

Neutrinos and our Sun – Part 2

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In this part we describe the chain of nuclear reactions that fuse protons into helium nuclei in the centres of stars. Neutrinos play an important role in the proton-proton chain and detection of these neutrinos is important for a direct insight into the processes taking place at the centre of the sun. Experiments for the detection of solar neutrinos and the emerging result from them, known as the Solar Neutrino Puzzle, are described. The puzzle refused to go away even with very carefully designed experiments. Its solution came from physics, by reviving the idea of neutrino oscillations, speculated many decades ago. Recent experiments have confirmed these ideas and have enriched our knowledge of these fundamental particles.

1. How does the Sun Shine?

How does the sun, or for that matter any star in the sky, shine? What is the ultimate fate of a star? These questions exercised the best scientific minds in the last two centuries until the correct answer was found in the 1930's. We have summarised in *Table 1* a few known parameters of the sun which we will use in our discussions below. The energy emitted by the sun per second is known as its luminosity. The total energy emitted by the sun during its lifetime of four and a half billion years is given by the product of the luminosity and the age of the sun (remember 1 year equals 3×10^7 seconds):

$$E_{\odot} = L_{\odot} \times T_{\odot} = 4 \times 10^{33} \times 4.5 \times 10^9 \times 3 \times 10^7 \\ = 5.4 \times 10^{50} \text{ erg.}$$

Keywords

Stellar energy source, p-p chain, solar neutrino detection-puzzle.

Items	Values
Mass (M_{\odot})	2×10^{33} gm
Energy output (L_{\odot})	4×10^{33} erg/sec
Radius (R_{\odot})	7×10^{10} cm
Age (T_{\odot})	4.5×10^9 years
Mean density (ρ_{\odot})	1 gm/cm^3
Surface temperature	6000 K
Central temperature	1.5×10^7 K
Sun to Earth distance	1.496×10^{13} cm

Table 1. Some of the solar parameters.

Two possible sources of this energy are: the gravitational energy release and energy released in nuclear fusion.

Gravitational Energy Source: The sun is a gaseous mass composed mainly of hydrogen ($\sim 75\%$ by mass) with some amount of helium ($\sim 23\%$ by mass) and a small amount of heavier elements ($\sim 2\%$ by mass). We may think of the sun as consisting of concentric spherical shells of this material. The total mass interior to any shell exerts a gravitational force on the shells external to it and the external layers are pulled inwards. There must be an opposing force which prevents the shells from collapsing to the central core. This force must be the same one which prevents our earth's atmosphere from collapsing and this is the pressure force of the gas. The balance between the attractive gravitational force and the pressure force of the gas at any radial point within is known as hydrostatic equilibrium. When a star like the sun starts to contract, it releases gravitational energy which is transformed into thermal energy and the star heats up. This gives rise to the pressure force which balances the gravitational force once equilibrium is achieved. The gravitational energy released due to the contraction of the sun to its present size is given by the following relation:

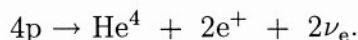
When a star like the sun starts to contract, it releases gravitational energy which is transformed into thermal energy and the star heats up.

$$E_G \approx \frac{GM_\odot^2}{R_\odot} = \quad \bullet$$

$$\frac{7 \times 10^{-8}(\text{cm}^3\text{gm}^{-1}\text{sec}^{-2}) \times 4 \times 10^{66}(\text{gm}^2)}{7 \times 10^{10}(\text{cm})} = 4 \times 10^{48} \text{ erg},$$

where G is the gravitational constant. E_G is clearly a factor of 100, too small compared to E_\odot .

Nuclear Energy Source: Let us now look at nuclear energy source as an option. We know from nuclear physics that energy is released when protons fuse into helium, which is a more tightly bound nucleus. The chain of reactions, called the hydrogen burning reactions, can be represented symbolically by the relation (see later for more details):



This fusion process releases about 26.7 MeV ($= 4 \times 10^{-5}$ erg). The mass fraction which is transformed into energy in this process is thus: $(26.7)/(4 \times 931) = 0.007$, or nearly 0.7% (we have used 931 MeV as the mass of a proton). So in a pure hydrogen star of a solar mass, one could expect a total energy release due to burning of hydrogen into helium, using Einstein's relation $E = Mc^2$, as:

$$E = (0.007 \times 2 \times 10^{33}) \times (3 \times 10^{10})^2 = 1.4 \times 10^{52} \text{ erg},$$

where we have used 2×10^{33} gm as the solar mass and 3×10^{10} cm/sec as the velocity of light.

