THE NEUTRINO - Curated Transcript of BBC In Our Time podcast
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In Our Time is hosted by Melvyn Bragg. Melvyn's guests on this podcast are:

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Professor of Physics at Exeter College at the University of Oxford

Susan Cartwright
Senior Lecturer in Particle Physics and Astrophysics at the University of Sheffield

David Wark
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Transcript:

[Melvyn Bragg] Hello. About 93 million miles above our heads is a star we call the sun. In the heart of this enormous ball of plasma, nuclear reactions are producing vast amounts of energy, energy which reaches the earth in the form of heat and light. But in addition to warming our planet and bathing it in light, the sun is also bombarding us with a storm of objects we don't even notice. They're called neutrinos, and billions of them pass straight through our bodies every second. Neutrinos are some of the strangest and most mysterious objects in the universe. They're invisibly tiny and can travel through solid rock and even stars as easily as they do through space. Scientists first proved their existence half a century ago. Today, neutrinos are offering us new

insights into the nature of the universe and of matter itself. With me to discuss the neutrino are
Frank Close, Professor of Physics at Exeter College at the University of Oxford, Susan Cartwright, Senior Lecturer in Particle Physics and Astrophysics at the University of Sheffield and David Wark, Professor of Particle Physics at Imperial College, London, and the Rutherford Appleton Laboratory.

[Melvyn Bragg] Frank Close, I've hinted at the sheer strangeness of these particles. You think they're the weirdest objects in the universe. Could you give us a bit more detail about them, what they are, how they behave so on?

[2:44]
[Frank Close] Well, they're probably as near to nothing as anything that we know. They've got no electrical charge. Until very recently, we thought they'd got no mass at all. If they have got any mass, it's too small to measure. If you put 100,000 of them on one side of a set of scales, they wouldn't even outweigh a single electron, which is the lightest other particle that we know. So they're very weird. As you alluded, [it's] been said that they pass through the earth as easily as a bullet through a bank of fog. So [with] the sun putting out all these neutrinos that are shining on us at the moment, half a second later they've passed out the other side of the earth and are shining up through the beds of people in New Zealand. So if we could see with neutrino eyes, night would be as bright as day. They're very strange. They're passing through the universe like mere spectators. In fact, there's probably more neutrinos in the universe than any other particle that we know. And yet, paradoxically, we know less about them than anything else, almost.

[3:36]
[Melvyn Bragg] When they pass through, do they do anything to us, to the earth? Is that what you're trying to find out?

[Frank Close] I suppose that's what we're trying to find out. I mean, 60 million of them are passing through our eyeballs every second without us seeing them, and they are totally harmless because they don't really interact with anything very much. The difficulty is trying to capture one or two. It's a bit like the national lottery. Enough people enter, somebody is lucky. If there's enough neutrinos around and you've got a big enough net, you might occasionally capture one, and I'm sure we'll talk about how you do that later on. But they're very difficult to capture and hence difficult to study, and that's why we know so little about them.

[Melvyn Bragg] Can you just beggar our imaginations a little more by what these neutrinos do? They go through nine trillion ...[kilometers of] lead... Just tell people what goes on with these things a little bit more.

[Frank Close] Well, ... they don't interact with things like normal things do. They don't feel electrical forces. They don't feel magnetic forces. Gravity is so feeble, you can't really make much use of that. They interact only by a force called the "weak force", which, by its very name, weak, means it's hardly likely to do very much. They [can], as you said, travel through, I think, a light year of lead without bumping into anything - [a] 50-50 chance that an individual neutrino will bump into something in a light year of lead. That's about as good as it gets. But if you've got a nuclear reactor, for example, which is pouring out millions and millions and millions of these things every second, then it is possible to capture one or two. And as we will hear later...

[Melvyn Bragg] And ... noticing them, began in the 1930s with a phenomenon known as beta decay. Can you bring us up to speed on beta decay?

[5:13]
[Frank Close] Beta decay is one form of radioactivity, where one atomic element changes into another, and in doing so, releases energy in the form of a particle, the electron. And if that was the whole story, that one element turns into another, emitting an electron, each and every time you do the experiment, the electron would appear exactly the same, the same speed, the same direction, the same energy. But that's not what happened. They found that sometimes the electron had quite a lot of energy, other times, almost none at all. In fact, a whole spectrum of energies from nothing up to a maximum. And this just didn't fit. And so what was the answer to this? What was it proving? Well, maybe energy wasn't conserved in nuclear reactions... That was one suggestion that was made in those days. The other idea, which we now know was the correct one, is that there was an unseen member at the feast, the neutrino.

[Melvyn Bragg] Can we talk about that with David Wark? The ..[Australian].. physicist Wolfgang Pauli proposed his solution to this problem. Can you develop that?

