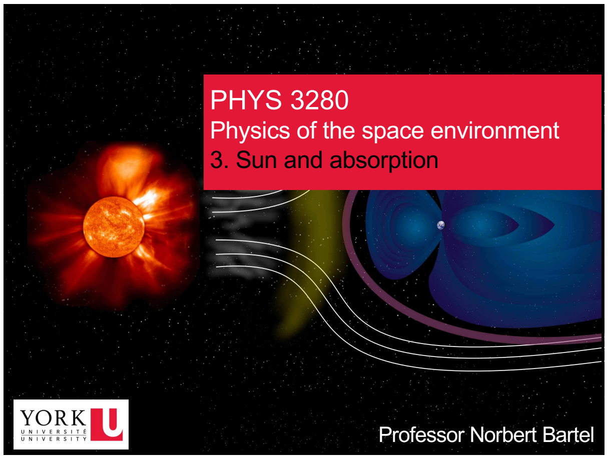

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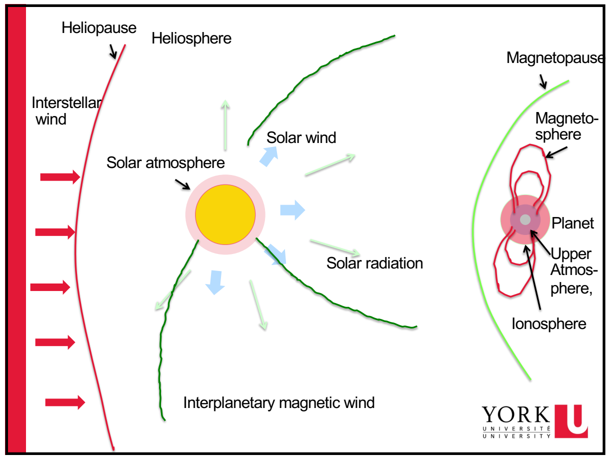

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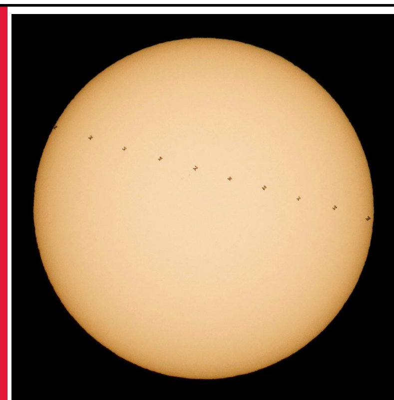

ISS solar transit

Photo credit: NASA Joel Kovsky 17 December 2016

4

The sun

- Provides all the heat input
- 99.9% of the solar system mass
- G2 yellow star (fairly ordinary star)
- Age: 5 x 10^9 years old – about half-way through its lifetime
- Luminosity 4 x 10^{26} W
- Solar constant, $P_{sqm,\ 1AU}$ =1.37 kW m^{-2}

5

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

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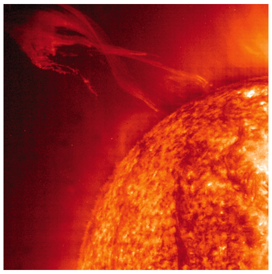
6

The Sun's energy is generated by thermonuclear reactions in its core



- The energy released in a nuclear reaction corresponds to a slight reduction of mass according to Einstein's equation
- $E = mc^2$
- Thermonuclear fusion occurs only at very high temperatures; for example, hydrogen fusion occurs only at temperatures in excess of about 10^7 K
- In the Sun, fusion occurs only in the dense, hot core

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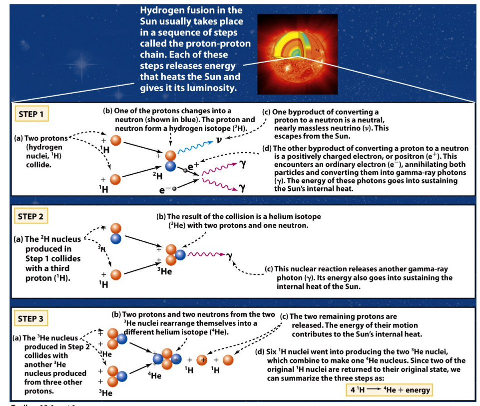

Toolbox 10-1 part 1
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9

…wait a minute..

- L_{sun}=3.9 x 10^{26} W
- $E=mc^2$
- Mass loss per second?
- Mass conversion per second?

10

Fusion reaction in Sun

- p+p ➔d+e^++v
- d+p ➔^{3}He + γ
- ^{3}He+^{3}He ➔^{4}He+2p
- ------------------------------------
- 4p ➔^{4}He + 2v's + γ's
- m(4p) = 6.693 x 10^{-27} kg
- m(^{4}He)= 6.645 x10^{-27} kg
- --------------------------------
- 0.048 x10^{-27} kg ~0.7% of mass converted into energy
- $E=mc^2$
- E=0.048 x 10^{-27} x (3.0x10^8) J
- E =4.3 x 10^{-12} J

11

Energy Transfer

- Conduction
- Convection
- (Electromagnetic) Radiation

12

A theoretical model of the Sun shows how energy gets from its center to its surface

- Hydrogen fusion takes place in a core extending from the Sun's center to about 0.25 solar radius
- The core is surrounded by a radiative zone extending to about 0.71 solar radius
  - In this zone, energy travels outward through radiative diffusion
- The radiative zone is surrounded by a rather opaque convective zone of gas at relatively low temperature and pressure
  - In this zone, energy travels outward primarily through convection

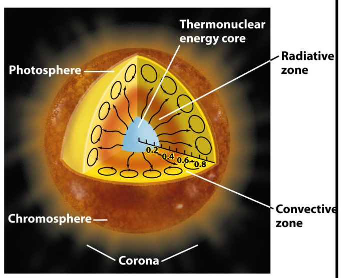

Figure 10-21a
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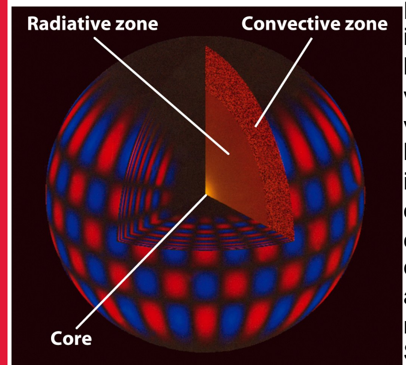
Astronomers probe the solar interior using the Sun's own vibrations



Helioseismology is the study of how the Sun vibrates. These vibrations have been used to infer pressures, densities, chemical compositions, and rotation rates within the Sun

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Profiles through the Sun

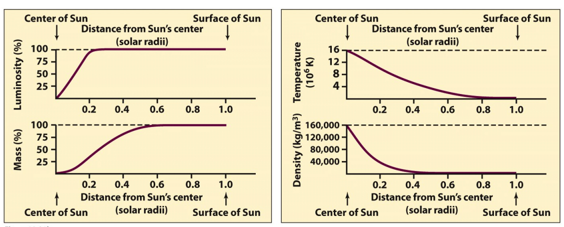

Figure 10-21b
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Element	Number of atoms (percent)	Percent of total mass
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.030	0.014
Sulfur	0.015	0.040

Figure 10-21c
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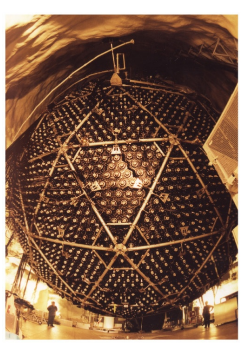
A Solar Neutrino Experiment

Located 2703 m (6800 ft) underground in the Creighton nickel mine in Sudbury, Canada, the Sudbury Neutrino Observatory is centered around a tank that contains 1000 tons of water. Occasionally, a neutrino entering the tank interacts with one or another of the particles.



Neutrinos emitted in thermonuclear reactions in the Sun's core have been detected. but in smaller numbers than originally expected. Now we know that neutrinos have mass and show oscillations changing their type:

➔Now observations consistent with theory

17

Class project

- Compute the rms speed, c_{rms}, for ^{1}H nuclei in the center of the Sun.
- Compute the kinetic energy of a ^{1}H particle (p) in the center of the Sun based on c_{rms} .
- How does that energy compare with the energy needed for p-p fusion of 1.2 MeV? Note:1 eV=1.6×10^{-19} J

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Quantum mechanics is needed to explain that it comes to fusion at these temperatures

- The temperature of about 10 Mill K (15 Mill K for the center of the Sun) is so high that the mean kinetic energy of the particles is about 2 keV for the center of the Sun.
- That is not enough for the particles to come so close together that the strong force can overcome the Coulomb barrier in the classical sense, even allowing for the tail of the Maxwell-Boltzmann speed distribution.
- Quantum mechanically the particles may find to be close enough together to fuse. The Heisenberg uncertainty principle through the uncertainty of a particle's position and momentum

$$\Delta x \Delta p_x \geq \frac{\hbar}{2}$$

makes fusion possible through tunneling.

