

Summary:

This report aims to highlight a little of the background to the formation of neutrinos and how neutrinos interact (or indeed how they don't to be more precise) with their surroundings, then it will go on to explain the project of writing a computer program to model neutrino energy loss in stellar interiors. The program is based around fitting formulae which use the two variables of temperature and density to determine the neutrino energy loss. (Itoh et al., 1996)

What is a neutrino?

Despite their fundamental nature and their abundance in the universe neutrinos have remained surprisingly illusive. Neutrinos are a type of lepton and so have spin of a half and are not affected by the strong nuclear force (characteristics of the other three leptons as well; the electron, muon and tau). The absence of the strong nuclear force, their electrical charge of zero, and extremely small mass mean that they very rarely interact with other particles. This attribute allows them to pass through objects like the earth without any interaction with it. This is also important as it allows them to 'escape' after their production in solar interiors and supernovae.

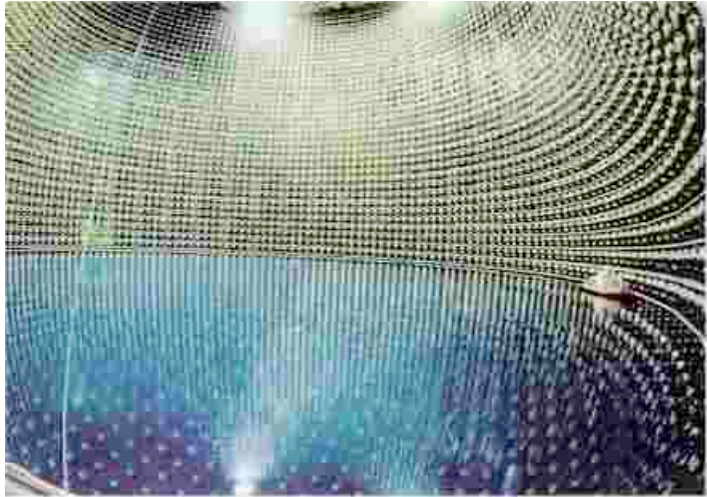
There are three types or flavours of neutrino and each has a charged partner which it corresponds to. The three charged particles are the electron, muon and tau and each has an antiparticle. These particles and antiparticles each have a corresponding neutrino or anti-neutrino as shown in the table below. Even although the charged particles can be created and destroyed the overall number of charged particles plus neutrinos is conserved. It has become apparent recently that the neutrinos can oscillate between these three flavours. This discovery means that, for example, an electron neutrino could spontaneously turn into a tau neutrino. The word oscillate is used as this transition works in both directions. This oscillation suggests that the neutrino must have mass to allow these transformations to occur however this as yet has not been linked with the neutrino energy losses.

Particle	Neutrino	Anti-particle	Antineutrino
Electron e^-	Electron neutrino ν_e	Positron e^+	Electron Antineutrino $\bar{\nu}_e$
Muon μ^-	Muon neutrino ν_μ	Anti-muon μ^+	Muon Antineutrino $\bar{\nu}_\mu$
Tau τ^-	Tau neutrino ν_τ	Anti-tau τ^+	Tau Antineutrino $\bar{\nu}_\tau$

How to detect neutrinos

Due to the neutrinos lack of interaction with the earth and any forms of detector for many years it proved very hard to actually collect any data about this particle. The first detector to be built was at the Hanford nuclear reactor in 1953. Recently newer methods have been devised to help study these neutrinos and so large detectors have been built. Examples of such detectors are the Super Kamiokande detector in Japan and a detector in Sudbury, Ontario. These detectors have helped to detect neutrinos from both the sun and also from the supernova 1987A.

The detectors are large underground water-filled chambers that are lined with photo-multiplier tubes. Even although the neutrinos cannot be detected directly either by photo-multiplier tubes, or any other method, the effect they have when they meet water can be studied. The photo multiplier tubes that line the chamber detect a faint radiation released as the neutrino meets the water and can detect illumination by as little as a single photon.



