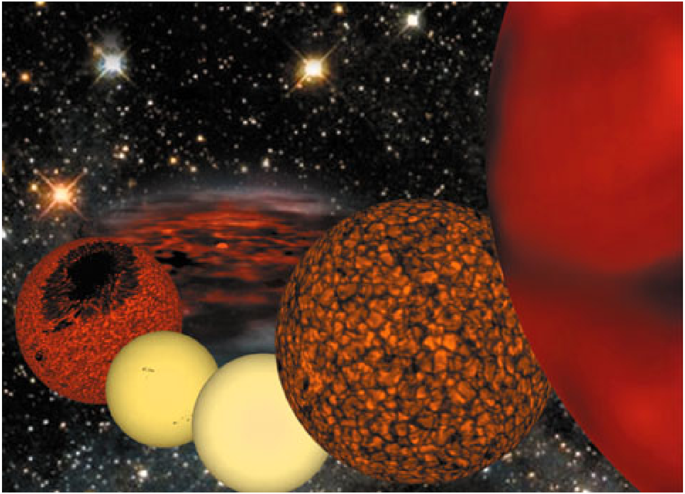
Lecture 4: The Sun as a Star

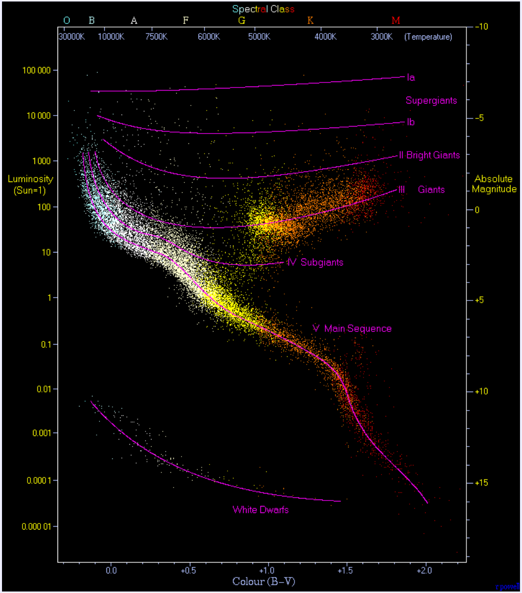
Outline

The Sun among the Stars

An Artist's Impression



trace.lmsal.com/POD/NAS2002_otherimages.html

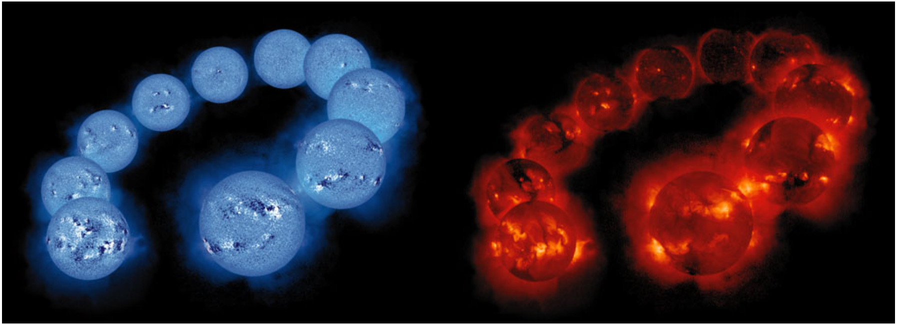


anzwers.org/free/universe/hr.html

Hertzsprung-Russell Diagram

- surface temperature $T_{\rm eff}$ (spectral class) vs. luminosity (absolute magnitude)
- $T_{\rm eff}$: black-body temperature with equivalent luminosity
- luminosity $\neq$ irradiance
- luminosity requires distance information
- contains radius information (see exercises)
- evolution as path in HR diagram