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Fusion reaction in Sun

Reaction		Reaction time
p+p	➔d+e^++v	$10^9 – 10^{10}$ yr
d+p	➔^{3}He + γ	< 10 s
^{3}He+^{3}He	➔^{4}He+2p	10^6 yr

- ------------------------------
- 4p ➔^{4}He + 2v's + γ's

- m(4p) = 6.693 10^{-27} kg
- m(^{4}He)= 6.645 10^{-27} kg
- --------------------------------
- 0.048 10^{-27} kg ~0.7% of mass converted into energy
- E=mc^2
- E=0.048 10^{-27} x (3.0x10^8) J
- E =4.3 x 10^{-12} J

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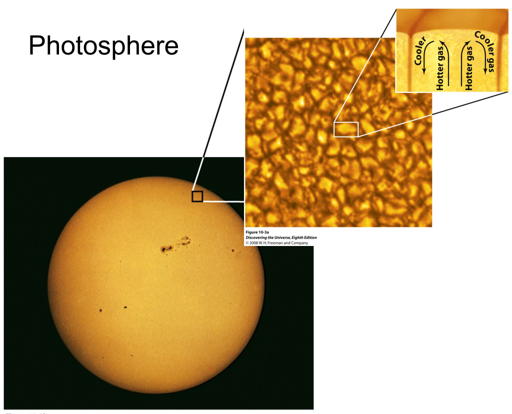
Photosphere



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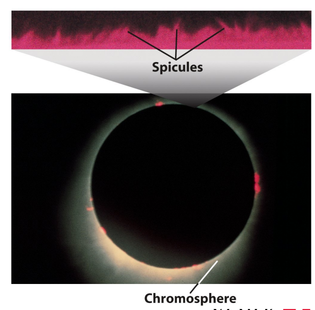
The chromosphere is characterized by spikes of rising gas

- 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



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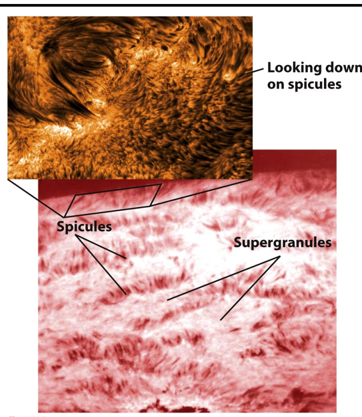

Figure 10-5a
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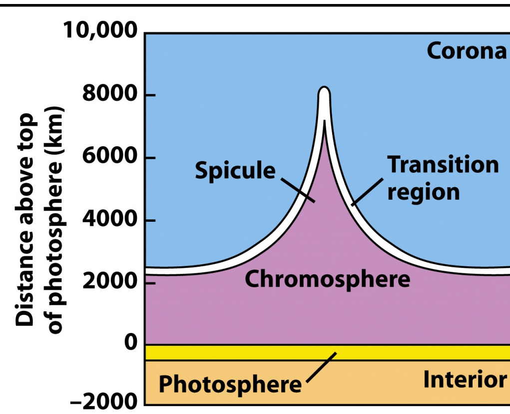

Figure 10-5b
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Corona

Figure 10-6a
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X-ray picture of the Sun

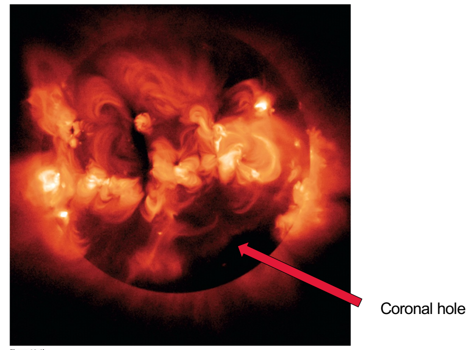

Figure 10-6b
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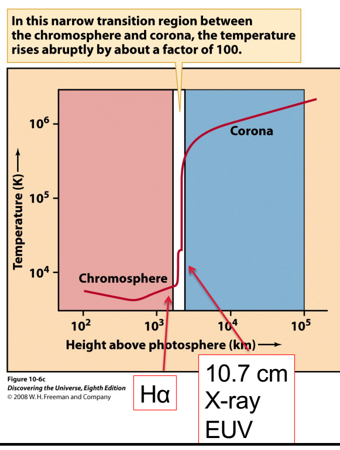

Figure 10-6c
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Corona characteristics

- Nearly all energy in UV and X-ray comes from the corona.
- Variability :
  - <1% in visible,
  - few % in UV,
  - >100% in X-ray (X-ray emissions may double or even increase by a factor of 10).
- Main cause of variability: sunspots, flares.

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Part of sun	Structure/activity	Outer temp/ Kelvin	Outer radius/ km
Core	Thermonuclear reactions. 34% of sun's mass, 0.8% of sun's volume	15,000,000	139,140
Radiative zone	Radiative diffusion, thermal conduction. Very dense - photons travel short distance before being absorbed or scattered by another particle, shift to longer wavelength. Takes 171,000 years for gamma rays to leave radiation zone.	1,500,000	494,000
Convective zone	Stellar convection: mass movement of plasma which forms circular current with heated plasma ascending and cooled descending	5,700-5,800	695,700 (sun radius)
Photosphere	Visible surface of the sun. Convection cells can be seen on the surface: granules. Plasma cells, 1000 km in diameter. Each granule lasts 8 minutes	5,700-5,800	695,700 (sun radius)
Chromosphere	Density of 10^{-4} times the photosphere, 10^{-8} times Earth atmosphere. Many structural elements: filaments (and prominences – filaments from the side), spicules (fingers of luminous gas like blades of fiery grass. Rise to top of chromosphere and sink again over 10 minutes), fibrils (horizontal wisps of gas which last about twice as long as spicules)	25,000 - 100,000	2-3000 km thick
Corona	Density of 10-12 times the photosphere. Outer edges transported away to form solar wind Not uniformly distributed across sun (coronal holes at poles in quiescent periods of sun activity). A number of active regions	2,000,000	Millions of km

Coronal exobase
1.5 Mill km altitude

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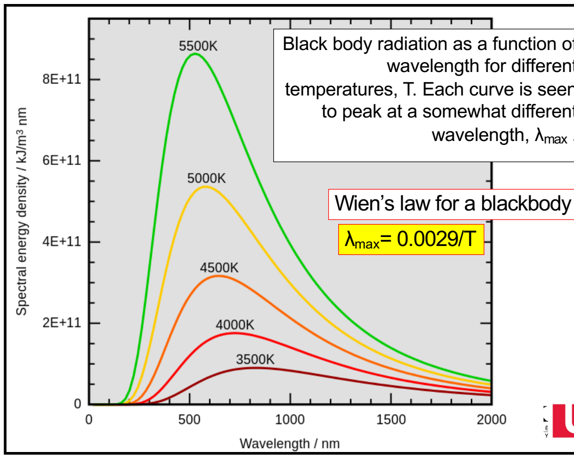

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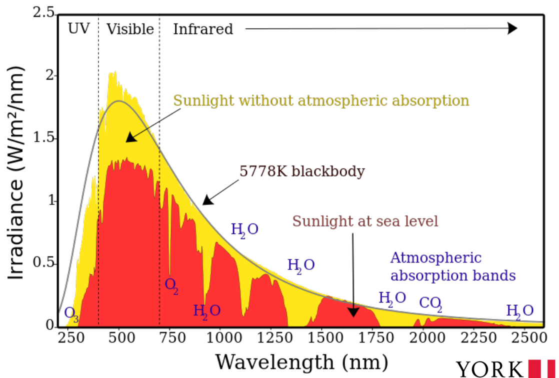
Spectrum of Solar Radiation (Earth)



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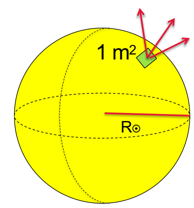
Luminosity

Stefan=Boltzmann law for a blackbody

$F=\sigma T^4$



$L=4\pi R_\odot^2 F$

F: Flux W m^{-2}

σ: 5.67 x 10^{-8} W m^{-2} K^{-4}

L: Luminosity W

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Average surface temperature of planet

- $P_{abs}=(L/4\pi d^2) \times \pi r_p^2$ (1-albedo)
- $P_{em}=4\pi r_p^2\, \sigma T_p^4$
- If no atmosphere then for thermal equilibrium:
- $P_{abs} = P_{em}$
- $T_p =[L/(4\pi d^2) \times (1\text{-albedo})/(4\sigma)]^{1/4}$
- For Earth:
- L=3.86 x 10^{26} W, d=1.5 x10^{11} m, albedo = 0.37, σ=5.67x10^{-8} J $m^{-2}K^{-4}s^{-1}$
- T_p = 247 K
- With average T=288K ➔ 41K due to greenhouse effect

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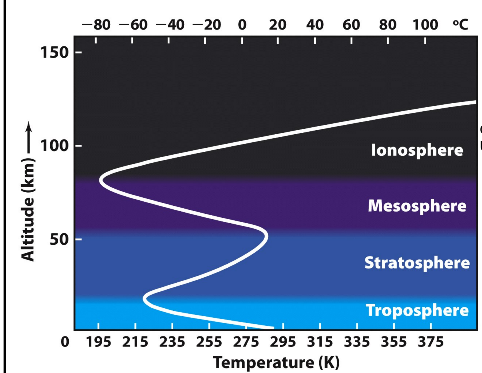
Temperature profile of Earth's atmosphere



O, N atoms absorb UV. Heat from above

Heat from below

O3 absorbs UV, heat from above

Heat from below

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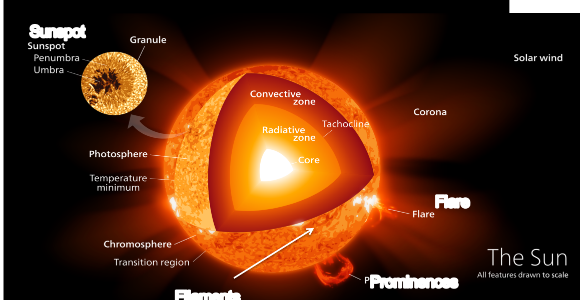
Solar properties



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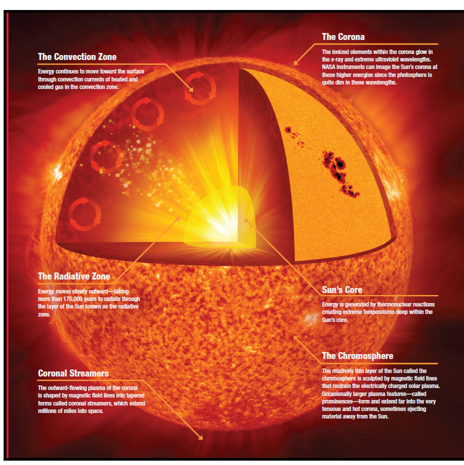

Credit: NASA/Jenny Mottar

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Active and quiescent regions

Active regions involve all the phenomena directly linked to the magnetic field:

- sunspots in the photosphere,
- filaments in the chromosphere,
- prominences in the chromosphere and transition region, and
- flares and coronal mass ejections in the corona and chromosphere.

