Neutrino Emission From Supernovae

At what distance will it kill you?

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Abstract

A supernova, one of the most gigantic and dramatic events that can occur in the whole universe, creates enormous amounts of neutrinos, the tiniest particle that we know exists. The neutrino emission from a supernova would, within a certain distance from the explosion, be enough to kill a human being. In this report, I will find an estimate for this critical distance by first explaining what neutrinos are, and how they interact with other particles. Then, I will introduce the star explosion that is the supernova, and how neutrinos play a crucial role in it in all it's stadiums. Further, I will describe how neutrinos might be detected here on Earth, and then finally I will sum up all of what I have written, and use it to calculate the answer to my subtitle problem.

Contents

1 Introduction

How close do you have to be to a supernova in order for it to be kill you by it's neutrino radiation? The answer to this seemingly silly and totally hypothetically problem will be the theme of this report. However, although the question might not seem relevant for anything, the answer itself requires a lot of knowledge of how the universe itself works on its' smallest and grandest scales, from elementary particles to super massive stars.

2 Neutrinos and Neutrino Interactions

2.1 Neutrinos in the Standard Model

Neutrinos are elementary particles, described by the Standard Model. The Standard Model is our currently best theory for particle physics, and it has all particles sorted into different classes, see figure 1. The two most prominent classes are quarks and leptons. Quarks are the particles in the atomic nucleus, whereas the leptons include the three charged leptons, that is the electron e^-, the muon μ^-, and the tau τ^-, and their corresponding, electrically neutral neutrinos: The electron-neutrino v_e, the muon-neutrino v_μ, and the tau-neutrino v_τ. The three types of neutrinos are called flavours. Like all other quarks and leptons, the neutrinos have "evil twins" in the form of anti-particles, called anti-neutrinos ($\bar{v}_e$, $\bar{v}_\mu$ and $\bar{v}_\tau$). One could say that the anti-neutrinos has the opposite traits of regular neutrinos, however it is not so easy to say what this means as the neutrinos themselves seemingly have very few traits. Neutrinos

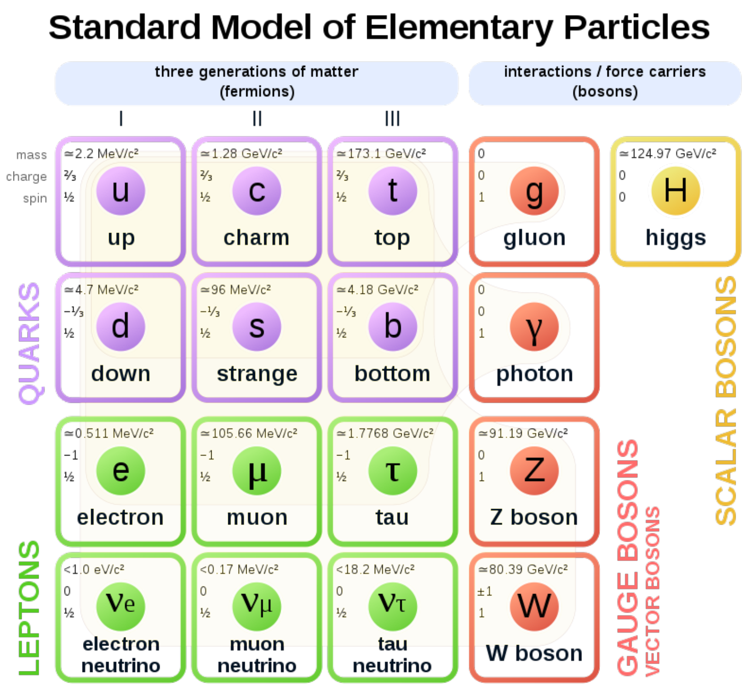

Figure 1: The Standard Model. The six quarks are at the right top in purple, the six leptons are at the left bottom in green. The red row is composed of the force carrying bosons, while the single yellow box is the Higg's boson. Picture source: wikipedia.com [14].

have just an infinitesimal mass and are not affected by the electromagnetic force, or the strong nuclear force that binds up the atomic nucleus, which means that most of the time neutrinos pass through other matter without a hint that they were even there. However, although the neutrinos rarely show themselves, they are extremely numerous. Several billions of them pass through you each second, and the neutrino is the second most common particle in the whole universe, after the photon [1]. Although hard to detect, luckily this "ghost" particle does interact sometimes, and that is by a force called the weak nuclear force.

