

HOW DO WE REALLY KNOW HOW IS THE ENERGY PRODUCED AND TRANSPORTED WITHIN THE SUN?

THE STANDARD SOLAR MODEL:

THE KNOWN PROPERTIES OF THE SUN:

$$L_{\odot} = 4 \times 10^{26} \text{ W} \quad M_{\odot} = 2 \times 10^{30} \text{ kg}$$

SURFACE TEMPERATURE = 6,000 K

CHEMICAL COMPOSITION (BY MASS):

73% H, 25% He, 2% ALL OTHER ELEMENT

ASSUMPTIONS:

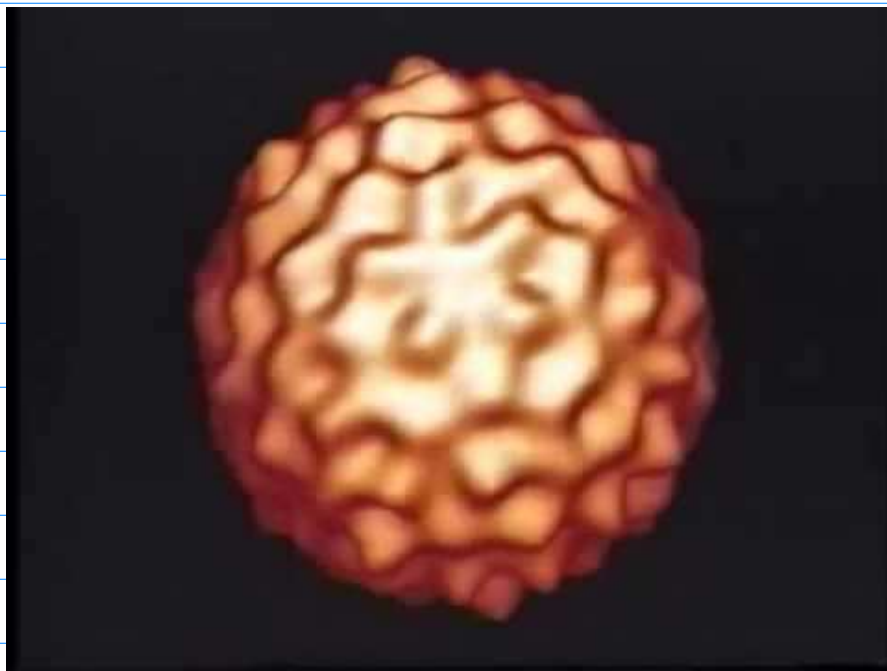
- CONDITION OF HYDROSTATIC EQUILIBRIUM
- THE ENERGY IS PRODUCED VIA PROTON-PROTON CHAIN
- THE ENERGY IS TRANSPORTED WITHIN THE SUN VIA RADIATION AND CONVECTION

GOAL: CALCULATE THE TEMPERATURE AND DENSITY PROFILES OF THE SUN AND COMPARE THEM WITH OBSERVATIONS

HOW DO WE TAKE A PEEK INSIDE THE SUN TO FIND THE TEMPERATURE AND DENSITY PROFILES?

HELIOSEISMOLOGY: THE STUDY OF HOW THE PRESSURE WAVES PROPAGATE WITHIN THE SUN.

MOTION OF MATERIAL AND ENERGY TRANSPORT INSIDE THE SUN RESULT IN WAVES ON THE SURFACE OF THE SUN:



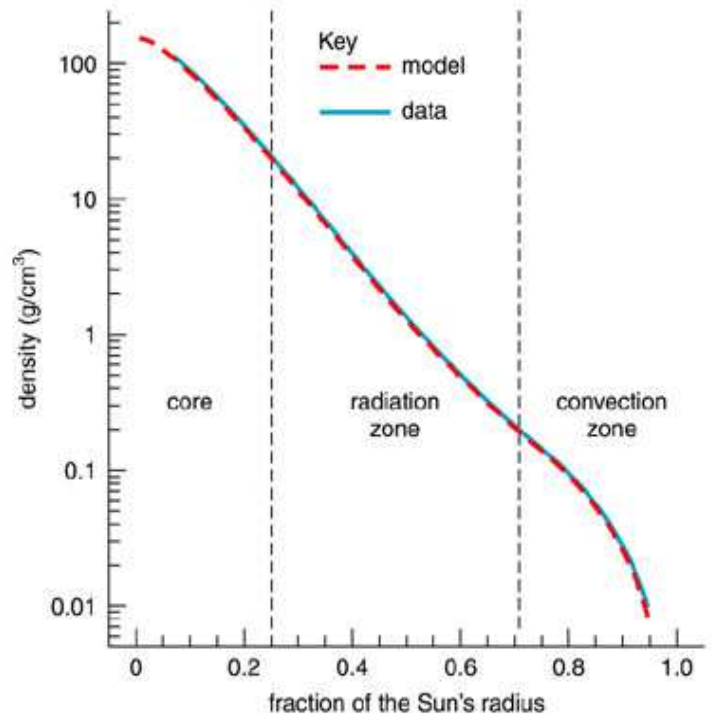
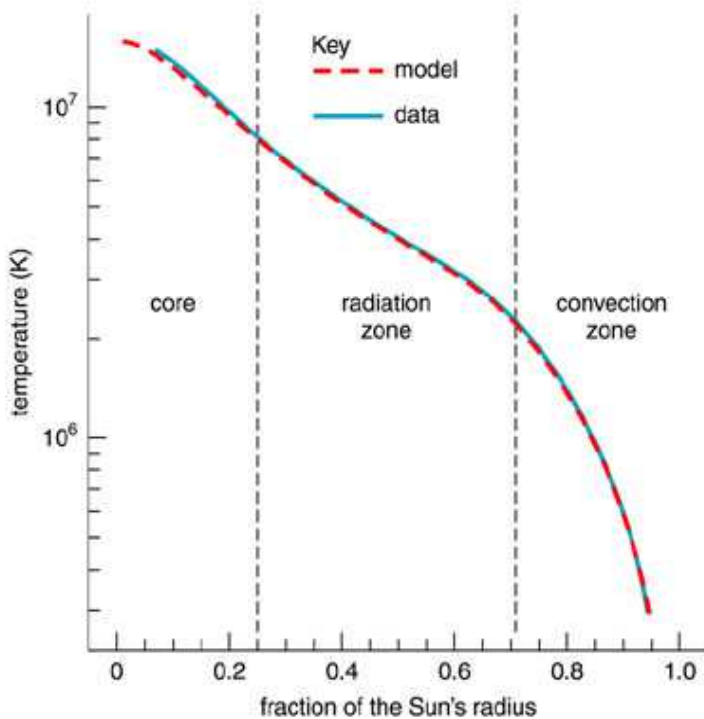
By ANALYZING THESE VIBRATIONS ONE CAN PROFILE THE VARIATIONS IN DENSITY AND TEMPERATURE WITHIN THE SUN.

ANALOGY : DUCK POND



By ANALYZING THE WAVELETS AT THE SHORE WE COULD SAY WHERE THE DUCKS ARE AND HOW FAST THEY ARE MOVING.

THESE STUDIES CONFIRMED THE STANDARD SOLAR MODEL WITH A HIGH DEGREE OF ACCURACY :