A few points may be noted here: (i) Nearly 75% of the solar mass is hydrogen and accordingly a reduction of 25% may be incorporated in the above estimate. (ii) If the sun could burn all its hydrogen and helium into iron (Fe^{56}), one would get an extra increase in the energy release of about 20%. Because an iron nucleus is the most tightly bound nucleus in the periodic table, a

Energy is released when protons fuse into helium, which is a more tightly bound nucleus.



fusion reaction involving iron nuclei is not possible and the chain of reactions must stop with the formation of iron in the core of the star. (iii) When about 10% of the hydrogen is used up in the centre due to burning, the structural characteristics of a star start changing, like the expansion of the envelope outside the core, ignition of shell-burning, etc., or in technical jargon, the star moves out of the main sequence phase.

Considering the above points, the total nuclear energy available to the sun is:

$$E_{\text{nuclear}} = 0.1 \times E \simeq 10^{51} \text{ erg},$$

which is nearly a factor of two larger than the total energy output by the sun so far, or in other words our sun will easily last for another five billion years. This can also be calculated by dividing the total nuclear energy available to the sun by the energy emitted by the sun per unit time (the luminosity):

$$t = \frac{E_{\text{nuclear}}}{L_{\odot}} \simeq \frac{10^{51}}{(4 \times 10^{33}) \times (3 \times 10^7)} \simeq 10^{10} \text{ years}.$$

Thus we see that the nuclear energy can sustain the sun for about ten billion years.

The amount of hydrogen to be burnt per second to provide the solar luminosity can be calculated from the mass fraction of hydrogen, 0.007, which is transformed into energy. That is one gramme of hydrogen on burning will yield an energy equivalent to: $0.007 \times c^2 = 0.007 \times 9 \times 10^{20} = 6 \times 10^{18}$ erg. We get the amount of hydrogen, which is burnt per unit time, by dividing the luminosity of the sun by the energy release per gramme of hydrogen: $(4 \times 10^{33}) / (6 \times 10^{18}) \simeq 6 \times 10^{14}$ gm/sec = 600×10^6 tons/sec. That is 600 million tons of hydrogen is burned every second in the sun.

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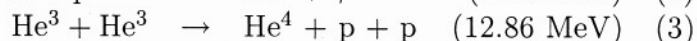
In the PP chain, hydrogen is converted directly into helium, while in the CN cycle nuclei of carbon and nitrogen act as catalysts.

1.1 *Hydrogen Burning Reactions*

There are two basic reaction chains which are responsible for the conversion of hydrogen into helium and they are operative in all stars during the bulk of their life: (a) Proton - Proton (PP) chain, and (b) Carbon-Nitrogen chain or the CN cycle. In the PP chain, hydrogen is converted directly into helium, while in the CN cycle nuclei of carbon and nitrogen act as catalysts.

(a) **PP chain:** In the PP chain, neutrinos are produced in four different reactions out of which three are the major ones.

(i) **pp-neutrinos:** The starting reaction is the interaction of two protons forming a nucleus of heavy hydrogen, called deuteron (d), with the emission of a positron (e^+) and a neutrino (ν_e). This proceeds via the weak interaction in which a proton converts itself into a neutron, positron and a neutrino. The deuteron then captures another proton forming a light isotope of helium (He^3); this reaction relies on electromagnetic interaction. At this stage there are two possibilities. The first possibility (86% probability) leads to an interaction of He^3 with another He^3 yielding a He^4 nucleus, also called an α particle; this reaction proceeds via the strong interaction. The second possibility (14% probability) leads to Be^7 neutrinos described later on. The details of the first interaction are as follows:



In order for reaction (3) to take place, we need two nuclei of He^3 , which means that reaction (2) has to occur twice, which in turn means reaction (1) has to also occur twice. Adding up the full chain consisting of five reactions, the net effect is the fusion of four protons into an alpha particle, with the release of two positrons and two

more complete description even oxygen nuclei are involved as catalysts and the complete chain is known as the CNO bi-cycle. Neutrino fluxes from these reaction are a factor of hundred less than those from the PP-chain.

