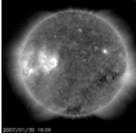


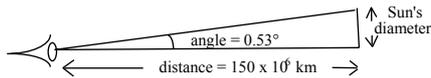
The Sun

Distance & diameter

- ★ Tiny parallax (about 8.8" arc)
- ★ Kepler's laws give only relative sizes in solar system. Scale by radar reflection from planets. Average distance from Sun 150×10^6 km
- ★ Diameter calculated from our simple triangle



↑ 2 weeks of Sun in extreme UV



Small angles:
 $\text{diameter} = \tan(\text{angle}) \times \text{distance}$
 $= 1.39 \times 10^6 \text{ km}$

Sun's Mass from Kepler's Law

- ★ Newton deduced Kepler's 3rd law in the form:

$$(M + m)P^2 = ka^3$$

M, m are masses of 2 objects
 P is period of rotation
 a is average dist between objects
 k is a constant depending on units used
 $(= 4\pi^2/G, \text{ where } G \text{ is grav. constant})$

- ☉ in this form the law can be used to compare different orbiting systems, e.g. Sun - Earth system and the Earth - Moon system

Applying Kepler's 3rd Law

$$(M_{\text{Sun}} + m_{\text{Earth}})P_{\text{Earth}}^2 = ka_{\text{Earth}}^3$$

$$(M_{\text{Earth}} + m_{\text{Moon}})P_{\text{Moon}}^2 = ka_{\text{Moon}}^3$$

- ☉ take the ratio of these relationships
- ☉ ignore m terms (i.e. $M + m \rightarrow M$) and rearrange:

$$M_{\text{Sun}} = \frac{a_{\text{Earth}}^3}{a_{\text{Moon}}^3} \times \frac{P_{\text{Moon}}^2}{P_{\text{Earth}}^2} \times M_{\text{Earth}}$$

$$= 389^3 \times 0.0748^2 \times M_{\text{Earth}}$$

$$= 330000 \times M_{\text{Earth}}$$

$$\approx 1.97 \times 10^{30} \text{ kg}$$

Solar Radiation

- ★ **Luminosity** of a star is its total radiant energy output per second (in **watts**)
- ★ Radiant energy reaching Earth is 1380 Wm^{-2}
 - ☉ area of sphere of radius 150×10^6 km is:

$\text{area} = 4\pi r^2 = 2.83 \times 10^{23} \text{ m}^2$
 - ☉ Sun's power output = $1380 \times \text{area} = 3.9 \times 10^{26} \text{ W}$
 - ☽ notice that the same power output is spread over an area that increases as the square of the distance from the Sun. Hence the radiation received per m^2 falls off as the inverse square of the distance from the Sun

More Deductions about the Sun



- ★ The surface area of the Sun is $4\pi r^2 = 6.07 \times 10^{18} \text{ m}^2$
- ★ Hence the power per $\text{m}^2 = \text{luminosity/surface area} = 64.3 \text{ MW m}^{-2}$
 - ☉ enough power to volatilise any material we know of
- ★ Stefan-Boltzmann radiation law links power m^{-2} (E) and surface temperature (T): $E = \sigma T^4$
 - ☉ hence surface temperature of the Sun is $\sim 5800 \text{ K}$

Source of Sun's Energy

- ★ Chemical energy quite insufficient
 - ☽ "The Earth was created in the year 4004 BC" Bishop James Ussher (1581 - 1656)
- ★ Energy released in bringing mass m of a star into a ball of radius r is $\frac{3}{5}G \frac{m^2}{r}$.
 - ☉ to produce its observed radiant energy the Sun needs to shrink at only 36 m per year
 - ☽ it could do this for a few hundred million years
- ★ To produce radiation for ~ 4.6 billion years (the Sun's life so far) needs nuclear power
 - ☉ the Sun is a nuclear fusion reactor

Mass to Energy

- Energy conversion from mass to radiation is governed by Einstein's famous equation

$$E = mc^2$$
- mass required to fuel Sun is $E/c^2 = 4.3 \times 10^9 \text{ kg s}^{-1}$
- Sun's mass could last up to 15,000 billion years if all were dispersed in radiation. This doesn't happen. **Nuclear fusion** builds heavier elements from lighter ones, the products having a little less mass than the constituents. This lost mass is what appears as energy

Nuclear Concepts

- The nucleus
 - proton
 - neutron
- The players
 - ^1_1H - a proton
 - e^+ - a positron
 - γ - radiation
 - ^3_2He - helium 3
 - ^2_1H - deuterium, an isotope of hydrogen with 1 proton and 1 neutron
 - ν - a neutrino
 - ^4_2He - helium 4