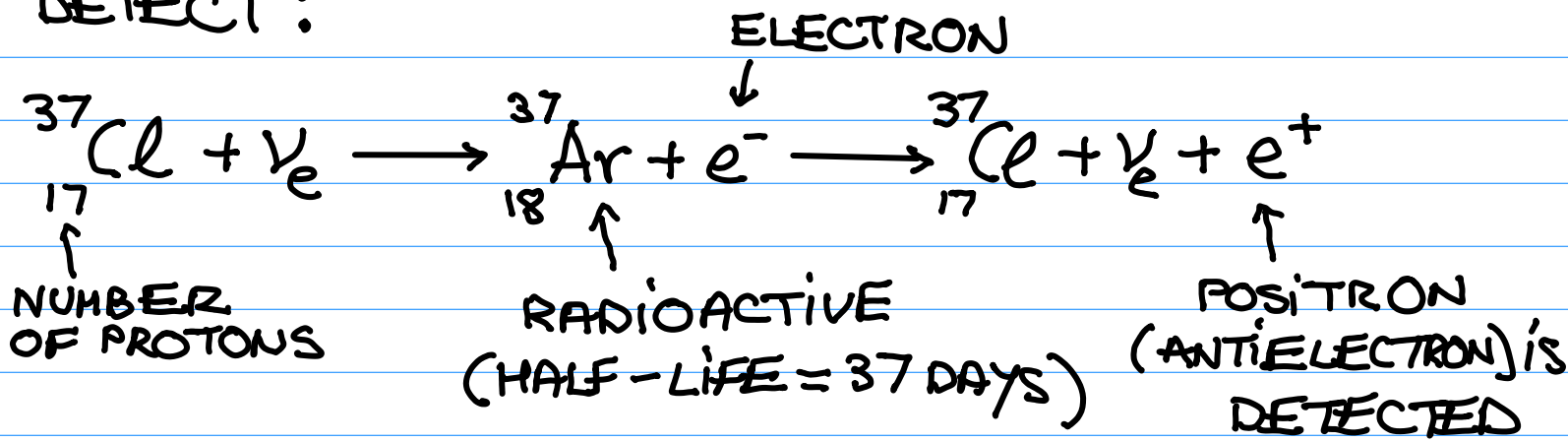


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THE SOLAR NEUTRINO PROBLEM

THE STANDARD SOLAR MODEL PREDICTS THAT THERE ARE 9.2×10^{37} PROTON-PROTON CHAIN REACTIONS IN THE CORE OF THE SUN EVERY SECOND AND EACH REACTION PRODUCES 2 NEUTRINOS. AT 1 AU FROM THE SUN THE SOLAR NEUTRINO FLUX SHOULD BE 6.4×10^{14} NEUTRINOS m^2s .

NEUTRINOS ARE HARD, BUT NOT IMPOSSIBLE, TO DETECT:



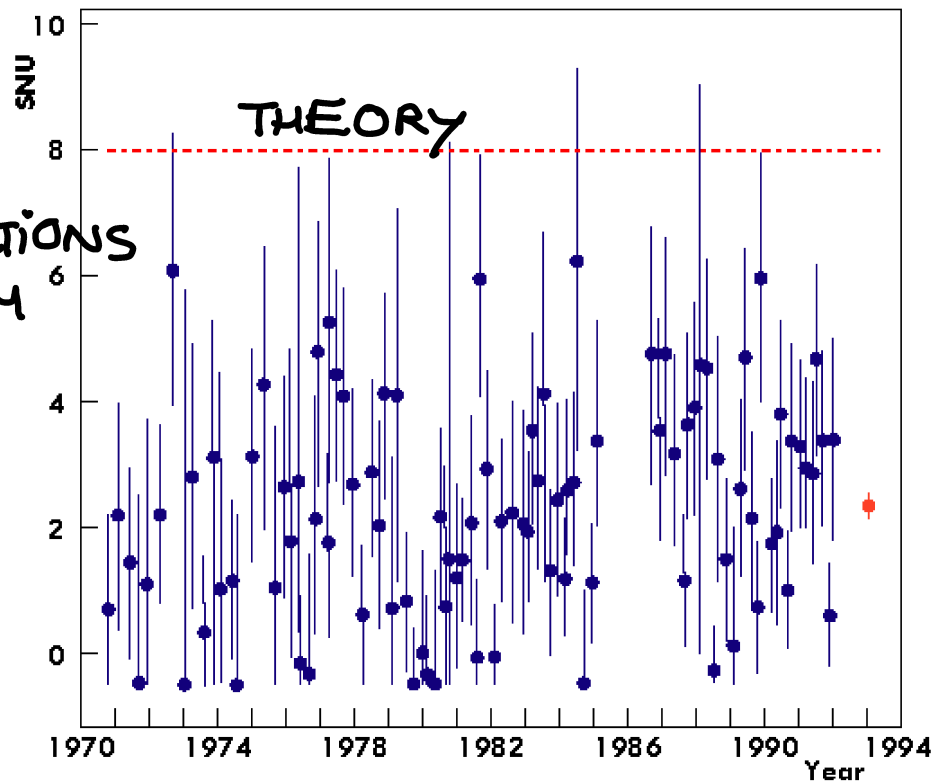
HOMESTAKE GOLD MINE EXPERIMENT (1965):



TANK FILLED WITH 380,000 LITERS OF DRY CLEANING FLUID C_2Cl_4 .

RESULTS:

$\text{SNU} = 10^{-36}$ REACTIONS
PER TARGET ATOM
PER SECOND



LESS NEUTRINOS WERE DETECTED THAN
WHAT WAS PREDICTED BY THEORY.