A point to be noted is that the sun produces only electron-neutrinos (ν_e).

1.2 *Evolution of a Star after Hydrogen Burning*

Once the hydrogen in the core of a star is used up, energy generation stops and the core starts contracting due to the gravitational pressure of the overlying layers. The slow gravitational contraction of the core is accompanied by heating and eventually the core reaches a temperature when the helium ash is ignited. Even before the actual ignition of helium, the hydrogen-rich regions outside the core are drawn to higher temperatures and densities and hydrogen starts burning in the shell. At this stage the star has a bloated appearance and is known as a red giant. Helium-burning produces carbon and oxygen and once the helium in the core is used up, energy generation there stops and a new cycle of core contraction begins. There is, in fact, a sequence of thermonuclear stages where the ash of one stage provides the fuel for the next at a higher temperature and density. Outside the core there are successive shells of burning, with the hydrogen-burning shell located farthest from the centre. In each stage there is release of energy through fusion as more and more tightly bound nuclei are formed. Burning of helium leads to the formation of carbon and oxygen; from carbon is formed neon and magnesium and oxygen, and then the burning of oxygen forms silicon and sulphur and finally Fe^{56} is formed. Further fusion cannot take place because Fe^{56} is the most tightly bound nucleus in nature. At this stage a star several times more massive than the sun has an onion-shell structure with a core of iron surrounded

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by shells of silicon, oxygen, carbon and helium with the outermost envelope retaining the pristine composition with which the star was born.

The number of stages of nuclear burning a star goes through, depends upon its mass. A star like our sun to one as massive as 3 or 4 times the sun does not reach a temperature at the core high enough to ignite carbon and its nuclear evolution stops with helium burning. When fusion ends in a star like the sun, it eventually shrinks to a small size, about the size of the earth and this burned-out star is called a white dwarf. A white dwarf in isolation can remain in this state indefinitely. S Chandrasekhar, more than seventy years ago, had asked the question what the maximum mass of a star should be that had consumed all its nuclear fuel and had to support itself against its own gravity. As the star contracts during its evolution, the atomic electrons are pressed tightly together to generate a pressure known as the degeneracy pressure (the density of matter at this stage is in the range of $10^4 - 10^8$ gm/cm³). Chandrasekhar showed that the degeneracy pressure of the electrons could counteract the gravitational pressure, if the mass of the star was less than a value now called the *Chandrasekhar mass* and he gave an accurate value for this mass which is 1.44 times the solar mass. This is the maximum mass of a stable non-rotating white dwarf. Chandrasekhar was awarded the Nobel Prize in Physics in 1983.

1.3 Neutrino Fluxes and Neutrino Energy Spectrum

Consumption of protons:
Since four protons are needed to complete the chain for emitting two neutrinos, the rate of consumption of protons needed to power the solar luminosity is just a factor of two more than the neutrinos emitted, that is 4×10^{38} protons per second.

Neutrinos are emitted in plenty by the sun and other stars continuously. Sun is the dominant source of neutrinos incident on the earth. A quick calculation of neutrino flux from the sun may be made using the energy release of 26 MeV in the pp-chain reaction (4) as follows. The total number of neutrinos emitted per second from

the sun can be written as:

$$\begin{aligned}
 N_{\nu}^{\text{tot}} &= \frac{2 \times L_{\odot}(\text{erg/sec})}{26(\text{MeV}) \times 1.6 \times 10^{-6}(\text{erg/MeV})} \\
 &= 2 \times 10^{38} \text{ sec}^{-1},
 \end{aligned}$$

where a factor of 2 in the numerator is due to two neutrinos emitted per pp-chain reaction¹. The neutrino flux incident on the earth can be obtained by dividing the total number of neutrinos by the surface area, $4\pi R_{S-E}^2$, where R_{S-E} is the distance between the sun and the earth:

$$\begin{aligned}
 F(\nu) &= \frac{N_{\nu}^{\text{tot}}}{4\pi R_{S-E}^2} \\
 &= 7 \times 10^{10} \text{ cm}^{-2}\text{sec}^{-1}.
 \end{aligned}$$

