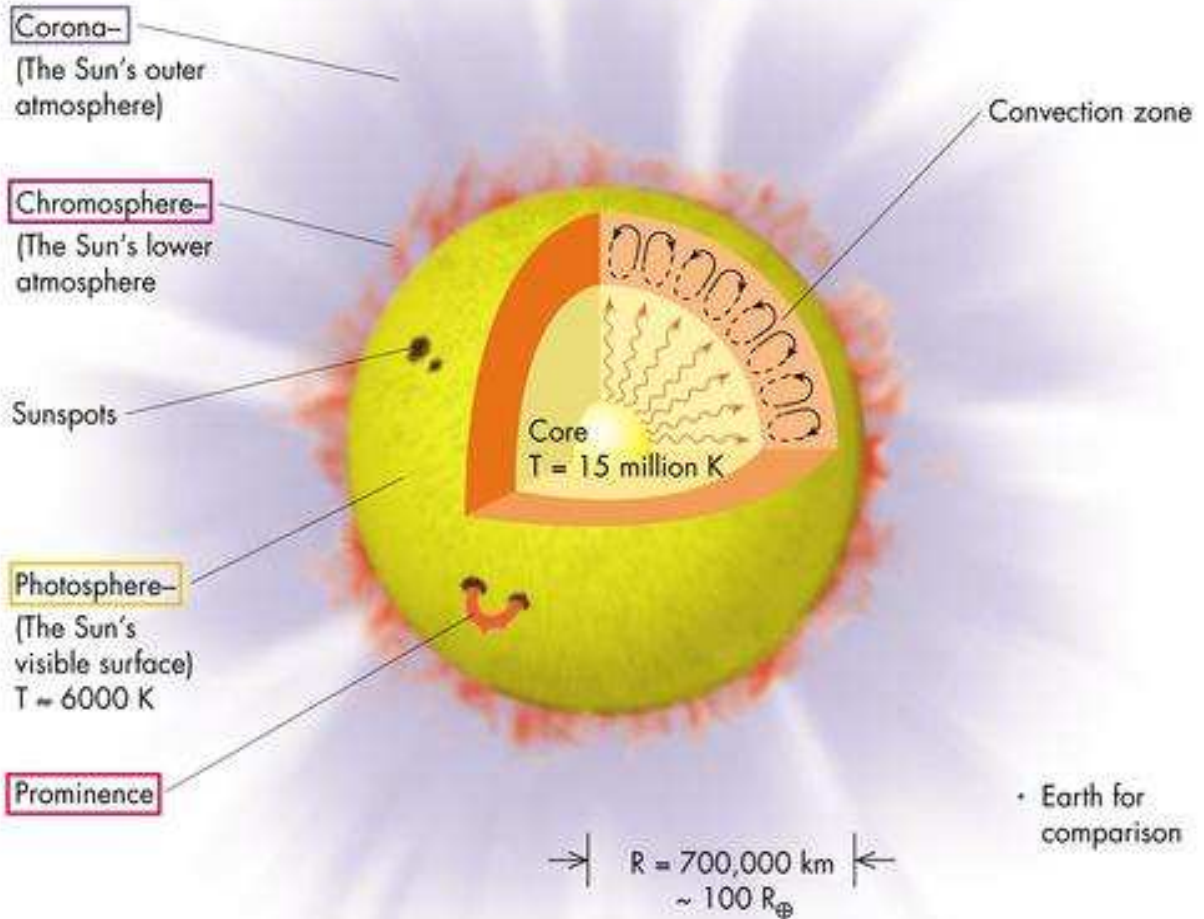
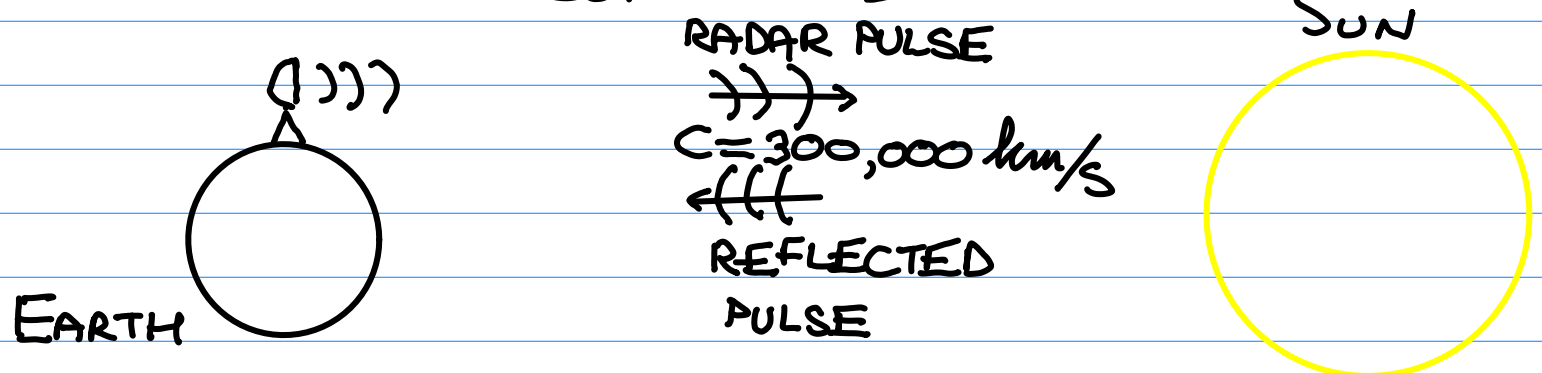


THE SUN



AVERAGE DISTANCE : 1 AU = 150 MILLION km

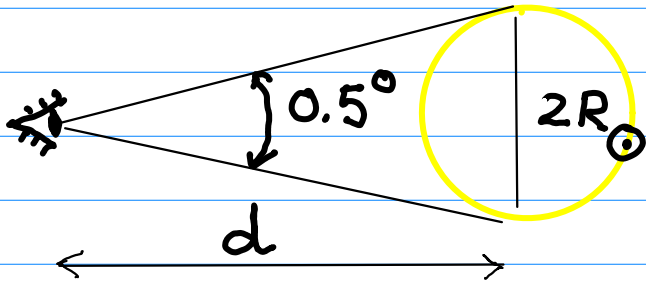
FROM RADAR MEASUREMENTS



THE DISTANCE = TIME OF FLIGHT (TO AND FROM) · C

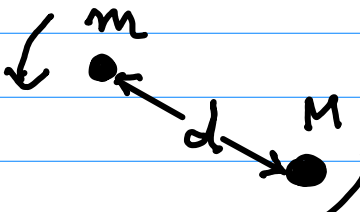
RADIUS: $R_{\odot} = 700,000 \text{ km} = 109 R_{\text{EARTH}}$