Quiescent prominences are large, cool dense structures which are observed as dark, "snake-like" ribbons (filaments) on the solar disc.

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The active sun

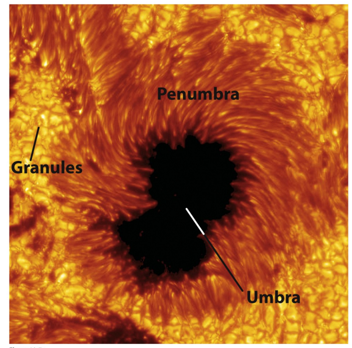

Figure 10-7a
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Sunspots

- Temporary phenomena on the photosphere of the Sun that appear visibly as dark spots compared to surrounding regions.
- Correspond to concentrations of magnetic field flux that inhibit convection
  - Result: reduced surface temperature - roughly 3,000–4,500 K compared to 5,780 K in the surroundings. Sunspots clearly visible as dark spots
- Sunspots usually appear in pairs of opposite magnetic polarity.
- Number of sunspots varies according to the approximately 11-year solar cycle.
- Size ranging from 16 kilometres to 160,000 kilometres in diameter
- Sunspots accompany secondary phenomena such as coronal loops (prominences) and reconnection events. Most solar flares and coronal mass ejections originate in magnetically active regions around visible sunspot groupings
- Sunspots have two parts: the central umbra, the darkest part, where the magnetic field is approximately normal to the Sun's surface, and the surrounding penumbra, which is lighter, where the magnetic field is more inclined.

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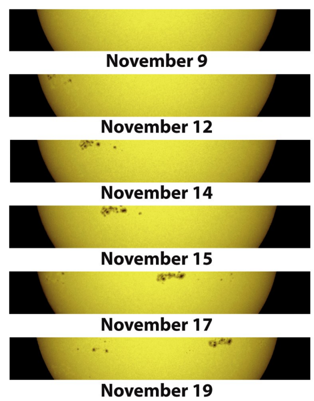

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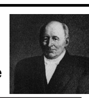
Solar cycle



Samuel Heinrich Schwabe

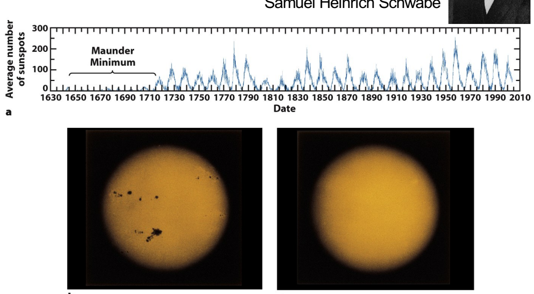


Figure 10-8
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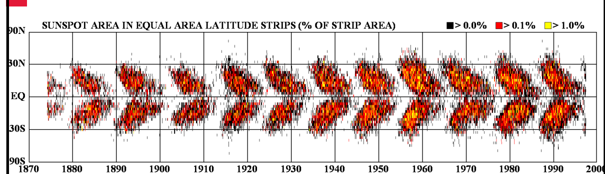

NASA

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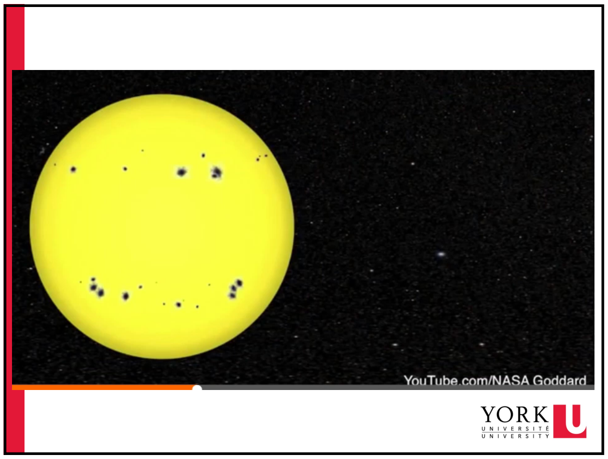

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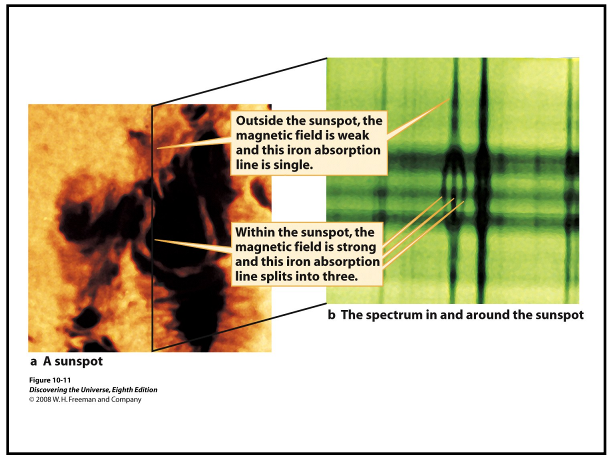

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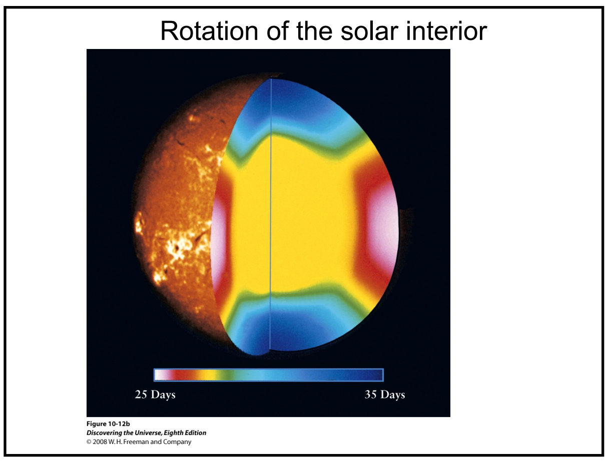

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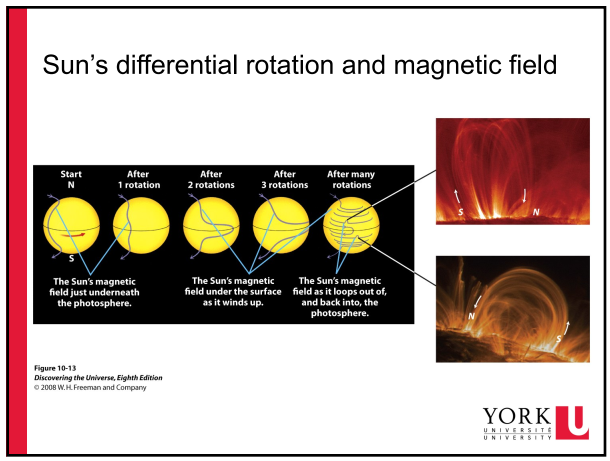

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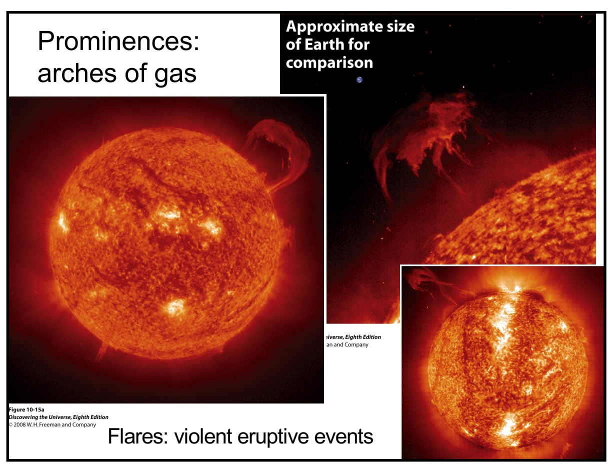

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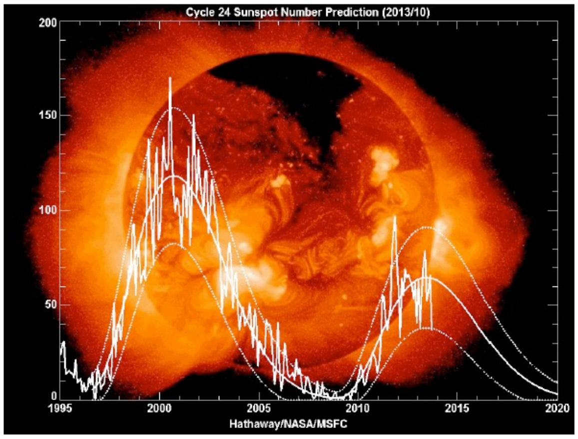