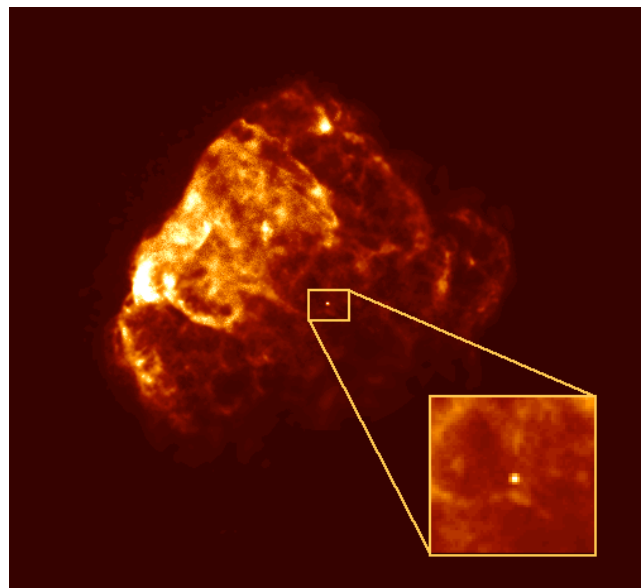
Inside of the Super Kamiokande detector (Japan)

As an neutrino passes through the tank of water there is a very small probability that it will directly hit the nucleus of an atom. The neutrino will be absorbed, and will form a charged particle. For example if a neutrino hits a proton then a neutron and a positron (a charge particle) will be formed. Light is emitted because if a charged particle travels through water faster than the speed of light in water then it displaces electrons in some of the atoms on its path and the displaced electrons form an electromagnetic wave. The electromagnetic wave is in the form of a very faint blue light, this is known as Cerenkov light.

This light falls on the photo-multiplier tubes as a ring shape. Measurements of brightness, shape and direction of the light help provide information about the particles energy, direction and type. The type can be observed through the characteristics of the ring shape as muon neutrinos produce a sharper edged ring than electron neutrinos.

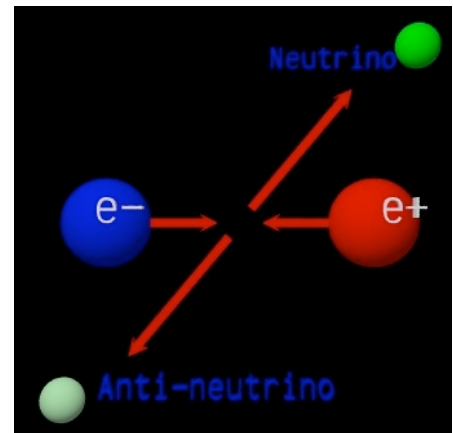
Neutrino formation

Neutrinos are formed through a very wide variety of processes. The first distinction of types is between atmospheric neutrinos and solar neutrinos. Atmospheric neutrinos are ones that form when cosmic rays hit the atmosphere and produce a burst of secondary particles to be formed including both muon and electron neutrinos. Solar neutrinos are formed through several processes that occur in stars. Solar neutrinos form primarily through nuclear fusion both in the proton-proton chain and the CNO cycle. Also creating neutrinos is the process of thermal emission, this process occurs when high enough temperatures and densities are reached, a good example of when a high enough temperature is reached is during a supernova (see picture on right).



The neutrino formation process that is dealt with in this report is thermal emission. There are three types of thermal emission: pair annihilation, plasma decay and photo annihilation. Depending on the temperature-density region these processes will each occur to different extents.

Pair annihilation: This is when an electron and a positron come together and annihilate each other. The annihilated particles must conserve spin and so a neutrino and an anti-neutrino.



Plasma decay: Plasma that is in an excited state will give off a neutrino and an anti-neutrino.

