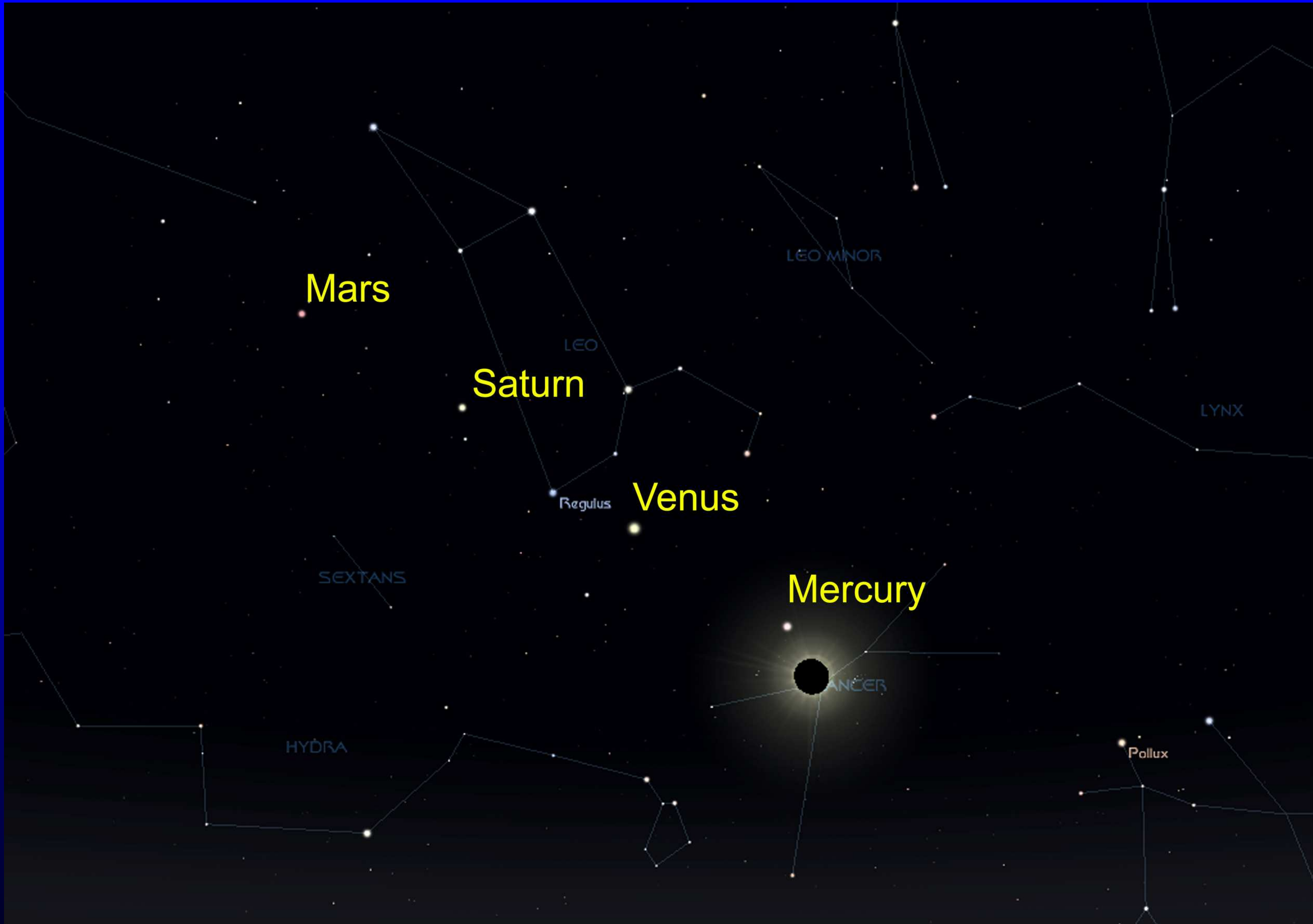

Total Eclipse
2008 Aug 01
Saros 126
Mag. = 1.039
Gam. = 0.831
Alt. = 34°
Dur. = 2m 27s
F. Espenak, NASA's GSFC



Total Solar Eclipse of 2008 - Average August Cloud Among Path
100
90
80
70
60
50
40
30
20
Mean Cloud Amount (%)
Longyearbyen, Spitzbergen
Resolute
Alert
Malye Karmakuly
Cambridge Bay
Yar Sale
Novyy Port
Xian
Novosibirsk
Barnaul
Hami
Jiuquan
Longitude along the Centre Line
-120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120
J. Anderson and F. Espenak