2.2 The Weak Nuclear Force

Put simply, the weak nuclear force is responsible for changing elementary particles into other types of elementary particles. Along with gravity, electromagnetism, and the strong nuclear force it is one of the four forces governing our universe [2]. It works on both leptons and quarks, unlike the strong force who only works on quarks. In the same way as the electromagnetic force is transferred between particles with photons, and the strong force is carried with gluons, the weak force is transmitted with particles called W- and Z-bosons [3]. As it's name implies, the weak force is relatively weaker than the strong force and also electromagnetism, but it is much stronger than gravity. The reason why gravity is much more famous and seems more present in our everyday lives is that gravity works over infinite distances and always attract masses to one another (electromagnetism too works over all distances, but attracting and repulsive forces cancel each other out on large scales), whereas the weak force only is effective over extremely short distances and is not attractive at all. The most famous phenomenon caused by the weak force is probably the beta decay [3], in which a neutron in an atomic nucleus spontaneously is changed into a proton, with an electron and an anti-electron neutrino emitted from the process. This might look insignificant compared to the importance of a force such as gravity, but without these sort of processes the world we know could not have existed. For example, without the different interactions caused by the weak force it would be impossible for the sun to shine and give life to our earth, so the weak force certainly makes a difference.

2.3 Neutrino Interactions

Neutrinos can interact with leptons and quarks via the weak force in several ways, and in this subsection I will describe four of them. Subsections 2.3.1 and 2.3.2 explain the electron capture process and neutrino/anti- neutrino pair production, which are dominant neutrino reactions in supernovae. 2.3.3 and 2.3.4 are about the inverse beta decay and the elastic scattering reaction respectively, reactions that are very important to the detection of neutrinos. The interactions are illustrated with Feynman diagrams, a common way to depict particle reactions first invented by Richard Feynman around 1950 [4].

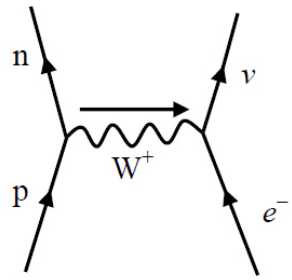

Figure 2: Feynman diagram for the electron capture. A positron and an electron merge via a charged W-boson, and a neutron and an electron neutrino are produced. Arrows indicate direction of time. Picture source: memrise.com [15].

2.3.1 Electron Capture

In the electron capture, an electron spiraling around an atom is captured by a proton in the nucleus, creating a neutron and an electron neutrino [5], as described in Figure 2 and by equation (1):

$$e^- + N_Z^X \rightarrow N_{Z+1}^X + v_e \tag{1}$$

In equation (1) N stands for nucleus, X is the total baryon (neutrons and protons) number in the nucleus and Z is the number of protons. The electron capture is a fundamental process in the reaction that transforms hydrogen into helium and energy in the sun, and it is also central in a supernova explosion.

2.3.2 Neutrino/Anti-neutrino Pair Production

Neutrinos and anti-neutrinos can, like all particles with mass, be created in pairs with one particle for each anti-particle [6]. This requires energy that can be converted into the masses of the particles, and this energy might come from for example particle-anti particle annihilation or gamma rays, both of which are abundant in supernovae. Figure 3 and equation (2) describe the annihilation of an electron and a positron, and the following production of a neutrino and an anti-neutrino.

$$e^+ + e^- \rightarrow v_x + \bar{v}_x \tag{2}$$

In equation (3) the x is meant to represent all of the neutrino flavours.

2.3.3 Inverse Beta Decay

Inverse beta decay happens when an incoming anti neutrino interacts with a proton, producing a neutron and a positron (if the anti neutrino is of positron

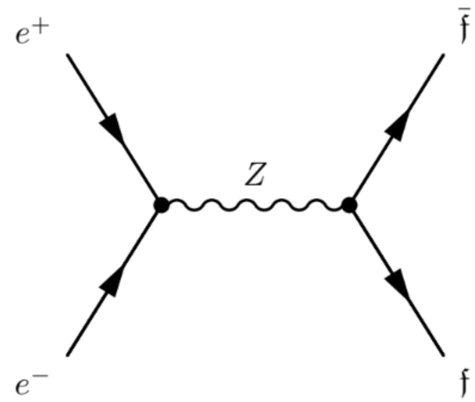

Figure 3: Diagram for a neutrino/anti neutrino pair production. An electron and a positron collide and eliminate each other, producing a Z boson, which in turn decays into a neutrino and an anti neutrino, here symbolized by f and $\overline{f}$. Figure from reference [6].

flavour), see Figure 4. Both free protons and protons bound in nucleus can take part in the interaction. Equation (3) describes the process with a free proton.

$$\overline{v}_e + p^+ \rightarrow n + e^+ \tag{3}$$

This process is important to many neutrino detectors.