The 11-Year Solar Cycle

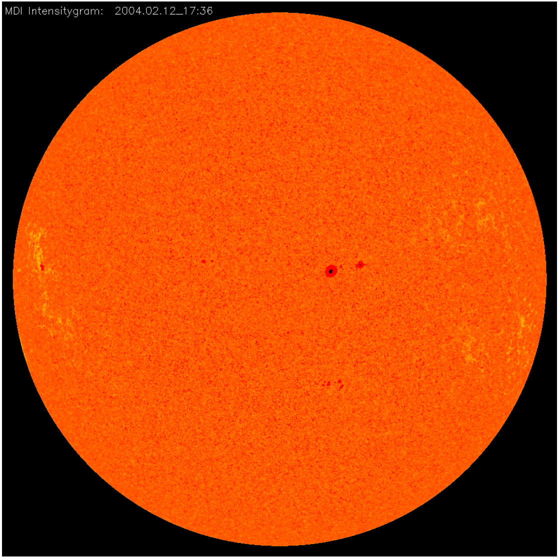


trace.lmsal.com/POD/NAS2002_otherimages.html

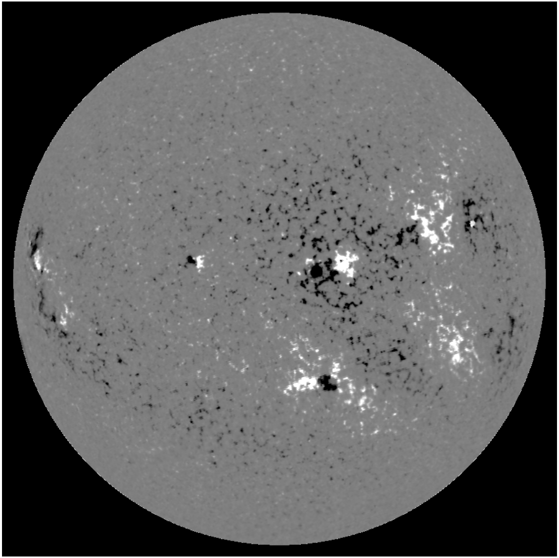
If the Sun had no magnetic field,
it would be as uninteresting as many astronomers think it is.

R.B.Leighton: unpublished remark (ca. 1965)

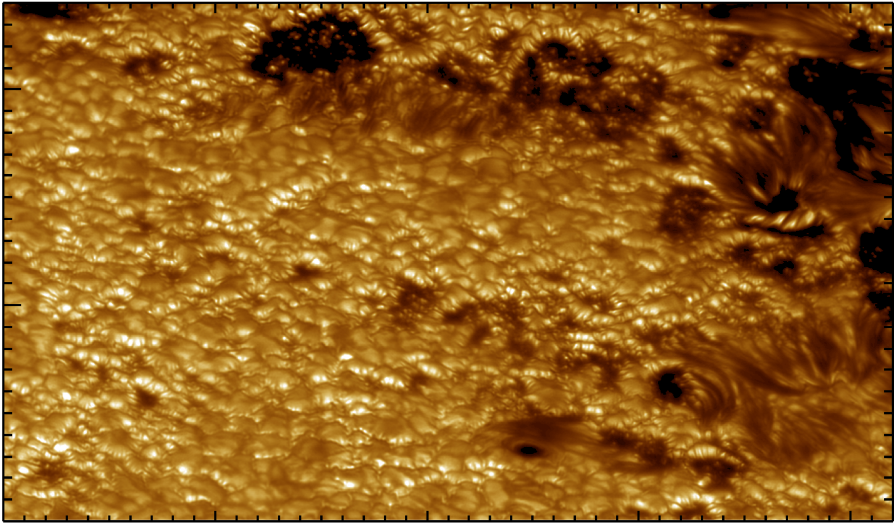
Spots and Faculae



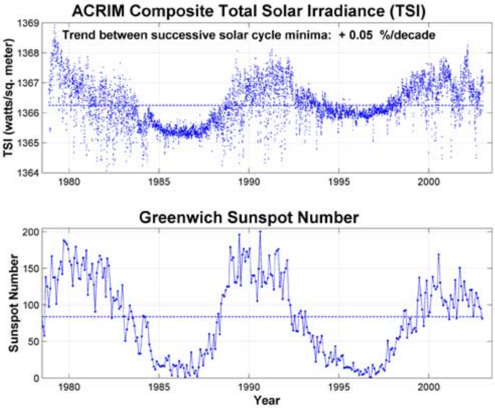
Magnetogram



Faculae at High Spatial Resolution



Irradiance and Sunspots

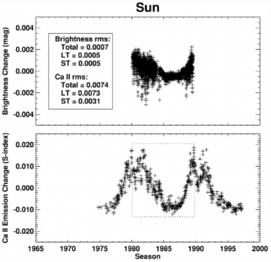


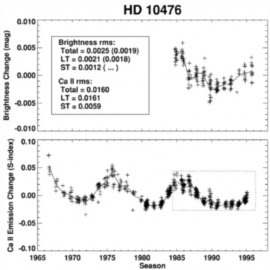
earthobservatory.nasa.gov/Newsroom/NasaNews/2003/2003032011367.html