LACERTA
CAMELOPARDALIS
Capella
AURIGA
CEPHEUS
Deneb
CYGNUS
DELPHINUS
URSA MINOR
DRACO
GEMINI
VULPECULA
LYNX
SAGITTA
LYRA
Vega
Pollux
URSA MAJOR
ORION
Altair
AQUILA
HERCULES
CANIS MINOR
Moon (x4.0)
Mercury
Procyon
LEO MINOR
CANCER
E
W
CANES VENATICI
CORONA BOREALIS
BOOTES
COMA BERENICES
LEO
Regulus
SCUTUM
Arcturus
SERPENS
OPHIUCUS
SEXTANS
Jupiter
Pluto
HYDRA
VIRGO
Spica
CRATER
LIBRA
PYXIS
CORVUS
Antares

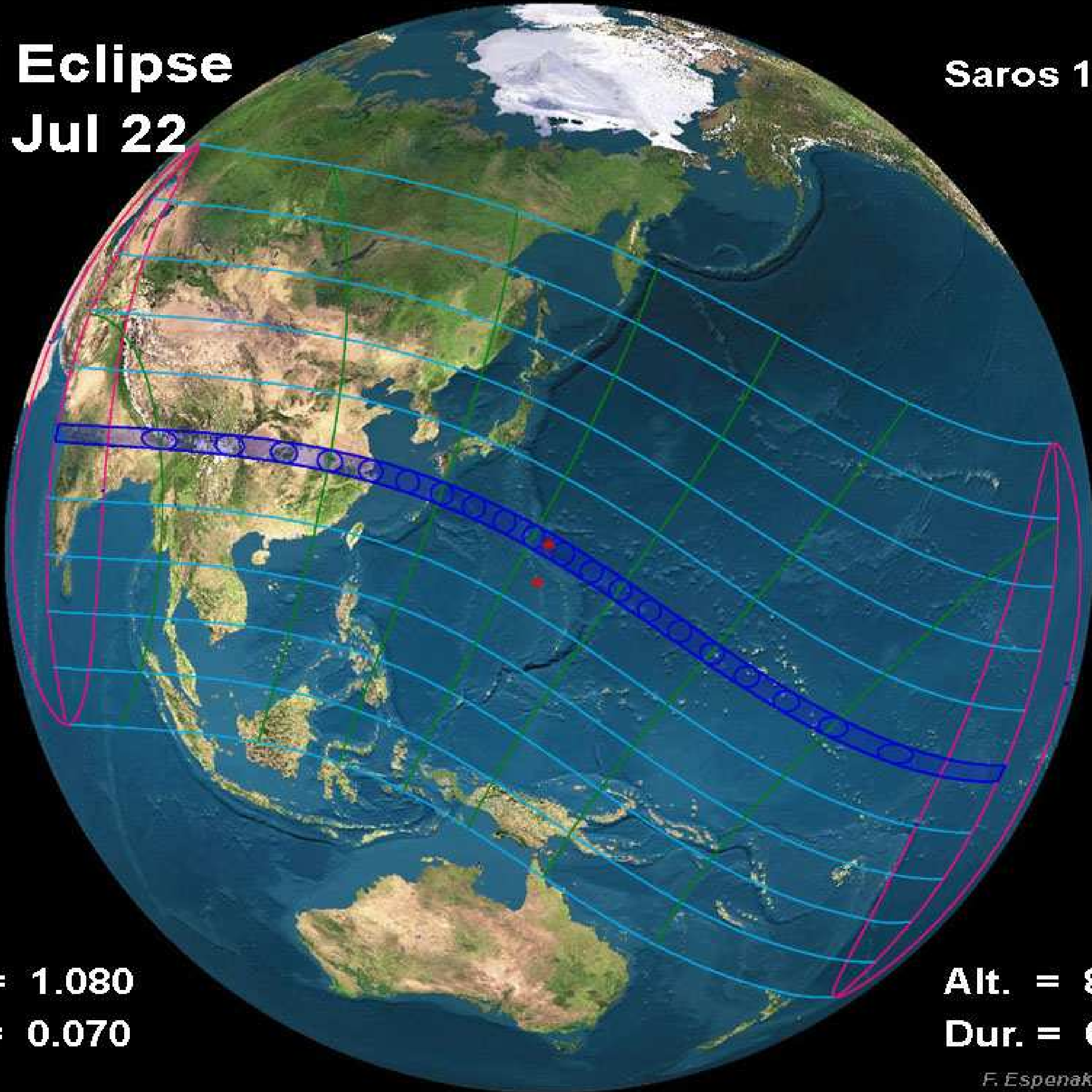


Mars
LEO
Saturn
LEO MINOR
LYNX
Regulus
Venus
SEXTANS
Mercury
ANCER
HYDRA