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Solar cycles (periodicities)

There are 4 main cycles of sun activity that can influence the Earth:

- The "diurnal cycle" – where on Earth is day and night depending on location pointing towards the sun – 24 h cycle
- The solar rotation period: 27-day cycle. Changes which part of the sun points to the Earth
- The semi-annual variation – how far away the sun is from Earth (and the tilt of the axis of rotation of the Earth changes where on Earth gets more warming – seasons)
- The solar cycle variation, tied to the magnetic field reversals on the sun: 11-year cycle

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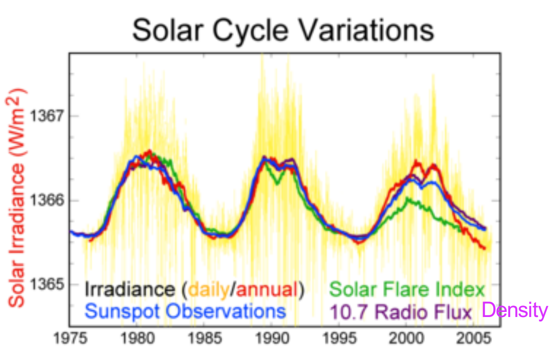

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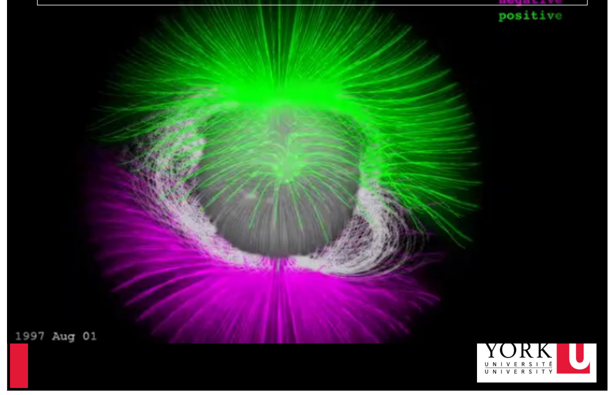
The polarity of Sun's magnetic field changes every 11 years



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Coronal events

Coronal event	Typical time-scale	Typical length-scale (Mm)
Active region flare	10 to 10,000 seconds	10–100
X-ray bright point	minutes	1–10
Transient in large-scale structures	from minutes to hours	~100
Transient in interconnecting arcs	from minutes to hours	~100
Quiet Sun	from hours to months	100–1,000
Coronal hole	several rotations	100–1,000

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Coronal loops

- The basic structures of the magnetic solar corona. These loops are the closed-magnetic flux cousins of the open-magnetic flux that can be found in coronal hole (polar) regions and the solar wind. Loops of magnetic flux well up from the solar body and fill with hot solar plasma.
- Solar plasma feeding these structures is heated from under 6000 K to well over 1,000,000 K from the photosphere, through the transition region, and into the corona. Often, the solar plasma will fill these loops from one foot point and drain from the other.
- Due to the heightened magnetic activity in these coronal loop regions, coronal loops can often be the precursor to solar flares and coronal mass ejections (CMEs).

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NASA's Solar Dynamics Observatory (SDO) captured a splendid example of expanding coronal loops seen in profile at the edge of the Sun (Oct. 14-15, 2014). The bright loops began to form and grow after a long-lasting M-class flare erupted. The arcs of the loops we see in extreme ultraviolet light are actually particles spiraling along magnetic field lines arcing above the active region that was the source of the flare. They are reorganizing the magnetic field after its disruption. To give a sense of scale, these huge loops are reaching out more than 15 times the size of Earth.

Credit: Solar Dynamics Observatory/NASA.
https://www.youtube.com/watch?v=vy2v1JbboA8

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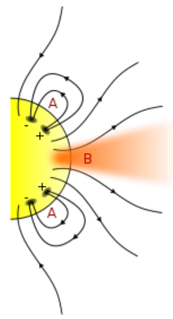

- Coronal arches connecting regions of opposite magnetic polarity (A) and the unipolar magnetic field in the coronal hole (B)

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Solar flares

- Flares take place in active regions and provoke a sudden increase of the radiative flux emitted from small regions of the corona.
- Flares are impulsive phenomena, of average duration of 15 minutes, even if the most energetic events can last several hours. Flares involve a high and rapid increase of the density and temperature.
- Usually, flares are only seen at EUV wavelengths and in the X-rays, typical of the chromospheric and coronal emission.

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Solar flare

- The sun emitted a mid-level solar flare on Oct. 2, 2014. When intense enough, such a flare can disturb the atmosphere in the layer where GPS and communications signals travel.
- This flare is classified as an M7.3 flare. M-class flares are one-tenth as powerful as the most powerful flares, which are designated X-class flares.

https://www.youtube.com/watch?v=C1Kact6QHG0

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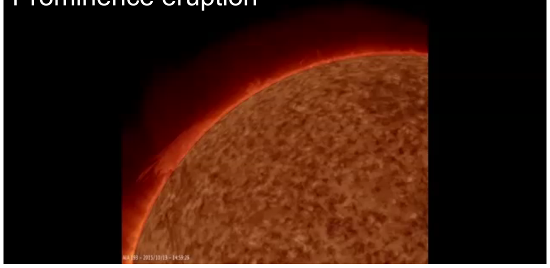
Prominence eruption



- A mass of solar material broke apart over a 10-hour period on Oct. 13, 2015.
- Prominences are unstable clouds of gas tethered above the surface of the sun by magnetic forces.
- The image and video were produced with a combination of two
- wavelengths of extreme ultraviolet light, 193 and 304 Angstroms.
- Credit: NASA/SDO https://www.youtube.com/watch?v=QdXB07FAJpk

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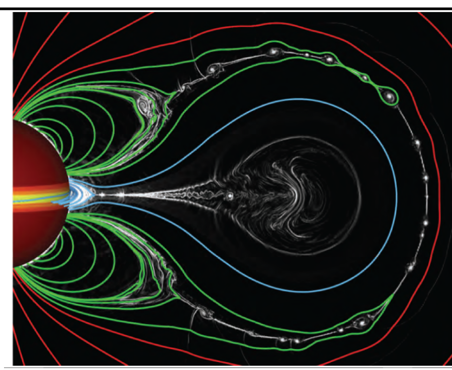

- Ultra-high-resolution numerical simulation of a reconnection-initiated CME and eruptive flare. The white contours indicate high current densities.

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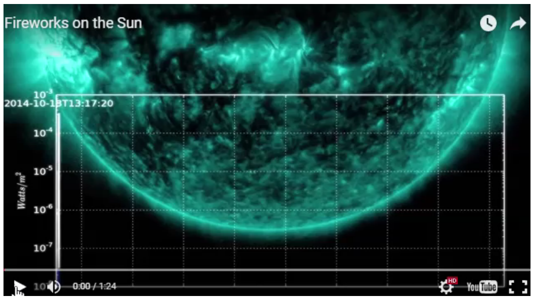

This movie shows fireworks on the sun as 10 significant flares erupted on the sun from Oct. 19-28, 2014. The graph shows X-ray output from the sun as measured by NOAA's GOES spacecraft. The X-rays peak in sync with each flare.
Credit: NASA/SDO/NOAA/GOES

https://www.youtube.com/watch?v=sUKxalPIQOc

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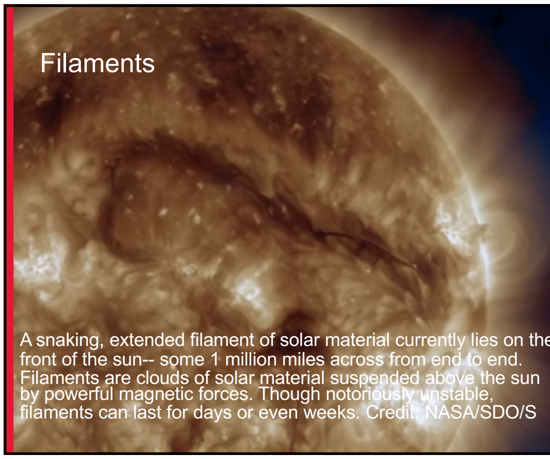
Filaments



A snaking, extended filament of solar material currently lies on the front of the sun-- some 1 million miles across from end to end. Filaments are clouds of solar material suspended above the sun by powerful magnetic forces. Though notoriously unstable, filaments can last for days or even weeks. Credit: NASA/SDO/S

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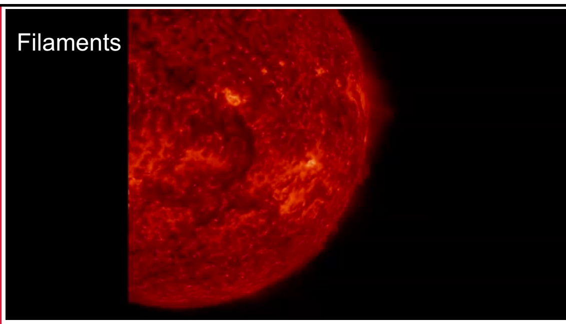
Filaments



- Dark strands of plasma tethered above the sun's surface by magnetic forces that, over time, often become disrupted and break away from the sun.
- Cooler clouds of gases (plasma) suspended above the Sun's surface by magnetic forces. The regions of intense magnetic field look dark in the images because they are empty of hot plasma – they have a comparatively cool temperature.
- In this movie, a dark, almost circular filament broke away from the sun on Nov. 15, 2015.
- This video was taken in extreme ultraviolet wavelengths and colorized in red.