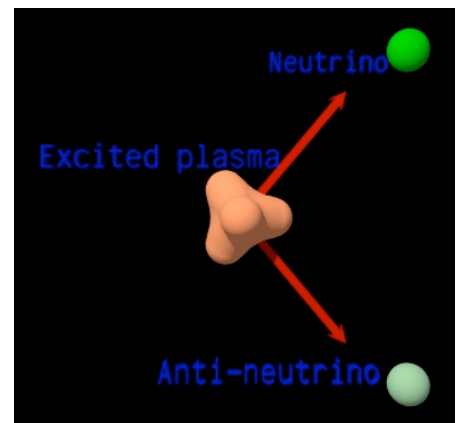
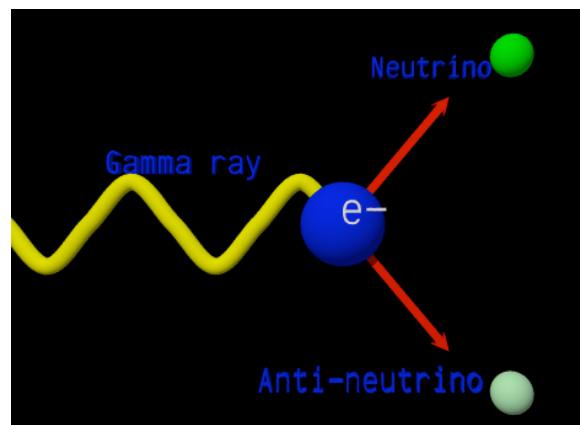


Photo annihilation: In this third process the energy of a gamma ray is enough to cause an electron to release a neutrino and an anti-neutrino. In this process the electron remains present.



Background to program

As already mentioned in the introduction the data and the fitting formulae applied by the computer program were obtained from a paper by Itoh et al. (1996). This particular paper is an update to earlier papers by the same research team. Along with the paper they have provided numerical tables. However for use in a general stellar evolution program, it is necessary to have a set of subroutines that apply the fitting formulae.

The program

The program written was required to process information and carry out calculations about energy loss through the main processes of thermal emission. An important element in the program writing was accuracy. The program is written in Fortran 90 and uses the fitting formulae. At several points the formulae have been rewritten so as to make the program run faster.

The program is based around three main subroutines that each calculate the neutrino energy loss through one of the thermal emission methods (i.e photo, pair and plasma). The program requires the input of the temperature (in Kelvin) and density (in g.cm^{-3}), these are taken as logs for ease of input. Along side the three process subroutines there is also another subroutine shared by the three processes as it is necessary for all three calculations.

During the writing of the program there were several problems that had to be overcome. The most significant problem was the two tables necessary for calculating the loss during the photo neutrino process. This was overcome by creating two fairly lengthy arrays containing values for three temperature ranges. A similar method was used in the neutrino pair process routines although was not strictly necessary.

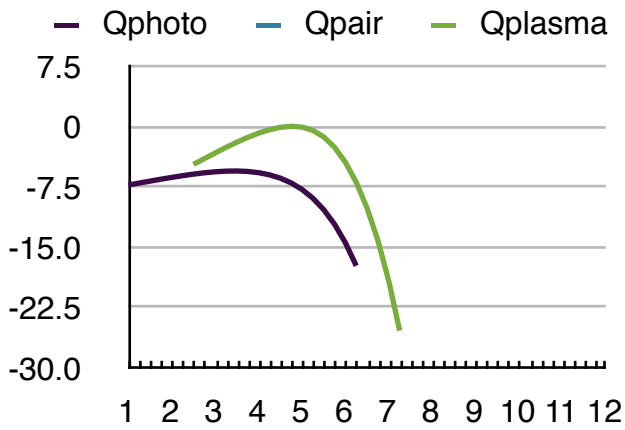
A second difficulty that is worth mentioning is the difficulty of inaccuracy of the fitting formula for the photo-neutrino process at some temperature-density regions. As the paper states; 'we caution that the accuracy of the [photo] fitting formula deteriorates outside the region in which the photo-neutrino process dominates.' This is reflected in the results gained from the program as the results produced by the program for the photo-neutrino process at 10^{11} Kelvin are all underestimates. This underestimate of the photo process is not significant when you work out the total energy loss by adding the energy loss from each of the three processes.

The values for the energy loss in the pair, photo and plasma processes are attributed the titles of Q_{pair} , Q_{photo} and Q_{plasma} . In the final program these three values are output when the program is given a density-temperature region, also output is the sum of these values. All outputs are in logs so as to help with easier graphing and also for comparison with the data from the numerical data that is presented in the paper.

