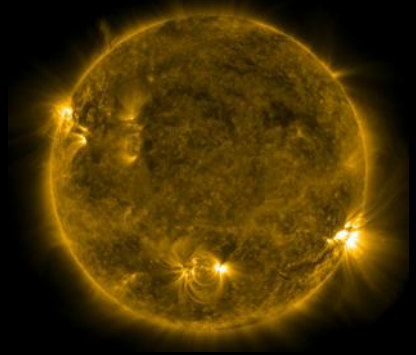
# Sun



# (Sol)

## Basic information

Average Density: 1.4 g/cm$^3$

Luminosity (J/s): a ***trillion-trillion*** 100 W bulbs!

Rotation Period (***equatorial***): 25 days

Surface temperature: ~5800 K

Core temperature: ~15,000,000 K

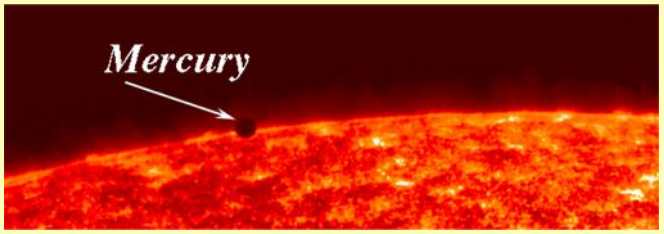
## The Sun (*Sol*)

- ***NEVER*** look directly at the Sun (***eg. Galileo***)
- an *average* star & the ***only one*** in our solar system
- composed of ***hot gas*** (mostly ***H***, ***He***)
- contains *99.9%* of the mass of *solar system*

***Q:*** *Do planetary orbits make sense given this?*

## Size

- *109 times* the ***diameter*** of ***Earth***
- about *1 million Earths* could fit ***inside*** Sun



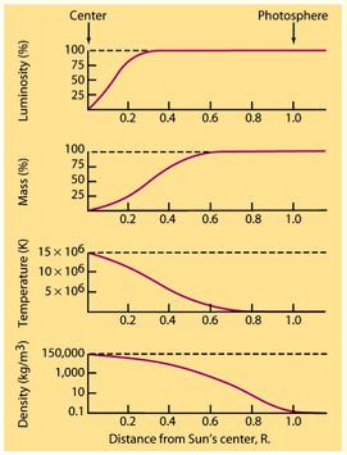

- *~330,000 times* as ***massive*** as ***Earth***

# Interior Structure

• *solar interior*: ***helioseismology*** & *observed solar output* as ***constraints***

• *95% of mass* within *inner 50%* of the Sun

• **all** *energy production* within *inner 25%* of Sun ***ie.*** Sun's ***core***




• *energy* is *transported* **outward** from ***core***

• ***conduction****: energy* transfer via *atomic collisions*

***(eg)*** *iron frying pan on the stove*

• ***convection****: energy* carried by *fluid motion*

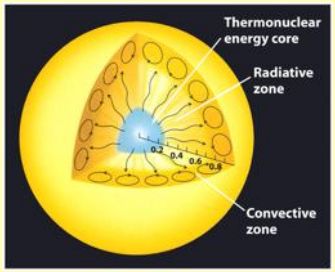
***(eg)*** *water on the stove; thunderheads*

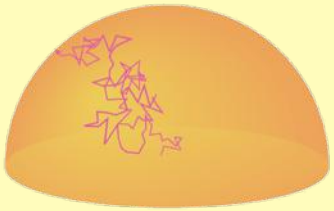
• ***radiation****: energy* radiated via *EM waves*

***(eg)*** *a nice fire;* ***you****!*

***CLICKER:*** *sunshine warms you mainly due to…*
*(a) conduction (b) convection (c) radiation*

• only ***radiation*** & ***convection*** operate inside ***Sun***
• *mode* depends on *temperature, density, gradient*



• average core velocity of *photons*: ***50 cm/hour***
• collisions with electrons *randomize* photon paths