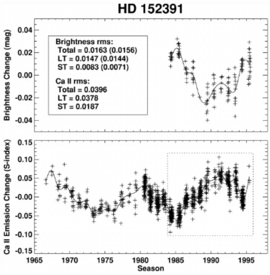
The Solar (not so) Constant

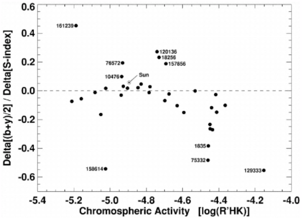
- correlation between irradiance and magnetic activity
- sunspots only temporarily reduce irradiance
- faculae more than compensate sunspot deficit
- solar constant varies by about 0.1%

Stellar Irradiance vs. Magnetic Variations



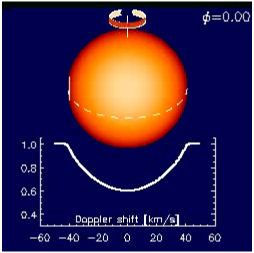






Radick et al. 1998

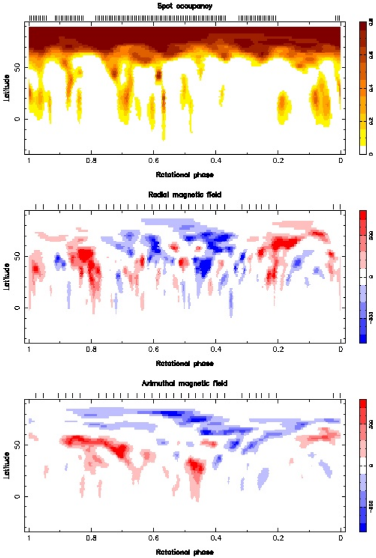
Doppler Imaging



www.astro.uu.se/˜ oleg/structures.html

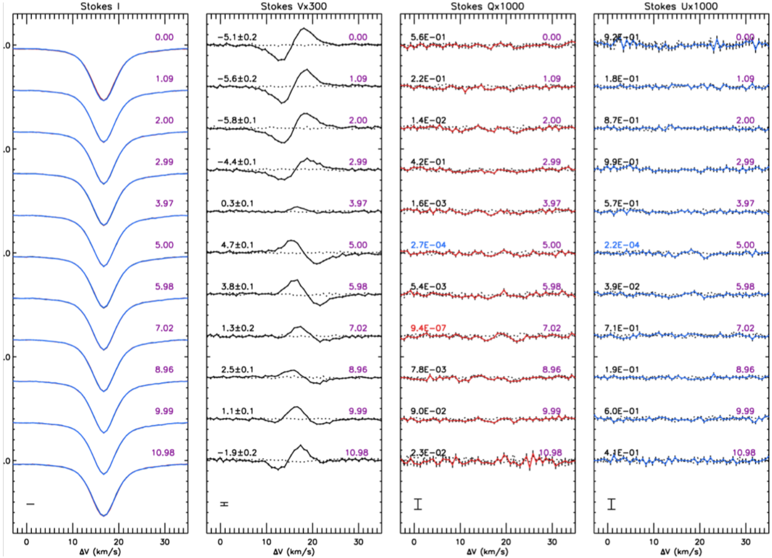
- quickly rotating stars
- many spectra per rotation period
- fit with ’spotted’ star model
- also possible for polarized spectra

Zeeman Doppler Imaging



www.ast.obs-mip.fr/users/donati/map.html

ϵ Eri with (Utrecht-Designed) HARPS Polarimeter



Internal Structure

The Basic Physics

- equilibrium between gas pressure and gravity
- equation of state: $P(T, \rho)$
- boundary conditions
- energy “production”
- energy transport by radiation, opacity
- energy transport by convection
- thermal and element diffusion