FROM DISTANCE AND ANGULAR SIZE



MASS: $M_{\odot} = 2 \times 10^{30} \text{ kg} = 300,000 M_{\text{EARTH}}$

FROM THE THIRD KEPLER'S LAW AS FORMULATED BY NEWTON

 $\frac{d^3}{P^2} = \frac{M + m}{\text{in } M_{\odot}} \approx M$ WHEN m IS MUCH LESS THAN M

IN AU → d^3 IN YEARS → P^2

AVERAGE DENSITY: $\frac{M_{\odot}}{V_{\odot}} \approx 1.4 \frac{\text{g}}{\text{cm}^3}$

$\frac{4}{3} \pi R_{\odot}^3$ → V_{\odot}

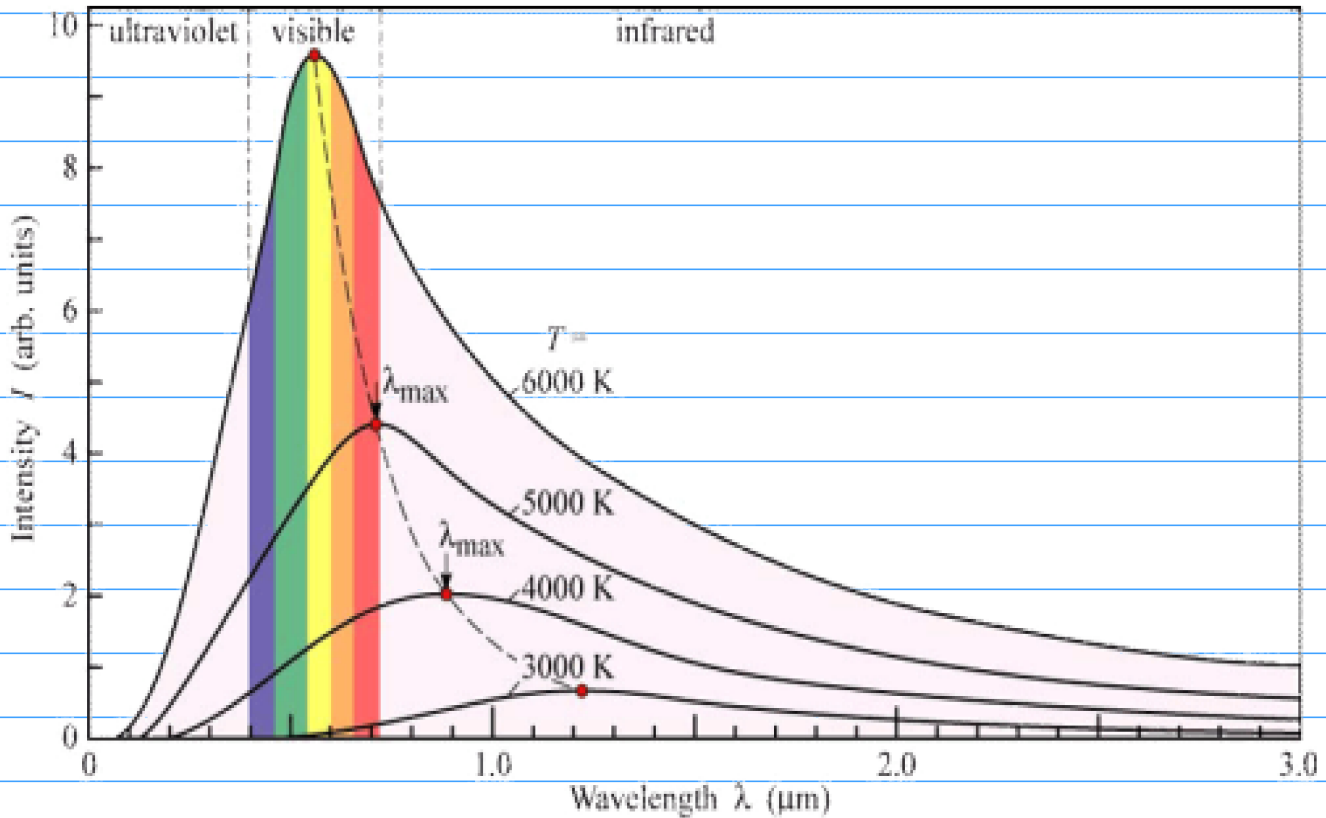
LUMINOSITY: $L_{\odot} = 4 \times 10^{26} \text{ WATTS}$

FROM d AND MEASURED BRIGHTNESS $B_{\odot} = 1.4 \frac{\text{kW}}{\text{m}^2}$

USING $B_{\odot} = L_{\odot} / (4\pi d^2)$

SURFACE TEMPERATURE: $T_{\odot} = 6,000 \text{ K}$

FROM SUN'S SPECTRUM USING THE WIEN'S LAW



CHEMICAL COMPOSITION BY MASS:

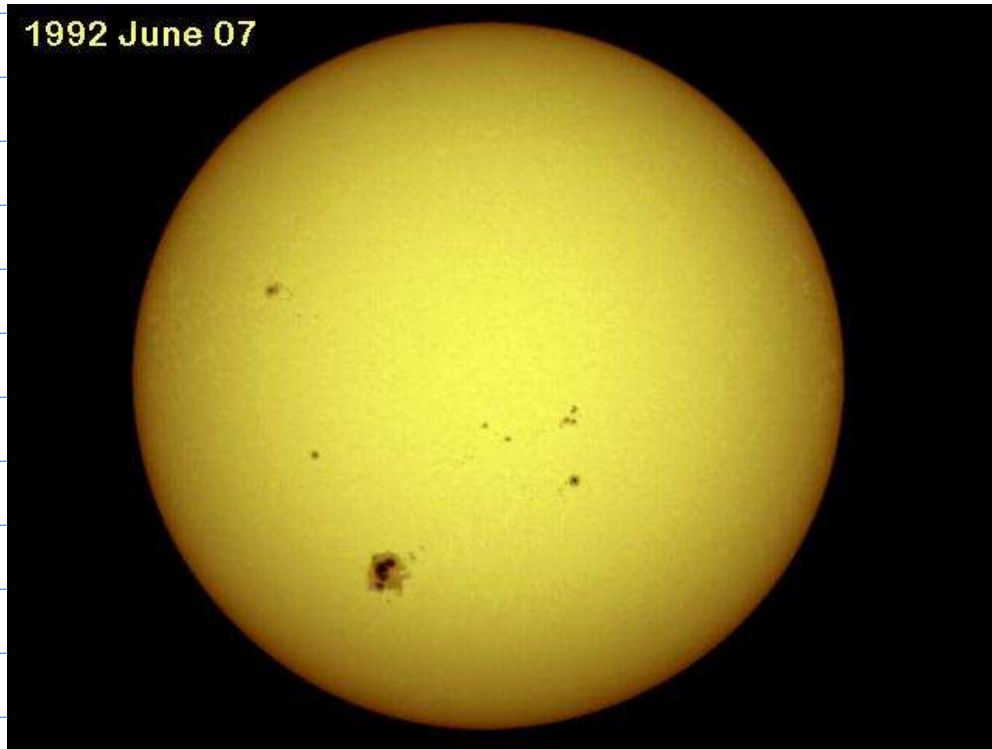
HYDROGEN (H) $\approx 73\%$

HELIUM (He) $\approx 25\%$

ALL OTHER ELEMENTS $\approx 2\%$

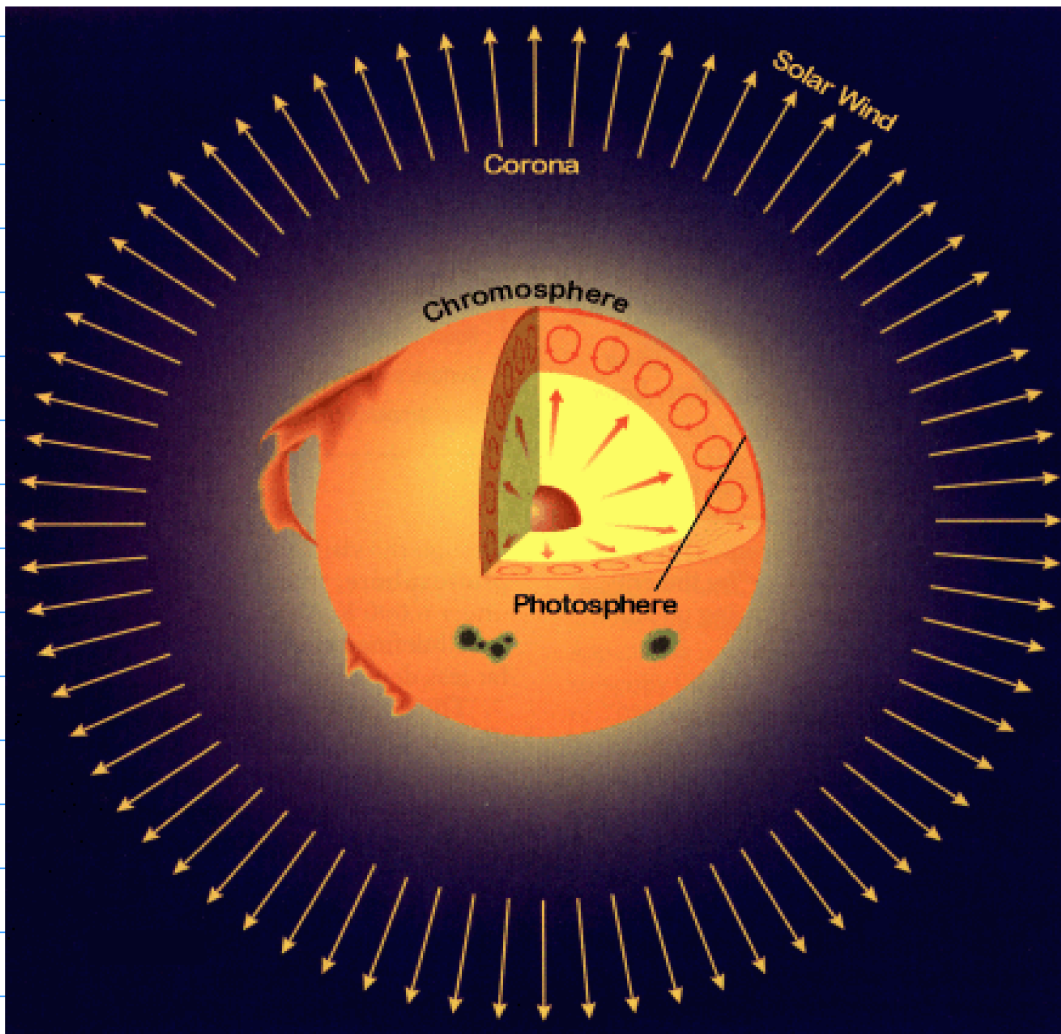
FROM ABSORPTION SPECTRUM

THE VISIBLE SURFACE OF THE SUN IS CALLED PHOTOSPHERE:

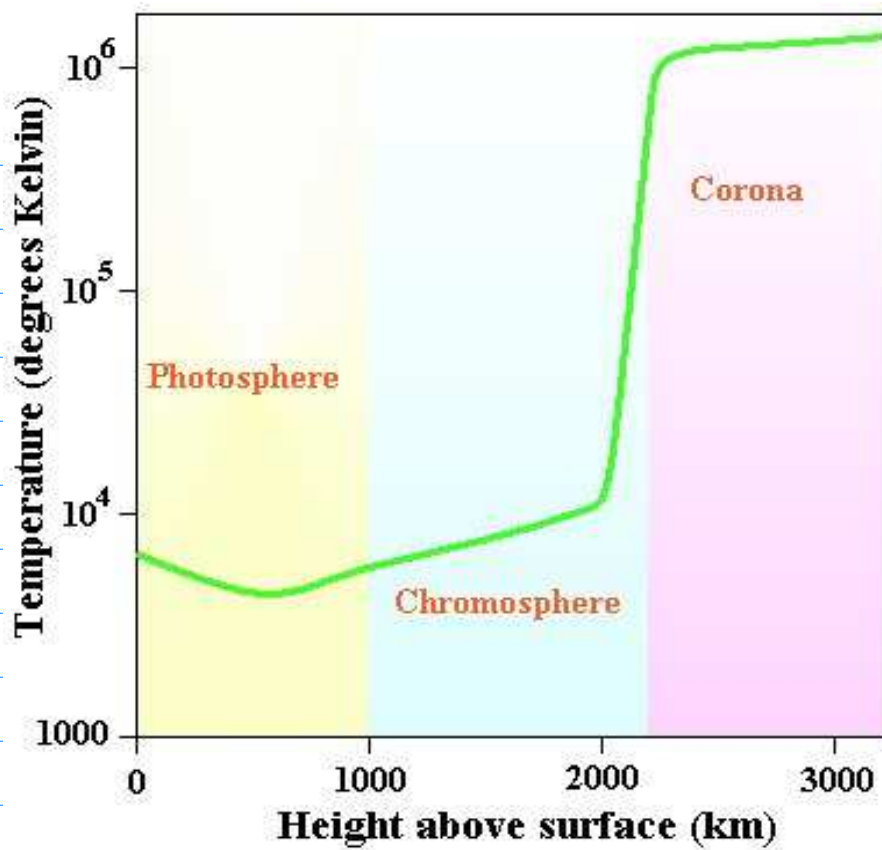


THE THICKNESS OF THE PHOTOSPHERE IS ABOUT 500 km (THE THINEST LAYER OF THE SUN). THE SUNSPOTS VISIBLE ON THE SURFACE ARE AREAS THAT ARE COOLER (RECALL THE STEFAN-BOLTZMANN'S LAW $L \propto T^4$).