Pollux

Total Solar Eclipse 2008

# Total Eclipse 2009 Jul 22

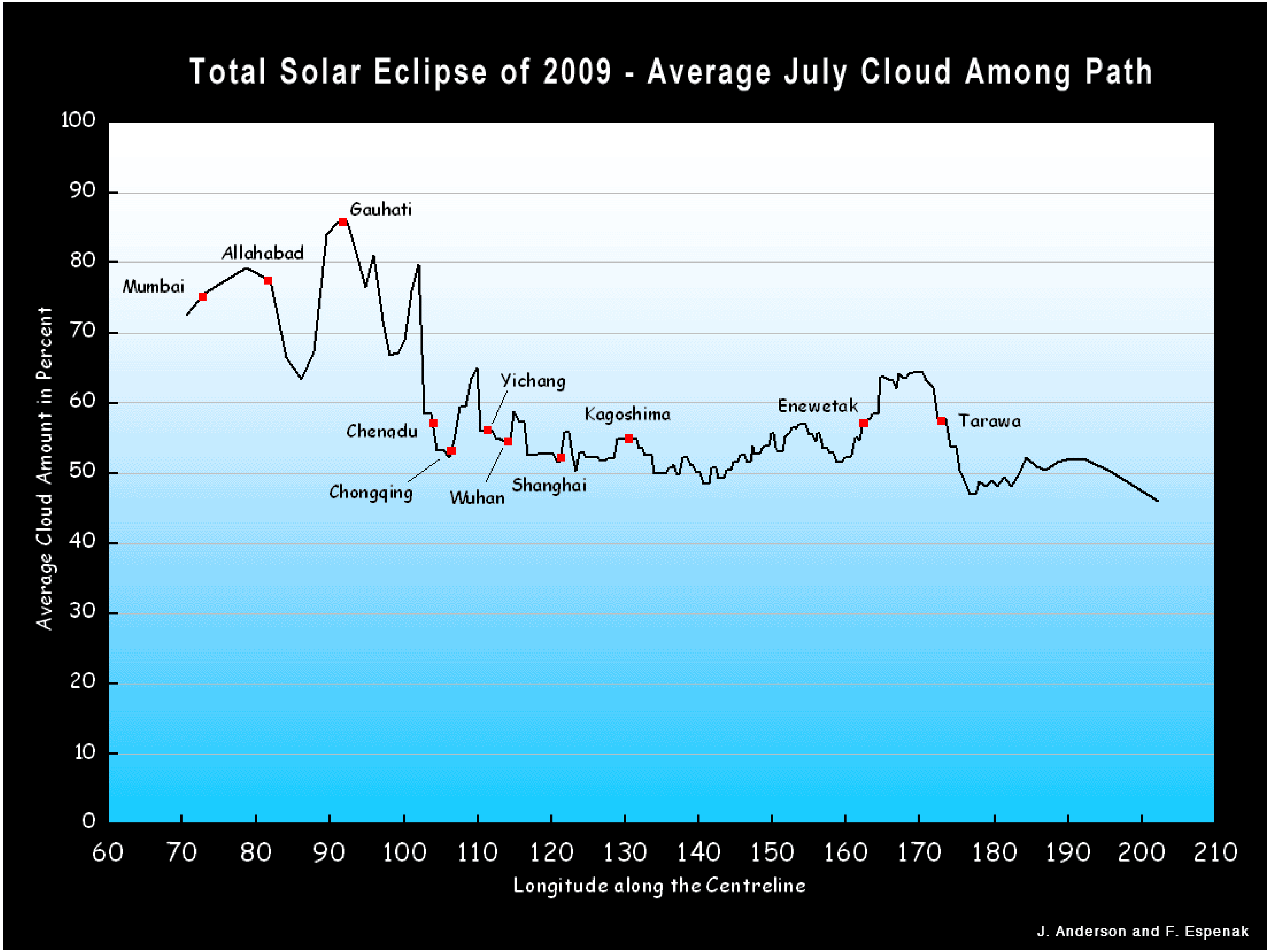
Saros 136



Mag. = 1.080
Gam. = 0.070

Alt. = 86°
Dur. = $6^m\ 39^s$

F. Espenak, NASA's GSFC



Total Solar Eclipse of 2009 - Average July Cloud Among Path
Average Cloud Amount in Percent
Longitude along the Centreline
100
90
80
70
60
50
40
30
20
10
0
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
Mumbai
Allahabad
Gauhati
Chenadu
Chongqing
Yichang
Wuhan
Shanghai
Kagoshima
Enewetak
Tarawa
J. Anderson and F. Espenak