Nobel Prize Winners

Ernest Rutherford
(1871 - 1937)
Radioactivity: 1908

Frederick Soddy
(1877 - 1956)
Isotopes: 1921

James Chadwick
(1891 - 1974)
Neutron: 1935

Wolfgang Pauli
(1900 - 1958)
Exclusion principle: 1945

Enrico Fermi
(1901 - 1954)
Neutron irradiation: 1938

Fred Hoyle

- Fred Hoyle in his famous 1946 paper, "The Synthesis of the Elements from Hydrogen" laid the foundations of our ideas on how stars work
 - he followed this up with a series of papers over the next 12 years describing how stellar evolution is predictable from nuclear physics
 - his popular books on Astronomy inspired many youngsters to become scientists
 - his Sci Fi novels like *The Black Cloud*, *A for Andromeda* and *October the First is Too Late* are still great stories

Links in the Proton - Proton Chain

- 2 protons make a deuterium nucleus

$$^1_1\text{H} + ^1_1\text{H} \rightarrow ^2_1\text{H} + e^+ + \nu \rightarrow ^2_1\text{H} + 2\gamma + \nu$$
 - this reaction is very hard to get going
- A deuterium and a proton make helium-3

$$^2_1\text{H} + ^1_1\text{H} \rightarrow ^3_2\text{He} + \gamma$$
- 2 helium-3 make helium-4 and 2 protons

$$^3_2\text{He} + ^3_2\text{He} \rightarrow ^4_2\text{He} + 2^1_1\text{H}$$
 - and so ^4_2He is built from H , with a surplus of energy

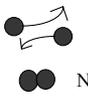
Nuclear Energy

- Proton - proton chain reaction results:

4 protons + 2 electrons \rightarrow ^4_2He + γ + ν + 26.7 MeV
- Loss of mass is about 0.7% (26.7 MeV per reaction)
 - using $E = mc^2$, energy available for 1 kg of hydrogen converted is $6.3 \times 10^{14} \text{ J}$.
 - Sun uses $6 \times 10^{11} \text{ kg s}^{-1}$ hydrogen to sustain energy o/p

Nuclear Reactions

- Two (positively charged) protons tend to repel each other
 - to make a nuclear reaction 'go', the protons have to be forced together against the inverse square law of repulsion (*another inverse square law*)
 - this needs high temperatures and pressures, found only deep within the Sun and other stars
- About 7% of H → He conversion in the Sun is achieved through the carbon cycle, using $^{12}_6\text{C}$



Protons repel

Nuclear fusion

A Digression

- “There is not the slightest indication that energy will ever be obtainable from the atom”
Albert Einstein
- “Atomic energy might be as good as our present day explosives, but it is unlikely to produce anything very much more dangerous.”
Winston Churchill in 1939




Inside the Sun

- Pressure** increases with depth into the Sun, because of the weight of material above
- Temperature** therefore also increases: $PV \propto T$
- Fusion takes place in the core of the Sun out to $0.1 \times$ radius
- The Sun is in **hydrostatic equilibrium**
 - the weight of overlying gas is balanced by the pressure of the hot gas within

Force

Pressure is force on unit area

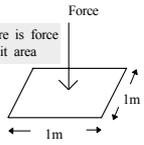
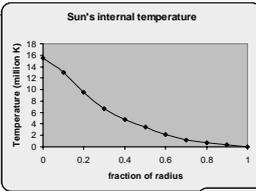


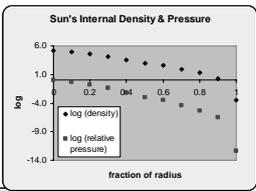


Diagram courtesy: SOHO group

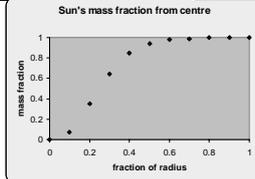
Standard Model of the Sun



↑ Central temperature reaches $>15 \times 10^6$ K



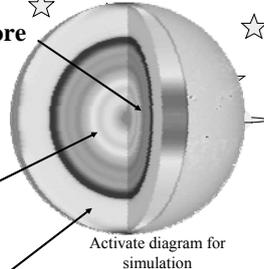
↑ Both pressure and density increase by many powers of ten towards the Sun's centre



Most of mass is in inner half of the Sun →

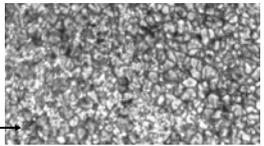
Heat Transfer Outwards

- Radiation** through a dense medium involves successive absorption and re-radiation
 - radiation from the centre of the Sun takes $\sim 10^6$ years to escape
- Convection** transports heat the last 150,000 km to the surface
 - the convection cells can be seen on the surface
- the **photosphere** is well stirred



Core

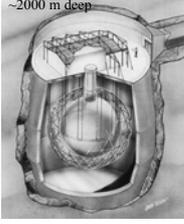
Activate diagram for simulation



Granules, courtesy: NASA

Sun's Composition

- 78% of mass of photosphere is hydrogen, 20% helium and 2% are remaining 60 elements. The composition is measured spectroscopically
 - the big bang produced about 25% helium by mass and 75% hydrogen 13.7 billion years ago
 - the Sun at about 5 billion years old is considered a 3rd generation star