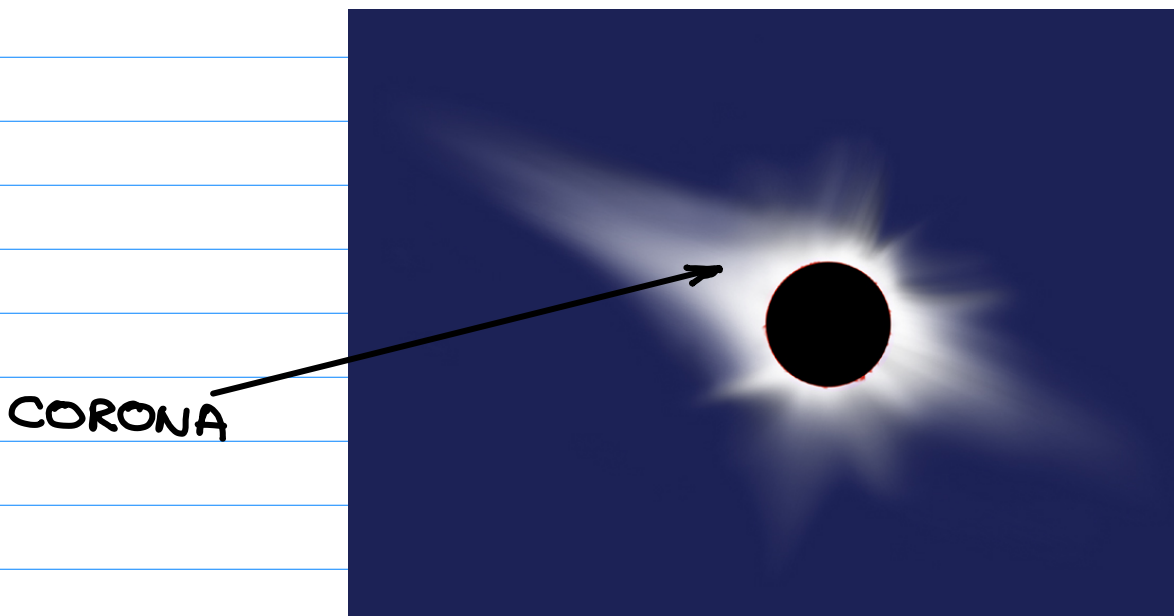
SOLAR ATMOSPHERE :



CHROMOSPHERE IS THE SUN'S LOWER ATMOSPHERE. IT HAS THICKNESS OF 2,000 km. IT'S COLOUR IS PURPLE FROM H-ALPHA EMISSION LINES. THE TEMPERATURE CHANGES FROM 6,000 K TO 20,000 K :



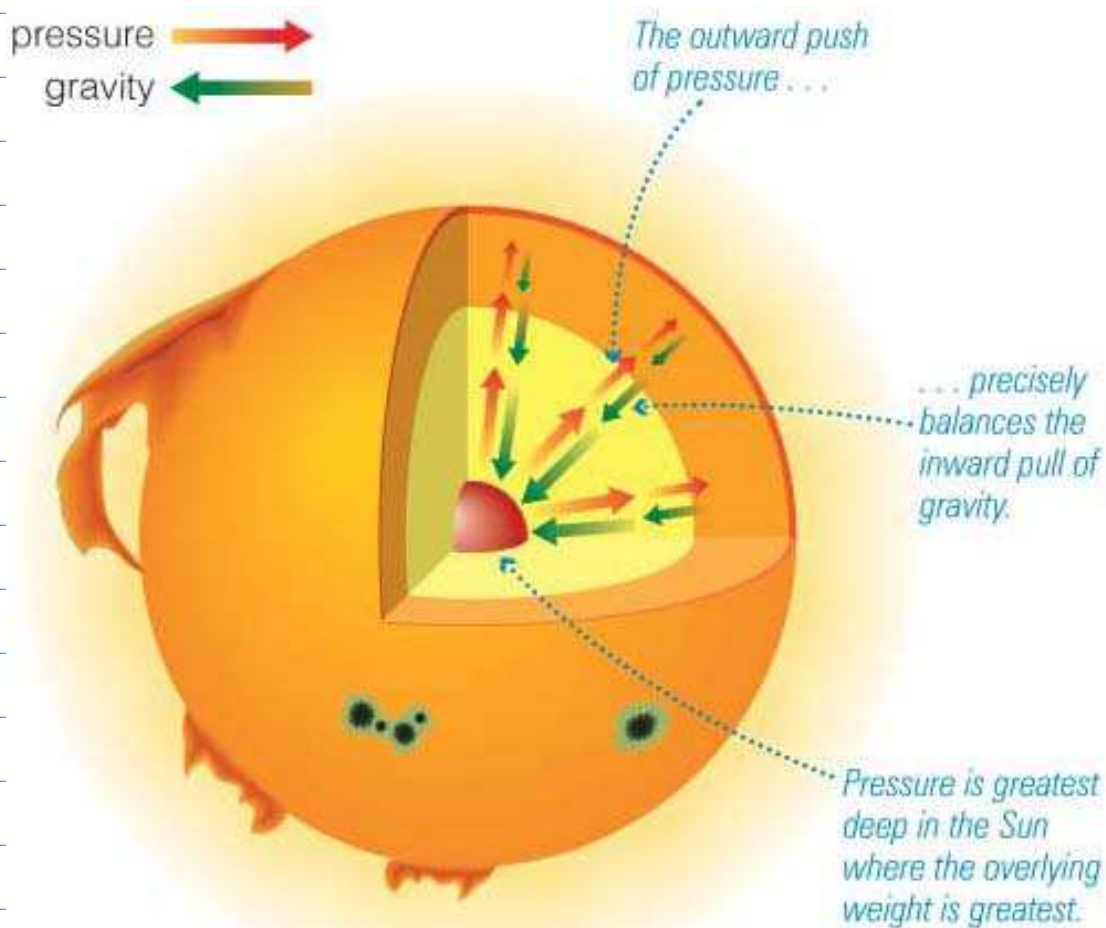
CORONA IS THE SUN'S OUTER ATMOSPHERE :



IT IS VERY LOW DENSITY BUT IT IS VERY HOT WITH A TEMPERATURE OF ABOUT 1 MILLION K (Fe EMISSION LINES ARE OBSERVED).