2.3.4 Elastic Scattering

The elastic scattering process can at first sight be mistaken to be the least exciting of the neutrino interactions, because the ingredients of the reaction

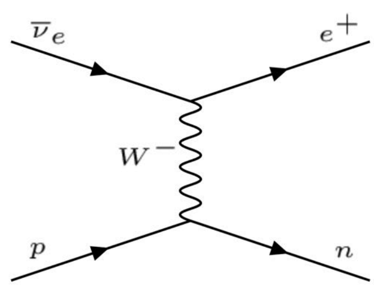

Figure 4: The Feynman diagram of the inverse beta decay. An anti electron neutrino and a proton exchange a W-boson, and a positron and a neutron is the result of the interaction. Picture from reaserchgate.net [16].

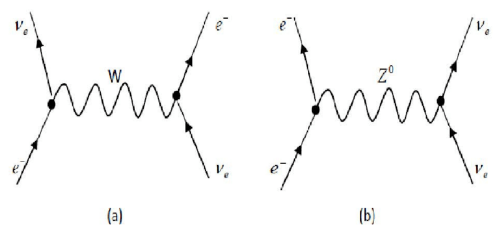

Figure 5: Feynman diagrams for neutrino-electron elastic scattering. Both the charged W-boson (a) and the neutral Z-boson (b) can be transmitted between the particles. Picture source: researchgate.net [17].

also are the products. In the elastic scattering, a neutrino and a charged lepton simply collide and exchange momentum and energy [6], see figure 5. The elastic scattering are of great importance though, because the conservation laws of momentum and energy can be used to calculate where the neutrino came from, if one manages to track the path of the lepton, typically an electron, after the collision in a detector.

3 Supernovae and Neutrinos

3.1 The Death of Stars

A supernova is an enormous explosion caused by the death of a massive star [6]. During a star's lifetime, it balances two opposite directed forces: The massive gravitational pull that forces everything inward towards the center of the star, and the heat-generated pressure that pushes everything towards the edges of the star. The star creates the necessary heat mainly by converting hydrogen into helium, which releases energy because the protons and neutrons of the helium nucleus weigh less than those of the hydrogen nucleus. This process can go on for a long time, most likely billions of years, since stars have almost infinite amounts of hydrogen. However, almost infinite is a lot different from infinite. Sooner or later, depending on the star, it will run out of hydrogen. When this happens, the star begins to transform helium instead into heavier elements, as this also releases energy. When the star has burnt through it's supply of helium, it starts merging the even heavier elements previously produced by hydrogen and helium, until these too are used up. This cycle repeats itself until the core of the star is made up of iron, see figure 6. Iron has the lightest nuclear particles of all the elements, so one cannot release energy by merging iron nuclei. When the star cannot produce the heat pressure needed to withstand the gravitational forces, it collapses, causing a massive explosion that releases so much energy that it shines brighter than all the stars in it's galaxy combined. This explosion is what we call a supernova, and what remains of the star post explosion is

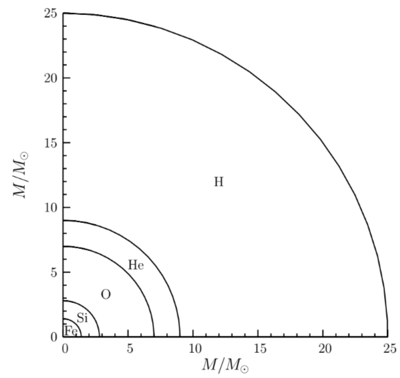

Figure 6: The layered structure of a star nearing its' end. Light elements like hydrogen and helium are abundant in the outer parts of the star, whereas heavier nuclei like oxygen and silicon lies more towards the center. The core is made of the element with the lightest nuclear particles, iron. Figure from reference [6].

either a densely packed neutron star, or, if the star is heavy enough, a black hole.

3.2 Neutrino emission from supernovae

Although a supernova, as previously mentioned, releases so much energy in the form of photons that it burns brighter than all the stars in a galaxy combined, 99 % of it's energy is actually carried away in the form of neutrinos [6]. The emission of neutrinos happens in different phases, and in this subsection I will describe each of them in detail.