Credit: NASA/SDO

https://www.youtube.com/watch?v=WhiGtxuIUIM

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Solar storm impacts on Earth atmosphere

- Flares can last minutes to hours. Traveling at the speed of light, it takes eight minutes for the light from a solar flare to reach Earth. Some of the energy released in the flare also accelerates very high energy particles that can reach Earth in tens of minutes.
- CMEs travel over a million miles per hour. The hot plasma takes up to three days to reach Earth.
- The energy from a flare can disrupt the upper Earth atmosphere leading to degradation and, at worst, temporary blackouts in navigation and communications signals.
- CMEs can funnel particles into near-Earth space. A CME can affect Earth's magnetic field creating currents that drive particles down toward Earth's poles. When these react with oxygen and nitrogen, they help create the aurora. Magnetic changes can affect technologies though: HF radio waves can be degraded, and GPS coordinates can stray by a few metres. The magnetic oscillations can also create electrical currents in utility grids that can overload electrical systems and transformers.

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Tracing the interplanetary magnetic field

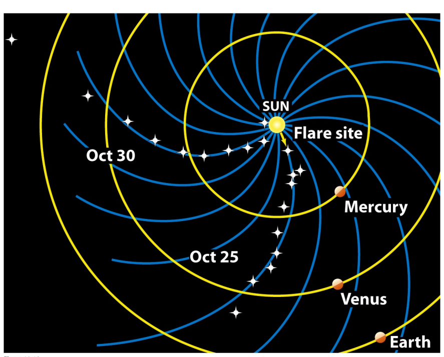

Figure 10-18
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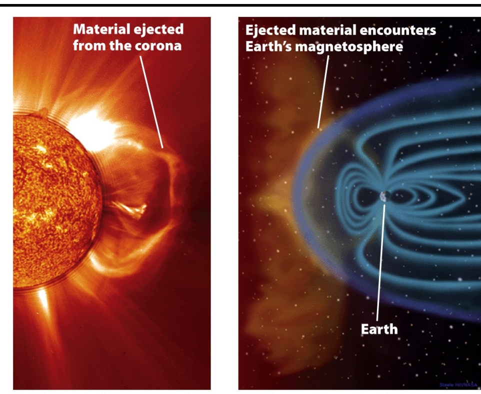

a A coronal mass ejection **b** Two to four days later

Figure 10-19
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Impacts on Earth

- Space weather poses increasingly greater threat because of the emergence of vulnerable technologies.
- The first example of the impact of space weather on technology was the electric telegraph.
- A number of space weather incidents have already disrupted electrical transformers and grids, for instance in Canada.
- We have to increase understanding the risk from both extreme events (for example, a major magnetic storm) and low-level risk (often a cumulative build up of minor damage from smaller storms).
- Space weather can cause problems such as corrosion on pipelines and incorrect signal settings on railways.

Lloyd's 360° Risk Insight Space weather: it's impact on Earth and implications for business

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Solar radiation storms

- Bursts of charged particles at very high energies (MeV to GeV) from flares and CME are a major threat to spacecraft as they can disrupt and damage electronics and power systems.
- Some of these particles enter the Earth's atmosphere, where they collide with oxygen and nitrogen molecules in the atmosphere to produce neutrons.
- During strong events these neutrons can travel to the Earth's surface and raise radiation levels above normal. This can disrupt digital systems in aircraft and on the ground and is a health risk for aircrew and passengers.
- Radiation storms can also produce an atmospheric layer that absorbs high-frequency (HF) radio waves across polar regions.

Lloyd's 360° Risk Insight Space weather: it's impact on Earth and implications for business

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Specific impacts to Earth

- Communication systems can be interrupted or damaged by these high-energy emissions.
- Navigation satellites may be disrupted or disabled.
- Radiation hazards, especially to flight crews and passengers, increase significantly during very high energy events.
- Magnetic storms can result in loss of power in transmission lines, or destroy transformers (which are very costly to replace and can take up to 12 months to rebuild).

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The life of our Sun

- The Sun originated from a cold cloud of gas and a bit of dust somewhere in our Galaxy, the Milky Way.
- The gas cloud started to collapse, perhaps triggered by the shock front of a nearby supernova.
- The collapsing cloud formed a disk due to increasing rotation and a hot center.
- The center became our Sun when fusion started from H to He at T=10 Mill K.
- The Sun has a life of about 10 Bill yr.
- At the end it fuses He into C and O and becomes a giant filling almost the orbit of Earth.
- It becomes a planetary nebula shedding huge amounts of gas into the interstellar medium.
- It ends its life as a white dwarf with a size as little as the Earth.

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Composition of the Interstellar Medium

	Particle number (%)	Mass (%)
Hydrogen (atoms and molecules)	**90**	**74**
Helium	**9**	**25**
Metals*	**1**	**1**

*Metals in astronomy are all elements beyond H and He. Metals mostly come from supernova explosions of massive stars.

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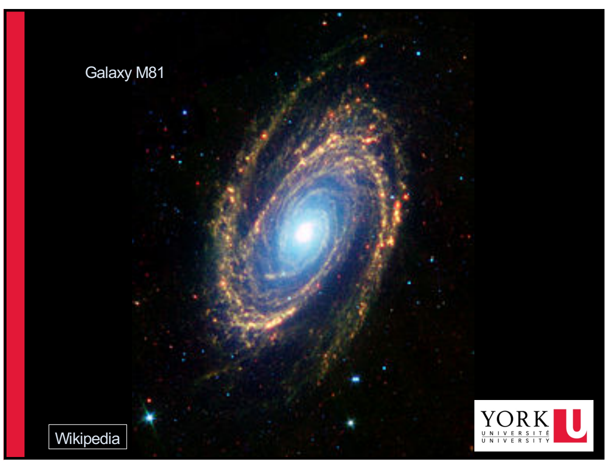

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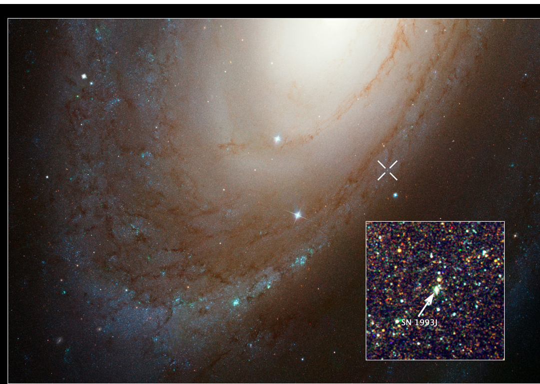

Supernova 1993J in Spiral Galaxy M81
Hubble Space Telescope ▪ ACS ▪ WFC3

NASA and ESA
STScI-PRC14-38b

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Movie of supernova 1993J --the explosion of a massive star--

from t = 50d to t = 22 yr

Free download: www.yorku.ca/bartel

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A cold cloud of gas and a little bit of dust

Chapter 12 Opener
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Contraction:

1) Triggered by
-supernova,
-star light pressure

2) Supported by gravity

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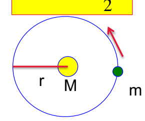
Contraction heats up the gas cloud

- Virial theorem for a system in equilibrium with K:kinetic energy and U potential energy and E total energy.
- As the cloud contracts, only half of the change of gravitational potential energy goes into the thermal energy that heats the gas, the other half is radiated away.

$$2\bar{K} + \bar{U} = 0$$

$$\bar{E} = \bar{K} + \bar{U} = \frac{1}{2}\bar{U}$$



Simple application:

$$K = \frac{1}{2}mv^2$$

$$K = -\frac{1}{2}U = G\frac{Mm}{2r}$$

$$F_g = F_{cf}$$

$$G\frac{Mm}{r^2} = m\frac{v^2}{r}$$

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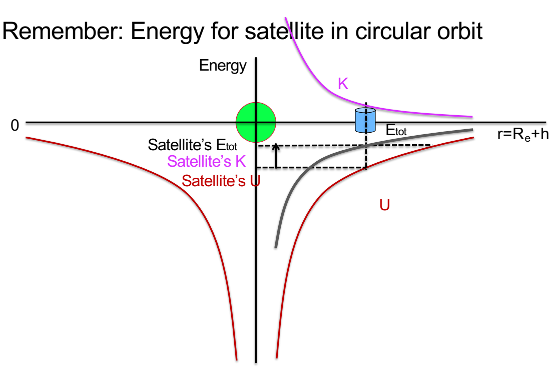
Remember: Energy for satellite in circular orbit



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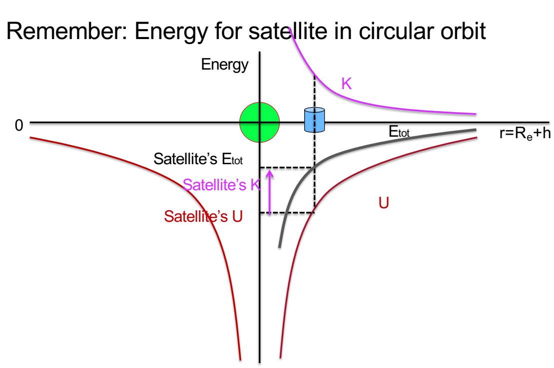
Remember: Energy for satellite in circular orbit



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Kinetic and potential energy of a gas cloud