WHAT MAKES THE SUN SHINE?

FIRST, LIKE ALL MAIN SEQUENCE STARS, THE SUN IS IN HYDROSTATIC EQUILIBRIUM:



THE PRESSURE IN THE CORE REGION MUST BE TREMENDOUS TO SUPPORT THE WEIGHT OF THE TOP LAYERS.

HIGH PRESSURE (P) IN THE CORE REGION IS PRODUCED BY HIGH TEMPERATURE (T):

$$p \propto nT$$

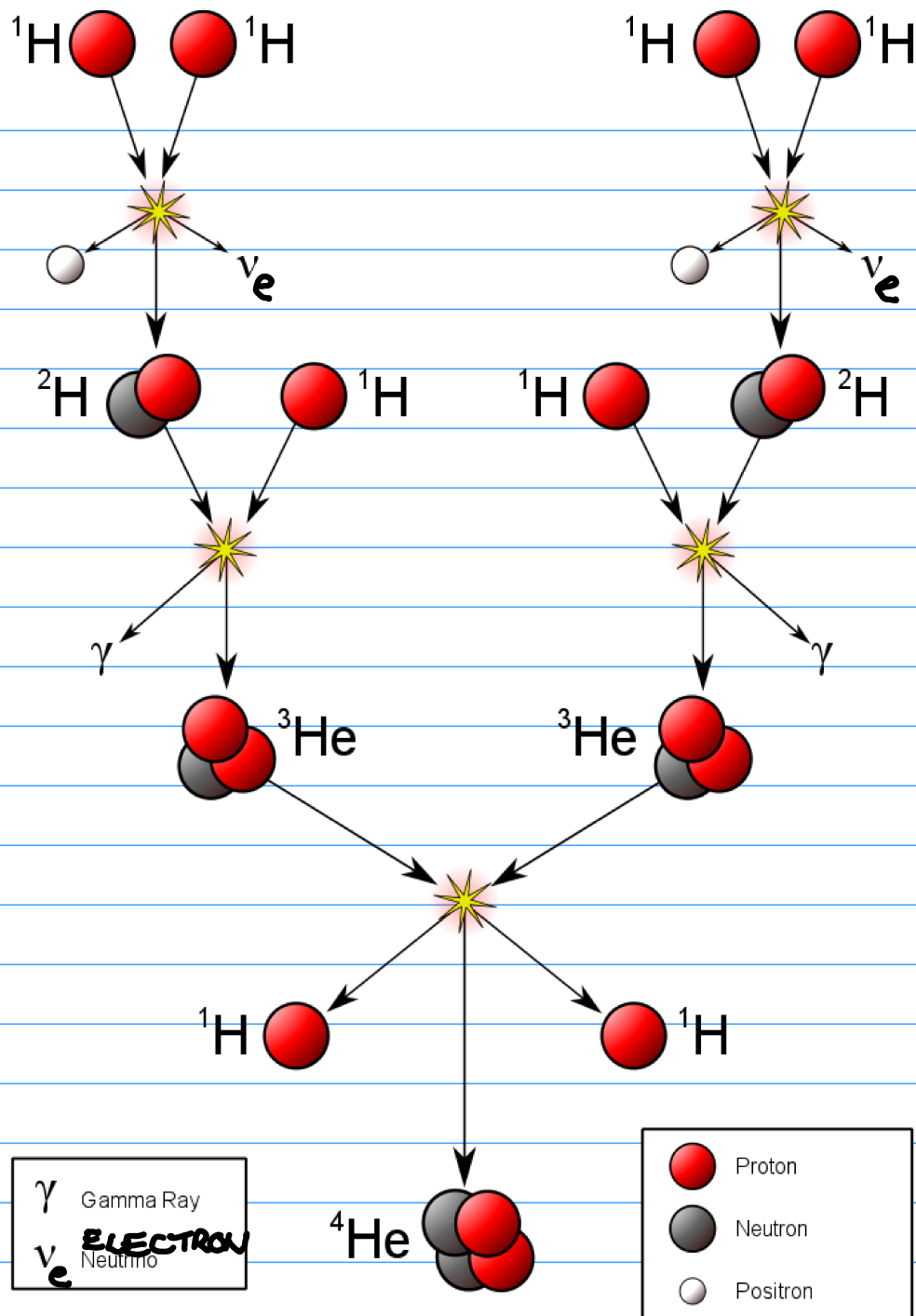


NUMBER DENSITY
(NUMBER OF PARTICLES
PER UNIT VOLUME)

HIGH TEMPERATURE IN THE CORE
IMPLIES HIGH ENERGY PRODUCTION
IN THE CORE REGION.

ONLY FUSION OF LIGHT NUCLEI (H) INTO
HEAVIER ONES (He) WITH A RELEASE
OF ENERGY CAN PRODUCE ENOUGH ENERGY
TO CREATE THE TEMPERATURE AND PRESSURE
NEEDED TO SUPPORT THE TOP LAYERS OF
THE SUN.

IN THE SUN AND OTHER STARS WITH
MASSES $\leq 2M_{\odot}$ THE FUSION OF HYDROGEN
INTO HELIUM WITH A RELEASE OF ENERGY
PROCEEDS VIA PROTON-PROTON (p-p) CHAIN:



STEP 1 TWO PROTONS (${}^1\text{H}$) ARE FUSED INTO THE NUCLEUS OF DEUTERIUM (${}^2\text{H}$), OR HEAVY HYDROGEN, WITH THE RELEASE OF POSITRON (OR ANTI-ELECTRON), ELECTRON NEUTRINO (ν_e) AND ENERGY (GAMMA RAY). FOR THIS TO HAPPEN THE TWO PROTONS MUST APPROACH EACH OTHER TO WITHIN 10^{-15}m . SINCE THE PROTONS REPEL

(LIKE CHARGES REPEL) THEY HAVE TO MOVE FAST ENOUGH TO GET THAT CLOSE TO EACH OTHER. THUS, THE FUSION WILL NOT BEGIN IF THE TEMPERATURE IS NOT AT LEAST 10 MILLION K (THE TEMPERATURE MEASURES THE AVERAGE SPEED OF THE CONSTITUENT PARTICLES).