3.2.1 The start of the collapse

The gigantic neutrino emission from a supernova begins at the very start of the stellar collapse. When gravitational forces finally win over heat pressure, the iron core will slowly begin to contract, growing ever more denser and hotter. The increased density allows for two reactions to happen: The production of gamma rays with sufficient energy to split iron nuclei into alpha particles and free protons and neutrons, and electron capture [7]. Both of these processes actually accelerates the core collapse. When gamma rays split up iron nuclei, thermal energy vital to keeping the core up is transformed into energy in the form of mass, which does not help the core at all. Electron capture also speeds up the collapse, because the repulsive electromagnetic forces between electrons is preventing matter from becoming too dense. In the electron capture, an electron and a proton is changed into a neutron and an electrical neutrino. Of course these particles does not have any charge, and the electrical forces pushing atoms apart is eliminated. The electron neutrinos created from the capture processes

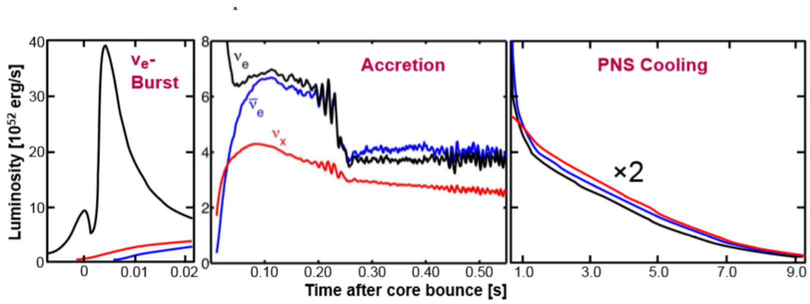

Figure 7: Graph showing the emission over time from a supernova. Electron neutrinos are black, anti electron neutrinos blue and all other neutrinos red. The emission of electron neutrinos start slowly as the star start to collapse, then there is a short dip in the emission during the neutrino trapping. This is followed by the electron neutrino burst after the shock wave. As time increases, the emission of all types of neutrinos will be roughly the same. PNS stands for Proto Neutron Star. Figure from reference [7].

quickly escapes the star, and these are the first neutrinos that can be detected from a supernova.

3.2.2 Neutrino trapping

During the definite collapse of the star, the matter that is falling in towards the center is packed so dense that for a short time, even the weakly interacting neutrinos cannot pass through it and escape into space [6][7]. This is shown as a small dip in the emission of electron neutrinos, see figure 7. All though, as previously mentioned, neutrinos can mostly pass through other matter like it was never there, a supernova can stack so many particles on so small spaces that even neutrinos cannot avoid interacting with some of them. This means that electron neutrinos created from electron capture during the final collapse cannot escape into the universe right away. Instead, they are scattered back by matter falling in towards the core, so for a small moment of time, no particles are leaving the star. However, this short dip in neutrino emission is soon followed by an enormous release of electron neutrinos.

3.2.3 The Bounce Back

There is a limit on how dense matter can be, and when the core of the supernova reaches this limit, matter from the outer laying parts of the star that is falling onto the in-compressible core (with velocities as high as 30 % of the speed of light) is bounced back in a massive shock wave [7]. The wave travels up through the in-falling matter, losing energy that is converted into heat and pressure. Behind the shock, enormous amounts of electron neutrinos are created from electron capture, which causes a high peak in the emission of electron neutrinos. It is to be noted that while the number of neutrinos suddenly emitted after the shock wave is very high, most of the energy from a supernova is not released in this burst. The shock wave also has other consequences for the emission of neutrinos. Since large numbers of electrons are basically converted into neutrinos due to electron capture, significant amounts of positrons, or anti-electrons, are allowed to live in the post-shock matter. These can interact with neutrons in reactions that create protons and anti-electron neutrinos, so now two types of neutrinos are escaping the star. Some amounts of muon and tau neutrinos (and their corresponding anti-particles) are also created in the post shock matter as a result of electron/positron annihilation.

3.2.4 After the Shock

Obviously, the shock wave releases much energy, but most of it is converted into heat and pressure in the matter the shock passes through on its journey out from the core, so this wave is not the explosion one regards as a supernova. That explosion is actually caused by neutrinos radiated from the star center when matter from outer layers of the star falls onto the core, which has now been been converted into a proto-neutron star [7]. When matter falls onto it, friction and heat causes the production of neutrinos of all flavours. These neutrinos can then interact with and transfer energy to other particles. The radiation of neutrinos is so intense that it pushes matter out in a gigantic explosion, which is what we call the supernova [7]. The proto-neutron star generates neutrinos of all flavours in roughly equal numbers, so the emission will be the same for all flavours after the shock. It is this emission that makes the bulk of the 99 % of the energy released by a supernova in the form of neutrinos.