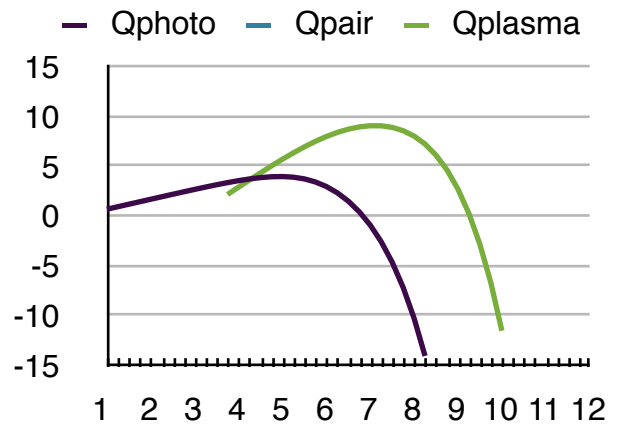
The results

Once complete the program was used to generate values for a range of densities and at varying temperatures. For each temperature, values were calculated for densities between 10 and 10^{12}g.cm^{-3} . The lower energy loss figures for plasma are not shown on the graph so that the graphs in this report bear a closer resemblance to those found in the original paper. Graphs have been drawn of the results obtained for the temperatures of $10^7, 10^8, 10^9, 10^{10}$ and 10^{11} Kelvin. Also included is a graph showing the total energy loss through neutrino processes at each temperature level. Below are the graphs showing these results.