- Mean kinetic energy per particle:

$$\frac{1}{2}mv_{rms}^2 = \frac{3}{2}k\bar{T}$$

- Mean kinetic energy of N gas particles:

$$\bar{K} = N\frac{3}{2}k\bar{T}$$

- The potential energy of the gas can be determined as follows:
  - We assume density, ρ(r), in a sphere of gas with radius, R
  - Gravitational forces of a shell of matter add up to 0 within the shell so that they can be ignored.
  - The mass within the shell can be taken as a point mass.
  - The gravitational potential, dU_i, of a mass, dm_i, of a particle away by, r, from the center is then…

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- Gravitational force on dm_i

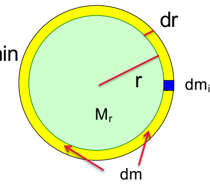
$$dF_{g,i} = G\frac{M_r dm_i}{r^2}$$

- Gravitational potential energy of dm_i

$$dU_{g,i} = -G\frac{M_r dm_i}{r}$$

- Gravitational potential energy of thin shell with mass, $dm = 4\pi r^2 dr\rho$

$$dU_g = -G\frac{M_r 4\pi r^2\rho}{r}dr$$



- Total gravitational potential energy

$$U_g = -4\pi G\int_0^R \frac{M_r(r)r^2\rho(r)}{r}dr$$

$$M_r(r) = \frac{4}{3}\pi r^3\rho$$

$$U_g = -\frac{16\pi^2}{15}G\rho^2R^5 = -\frac{3}{5}G\frac{M^2}{R}$$

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- As the cloud contracts to form a star, half of the potential energy goes into heat and the other half is radiated away. For the Sun..

$$\Delta E_g = \frac{3}{10}G\frac{M_{sun}^2}{R_{sun}}$$

- With the luminosity of the Sun of $L_{sun} = 3.8\text{x}10^{26}$ W, a mass of 2 x 10^{33} kg, and a radius of 7x10^8 m, the Sun would be able to have lived for only

$$\tau_{KH} = \frac{\Delta E_g}{L_{sun}} = 1x10^7\,yr$$

- This timescale is called, Kelvin-Helmholtz timescale. It is much too short to account for the 500 times older age of the Sun. Indeed, another process, other than gravitational energy has to account for the luminosity of the Sun. That is indeed nuclear fusion.
- But conversion of gravitational potential energy into heat and radiation played a significant role during the contraction phase

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The average temperature of the Sun

- Since half of the gravitational potential energy goes into kinetic energy of the gas, we have..

$$\bar{K} = \frac{1}{2}mv_{rms}^2 = \frac{3}{2}k\bar{T}$$

$$\frac{3}{2}k\bar{T}N = \frac{3}{2}k\bar{T}\frac{M}{m} = \frac{3}{10}G\frac{M^2}{R}$$ where, N, is the number of particles with mass, m.

$$\bar{T}_{sun} = \frac{1}{5}G\frac{M_{sun}m}{kR_{sun}}$$

$$\bar{T}_{sun} = 5x10^6\,K$$

- This temperature is close to T= $1\text{x}10^7$ K , needed for starting the p-p cycle, of fusion. This is the main cycle for fusing $4\,^1H$ into $1\,^4He$ as discussed earlier.

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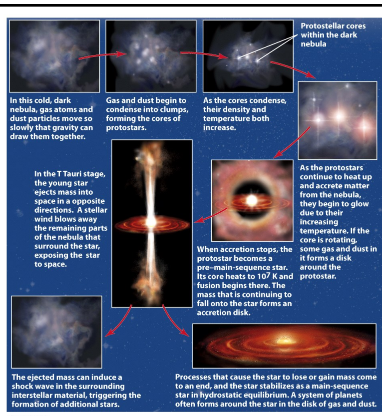

Figure 12-19
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Figure 12-18a
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Young stars

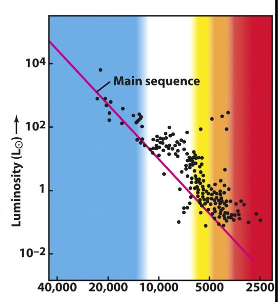

Figure 12-18b
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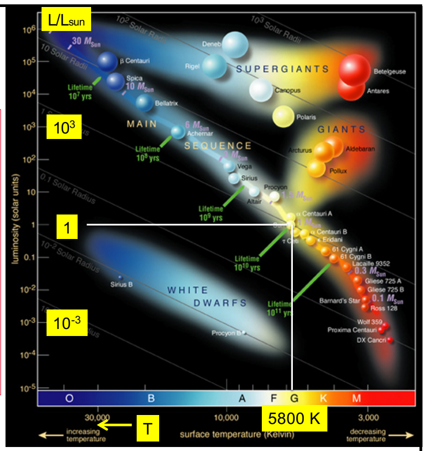
Hertzsprung-Russell diagram

Plot of each star on a temperature (colour) vs. luminosity chart.

The diagonal line is the **Main Sequence.** This is where stars fuse H into He. The Sun is a G2 star.



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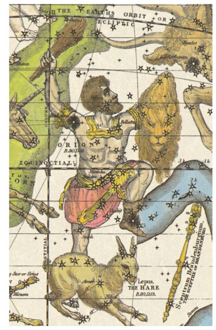
Surface temperature, T



- Ancient peoples looked at the stars and imagined groupings made pictures in the sky and gave them meaning.
- But they were on the wrong track.
- Today we look at the colours and get the surface temperature and the energy flux per m^2.
- With the parallax and apparent brightness we get the luminosity and the radius.

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Orion

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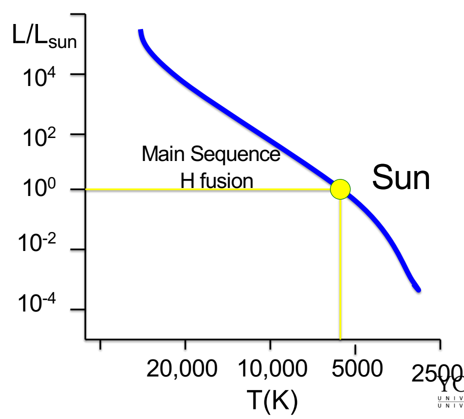

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TABLE 12-2 Main-Sequence Lifetimes

Mass ($M_\odot$)	Surface temperature (K)	Luminosity ($L_\odot$)	Time on main sequence (10^6 years)	Spectral class
25	35,000	80,000	3	O
15	30,000	10,000	15	B
3	11,000	60	500	A
1.5	7000	5	3000	F
1.0 (Sun)	6000	1	10,000	G
0.75	5000	0.5	15,000	K
0.50	4000	0.03	200,000	M

Table 12-2
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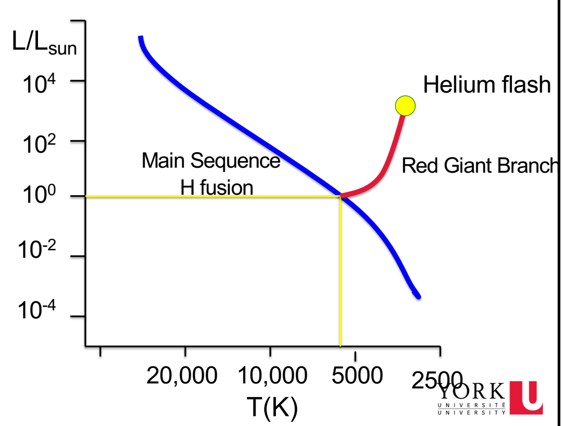

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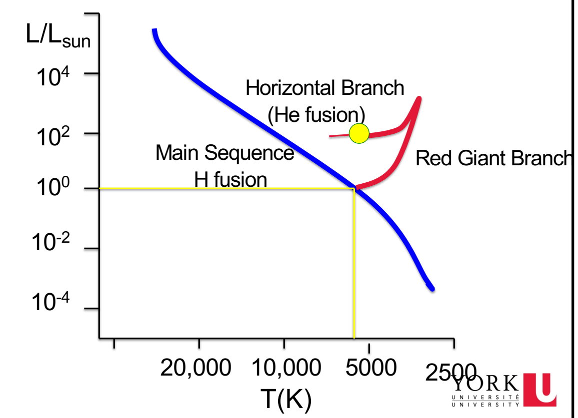

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Medium mass stars M=0.4 to 8 M_{sol}

- Our sun is a medium mass star
- $4\,^1H \rightarrow 1\,^4He + \gamma's + 2\nu$ H fusion (p-p cycle) in the core.
- $3\,^4He \rightarrow {}^{12}C + \gamma's$, He fusion (burning) in the core, H fusion in the shell around the core.

  $1\,^4He + {}^{12}C \rightarrow {}^{16}O + \gamma's$
- No further fusion (burning).

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Star changes

- When a star exhausts the supply of hydrogen by nuclear fusion processes in its core, the core contracts and its temperature increases, causing the outer layers of the star to expand and cool.
- The star's luminosity increases greatly, and it becomes a red giant, following a track leading into the upper-right hand corner of the HR diagram.
- Eventually, once the temperature in the core has reached approximately 3×10^8 K, helium burning (fusion of helium nuclei) begins. The onset of helium burning in the core halts the star's cooling and increase in luminosity, and the star instead moves down and leftwards in the HR diagram. This is the horizontal branch.
- After the completion of helium burning in the core, the star again moves to the right and upwards on the diagram. Its path is almost aligned with its previous red-giant track, hence the name asymptotic giant branch. Stars at this stage of stellar evolution are known as AGB stars.