• *~200,000 years* for core energy *to reach surface*

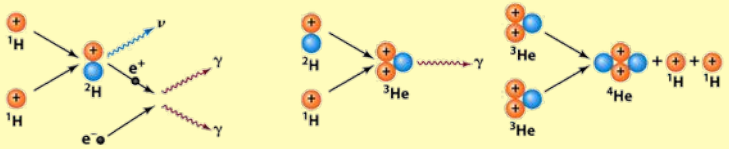
# Fusion

• ***energy*** can't be from *burning*, *chem rxn*, *grav cont*

• at *temp >10 million K*, ***H*** *fuses* into ***He*** (in ***core***)

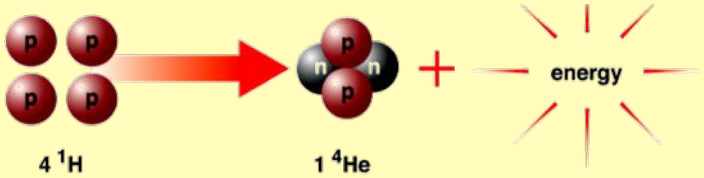
• ***Sun*** fuses *600 million metric tonnes* of ***H*** **per sec**

• occurs in *steps*: ***proton-proton chain***



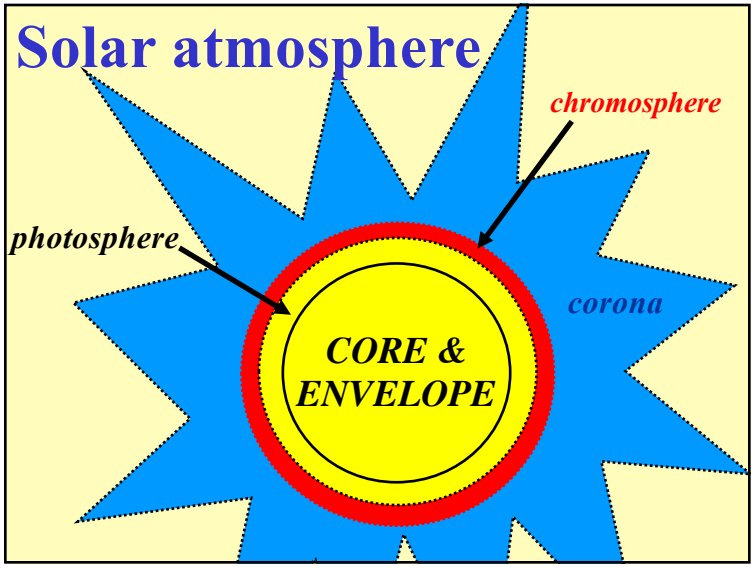

• produces ***gamma ray photons*** ($\gamma$) & ***neutrinos*** ($\nu$)

• *mass* of ***4 H*** is *greater* than ***1 He (& 2 positrons)***




• "lost" *mass* is converted to *energy:* $\mathbf{E = mc^2}$

***(eg)*** converting *1 kg* of ***H*** to ***He*** releases the *same energy as burning 20,000 tonnes of coal!*




# Photosphere

• "*sphere of light*"

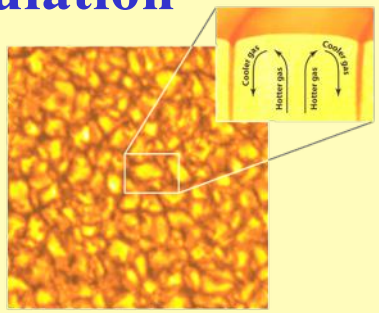
• *~ 400 km thick*
• *temperature: ~5800 K*

• *visible layer* ("*surface*") of ***Sun***; only ***appears*** solid
***(eg)*** *like looking into fog*