Mechanical Equilibrium

- hydrostatic equilibrium of star with radius R and mass M
  - Mass M_r within radius r:

$$\frac{\partial M_r}{\partial r} = 4\pi r^2 \rho$$

  - boundary condition $M_r(r = 0) = 0$
  - pressure gradient

$$\frac{\partial P}{\partial r} = -\frac{GM_r}{r^2}\rho$$

- pressure as restoring force $\Rightarrow$ dynamic mechanical time scale $t_{\mathrm{dyn}} = \frac{1}{\sqrt{G\overline{\rho}}} \approx 1$ hour
- pressure at center from integration of pressure gradient

$$P(0) - P(R) = G\int_0^R \frac{M_r \rho}{r^2} dr \approx G\frac{M^2}{R^4}$$

assumptions: $P(R) = 0,\ M_r = M, \rho = \frac{M}{(4\pi/3)R^3}$

Central Temperature

- radiation pressure not important $\Rightarrow$ total pressure = gas pressure
- ideal gas equation of state

$$P = P_g = kNT = \frac{k}{\mu m_H}\rho T$$

- mean molecular weight $\mu \approx 0.5$ for Sun (only H)
- pressure at center from previous slide

$$P = P_0 \approx G\frac{M^2}{R^4}$$

- $T_0 \approx 10^7$ K ($T_0 = 1.55 \times 10^7$ K)

Energy Transport Mechanisms: Radiation

- Electromagnetic radiation
  - photons could leave Sun in 2.5 s
  - but opacity is so high that they are absorbed very quickly
  - time scale about 10^7 years

$$t \approx \frac{E_{\mathrm{thermal}}}{L}$$

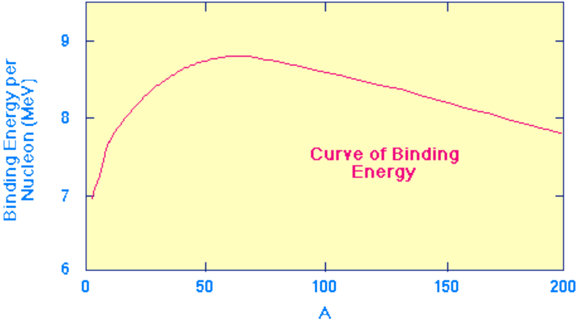
  - (see exercises on how to calculate E_{thermal})
  - details require radiative transfer and knowledge of opacities
- By the way ...
  - Conduction can be neglected in the solar interior, but not in more massive stars
  - Neutrinos are not reabsorbed in stellar interior

Energy Transport Mechanisms: Convection

- more effective than radiation for large temperature gradients (convective instability, Schwarzschild criterion)
- rise velocity in Sun about 1 km/s
- time scales: minutes to days depending on the size of the convective motion
- mixing of solar convection zone within 1 month
- Lithium-'Problem': $T > 2.0 \cdot 10^6$ K: $Li^6 + H^1 \Rightarrow He^4 + He^3$
  $T > 2.4 \cdot 10^6$ K: $Li^7 + H^1 \Rightarrow 2\,He^4$
- Sun: no Li^6, but Li^7, depth about 200000 km
- convection increases depth of convection zone
- convection in other stars
  - for small T_{eff} convection in deeper layers
  - O to A: no outer convection zone
  - F to M: outer convection zone
  - high-mass stars: convection in core

Nuclear Fusion

- Core: 25% of radius, 1.5% of volume, 50% of mass
- Binding energy per nucleon ⇒ fusion and fission



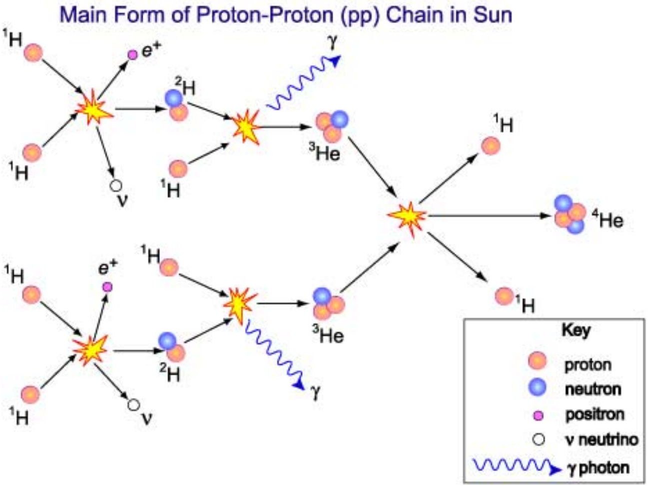
csep10.phys.utk.edu/astr162/lect/energy/bindingE.html

- Why do stars not explode like hydrogen bombs?
- Do fusion reactors on Earth simulate stars?