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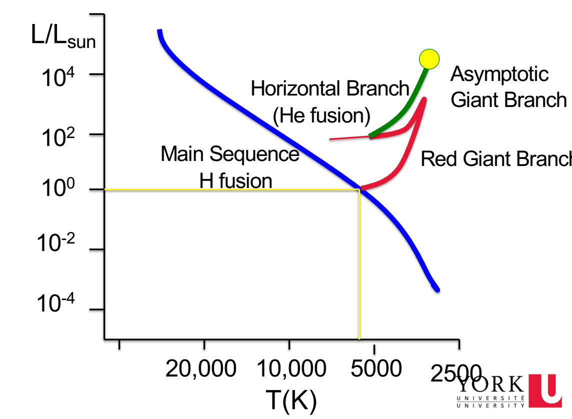

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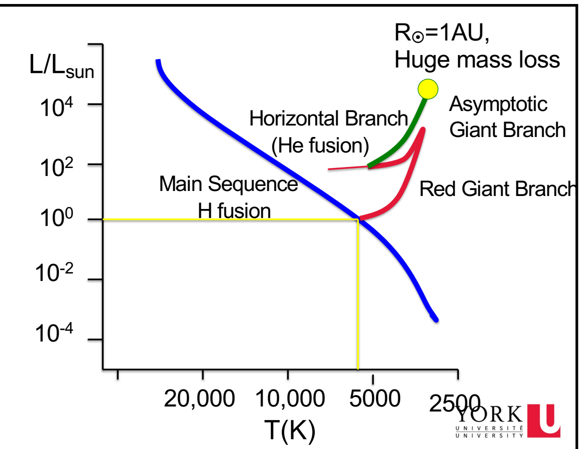

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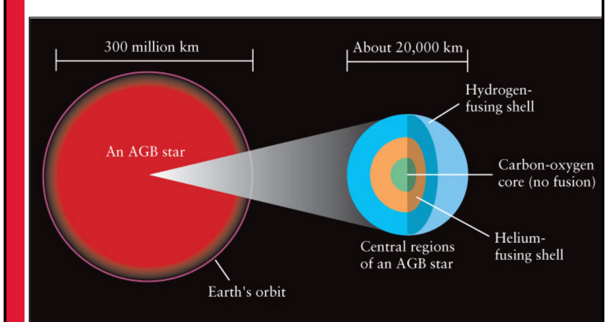
The Structure of an Old Medium-Mass Star



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Electron degeneracy pressure

- The He-rich core of a medium-mass giant is supported by electron degeneracy pressure. It is based on the…
- Pauli exclusion principle: Two identical particles cannot exist at the same place at the same time
- Electron degenerate pressure does not change with temperature.

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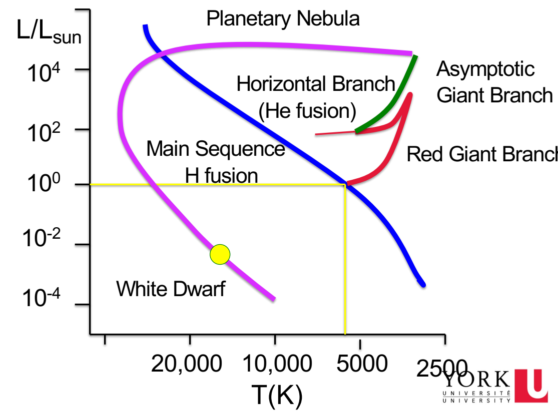

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The end of the life of our Sun

- The "planetary nebula" is composed of the ejecta from the star. The core remains as a degenerate and inert mass of (primarily) Carbon and Oxygen in roughly equal amounts.
- At first, the core's temperature is >100 million K, but it rapidly cools, contracts a bit and stabilizes as a White Dwarf.
- The Sun will end its life as a White Dwarf with a radius of about 10,000 km, not much larger than that of Earth.

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Atmospheric effects on EM radiation

- Scattering
  - Rayleigh scattering
  - Mie scattering
- Absorption

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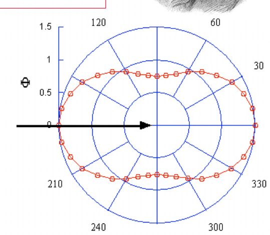
Rayleigh scattering

$$I = I_0 \frac{N}{2R^2}\left(\frac{2\pi r}{\lambda}\right)^4 r^2 \left(\frac{n^2-1}{n^2+2}\right)^2 \left(1+\cos^2\theta\right)$$

I: intensity
N: number of scattering particles
R distance to scatterer
r: radius of particle
λ : wavelength
n: refractive index
θ : scattering angle



Integrating over all angles gives the Rayleigh scattering cross section, σ.

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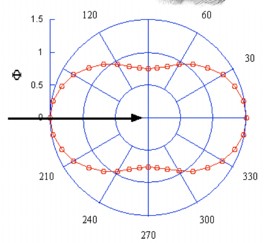
Rayleigh scattering

$$I = I_0 \frac{N}{2R^2}\left(\frac{2\pi r}{\lambda}\right)^4 r^2 \left(\frac{n^2-1}{n^2+2}\right)^2 \left(1+\cos^2\theta\right)$$

Blue light is more scattered than red light

I: intensity
N: number of scattering particles
R distance to scatterer
r: radius of particle
λ : wavelength
n: refractive index
θ : scattering angle



Integrating over all angles gives the Rayleigh scattering cross section, σ.

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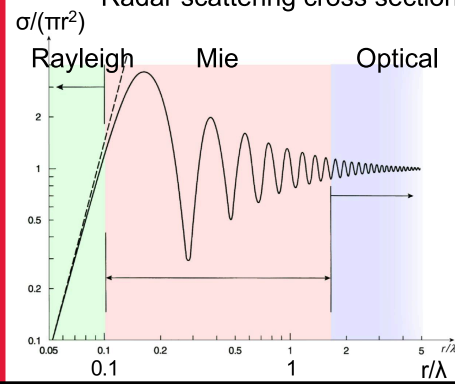
Radar scattering cross section



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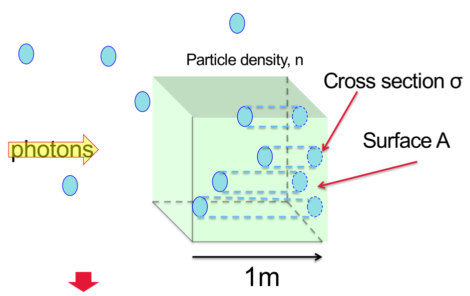

Fraction of light colliding with molecules per m: $n\sigma$

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Meaning of cross section

- Fraction of light scattered per m :n•σ
- At surface there are about 2•10^{25} molecules per m^3.
- σ (N_2) at λ=532 nm (green)= 5.1 •10^{-31} m^2
- n•σ=10^{-5} m^{-1} for every meter light travels through the atmosphere

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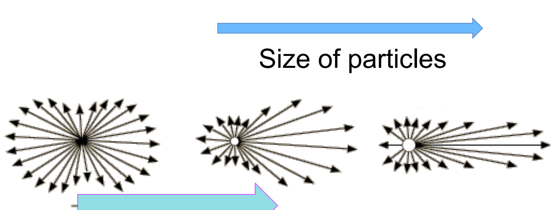
Rayleigh Mie Mie

Size of particles



Direction of incident light

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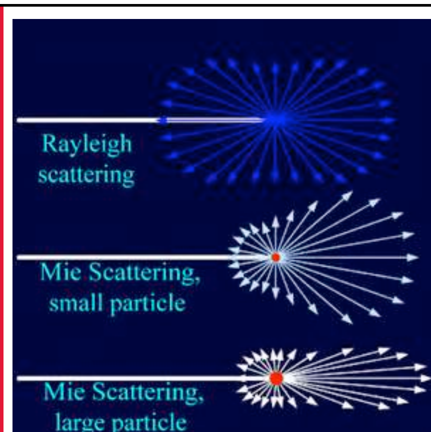

Wikipedia

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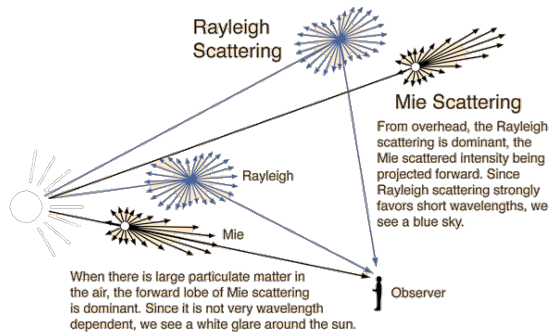

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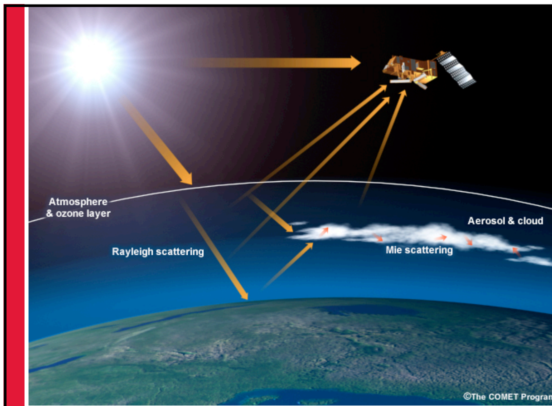

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Rayleigh scattering and Mie scattering