IN ADDITION TO GETTING CLOSE ENOUGH, ONE OF THE TWO PROTONS MUST, AT THE MOMENT OF THE CLOSEST APPROACH, DECAY INTO A NEUTRON AND POSITRON (THE TOTAL ELECTRIC CHARGE IS CONSERVED). THE PROBABILITY OF THIS TO HAPPEN IS EXTREMELY LOW (ONCE EVERY 14 BILLION YEARS). HOWEVER, SINCE ABOUT $\frac{3}{4}$ OF THE SUN'S MASS (2×10^{30} kg) IS HYDROGEN (MASS = 1.67×10^{-27} kg) THERE ARE ABOUT 9×10^{56} PROTONS IN THE SUN.

THEREFORE, ALTHOUGH THE PROBABILITY OF REACTION PER SECOND IS $(1.4 \times 10^0 \cdot 3.16 \times 10^{-7})^{-1} = 2.2 \times 10^{-16}$, THERE WILL BE SOME 10^{41} REACTIONS TAKING PLACE EVERY SECOND.

THE ENERGY (GAMMA RAY) IS RELEASED BECAUSE THE MASS OF ${}^2\text{H}$ IS SLIGHTLY LESS THAN THE MASS OF THE TWO ${}^1\text{H}$ USED TO MAKE IT.

THE MASS DIFFERENCE (m) IS CONVERTED INTO ENERGY (E) ACCORDING TO THE EINSTEIN'S RELATION

$$E = mc^2.$$

NOTE THAT THE LOW PROBABILITY OF THE FIRST STEP IN P-P CHAIN HAS A PROFOUND EFFECT ON THE EXISTENCE OF HUMANS ON EARTH. IF THIS STEP WAS 10 TIMES FASTER THE SUN WOULD EXHAUST ITS ENERGY SUPPLY IN 1 BILLION YEARS INSTEAD OF IN 10 BILLION YEARS. 1 BILLION YEARS IS NOT ENOUGH TIME FOR THE HIGHER FORMS OF LIFE TO EVOLVE.

STEP 2 ${}^2\text{H}$ FUSES WITH ${}^1\text{H}$ TO FORM UNSTABLE NUCLEUS OF ${}^3\text{He}$ WITH A RELEASE OF ENERGY (GAMMA RAY).

STEP 3 TWO ${}^3\text{He}$ MUST APPROACH CLOSE ENOUGH DURING THEIR SHORT LIFETIME TO FUSE INTO A STABLE ${}^4\text{He}$ NUCLEUS WITH A RELEASE OF TWO PROTONS ($2{}^1\text{H}$) WHICH COULD TAKE PART IN THE FURTHER FUSION REACTIONS.

THE NET RESULT OF p-p CHAIN IS THAT $6 - 2 = 4$ PROTONS (${}^1\text{H}$) HAVE BEEN FUSED INTO THE NUCLEUS OF ${}^4\text{He}$.

$$\text{THE MASS OF } 4 {}^1\text{H} = 4 \cdot 1.6734958 \times 10^{-27} \text{ kg}$$

$$\text{THE MASS OF } {}^4\text{He} = 6.6464076 \times 10^{-27} \text{ kg}$$

$$\text{MASS LOST } m = 4.75756 \times 10^{-29} \text{ kg}$$
$$= 0.71\% \text{ OF THE MASS OF } 4 {}^1\text{H}$$

$$E = mc^2 = 4.75756 \times 10^{-29} \text{ kg} \cdot \left(3 \times 10^8 \frac{\text{m}}{\text{s}}\right)^2$$
$$= 4.3 \times 10^{-12} \text{ kg} \frac{\text{m}^2}{\text{s}^2}$$

$$\underbrace{\hspace{10em}}_{1 \text{ JOULE (J)} = 1 \text{ Ws}}$$

0.1×10^{-12} Ws IS TAKEN UP BY THE NEUTRINOS AND THE REMAINING 4.2×10^{-12} Ws IS CARRIED BY GAMMA RAYS (RADIATION).

HOW MUCH MASS IS SUN LOSING EVERY SECOND?

$$\frac{L_{\odot}}{\text{ENERGY OUTPUT OF SINGLE p-p REACTION IN THE FORM OF RADIATION}} = \frac{3.85 \times 10^{26} \text{ W}}{4.2 \times 10^{-12} \frac{\text{W s}}{\text{REACTION}}} = 9.2 \times 10^{37} \frac{\text{REACTIONS}}{\text{s}}$$

$$\text{MASS LOST PER SECOND} = 4.8 \times 10^{-27} \frac{\text{kg}}{\text{REACTION}} \cdot 9.2 \times 10^{37} \frac{\text{REACTIONS}}{\text{s}} = 4.4 \times 10^9 \frac{\text{kg}}{\text{s}}$$