# Granulation

• *blotchy patterns* visible on the ***photosphere***

• ***convection*** *cells* transport ***energy*** from *interior*

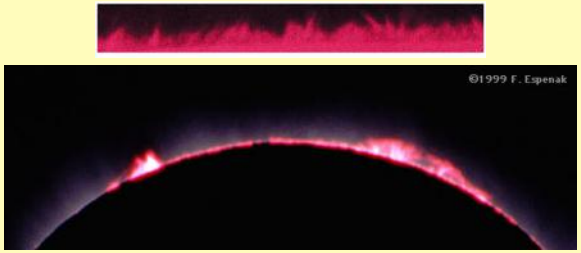



• *granules ~ 1000 km* wide - *bigger* than ***Texas****!*

***Q:*** Why are they dark *along their edges*?

# Chromosphere

- "*sphere of colour*"




- *dim, low density gas* layer visible during *eclipses*
- *emission line spectra* ***(eg)*** $H_\alpha$ *(Balmer), 656 nm*
- *~2000 km* thick; temperatures up to *25,000 K*

# Chromosphere (*Venus transit*)

# Corona

- *outermost layer*
- ***very*** *high temperature,* ***very*** *low density* gas
- ***emission line*** *spectra*
- *ionized species*

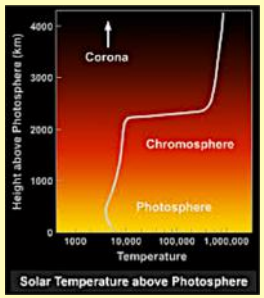
⇒ *high temperatures*

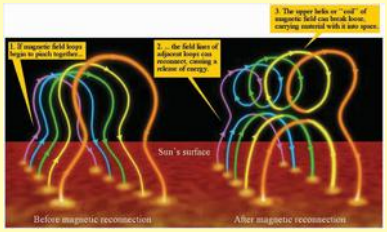
- 1930's: *1-2 million* K

***Q:*** *High temperature* but not "***hot***" … ???

***Q:*** *Why is temperature of* ***corona*** *so incredibly high?*

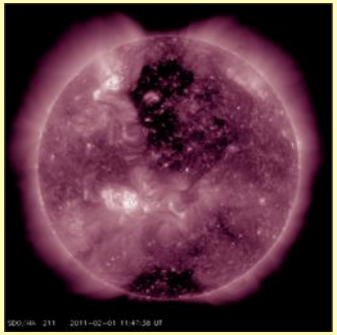
- *magnetic field* energy released during ***reconnection*** of *coronal arches (****nanoflares****)*



• corona *emits* ***UV & X-rays***

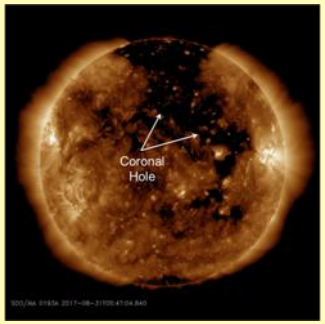
• *only one millionth* as bright as ***photosphere***
• "like" *full moon*



***CLICKER:*** *The corona is very dim relative to the photosphere because…?*
*(a) most of the emission is not in visible light*
*(b) the density is very low*
*(c) it contains colder gas than the photosphere*
*(d) magnetic field lines are unable to trap hot gas*
*(e) both a & b (f) both b & c (g) both c & d*

# The Solar Wind

• *mass loss* from ***corona***
• ***electrons***, ***H*** & ***He nuclei***
• *one million tonnes/second*




• *preferential loss* via **open** field lines: ***coronal holes***

• **average** speed & density: 450 km/s & < 5 per $cm^3$

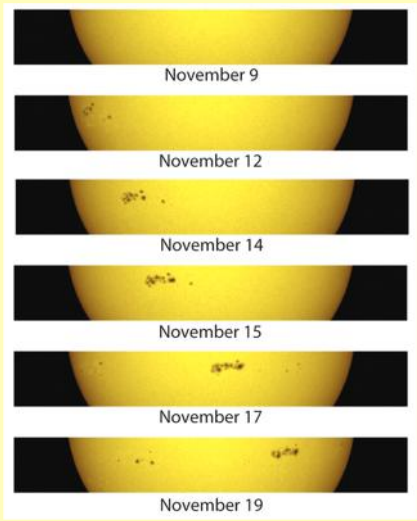
• SW loss ~ *0.1 %* of ***Sun's*** *mass* over *lifetime*