Hydrogen to Helium Fusion

- all four fundamental forces are crucial
  - gravitation (Newton, General Relativity)
  - electromagnetism (Maxwell, Standard Model)
  - weak interaction (Standard Model)
  - strong interaction (QuantumChromoDynamics, QCD)
- electrostatic repulsion of protons has to be overcome for strong interaction to dominate
- probability in solar interior: classically 10^{-430} per s per proton
- but only 10^{57} protons in the Sun
- quantenmechanical tunneling increases probability to 10^{-18} per second (Gamow Peak)
- p-p process
- CNO (Bethe-Weizäcker) cycle (about 1% of solar energy output)

Proton-Proton (p-p) Process in Detail



outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_mainsequence.html

Evolution of the Sun

Numerical Models

- include all relevant physics including rotation
- start with chemically homogeneous star with current solar mass
- solve partial differential equations (PDE) for each time step
- adjust abundances after each time step
- have to produce currently observed Sun
  - age
  - luminosity
  - radius
  - surface composition
  - helioseismic frequencies)
- adjustments for initial conditions:
  - initial helium content ($\approx$ 25%)
  - convective properties (mixing length parameter l)

The Standard Solar Model

- numerical model based on most plausible assumptions and best available physical input
- spherically symmetric
- all parameters only depend on radial distance from center
- internal rotation assumed to be sufficiently slow
- internal magnetic fields assumed to be sufficiently weak
- element abundance: $X + Y + Y_3 + Z = 1$
  - X: hydrogen abundance
  - Y: helium abundance
  - Y_3: helium 3 abundance
  - $Z \approx 0.02$ everything else, normally constant

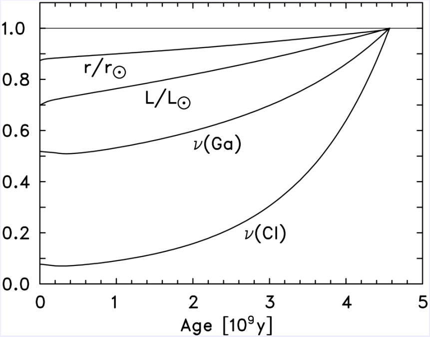
The Past Sun

- current age: 4.57×10^9 years (22 times around galaxy center)
  - well known from meteorite studies
  - measure abundance of radioactive ^{87}Rb ($4.8 \cdot 10^{10}$ years half-life) and daughter product ^{87}Sr relative to constant ^{86}Sr
- collapse of interstellar cloud when Jeans criterion is satisfied

$$\frac{Gm_c}{r} > \frac{RT}{\mu}$$

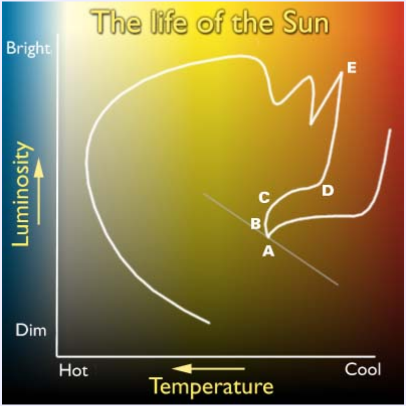
- removal of angular momentum and magnetic field (not well understood)
- slow contraction on Kelvin-Helmholtz time-scale

$$t_{\mathrm{KH}} = \frac{Gm^2}{rL}$$



Very Young Sun

- 70% of current luminosity
- 125 K colder surface
- 13% smaller
- very active chromosphere and corona
- strong solar wind
- rotation period only 9 days
- how could life on Earth start and survive?