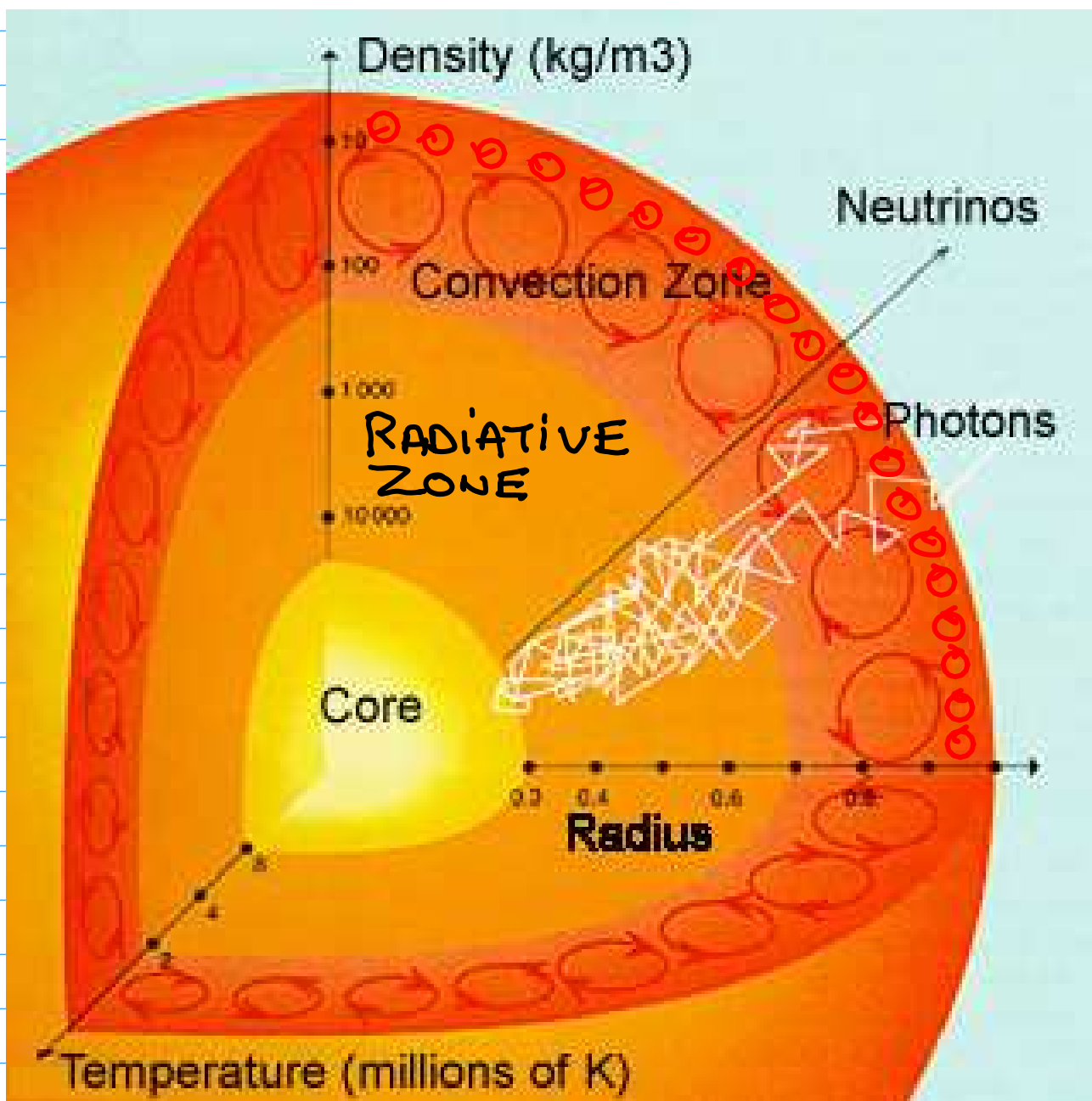
OVER 4.6 BILLION YEARS SINCE THE SUN WAS FORMED THE TOTAL MASS LOSS IS

$$4.6 \times 10^9 \cdot \underbrace{3.156 \times 10^7 \text{ s}}_{1 \text{ YEAR}} \cdot 4.4 \times 10^9 \frac{\text{kg}}{\text{s}} = 6.4 \times 10^{26} \text{ kg}$$

THE CURRENT MASS OF THE SUN IS $2 \times 10^{30} \text{ kg}$ AND THE LOST MASS IS ONLY $\frac{6.4 \times 10^{26} \text{ kg}}{2 \times 10^{30} \text{ kg}} = 3.2 \times 10^{-4} = 0.03\%$ OF ITS CURRENT MASS.

THE CALCULATIONS SHOW THAT THE SUN WILL CONTINUE ITS MAIN SEQUENCE LIFE FOR ANOTHER 5 BILLION YEARS.

ENERGY TRANSPORT FROM THE FUSION CORE TO THE SURFACE



THE FUSION CORE HAS A RADIUS OF ABOUT $0.3 R_{\odot}$.

THE NEUTRINOS ARE GHOSTLY PARTICLES - THEY HAVE NO ELECTRIC CHARGE, NO MAGNETIC MOMENT, AND NEARLY NO MASS.

THEY INTERACT WITH OTHER PARTICLES ONLY VIA THE WEAK NUCLEAR FORCE. AS A RESULT THEY SHOOT THROUGH THE INTERIOR OF THE SUN AT NEARLY THE SPEED OF LIGHT. THERE ARE

$$2 \frac{\text{NEUTRINOS}}{\text{REACTION}} \cdot 9.2 \times 10^{37} \frac{\text{REACTIONS}}{\text{S}} = 1.8 \times 10^{38} \frac{\text{NEUTRINOS}}{\text{S}}$$

EMITTED BY THE SUN. AT A DISTANCE OF 150 MILLION $\mu\text{m} = 1.5 \times 10^{11} \text{m}$ FROM THE SUN THERE ARE

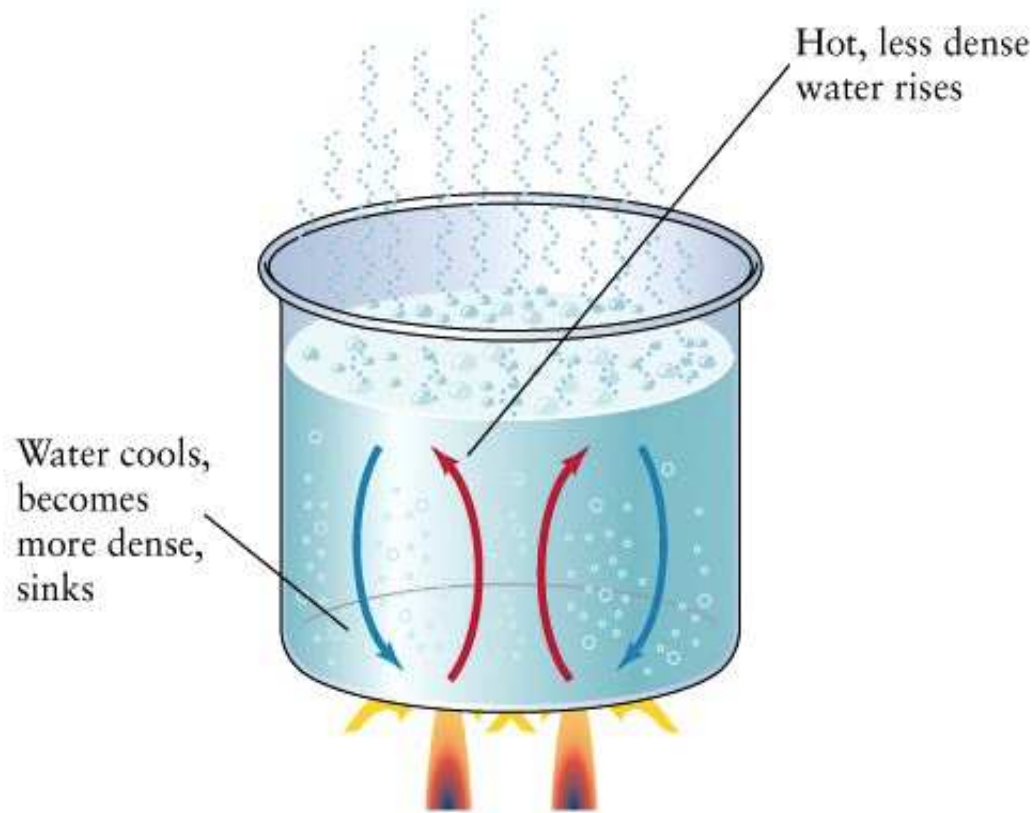
$$\frac{1.8 \times 10^{38} \text{ NEUTRINOS/S}}{4\pi (1.5 \times 10^{11} \text{ m})^2} = 6.4 \times 10^{14} \frac{\text{NEUTRINOS}}{\text{m}^2 \text{ S}}$$