# Sunspots

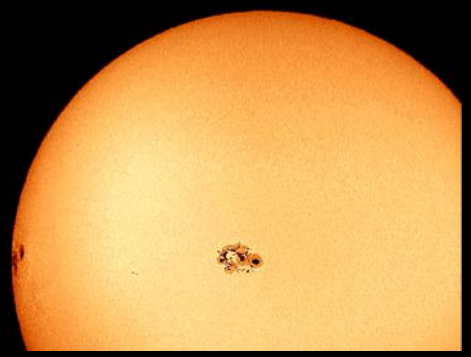
• ***Earth*** sized *dark regions* on ***photosphere***

• ***rotation*** of ***Sun***:
- 25 days at *equator*
- 35 days at *poles*

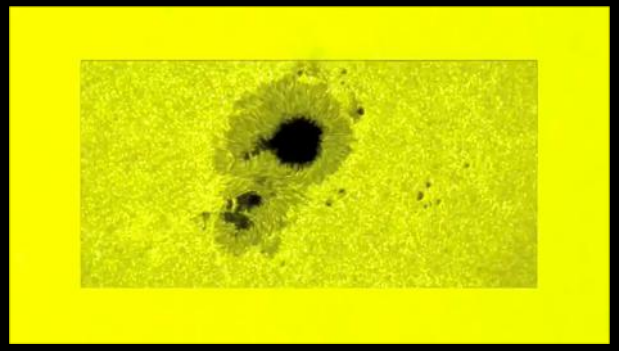
• ***differential rotation*** (***Sun*** is *not* a solid)



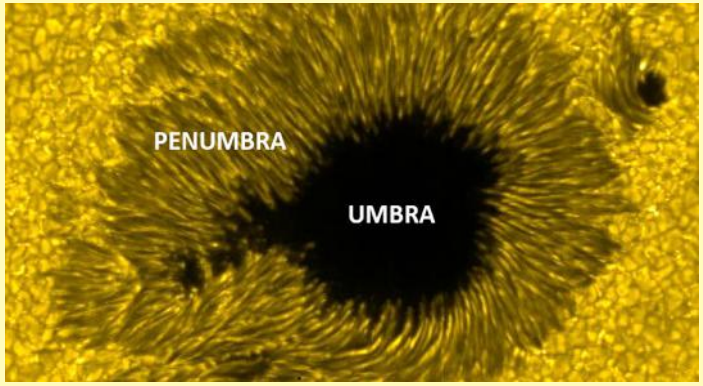

# Sunspot Groups



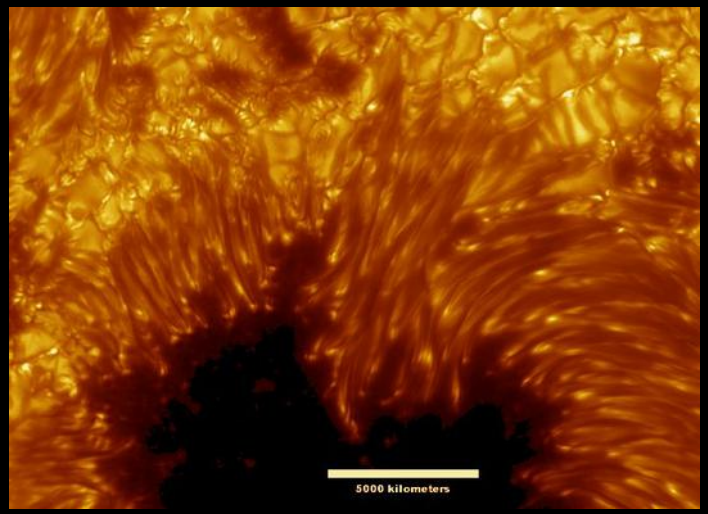
# Sunspots & granulation



***Q:*** why do *sunspots* **appear** *dark? Are they?*




• at *lower* temp *than ambient gas* (*~ 4300 K*)