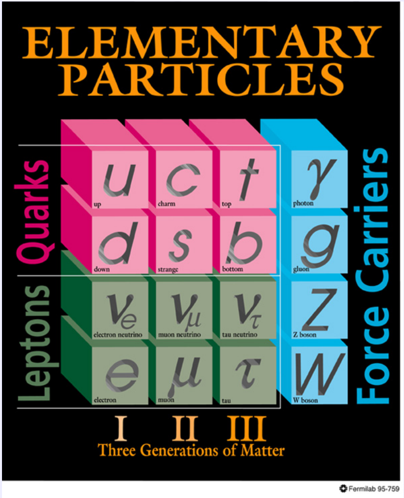


www.astro.uva.nl/demo/sun/leven.htm

The Future of the Sun

- B 50% of available H in core used up (now)
- C all H in core used up, H fusion in shell, 40% larger, twice as bright
- D 1.5×10^9 years later 3 times normal size, temperature 4300 degrees; 0.25×10^9 years later, 100 times larger, 500 times more luminous
- E critical core temperature, all He fuses into C, explosion throws out $\frac{1}{3}$ of solar mass into space, planetary nebula and white dwarf (2000 kg/cm^3)

Neutrinos



www.fnal.gov/pub/presspass/vismedia/gallery/graphics.htm

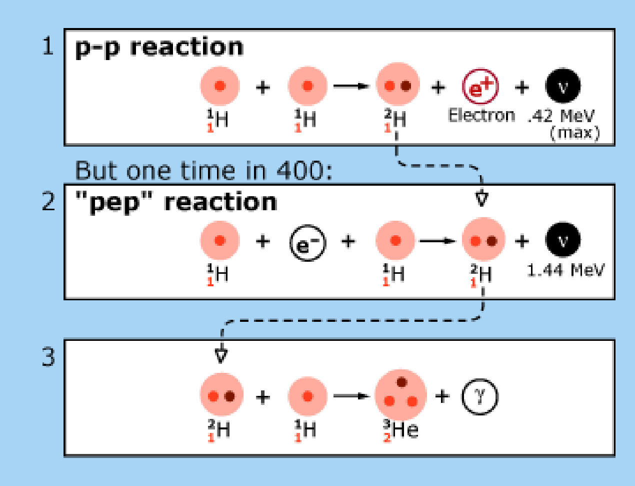
Basic Properties

- Neutrino (ν) predicted around 1930 by Wolfgang Pauli to save energy conservation for certain radiactive decays
- first neutrino detection published in 1956
- 6 different kinds: ν_e, ν_μ, ν_τ and their anti-particles $\bar{\nu}_\mathrm{e}$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$
- no electrical charge, almost massless, propagate at almost the speed of light, have only weak interaction
- could penetrate one light year of lead without problems

Solar Neutrinos

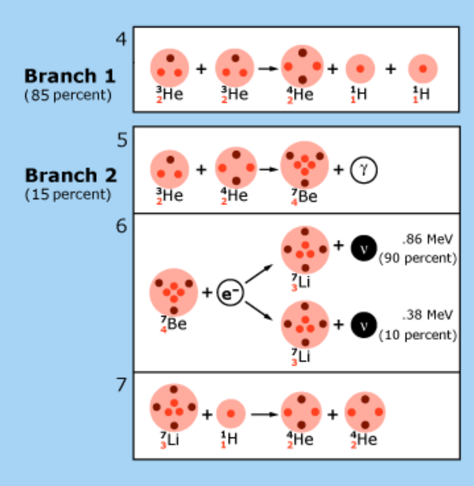
- no direct electromagnetic radiation from solar interior
- luminosity, age of the Sun (4.5×10^9 years) $\Rightarrow$ nuclear fusion
- knowledge of stellar interiors largely based on model calculations
- *helioseismology* measures sound speed as function of depth
- neutrinos from solar core are the only direct measurement
- ν_e are produced in fusion reactions, leave the Sun within 2.3 s
- on Earth each cm^2 is penetrated every second by $4 \cdot 10^{10}$ solar ν_e
- ν–telescope makes ν–images of the solar core
- weak interaction only, ν hard to detect $\Rightarrow$ very large detectors