PASSING THROUGH. WE DO NOT NOTICE IT BECAUSE THEY INTERACT WEAKLY WITH THE PARTICLES IN OUR BODIES.

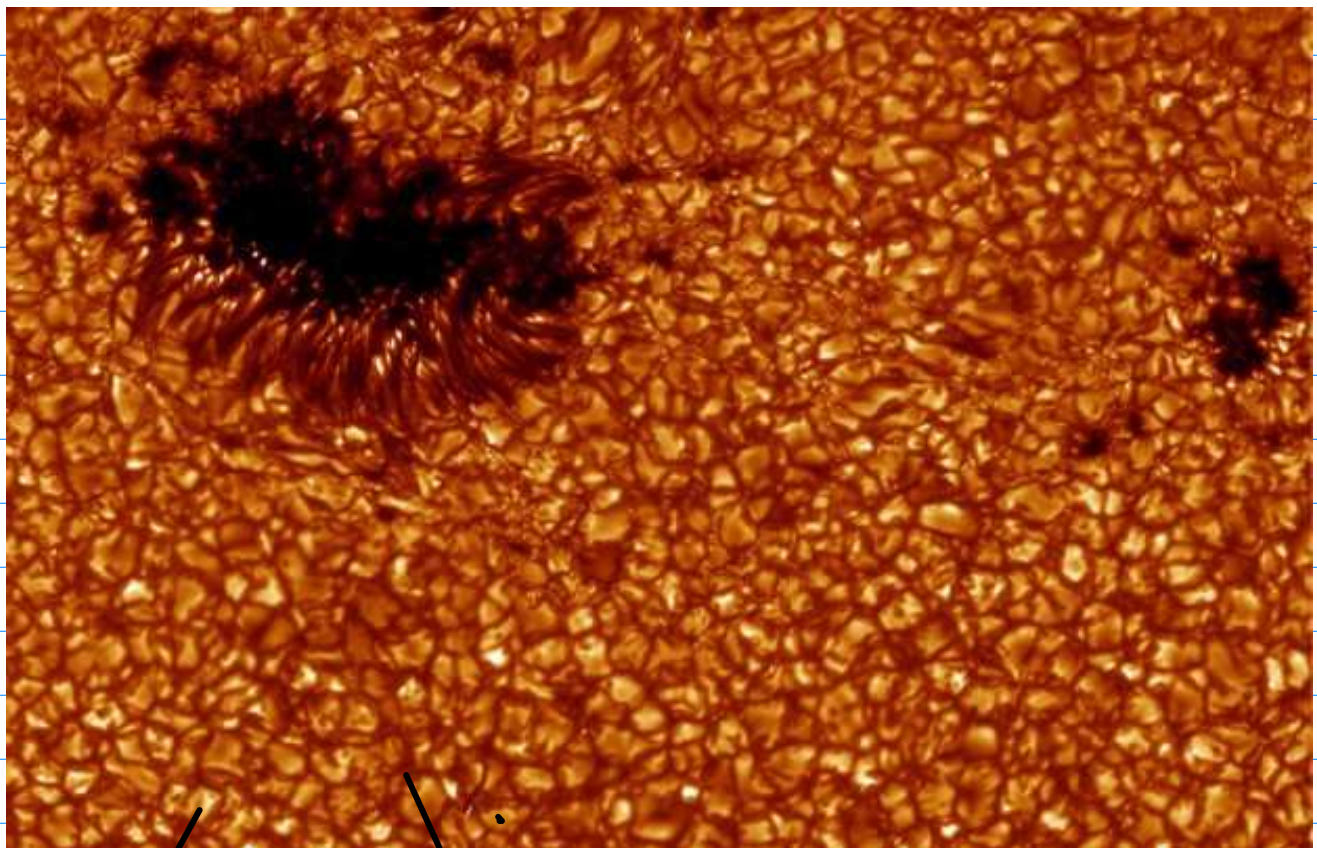
PHOTONS (INITIALLY GAMMA RAYS) INTERACT STRONGLY WITH A DENSE MIXTURE OF CHARGED PARTICLES (ELECTRONS, PROTONS AND ${}^4\text{He}$ -NUCLEI) OUTSIDE THE FUSION CORE. THEY ARE CONSTANTLY SCATTERED BY CHARGED PARTICLES IN RANDOM DIRECTIONS AND AS A RESULT THEY UNDERGO SO-CALLED RANDOM WALK. IN THE PROCESS THEY GIVE UP ENERGY TO THE CHARGED PARTICLES AND AS THEY PROPAGATE TO THE SURFACE MOVING THROUGH THE REGIONS OF LOWER AND LOWER TEMPERATURE THEIR WAVELENGTH GRADUALLY INCREASES. THIS IS HOW THE ENERGY PRODUCED IN THE CORE IS TRANSPORTED FROM $0.3 R_{\odot}$ TO ABOUT $0.7 R_{\odot}$ AND THIS REGION IS CALLED THE RADIATIVE ZONE.

IT TAKES ON AVERAGE A FEW HUNDRED THOUSAND YEARS FOR THE "RANDOM-WALKING" PHOTONS TO MOVE THROUGH THE RADIATIVE ZONE.

FROM ABOUT $0.7 R_{\odot}$ TO THE SURFACE ($1 R_{\odot}$) THE ENERGY IS TRANSPORTED MORE EFFICIENTLY VIA CONVECTION:



GRANULATION OF THE SUN'S SURFACE IS A RESULT OF CONVECTION:



HOTTER COOLER ($L \propto T^4$)

BOUNDARY (COOLER AND DARKER)

← GRANULA →