4 Detection of Neutrinos

4.1 Looking for ghost particles

To extract information from supernova neutrinos we have to detect and observe them. The measuring of a neutrino's flavor, energies and other traits can give much needed information about mysteries such as elementary particle physics, the mechanisms that makes stars shine and how the universe was created. As previously mentioned, neutrinos very seldom interact with other particles, so to observe neutrinos and extract information from them is very difficult and requires highly advanced detectors. Today there is a number of them built all around the world, from Canada to Japan to the South Pole. Since supernovae occur rarely (the last supernova to emit detectable neutrino radiation was in 1987, more on that in section 4.2), the detectors usually do not have the observing of supernova neutrinos as their primary goal. Instead, most of them are focused on looking at neutrinos created elsewhere, such as in the earth's atmosphere or in the Sun. Furthermore, neutrinos from supernovae does not have very high energies. This makes them relatively hard to detect compared to other neutrinos, because the higher the energy of a neutrino, the likelier it is to interact with matter in a detector and be observed. The way a neutrino interacts with matter in a detector and deposits energy there would be roughly the same as how it would deposit energy in the form of dangerous radiation in a human body, so in order to determine what is a lethal dose of supernova neutrino radiation it is useful to study how neutrinos are observed in detectors. The next subsections describe different types of neutrino detectors capable of seeing neutrinos created from supernova.

4.1.1 Water Cherenkov Detectors

Water Cherenkov detectors are, simply explained, huge tanks of water viewed by light-sensitive sensors called photomultiplier tubes [8]. When neutrinos come into the water tanks, they may interact with particles in the water. This will create charged particles that travel through the water, and as these particles collide with other particles they will lose energy and emit it in the form of photons, or light. In water, this light radiation will take the form of a cone with an angle of approximately 42 degrees [8]. The photomultiplier tubes can register this light, and because of the prominent cone shape of the light it is possible to determine where the charged particle came from and how much energy it had. The dominant reaction caused by supernova neutrinos in a water detector is the inverse beta decay described by equation (3), where anti electron neutrinos are captured by free protons in the water [8]. This process leads to the most observations of supernova neutrinos, however, some neutrinos can also be detected via elastic scattering, which can give more information about the neutrinos direction of the neutrinos. In inverse beta decay, the neutrino is swallowed by the proton, and a neutron and an electron will be created. These particles will have velocities in more or less random directions, this means that one cannot know in which direction the original neutrino came from. In the elastic scattering, however, the electron that bounces off a neutrino will gain speed in the same direction as the neutrino had speed before the collision. Hence, one can use the Cherenkov light caused by the electron to decide in which direction the neutrino came from. As earlier written, most neutrinos will cause Cherenkov light cones in random directions due to the anti electron capture, but a few cones caused by elastic scattering might point in exactly the same direction, which can give big clues to where to look for a supernova. Today there exists only one water Cherenkov detector, it is called the Super-Kamiokande detector and is located in Japan [8].

4.1.2 IceCube

The IceCube detector is a neutrino detector located on the South Pole. Like liquid water Cherenkov detectors, IceCube is able to spot neutrinos due to the Cherenkov light emitted by charged particles created by neutrino interactions. The difference is that where water detectors use water as their detector medium, IceCube uses ice. The IceCube detector consists of 86 cables with photomultiplier tubes lowered into the antarctic ice cap, and it covers a volume of approximately 1 cubic kilometre [9]. The top of the cables are lowered ca 1,5 kilometres into the ice to shield them from as much background noise as possible, the length of the cables is roughly 1 kilometre so the bottom of the cables are located about 2,5 kilometres under the ice surface. Compared to water detectors, IceCube has both advantages and disadvantages. IceCube is not able to say anything about where the neutrinos come from or what energies they have, which would have been very useful [8]. However, because of IceCube's massive size of one cubic kilometre, it is able to detect a very high number of neutrinos. This can be used to make a very continuous graph over neutrino interaction events over time, which in turn could be used to confirm or alter our understanding of how neutrinos are emitted from supernovae, described in the previous section.

4.1.3 Other types of neutrino detectors

The two types of detectors described above both rely on neutrino interactions in liquid or frozen water that create Cherenkov light cones, however, there are many neutrino detectors that use completely different mediums for neutrinos to collide with.
One important type of detector are scintillator detectors. The medium in these are hydrocarbons, most of which can be described with the formula C_nH_{2n} [8]. Like with the detectors previously described, the most common neutrino interaction in scintillator detectors is the inverse beta decay described by equation (3). In the hydrocarbon liquid these reactions will produce light which can be observed by photomultiplier tubes. The lowest energy a neutrino can have in order to be seen by a scintillator detector is lower than what is required in a water detector, so scintillator detectors are good for detecting low-energy neutrinos. However, Cherenkov light emission is not possible in hydrocarbon liquid, so they cannot give information about where the neutrinos came from. There is a number of scintillator detectors around the world, examples of these include KamLAND in Japan (located near the Super-Kamiokande), Borexino in Italy and Baksan in Russia [8].
The element argon can also be used to look for neutrinos. These detectors are different to the ones previously described in that the most prominent neutrino interaction in them is not the inverse beta decay, but the capture of electron neutrinos on argon nuclei [8], described by equation (4):

$$v_e + Ar^{40}_{18} \rightarrow e^- + K^{40}_{19} \tag{4}$$

This reaction produces gamma rays which are detectable. One advantage with the argon detectors are that they are sensitive to regular electron neutrinos, which make up the majority of neutrino flux in the early fazes of a supernova outburst. Today there exists one argon detector, it is located in Italy and is named ICARUS [8].