Neutrinos from p-p process



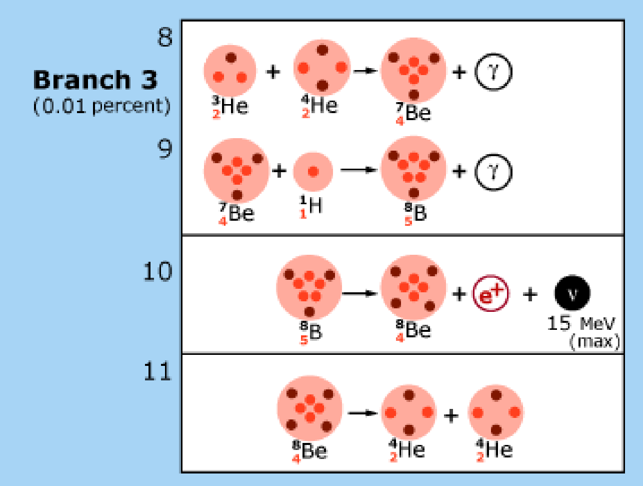
nobelprize.org/physics/articles/fusion/sun_pp-chain.html

Neutrinos from p-p process



nobelprize.org/physics/articles/fusion/sun_pp-chain.html

Neutrinos from p-p process



nobelprize.org/physics/articles/fusion/sun_pp-chain.html

Neutrino Observations

Homestake Gold Mine

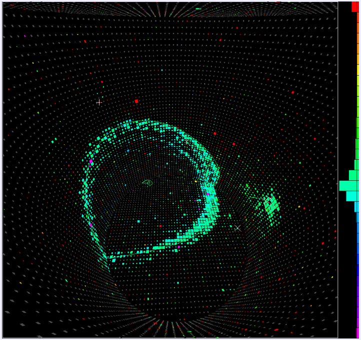
www.bnl.gov/bnlweb/raydavis/pictures.htm

The First Neutrino Experiment

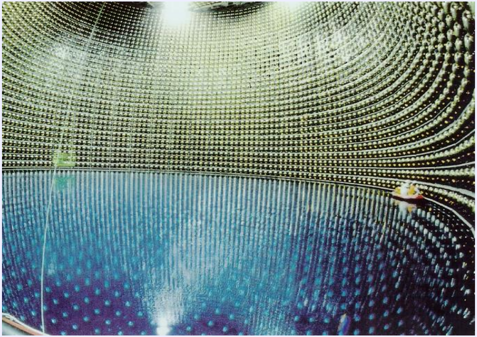
- 1970-2001, South Dakota, USA
- 1600 m deep to shield cosmic radiation
- 400'000 l of liquid tetrachloroethylene (C_2Cl_4)
- $\nu_e + {}^{37}Cl \Rightarrow {}^{37}Ar + e^-$
- gaseous ^{37}Ar extracted every 100 days, counted single atoms
- expected 1.5 Argon atoms per day, observed 0.5 $\Rightarrow$ *Solar Neutrino Problem*
- Nobel prize in physics 2002 for Raymond Davis

Observations using Gallium

- can measure all neutrino energies, not just high-energy neutrinos
- Soviet–American–Gallium–Experiment (SAGE), Baksan (Kaukasus):
  - 60 Tonnen Gallium
  - $^{71}\mathrm{Ga} + \nu_\mathrm{e} \Rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$
  - gaseous Germanium is blown out of liquid Gallium
  - measures about 50% of expected neutrino flux
- GALLEX in Gran Sasso tunnel near Rom:
  - 30 tons of Gallium for 10 million Euros
  - half of the yearly world production
  - measures about 50% of expected neutrino flux



neutrino.kek.jp/figures.html

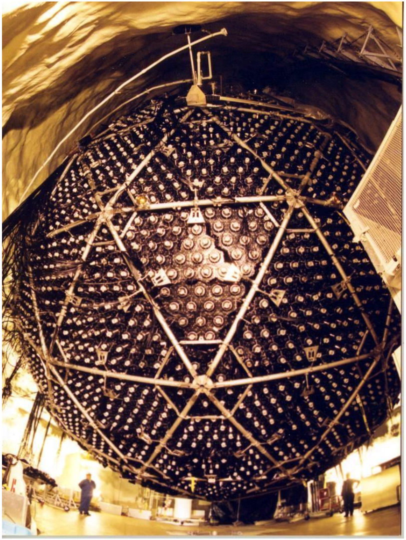


antwrp.gsfc.nasa.gov/apod/ap971028.html

Kamiokande Detectors in Kamioka, Japan

- Kamiokande II with 2000 tons of water, confirms results by Davis
- $e^- + \nu_e \Rightarrow e^- + \nu_e$
- sees Cerenkov-radiation of scattered electrons
- measures direction, confirms solar origin
- measures exact arrival time, detected neutrinos from SN 1987A
- Super-Kamiokande has 50,000 tons of water