EXPLANATION (L. WOLFENSTEIN, S. MIKHAYEV
AND A. SMIRNOV): THERE ARE THREE
TYPES (FLAVORS) OF NEUTRINOS -

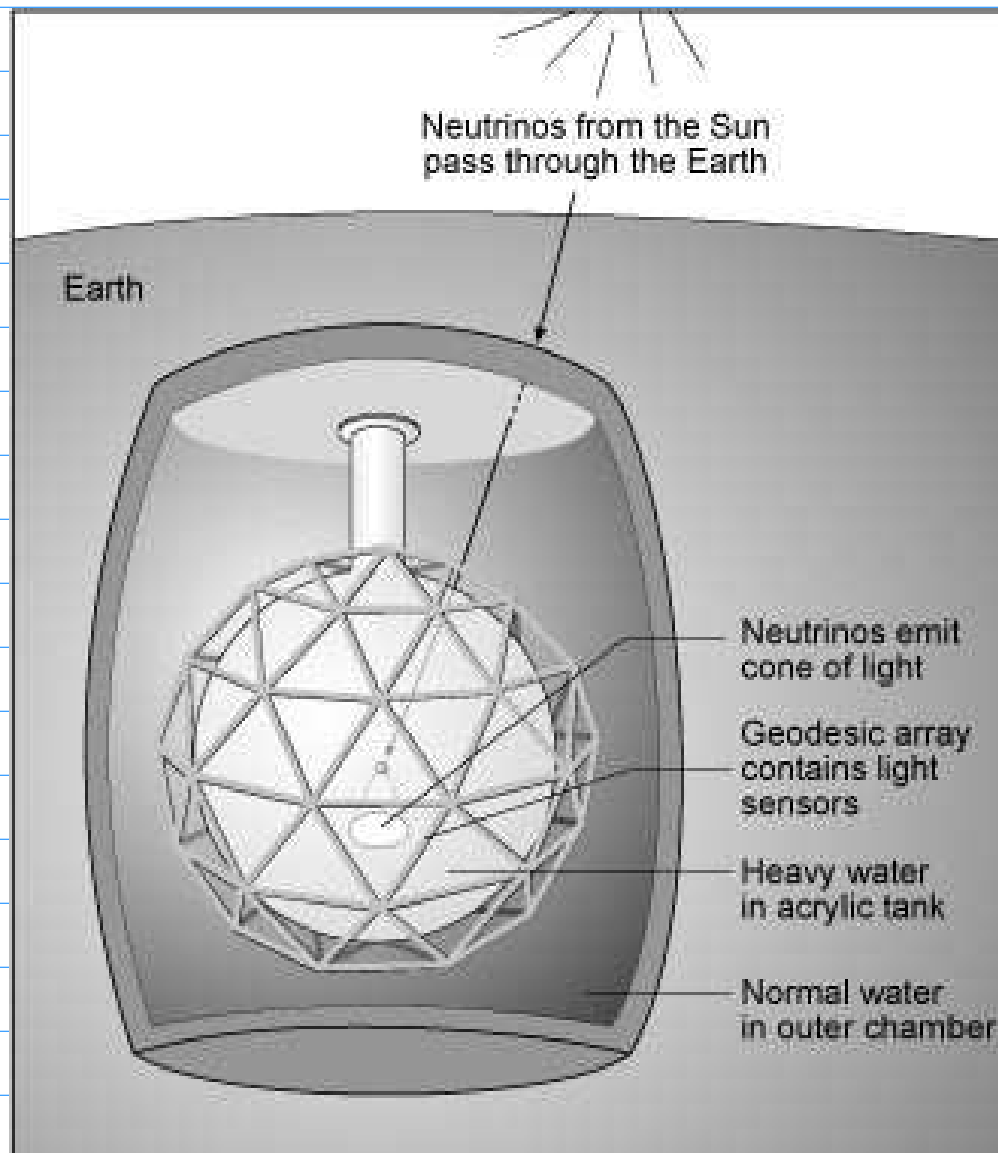
ELECTRON NEUTRINO (ν_e) PRODUCED IN PP CHAIN

MUON NEUTRINO (ν_μ)