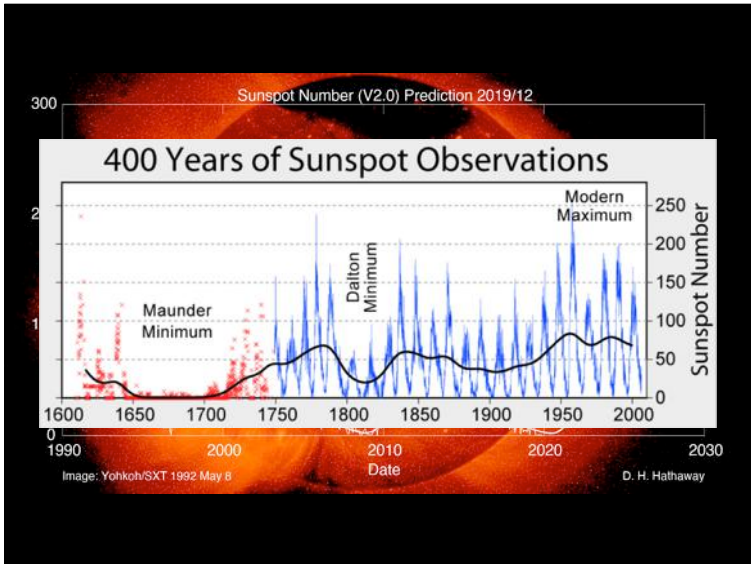

## Solar Cycle

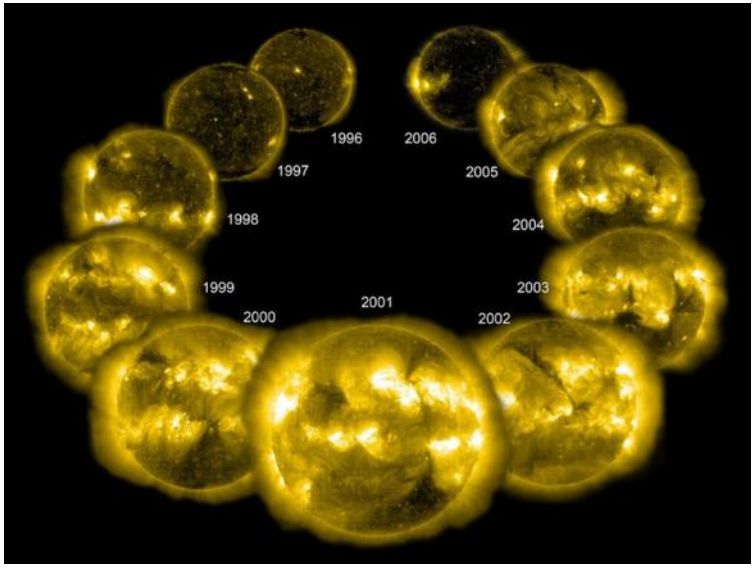
• ***Sun*** has a ***magnetic field*** of *varying strength*
***(eg)*** *Earth:0.5 G; Sun:1-100 G; sunspots:1000's G*

• ***sunspot*** formation *related* to ***magnetic field***

• ***sunspots***: regions of ***concentrated magnetic field***

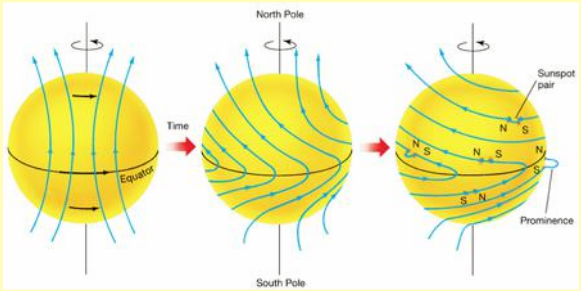
• ***sunspot cycle*** takes *~11 years*, *max* to *max*
• ***magnetic field orientation***: *22 year* ***solar cycle***




# Sunspot Origin

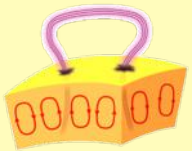
• ***Sun's*** *magnetic field* causes ***sunspots***