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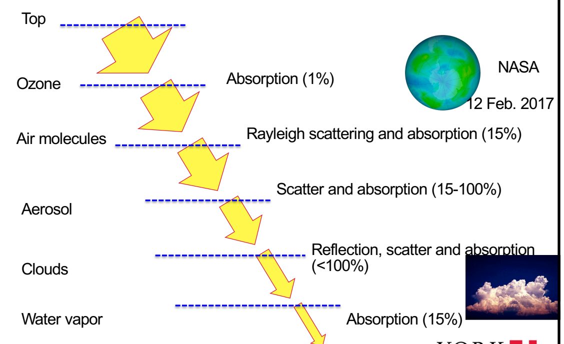
Path of solar radiation through the Earth atmosphere



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Source DLR

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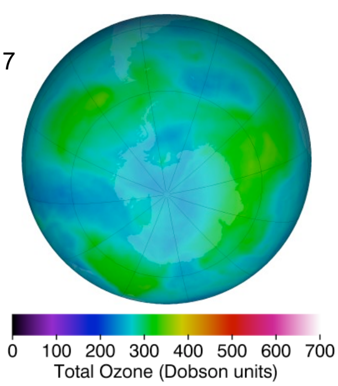
Ozone

12 Feb. 2017

GFSC, NASA



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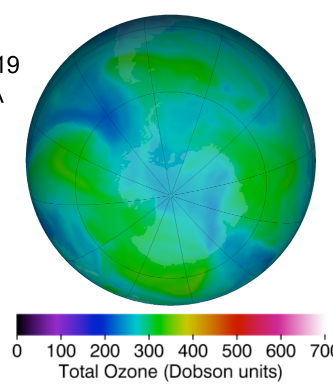
Ozone

10 Feb. 2019

GFSC, NASA



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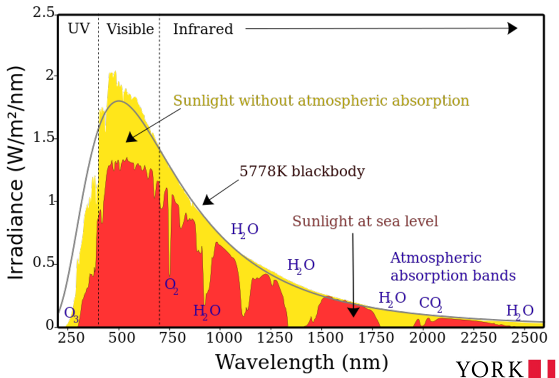
Spectrum of Solar Radiation (Earth)



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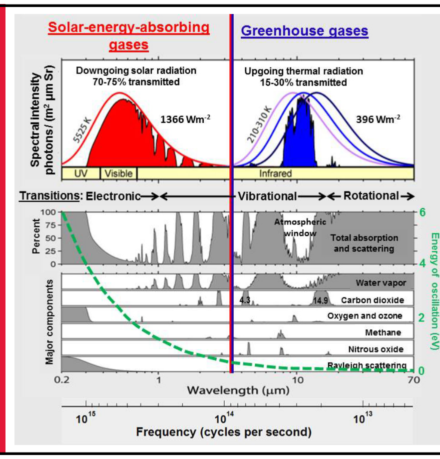

Newland

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Absorption processes

- Photodissociation (λ≤242 nm)
  - O_2 + photon ➔ O + O
- Photoionization (λ≤103 nm)
  - O + photon ➔ O^+ + e
  - N_2+ photon ➔ N_2^+ + e
  - O_2+ photon ➔ O_2^+ + e
- Dissociative photoionization (λ≤72 nm)
  - N_2+ photon ➔ N^+ + N + e

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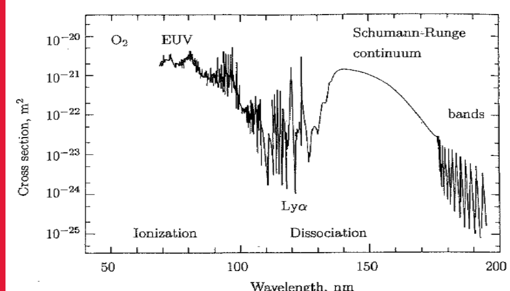
Absorption cross section of O_2 --- σ_{O2}



Banks, Kockarts, 1973, also Proelss, 2010

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Optical depth

- We know about collision of particles with other particles and the mean free path.
- Now we want to consider the collision of photons with particles.
- How is the photon flux (intensity of radiation) lowered by gas, or how is the final photon flux related to the initial photon flux?
- Several factors have to be considered
  - The greater the distance the beam of radiation travels the more light will be extinguished (scattered or absorbed).
  - The greater the density of the gas, the more extinction.
  - The cross section of the gas atoms or molecules.

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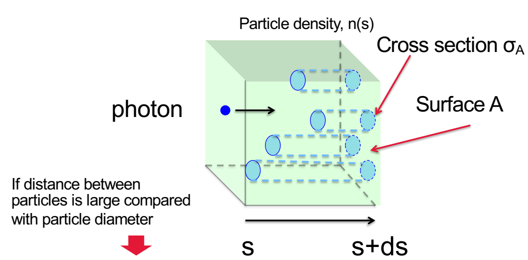

$$dw_{col}(ds) = \frac{\left(\sum \sigma_A\right)}{A} = \frac{(\sigma_A n(s) A ds)}{A} = \sigma_A n(s) ds$$

Collision probability

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Extinction of photon flux in a gas volume

- Number of photons per unit area and time that get absorbed while passing through a distance ds of gas is..
  $\phi_{ph}(s)dw_{col}(ds)$
- Change in photon flux is…
  $d\phi_{ph}(s) = -\phi_{ph}(s)dw_{col}(ds) = -\phi_{ph}(s)\sigma_A n(s)ds$
- Integration leads to..

$$\phi_{ph}(s) = \phi_{ph}(s_0)e^{-\tau(s)}$$
$$\tau = \int_{s_0}^{s} \sigma_A n(s')ds'$$

← τ : Optical depth

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Opacity

- The differential optical depth is…
  $d\tau = \sigma_A n(s)ds$
- This can also be written in terms of the density, ρ, and opacity, κ, as..
  $d\tau = \kappa\rho(s)ds$
- The opacity or absorption coefficient, κ, is a measure of the efficiency with which the gas absorbs or scatters light.
- Its unit is $m^2\ kg^{-1}$

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- Instead of photon flux we often have also in the literature the intensity, I. For a density, ρ=constant, of a gas, we can then also write:

$$\frac{I}{I_0} = e^{-\kappa\rho s} = e^{-\tau}$$

- For an optically thin medium, the optical depth is <<1. Then…
  $\frac{I}{I_0} \approx 1 - \tau$
- Note: the cross section, opacity and optical depth are in general functions of wavelength

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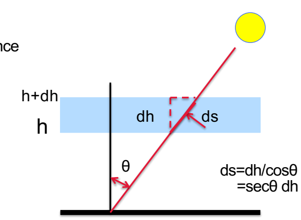
Vertical atmospheric path and slant path

- how to measure the optical depth in the atmosphere

$$t = \frac{I(\theta)}{I_0} = e^{-\sec\theta \bullet \tau}$$

t: transmittance

Sun photometer
Cimel 318A in Toravere, Wikipedia



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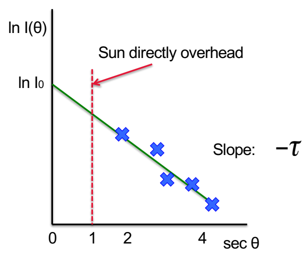
Measurement of $-\tau$



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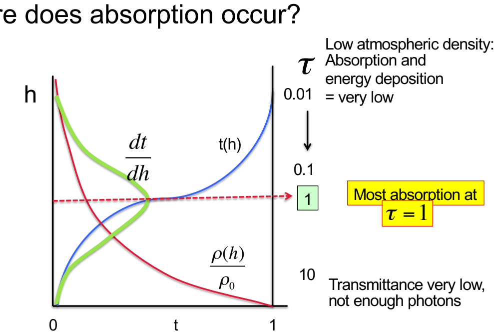
Where does absorption occur?



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Derivation for pundits

- At which height and which optical depth does the transmittance change the most?

$$n(h) = n(h_0)e^{-\frac{h-h_0}{H_P}}$$

$$t(h) = e^{-\tau} = \exp\left\{-\int_{h_0}^{h} \sigma_A n(h_0) e^{-\frac{h-h_0}{H_P}} dh\right\}$$

$$d\tau = \sigma_A n(h)dh$$

$$\frac{dt}{dh} = -e^{-\tau}\frac{d\tau}{dh} = -e^{-\tau}\sigma_A n(h_0)\left(-\frac{1}{H_P}e^{-\frac{h-h_0}{H_P}}\right) = -t(h)\sigma_A n(h_0)\left(-\frac{1}{H_P}e^{-\frac{h-h_0}{H_P}}\right)$$

$h/H_P >> 1$ ➔ $t=1$, $n<<1$ ➔ $dt/dh \sim 0$
$h/H_P << 1$ ➔ $t=0$, $n>>1$ ➔ $dt/dh \sim 0$

Peak for $t \sim 1/e$ ➔ $\tau = 1$

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Sources of attenuation of radiation particularly at radio frequencies

- Precipitation
- Faraday rotation --- proportional to $1/f^2$ important for f< 1 GHz
- Scintillation --- caused by refractive index variation due to temperature, pressure, humidity variations
- Multipath ---radiation arrives via different paths leading to interference and fading
- Wave front incoherence --- decrease of effective antenna gain due to decorrelation across the aperture of an antenna
- Ionospheric scintillation --- caused by free electrons in ionosphere, proportional to $1/f^2$, important for f << 1 GHz

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