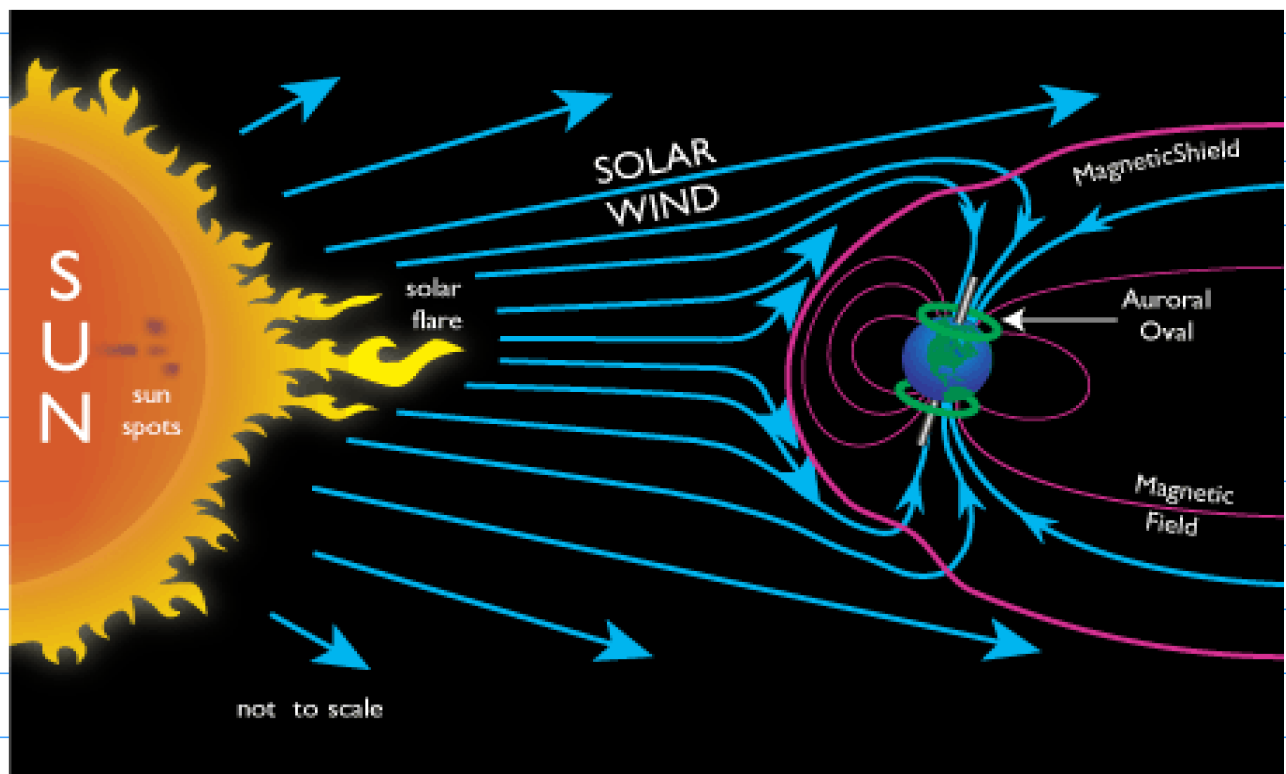
TAU NEUTRINO (ν_τ)

THE THEORY PREDICTS THAT WHEN ν_e PROPAGATES THROUGH HIGH DENSITY ELECTRONS WITHIN THE SUN IT CAN TRANSFORM INTO ν_μ AND ν_τ AND THE HOMESTAKE DETECTOR COULD NOT DETECT THEM.