☆ ☆  ☆ SNO →  ~2000 m deep

The Great Neutrino Puzzle - Solved

- ★ The *standard solar model* describing the Sun's interior predicts about 6.6×10^{14} neutrinos $m^{-2} s^{-1}$ at the distance of the Earth
- ★ Careful experiments detect barely half of this flux
- ★ What is wrong with our understanding?
 - ⊛ do solar neutrinos decay into other neutrinos in flight?
 - ⊛ yes! This implies neutrinos have a very small mass (~0.1eV)

☆ ☆  ☆

Sun's Outer Reaches



- ★ **Chromosphere** 2000 - 3000 km thick, optically thin, red light showing bright spectral lines particularly of hydrogen
 - ⊛ seething ferment of rising *spicules* of gas getting hotter the further out it goes
 - ⊛ flares send hot gases outward very far and fast
- ★ **Corona** - very extensive, irregular, temperature rises to over 10^6 degrees, emits x-rays, strongly magnetic
 - ⊛ **solar wind** appears to come from coronal holes

☆ ☆  ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆

Solar Wind

- ★ Plasma mainly of protons, He ions and electrons, with trapped magnetic field
- ★ $\sim 10^6$ particles m^{-3} reach Earth at ~ 400 km s^{-1}
- ★ Solar flares greatly increase solar wind
 - ⊛ solar wind blows out comets' tails
 - ⊛ influences upper atmosphere
 - ⊛ interacts strongly with Earth's magnetic field, one consequence of which is to produce aurora
 - ⊛ can affect radio communication around Earth

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The Aurora



← Alaskan aurora courtesy Jan Curtis

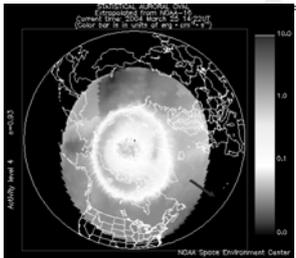


Aurora from the Space shuttle ↓

☆ ☆  ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆ ☆

Current Auroral Oval

- ★ Image from NOAA - 16 Polar-orbiting Operational Environmental Satellite →



NOAA Space Environment Center
<http://sec.noaa.gov/pmap/pmapN.html>



http://www.gi.alaska.edu/aurora_predict/map4/0.html

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Space Weather

← Space weather dials

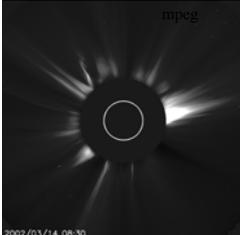


2003 Mar 13 18:23 UTC
Magnetic Field B_z component
Speed
Dynamic Pressure

Coronal view from SOHO ↓



Coronal mass ejection



2007/03/14 08:30

Monitoring the Sun - 1

The Sun in H α light →

The Sun in extreme UV in false colour (SOHO) ↓

2005/03/13 07:19

Monitoring the Sun - 2

Sunspots 24 - Mar - 2004 →

Magnetogram 24th March 2004 ↓

2004 03 24 17:42

← <http://sohowww.estec.esa.nl/>

Sunspots

- * Cooler (4800°C), slightly depressed regions with relatively dark centre
- ⊕ strong magnetic field (×5000 Earth's) that inhibits convection
- ⊕ occur in pairs, last from a few days to a few months
- * 22 year cycle with minima and maxima every 11 years
- ⊕ increase in flares and hence strong solar wind; ¹⁴C abundance correlates inversely with solar wind
- ⊕ increase in radiation flux - influence on climate

Longer term fluctuations

- * Longer term cycles than 11.3 years (on average) are emerging, e.g. ~90 years found by Gleissberg
- ⊕ note the Maunder minimum, when sunspots disappeared

Butterfly Diagram

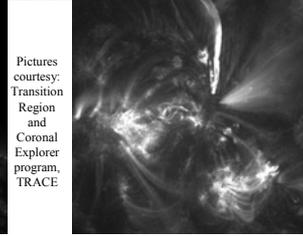
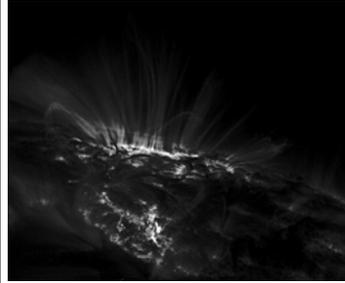
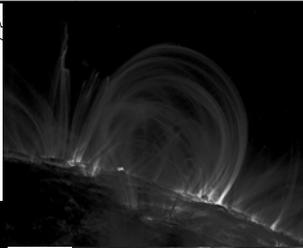
DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

1970 1980 1990 2000 2010

Sunspot Polarity Changes

- * In successive 11 year cycles, the polarity of pairs of sunspots changes order

☆ ☆ ☾ ☽
☆☆☆☆
☆☆☆☆ Hairy Ball Model of
☆☆☆☆ Sun's Magnetic
☆☆☆☆ Field



Pictures courtesy:
Transition
Region
and
Coronal
Explorer
program,
TRACE