Several detailed calculations of neutrino fluxes have been carried out in the framework of the standard solar model, with major input parameters as various nuclear parameters, equation of state, solar luminosity, elemental abundances, etc. We summarise the results in *Table 2* [1]. The uncertainties in the calculated neutrino fluxes are: $\approx 1\%$ in the pp neutrinos, about 10% in Be^7 neutrinos and about 20% in B^8 neutrinos.

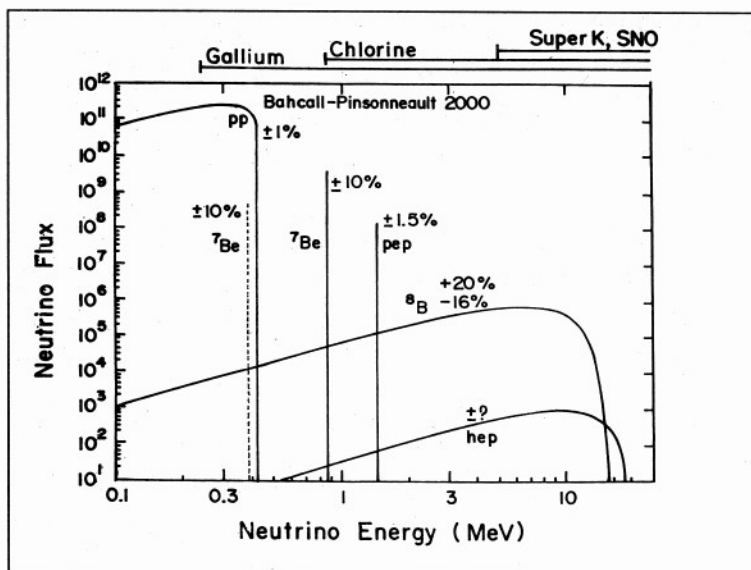
Thus the flux of neutrinos, as seen from the table, incident on the earth is about $7 \times 10^{10} \text{ cm}^{-2} \text{ sec}^{-1}$, which is the number of neutrinos hitting a surface area of one square centimetre every second. The number of neutrinos that we receive from stars in our galaxy, other than the sun, is about $10^2 \text{ cm}^{-2} \text{ sec}^{-1}$ which is several orders of magnitude smaller, since the stars are much further away than the sun. Later we will also discuss another source of neutrinos, called atmospheric neutrinos, which arise due to collisions of cosmic ray particles with air-nuclei of our earth; these collisions produce charged mesons and their decay products yield about $10^{-1} \text{ cm}^{-2} \text{ sec}^{-1}$ neutrinos².

Neutrino source	Flux ($\text{cm}^{-2}\text{sec}^{-1}$)
pp	6×10^{10}
pep	1.4×10^8
Be^7	4.7×10^9
B^8	5.8×10^6
hep	8×10^3
CN-cycle	1×10^9

Table 2. Solar neutrino fluxes

² Other sources of neutrinos: (i) Natural radioactive decays in the interior of the earth give out neutrinos at the rate of about $6 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$ with energy 1 MeV. (ii) The relic neutrinos, which are left over from the early epochs of the evolution of the Universe; they have a number density of $\sim 110 \text{ cm}^{-3}$ for each neutrino species with an average energy of $\sim 10^{-3} \text{ eV}$. (iii) A very rare and short-lived source of about 10 seconds is a supernova of type II, which emits $\approx 6 \times 10^{58}$ neutrinos of all flavours with energies less than $\sim 30 \text{ MeV}$. (iv) Then there are man-made high energy neutrinos produced by the particle accelerators with energies going up to about 100 GeV, and low energy neutrinos from nuclear reactors with energies around 4 MeV.

Figure 2. Neutrino energy spectrum from the sun as calculated by Bahcall et al (taken from [1]).



The neutrino energy spectrum as predicted by the standard solar model is shown in *Figure 2*, (see also [1]).