4.2 Supernovae in the past and future

4.2.1 SN1987A

Only one supernova has ever been studied by its' neutrino emission. This supernova has been named SN1987A after the day it was discovered, 24 February 1987, not by neutrinos, but by regular light [6]. In fact, SN1987A was the first supernova since the Kepler supernova in 1604 to be visible to the naked eye. It was found to be located in the Large Magellanic Cloud, more or less 50 kilo parsecs (one parsec equals roughly $3 * 10^{19}$ meters) away from earth. SN1987A is the best studied supernova in history, and it was also detected by it's neutrino emission. In 1987, four detectors were able to observe supernovae neutrinos [6]. These were called Kamiokande-II, IBM, Baksan and LSD. All of them recorded more neutrino events than usual on 24 February, but the LSD events happened several hours earlier than the events in the three others, and are usually excluded from analysis. The Kamiokande-II, a predecessor to today's Super-Kamikokande, was a water Cherenkov detector in Japan. On the day of the supernova, it recorded 16 events in the energy range of supernova neutrinos. The IBM, also a water Cherenkov detector, is set deep underground in Ohio, USA. On the event day it recorded 8 neutrino interactions that might have come from the supernova. Lastly, the Baksan scintillator detector in Caucasus, Russia, registered five events likely to be caused by SN1987A. All this data has been heavily analyzed over the years, and it has strengthened our theories about neutrinos from supernovae. It is important to note that while scientists were able to detect supernova neutrinos in 1987, they were not prepared for it. Neutrinos from supernova reach the Earth before the photons does, so one should be able to detect the supernova with neutrino detectors before one saw it. This was not the case with SN1987A, here, one first saw the supernova with regular telescopes, then scientists looked for it in the recorded neutrino data and found it afterwards. Furthermore, and somewhat astonishingly to think about, both Baksan and Kamiokande-II had huge uncertainties in something as elemental as the time in which their data was recorded [6]. From 17 February to 11 March the Baksan clock had had a forward shift of 54 seconds, which nobody knows exactly when happened, leading to an uncertainty in time of 54 seconds. In Kamiokande-II, there is an uncertainty of about one minute on the time of the events due to the fact that the clock was set manually by hand because the scientists did not believe that accurate timing was important. Fortunately, the science community has learned from these mistakes and today we are well prepared to receive neutrinos from supernovae.

4.2.2 SNEWS

Because neutrinos escape the super dense material of a supernova much easier than photons, supernovae in the future are likely to be seen by their neutrino emission before they are observed by regular telescopes. The neutrinos from SN1987A were recorded 2.5 hours before light from the explosion reached the Earth, but as we have seen, scientists saw this in their data only after the supernova had already been seen by it's electromagnetic radiation [6]. Today, a collaboration between several neutrino detectors called The SuperNova Early Warning System (SNEWS) is working to ensure that scientists are alerted as soon as the detectors observe a supernova. If one could point to the location of a supernova from it's neutrino emission, one could tell astronomers where to look for it before it was actually visible. This would be extremely useful for astronomers wanting to study the full development of a supernova. Today, the detectors that make up SNEWS are IceCube, Super-Kamiokande, Borexino and five other detectors of various types.

5 The Calculation

The following paragraph is a brief description of how I plan to estimate how close you have to be to a supernova to be killed by it's neutrino radiation. Firstly, I will investigate how much radiation that is needed to be lethal to a human being, and how many neutrinos would have to pass through a human body so enough of them could cause that radiation. Secondly I will use the number of detected neutrino events in Kamiokande-II from SN1987A to calculate how many supernova neutrinos a human would absorb at the same distance from SN1987A as Kamiokande was. Finally, I will estimate how much that distance would need to be reduced in order for the supernova neutrino flux to be dense enough to kill a human being.