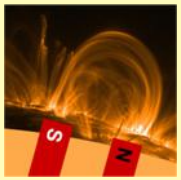



• *magnetic field lines* in ***photosphere*** are "concentrated" by ***differential rotation***

• ***convection*** causes *field lines* to *tangle* & *twist*

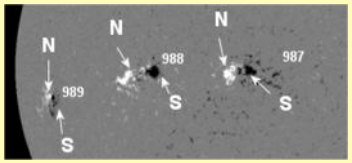
• *kinks form,* poking through ***photosphere***






• kinked *field line* = *intense* magnetic field

• *sunspots* form *at base* of each loop (*in pairs*)




• ***hot plasma*** *repelled by* magnetic field ⇒ *cooler*

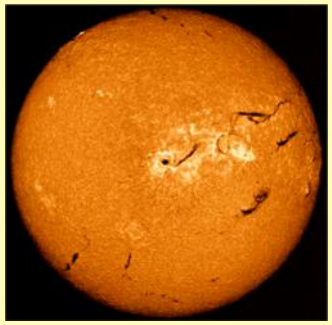
***Q:*** *Why do* ***sunspots*** *eventually disappear?*

• ***prominences***: *loops of gas* from ***chromosphere***
• eventually *fall back* into ***Sun***

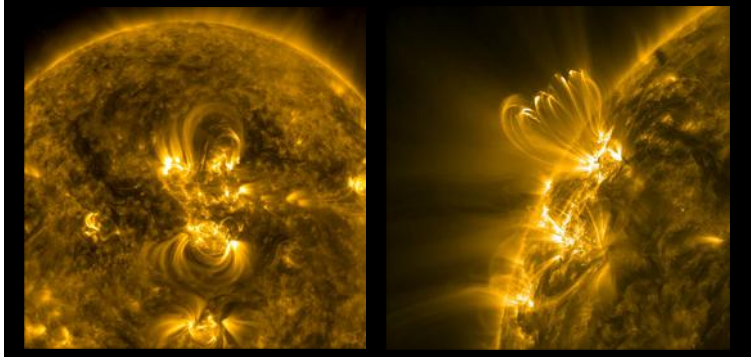
***Q:*** Why are they *loops*?

• ***filaments***: *prominences* viewed from *above*

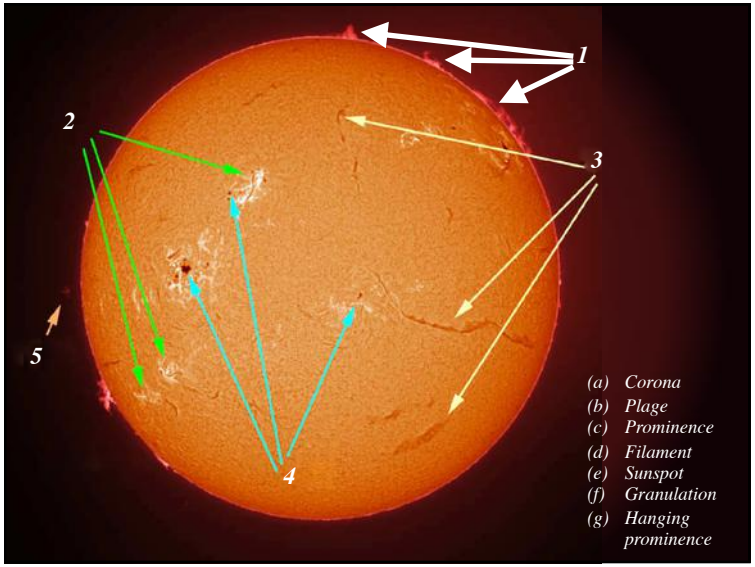
• ***plages***: bright regions in ***chromosphere*** prior to appearance of ***sunspots***



## Prominences



## Hanging Prominence



# Flares & CMEs

- ***speed*** & ***density***: up to 1000 km/s, 100 $cm^{-3}$
- may *penetrate Earth's magnetic field* & *cause* electrical *disruptions* ***(eg)*** *1989 Hydro Quebec*
- *classes:* ***A<B<C<M<X***
- *associated* with ***sunspots***