2. Detection of Neutrinos

Since neutrinos have very weak interaction with matter, they are very difficult particles to detect. This property of neutrinos is actually a boon to us from mother nature. Because of this property neutrinos can reach us practically from any region they are emitted, howsoever far, carrying the original information like direction, energy and its flux. Solar neutrinos can thus be used to understand the nuclear energy generation in the interior of the sun. However, to detect these neutrinos the experiments must run for years to collect a reasonable sample of events and make use of detectors that contain a large number of target atoms. We describe below experiments to detect the solar neutrinos. These experiments first indicated of a deficiency in the neutrino flux received from the sun and a search for the solution to this puzzle eventually led to new insights into the property of neutrinos called neutrino-oscillation, and its immediate effect was the possibility of determining for the first time the very small masses of the neutrinos.

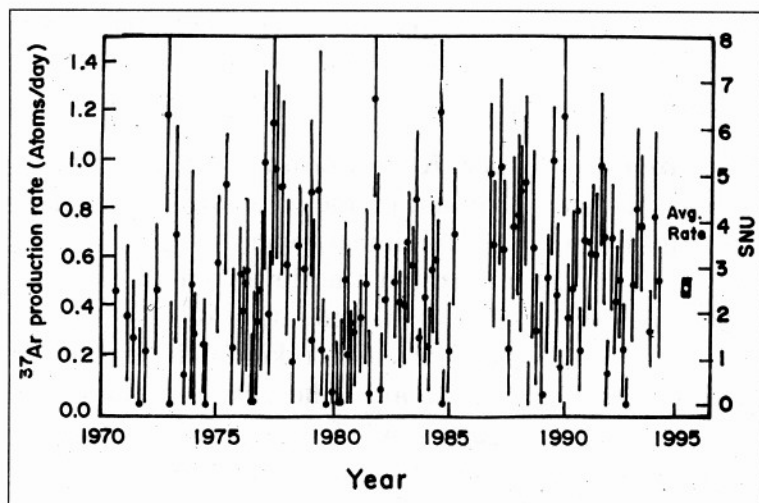


Figure 3. The production rate of Ar^{37} in the Homestake experiment (taken from [4]).

2.1 Detection of Electron-Neutrinos from Sun

Homestake: The first detector to detect solar neutrinos was setup in 1968 by R Davis and his collaborators at the Homestake mine, South Dakota, USA, at a depth of 4850 feet. The target chosen for this experiment was chlorine-37 (Cl^{37}) in the form of C_2Cl_4 liquid. A large tank was specially built to hold a total quantity of about 615 tons of C_2Cl_4 , containing nearly 2×10^{30} atoms of Cl^{37} . The large quantity is necessary to increase the probability of neutrino interactions. The underground location had the advantage of minimising the background events from cosmic rays. The reaction used for the detection of neutrinos is: $\nu_e + \text{Cl}^{37} \rightarrow e^- + \text{Ar}^{37}$; a neutron in the chlorine-37 nucleus is transformed into a proton to form the argon-37 nucleus with the emission of an electron. The threshold energy of neutrinos for this reaction to occur is 0.8 MeV and hence the reaction is sensitive to neutrinos from the Be^7 reaction ($E_\nu < 0.86$ MeV) and B^8 decays ($E_\nu < 14.6$ MeV). The production rate of Ar^{37} is one atom in two days. The dissolved argon atoms are removed chemically from the liquid periodically and are counted using proportional counters. This experiment has been running for the last 30 years and its measurements of neutrino flux is found

The Homestake experiment has been running for the last 30 years and its measurements of neutrino flux is found to be a factor of three below the predictions of the standard solar model.

The discrepancy between the measured and predicted solar neutrino flux from the Homestake experiment generated a lot of excitement. It also motivated the development of other new experiments.

to be a factor of *three* below the predictions of the standard solar model, (see *Figure 3*). This discrepancy is referred to as the *solar neutrino problem*.