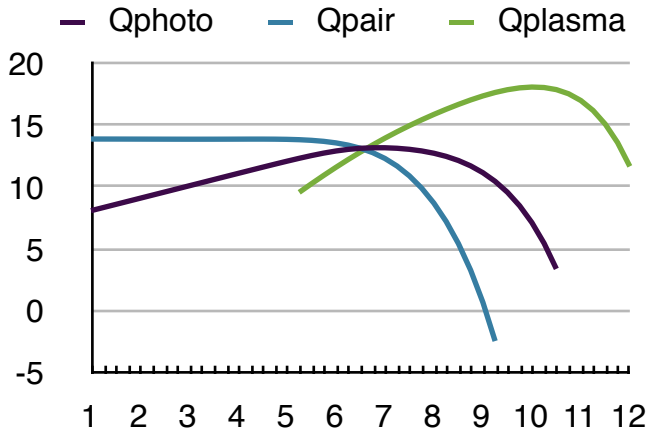
Graph for $T=10^7$



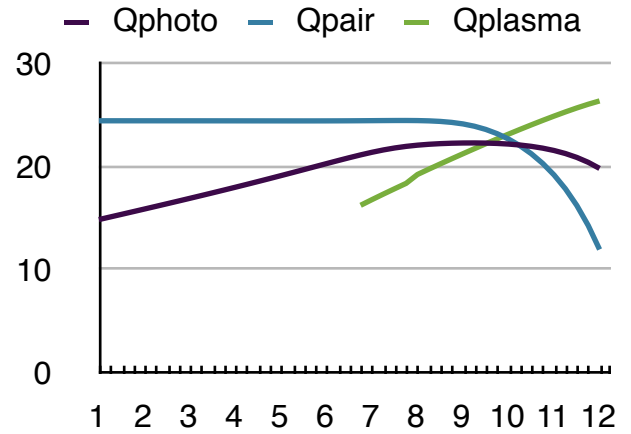
Graph for $T=10^8$



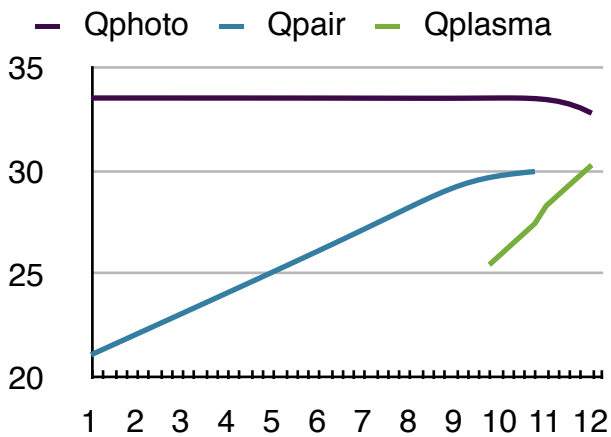
Graph for $T=10^9$



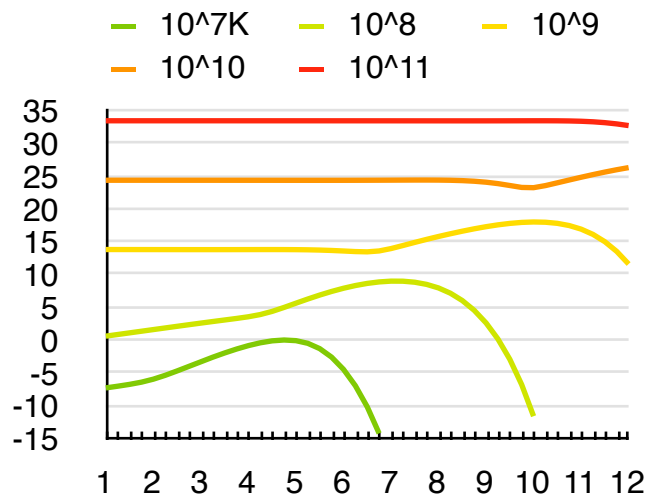
Graph for $T=10^{10}$



Graph for $T=10^{11}$



Graph for total energy loss

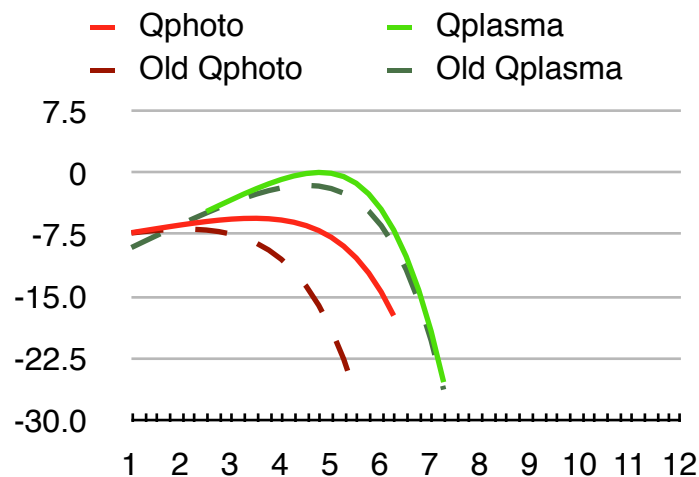


These graphs of the output from the program correspond very closely with the published graphs (Itoh et al., 1996). In the graphs shown the y-axis is the log of energy loss (in ergs $\text{cm}^{-3} \text{s}^{-1}$) and the x-axis is the log of the density (ρ/μ_e) in g.cm^{-3} . Qpair values are not shown on the 10^7 Kelvin and 10^8 Kelvin graphs as they are very large negative numbers.

Analysis

The underestimating of the photo-neutrino process is a slight difficulty however other than this anomaly the programs' fitting formulae produces very similar results to those obtained by using numerical tables. This close match suggests that the program is working correctly and to a high enough level of precision to be useful if combined with a larger stellar evolution program

This program was written to update the stellar evolution program. This update was necessary as the stellar evolution program was using an older version of the fitting formulae that was established by Beaudet, Petrosian and Salpeter (1967). An example of the improvement in the results from the updated fitting formulae (Itoh et al.) and the fitting formulae used previously (Beaudet, Petrosian and Salpeter) can be seen in the graph below where the dotted line shows the old fitting formulae and the solid line shows the new fitting formulae. The graph shows the processes at a temperature of 10^7 Kelvin.



References

Itoh N., Hayashi H., Nishikawa A., Kohyama Y. (1996) Neutrino energy loss in interstellar interiors, *The astrophysical journal supplement series*, 102:411-424

Beaudet G., Petrosian V., Salpeter E., 1967. *Astrophys.J.*,150, 979.

Shapiro S., Teukolsky S. (1983) *Black Holes, White Dwarfs and Neutron Stars* 18.4:520-521

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