5.1 Lethal radiation

Ionizing radiation dose is measured in two units called Grays (Gy) and Sieverts (Sv). Somewhat confusingly, both of these have the same SI-unit, J/kg, but they represent different things. Sieverts are derived from Grays, so I will explain the Gray first. Grays measure the absorbed dose of radiation energy in matter, and are given simply by equation (5):

$$Gy = \frac{J}{kg}. \tag{5}$$

This means that 1 Gy corresponds to 1 kg of matter absorbing 1 Joule of energy [10]. However, different kinds of radiation affect biological matter differently, so being exposed to 0.1 Gy of gamma radiation, say, would be much less dangerous for a human than being exposed to 0.1 Gy of alpha particle radiation. This is were the Sievert comes in. The Sievert is the Gray multiplied by a certain weighting factor that reflects how damaging that particular radiation is to biological matter. The weighting factor ranges from 1 for photons and electrons, to 20 for alpha particles [10]. The weight-adjusted radiation dose is called the equivalent dose. For this paper however, it would be too complicated to take into account the relevant weighting factors for the particles that are created from supernova neutrinos, and so to simplify my calculations I will pretend that one Sv always equals 1 Gy. This is discussed more in section 5.4, where I go

through some of the simplifications I make in this paper.
According to the United States Nuclear Regulatory Commission, a human being that is exposed to 4 Sv has a 50 % chance of dying within 30 days [11], and I will use this as my definition of lethal here. Let us also imagine that the person in risk of being killed by a supernova is a person weighing 7o kg. A radiation dose of 4 Sv would result in the absorption of 320 J in this persons body. The mean value for the energy of a supernova neutrino lies between 5 and 15 MeV [6]. Here, I will use the value 10 MeV = $1.6 * 10^{-12}$ J. Then, if one supposes that all the energy in a neutrino is converted into ionizing radiation in an interaction, the number of supernova neutrinos N needed to deposit 70 J in a human body is

$$\frac{70J}{1.6 * 10^{-12} J/N} = 2 * 10^{14} N \tag{6}$$

5.2 Kamiokande-to-human comparison

In this section, I will use the recorded neutrino events in Kamiokande-II to calculate how many neutrinos that would have interacted in a human during SN1987A. The Kamikokande-II detector consisted of water, and in my calculations I will treat the human body as an object completely consisting of water in order to make it comparable to Kamiokande.

Kamiokande detected 16 neutrinos during the supernova event [6]. I will assume all of these came from the supernova, but that may perfectly well not be the case. In addition, Kamiokande most certainly did not record every neutrino that it absorbed, because firstly the photomultiplier tubes did not cover the whole volume of the tank, and secondly the neutrinos need to have energies above a certain threshold to produce the noticeable Cherenkov light cone. In this report however, I will not investigate how many neutrinos probably interacted in Kamiokande and limit myself to calculate with the official number of 16. There were 2142 tons of purified water used as detector medium in Kamiokande, which equal 30'600 people each weighing 70 kg. Thus, if Kamiokande had the size of a human and could detect "decimal" neutrinos it would have detected

$$\frac{16n}{30'600} = 5.2 * 10^{-4} n \tag{7}$$

It is important to keep in mind that SN1897A happened about 50 kiloparsecs (kpc) from the Earth, which equal $1.5 * 10^{21}$ meters.

5.3 The Crucial Distance

So we know that at a distance of $1.5 * 10^{21}$ meters from a SN1897A-like supernova, a human would statistically absorb $5.2 * 10^{-4}$ neutrinos, and the lethal neutrino absorption number is $2 * 10^{14}$ neutrinos. This means that one would need a neutrino flux

$$\frac{2 * 10^{14}}{5.2 * 10^{-4}} \approx 3.8 * 10^{17} \tag{8}$$

times stronger than the flux that came to the Earth from SN1897A in order to kill a human. When the neutrinos leave the supernova, they spread out on a surface shaped like a sphere. The area of this sphere is given by

$$A = 4\pi r^2 \tag{9}$$

where A is the area and r is the distance the neutrinos have travelled from the center of the sphere, which is the supernova. The flux Φ is defined by the number of neutrinos divided on this area, as shown in the below equation:

$$\Phi = \frac{n}{4\pi r^2} \tag{10}$$

From equation (10) it is evident that if one wants to increase the flux by a certain magnitude, one has to decrease the distance r to the supernova by the square root of that magnitude. Thus, if one wants a flux $3.8*10^{17}$ times stronger than what one has, one has to reduce the distance to the supernova by a factor of $\sqrt{3.8 * 10^{17}} = 6.2 * 10^8$. Dividing the distance between Earth and SN1987A with that number, I obtain the distance

$$\frac{1.5 * 10^{21} m}{6.2 * 10^8} = 2.4 * 10^{12} m \tag{11}$$

which from my calculations is where the neutrino flux would be lethal to a human. $2.4 * 10^{12}$ m correspond to approximately 16 AU, where AU is the astronomical unit, the average distance between the Earth and the Sun.