Kamiokande/Super-Kamiokande: The discrepancy between the measured and predicted solar neutrino flux from the Homestake experiment generated a lot of excitement. It also motivated the development of other new experiments. The next generation of experiments was designed in 1986, situated 1 km underground at the Kamioka mine in Japan. The detector, known as Kamiokande, used 3000 tons of water (H₂O) and took data up to 1995; from 1996 onwards it got upgraded to what is known as Superkamiokande (or SK in short) which uses 50,000 tons of water (H₂O) as target. Neutrinos are detected via elastic scattering with electrons in the water molecules: $\nu_e + e^- \rightarrow e^- + \nu_e$. The threshold energy of neutrinos for this reaction is 7 MeV; hence the reaction is sensitive to neutrinos from B⁸ decays ($E_\nu < 14.6$ MeV). Due to an unfortunate accident in November 2001, this detector stopped taking data and it is expected to resume taking data in the near future.

The fast moving electron from the reaction emits light, called Cerenkov-radiation, while passing through water. An array of photomultiplier tubes surrounding the water target detects the Cerenkov-radiation. (Charged particles passing through a medium radiate light, called Cerenkov radiation, in a cone of half angle $\theta_c = \arccos(c/vn)$ if their velocity v were greater than c/n , where c is the velocity of light and n the index of refraction of the medium.) Electrons in the above reaction are emitted within 20 degrees with respect to the direction of the incident neutrinos; as a consequence the measurement of angular distribution of electrons reflects the direction of incidence of the neutrinos. Indeed, the angular distribution of electrons gave the first real proof that neutrinos involved in the elastic scattering were from the sun. After several years of data acquisition, the neutrino flux

from the sun as measured in this experiment turned out to be only *half* of the flux predicted by theory.

SAGE and Gallex/GNO: Two more detectors called SA-GE and Gallex, using Gallium as the sensitive target, came into operation since 1990. The SAGE detector with 60 tons of Gallium is situated underneath a high mountain in the Baskan Valley of the Soviet Union, and the Gallex detector with 30 tons of Gallium is located in the Gran Sasso underground laboratory in Italy; in 1996 the Gallex detector got replaced by GNO, the Gallium Neutrino Observatory. Neutrinos are detected by using the reaction: $\nu_e + \text{Ga}^{71} \rightarrow e^- + \text{Ge}^{71}$. Germanium atoms are detected by a radiochemical method. The threshold energy of neutrinos for this reaction is 0.2 MeV and hence these two detectors are sensitive to the full neutrino energy spectrum from the sun. These two experiments also observed only **half** of the flux predicted by theory.

Thus the data collected over several years of hard work from the four pioneering experiments: Homestake, Kamiokande (plus Super-Kamiokande), Gallex (plus GNO) and SAGE, provided information about the electron-neutrinos from the sun by sampling the complete energy spectrum of neutrinos from proton-proton, beryllium-7 and boron-8 reactions. In all cases the experimental results are significantly below the predictions of the well-known standard solar model by a factor of two to three (see *Table 3*). Attempts to solve the problem astrophysically by changing the parameters of the standard solar model failed and other solutions had to be explored.

In the last part of this article we shall describe the recent breakthrough that was made by reviving the idea of neutrino oscillations and how the latest experiments have confirmed the existence of these oscillations. The long-standing Solar Neutrino Puzzle has now been solved.

Attempts to solve the problem astrophysically by changing the parameters of the standard solar model failed and other solutions had to be explored.

Experiment	Data	Theory	Data/Theory
HOMESTAKE	2.56 ± 0.21	$7.6_{-1.1}^{+1.3}$ SNU	$34 \pm 3\%$
SAGE	67.2 ± 8.0	128_{-7}^{+9} SNU	$53 \pm 6\%$
GALLEX/GNO	74.1 ± 6.8	128_{-7}^{+9} SNU	$58 \pm 5\%$
Kamiokande	$2.80 \pm 0.38 \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}$	$5.1_{-0.8}^{+1.0} \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}$	$55 \pm 8\%$
Super Kam.	$2.32 \pm 0.09 \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}$	$5.1_{-0.8}^{+1.0} \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}$	$45.5 \pm 1.7\%$

(1 SNU = 1 neutrino interaction per second for 10^{36} target atoms)

Table 3. Experimental results from solar neutrino.

Suggested Reading

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