Sudbury Neutrino Observatory

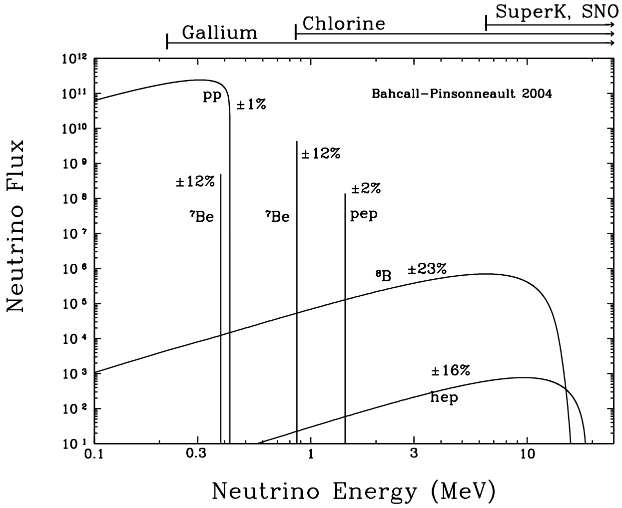


www.sno.phy.queensu.ca/sno/images/

Observations using Heavy Water

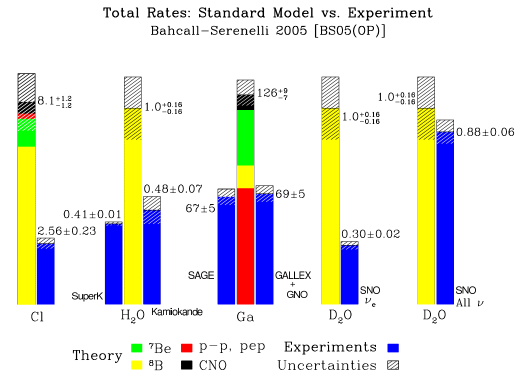
- 1000 tons of D_2O (on loan) in Ontario, Canada
- measures direction and energy since 1999
- $d + \nu_e \Rightarrow p + p + e^-$
- $e^- + \nu_x \Rightarrow e^- + \nu_x$
- $d + \nu \Rightarrow n + p + \nu$
- third reaction has equal detection probability for all three kinds of neutrinos
- total number of neutrinos corresponds to expected ν_e flux

Solar Neutrino Spectrum



www.sns.ias.edu/ jnb/SNviewgraphs

The Data



www.sns.ias.edu/ jnb/SNviewgraphs

Observations and Standard Models Disagree

- Wrong standard solar model? But helioseismology excludes non-standard solar core models
- Wrong standard model of particle physics? But neutrinos might have mass

Neutrino Propagation in Vacuum

- Neutrino flavors ν_e, ν_μ, ν_τ 'good' states for interactions
- Neutrino masses ν_1, ν_2, ν_3 'good' states for propagation
- flavor eigenstates $\neq$ mass eigenstates
- probability to detect muon neutrino from initial electron neutrino after a certain time t is

$$|\langle\nu_\mu|\nu_e\rangle|^2(t) = \sin^2 2\theta \sin^2\left(t\frac{m_1^2 - m_2^2}{4p}\right)$$

- still 90% of the solar electron neutrinos would make it to Earth without being mixed
- cannot explain the solar neutrino problem

The Solution

Neutrino Oscillations in Matter

- Mikheyev–Smirnov–Wolfenstein effect
- interaction with matter: ν_e and e^- can interact through W^- or Z^0, ν_μ and ν_τ can only interact with e^- through Z^0
- most neutrinos from Sun will pass through resonance density region inside the Sun
- even very small mixing angles and mass differences can make most ν_e into ν_μ
- all solar data and also reactor experiments deliver consistent combinations of mixing angle and difference of squared masses