5.4 Simplifications

It does not take a neutrino scientist to see that my calculations heavily depend on several simplifications. These were briefly mentioned in the calculations, but I will go through them again and more thoroughly here.

Firstly, when I calculated the lethal neutrino number, I neglected weighting factors for different kinds of radiation and made the simplification that the equivalent radiation dose from neutrinos, measured in Sv, was equal to the absorbed radiation dose, measured in Gy. This is wrong. The dominant neutrino interaction in Kamiokande-II was the inverse beta decay, where the products are a positron and a neutron. The positron will most likely have a weighting factor similar to the electron, which is 1 [10], so if positrons were the only product then the absorbed dose and the equivalent dose would in fact be equal. However, neutron radiation is one of the most damaging radiation types, and therefore neutrons have a weighting factor between 5 and 20, depending on the energy of the neutron. Taking this into account, it would probably take less neutrino radiation to kill a human than what I have estimated in this paper.

Secondly, I assumed that all of the neutrino energy that were absorbed by the human body led to dangerous ionizing radiation. I have not investigated how neutrino energy is divided and transformed when neutrinos interact with other matter, but one could imagine some of it being transformed into for example harmless heat. I also took the average neutrino energy to be 10 MeV, while it may range from 5-15 MeV. In addition to this, I neglected the fact that neutrinos have to have energies higher than a certain threshold both to react via the inverse beta decay and to create the detectable Cherenkov light cone [6], and the effect of neutrinos with energies below that threshold is not included here since they would not have been detected by Kamiokande-II. It is hard to say what impact the sum of these simplifications would have had on my lethal distance answer, more investigation is needed.

It is also worth noting that my estimate relies most of all on the number of neutrino interactions detected by Kamiokande-II from SN1987A, which was 16. When one takes in mind that the number of neutrinos emitted by a supernova is in the scale of 10^{58} [6], 16 is a very small number to base general probabilities on, and leads to huge uncertainties in the final result. Also, not all supernovae are similar to SN1987A and might release more or less neutrinos with higher or lower energies than 1987A did. Another modulation I made is that I assumed that the human body behave exactly like the purified water in the Kamiokande detector, when of course people consist of many other elements in addition to water. How well for example skeleton bones are at absorbing neutrinos is not a question I can answer now.

Lastly, it should be mentioned that I in this paper has been imagining a human floating isolated in free space, so that radiation from neutrino absorption in matter around the human does not exist.

5.5 Comparison

The lethal supernova neutrino distance has actually been calculated before. In his book *What If?* Randall Munroe [12] comes up with a number of 2.3 AU. The number is based on a cosmological radiation paper by radiation expert Andrew Karam [13]. In his paper, Karam uses two equations to calculate exactly the equivalent radiation dose that would come from a neutrino flux. The first equation returns the equivalent dose as a function of the probability for a neutrino to interact in biological matter, and the second equation returns that probability as a function of the average energy of the neutrinos in the flux. It is fair to say that his methods depend much less on simplifications than mine, and that his results should be taken much more seriously. It is interesting to note though, that while 16 AU and 2.3 AU are indeed different values, the distance between them is not drastically large considering that the calculations needed to produce them depend on values on both truly macroscopic and microscopic levels, Karam for example takes the number of neutrinos released in a supernova to be 10^{57}. This value is actually interesting on it's own, because other references, such as ref [6] takes it to be 10^{58}. How many neutrinos that were released in SN1987A is not certain, but altering Karam's neutrino emission number to somewhere between 10^{57} and 10^{58} could possibly produce an answer very similar ro my own. Considering the huge simplifications I have made in my own estimate, though, trying to work down the difference between the answers should probably not be a goal, as one reason that the numbers are not farther apart might just be luck.

6 Epilogue: Are we in trouble?

Is Earth threatened to be destroyed by neutrino radiation from a supernova? Definitely not. If you went 16 AU from the Earth you would still be well inside the solar system, and of course the solar system contains only one star, the Sun. The Sun is not going to collapse any time soon, and when it does, it won't go supernova. If, however, by some very unhappy circumstance you were to find yourself only 16 AU from a supernova, neutrino radiation would be a big problem, but definitely not the biggest. In the aforementioned paper by Andrew Karam, it is shown that ionizing radiation caused by supernova neutrinos is insignificant compared to the gamma radiation caused by the same supernova. If you were 16 AU from a supernova, you would probably live some time after the neutrino emission passed, but when the gamma rays hit you, it's game over.

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