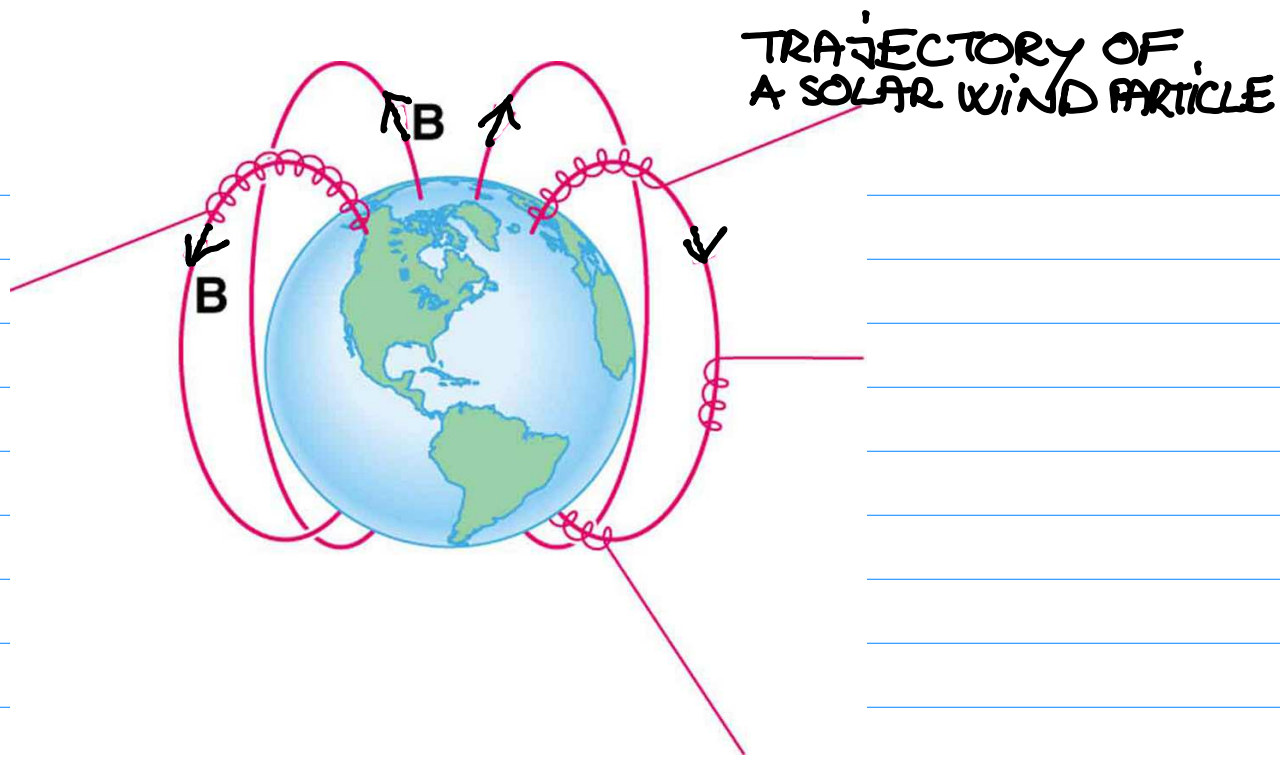
THE THEORY WAS CONFIRMED IN 2001 IN SUDBURY NEUTRINO OBSERVATORY (SNO) WHERE ALL THREE FLAVORS OF NEUTRINOS COULD BE DETECTED:



IN ADDITION TO LIGHT AND NEUTRINOS THE SUN EMITS THE SOLAR WIND - OUTFLOW OF CHARGED PARTICLES (PROTONS AND ELECTRONS). NEAR THE EARTH THE CHARGED PARTICLES MOVE AT SPEED $400 \frac{\text{km}}{\text{s}}$ - $800 \frac{\text{km}}{\text{s}}$. THE EARTH'S MAGNETIC FIELD SHIELDS THE EARTH FROM THE SOLAR WIND:



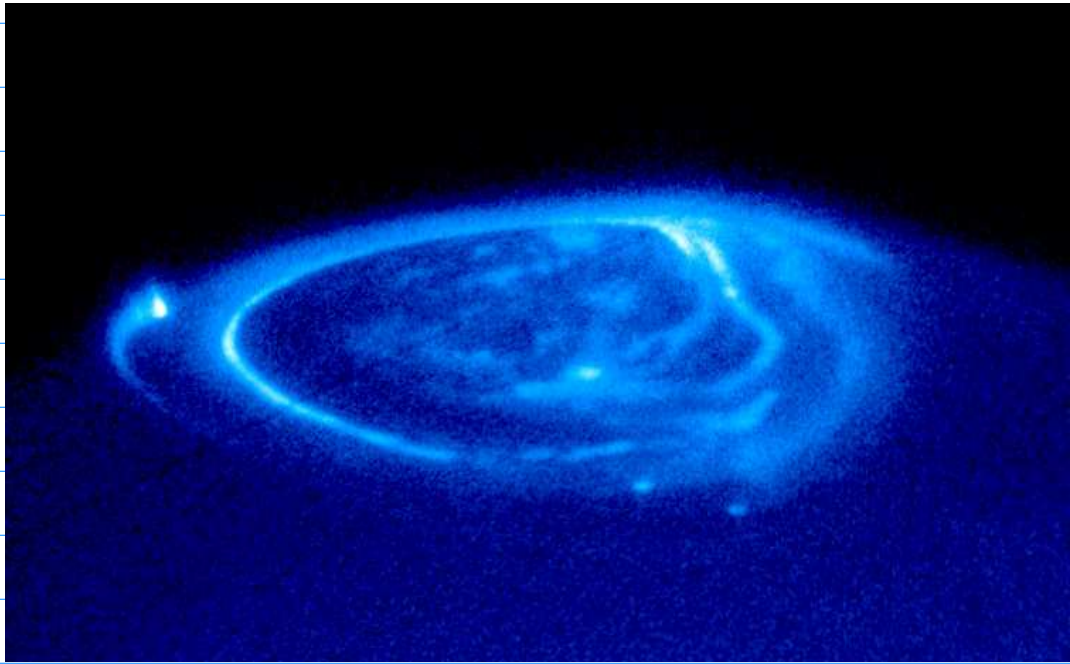
THE REGIONS NEAR THE MAGNETIC POLES OF THE EARTH ARE UNPROTECTED AND THE SOLAR WIND PARTICLES CAN COME DOWN NEAR MAGNETIC POLES AND COLLIDE WITH THE MOLECULES OF THE ATMOSPHERE PRODUCING AURORAE.



AURORA OVER ICELAND IN 2012 (IMAGE CREDIT AND COPYRIGHT: STÉPHANE VETTER (NUITS SACRÉES))

THE MOLECULES IN THE AIR PRODUCE LIGHT VIA FLUORESCENCE.

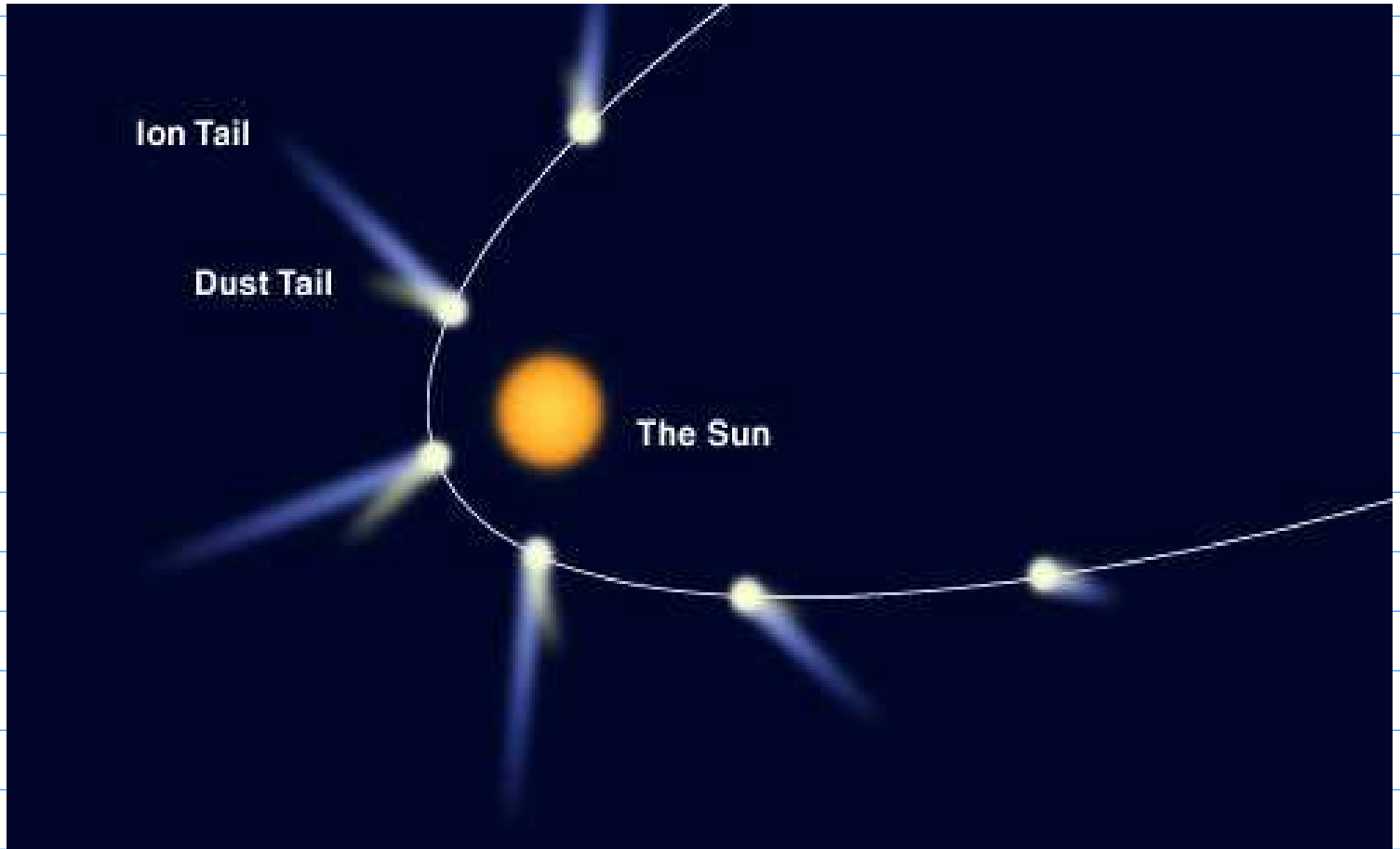
JUPITER:



SATURN:



SOLAR WIND ALSO CAUSES THE TAIL OF A COMET TO POINT AWAY FROM THE SUN:



ION TAIL: SMALL CHARGED MOLECULES (IONS) ARE PUSHED AWAY FROM THE SUN BY SOLAR WIND AND BY THE RADIATION PRESSURE (PHOTONS HAVE MOMENTUM)

DUST TAIL: LARGER PARTICLES ARE PUSHED AWAY BY RADIATION PRESSURE BUT THEY MOVE MORE SLOWLY BECAUSE OF THEIR LARGER MASS; AS A RESULT THE DUST TAIL IS SLIGHTLY CURVED.

THE SUN (LIKE ANY OTHER MAIN SEQUENCE STAR) MAINTAINS THE HYDROSTATIC EQUILIBRIUM VIA THE PRESSURE - TEMPERATURE THERMOSTAT:

IF TOO MUCH ENERGY IS PRODUCED IN THE CORE ITS TEMPERATURE AND PRESSURE INCREASE PUSHING THE TOP LAYERS OUT. AS THE CORE EXPANDS IT COOLS AND THE RATE OF ENERGY PRODUCTION RETURNS TO NORMAL.

ANALOGY:
COVERED BOILING
POT OF WATER



ON THE OTHER HAND, IF THE REACTION RATE IN THE CORE SLOWS DOWN, THE PRESSURE IN THE CORE DROPS AND IT CONTRACTS UNDER THE WEIGHT OF THE TOP LAYERS. CONTRACTING CORE HEATS UP AND THE RATE OF REACTIONS IN P-P CHAIN (PROPORTIONAL TO T^4) RETURNS TO ITS NORMAL VALUE.

OVER TIME, HOWEVER, THE LUMINOSITY OF THE SUN (AND ANY OTHER MAIN SEQUENCE STAR) SLOWLY INCREASES. AT PRESENT THE SUN IS 30% MORE LUMINOUS THAN WHEN IT WAS FORMED 4.6 BILLION YEARS AGO. THE REASON FOR EVER INCREASING ENERGY PRODUCTION RATE IS THE RELATION BETWEEN PRESSURE (p) IN THE CORE, ITS TEMPERATURE (T) AND THE PARTICLE NUMBER DENSITY (n):

$$p \propto n T$$

↑
NUMBER OF PARTICLES/NUCLEI
PER UNIT VOLUME

IN EACH p - p CHAIN REACTION 4 PARTICLES (PROTONS) ARE REPLACED BY 1 (${}^4\text{He}$ NUCLEUS). AS n DECREASES T HAS TO INCREASE IN ORDER TO MAINTAIN THE SAME PRESSURE NEEDED TO SUPPORT THE TOP LAYERS. INCREASE IN T IS REALIZED THROUGH INCREASED RATE OF ENERGY PRODUCTION (L).

IN ABOUT 0.5-1 BILLION YEARS THE SUN'S LUMINOSITY WILL BE HIGH ENOUGH TO CAUSE THE TEMPERATURE ON EARTH TO BE SUCH THAT ALL THE WATER (OCEANS, LAKES, RIVERS) WILL EVAPORATE.