[6:14]
[David Wark] Well, yeah, Wolfgang Pauli, who's actually Austrian but he was at ETH in Zurich when he proposed this. He was baffled by this fact that the electrons emitted in beta decay didn't always have the energy they should. And, as Frank pointed out, there were some suggestions around at the time that perhaps energy conservation, conservation of angular momentum, which was also seemed to disappear in beta decays, were just statistical things. They didn't happen in every single decay, that only on average were they conserved. And Pauli was horrified by this, because he thought that it did horrible things to the mathematics. And so he came up with this idea that in addition to the things we see emitted, something else was emitted that carried away the excess energy. And at the time, that was quite a dramatic thing to propose, because there were only two known particles at the time, the proton and the electron, and he called this third particle the "neutron". It was later dubbed the "neutrino", after Chadwick discovered the thing we now call the neutron, and this was a very dramatic proposal. At the time... so you would imagine that a dramatic proposal like that would be...

[Melvyn Bragg] Why did you say "dramatic"? Sorry...

[David Wark] Well, because scientists, I would say, ... were more conservative about such things back then. They took a lot of convincing that another particle existed. As time has gone on, theorists have been more and more ready to propose the existence of new particles, to try to explain deviations from our predictions. Back then, it took a lot of effort to convince somebody there was a new particle in the world. Like I said, there were only two known particles. So proposing a 50% increase in the number of [known] particles in the world just to cover up the fact that a little energy seemed to be disappearing in this one obscure radioactive decay seemed quite a dramatic proposal.

[Melvyn Bragg] So ...was he taken seriously? He's predicting a particle which it had been impossible to detect, but he's saying that, according to his theory, it ought to be there. Now, briefly, what was his theory? And secondly, did people take this on trust?

[8:38]
[David Wark] Well, he originally just proposed that this particle would be emitted. It wasn't really turned into a fully mathematical model until Fermi got his hands on it and he [Fermi]produced a theory of the weak interaction, which would mediate this beta decay and produce these neutrinos. I think people did take it seriously because there was really no other way to understand what was happening in beta decay. But as you say, Pauli apologized for having predicted the existence of a particle that could never be observed. (I only wish theorists these days would apologize when they predict the existence of particles that can't be observed!) But, luckily for Pauli, Fermi did the calculation and worked out that you ought to be able to observe them.

[Melvyn Bragg] Can we just take a step back? He offered a box of champagne to... Is that right? [A box of]champagne, [to] anybody who could detect these things? Can we just [discuss]... why are they so difficult to detect? There are billions and billions [of them] as we've now said... why are they so difficult to detect?

[9:48]
[David Wark] Well, it just has to do with the interactions that they feel. There's sort of four forces of nature that we know of. There's gravity. There's the strong nuclear force that binds together the nuclei of atoms. Then there's the weak nuclear force. Okay? And then there's electromagnetism. Now everything feels gravity, but gravity is so weak ...In particle terms, it's almost impossible to observe any effect of gravity on particles. The only reason that we think of gravity as strong is because gravity always adds up with the same sign. And so we feel the pull from all the particles in the earth, and it's only by having that huge number of particles that it's strong enough you can feel it. The other forces act at much shorter ranges.. Or, rather, the strong force acts in a much shorter range, the weak force acts a much shorter range, and the electromagnetic force.. you have [to have]... half plus and half minus [charges]... So the effect of this is that the strong force, which binds together the nuclei of atoms, is very strong. The electromagnetic force also has quite a bit of strength. The weak force... has an extremely small effect upon particles. If you think about glass and you think about light, you can see through glass, because the light doesn't interact very much with the glass, it goes right through it. However, if you had a piece of glass that was a foot thick, it would start to look dark and if you had a piece of glass that was 100ft thick, you couldn't see through it. So the light does interact with glass, just not very much. It's the same effect, but carried to a much greater extent with a neutrino. The earth is far more transparent than any piece of glass is and, as Frank says, you need light-years of lead to have the effect of an inch of glass.

[Melvyn Bragg] So we only know [of the existence of neutrinos] when ... we see a reaction. ... And they began to get underway doing that, thinking about it properly, in the 1930s. But, Susan Cartwright, ... in 1956, the Eureka moment, [occured when] neutrinos were detected for the first time. ...How was that achieved?

[12:05]

[Susan Cartwright] Well, that was achieved using the reverse of the reaction that first caused powdery to believe that the neutrino existed. In beta decay, a neutron turns into a proton and it emits an electron and this mysterious neutrino. And in the 1950s, Fred Reines in Los Alamos realized that the inverse process was also possible. If you hit a neutron with a neutrino, you can get a proton out, or rather a proton and an electron. Or if you hit a proton with a neutrino, you can get a neutron and a positron. And the key fact is that a positron, being the antiparticle of an electron, will annihilate in matter, producing radiation, which you can detect. And the neutron a little bit later will be captured and will also produce radiation that you can detect. So he figured if he could get a sufficiently intense source of anti-neutrinos, he could detect this reaction that converts a proton to a neutron. At first, being at Los Alamos, he thought he might use a bomb. The difficulty with using a bomb is having your experiment survive the experience. So although he did get quite far in planning an experiment using a bomb (he had plans to drop it down a shaft so that it wouldn't be vaporized by the shockwave, and then have feathers and things at the bottom to prevent it from smashing into bits) eventually, he realized that the next most intense source of.

[Melvyn Bragg] Is this a scientist we can really trust?

[Susan Cartwright] He won the Nobel Prize a long time later, but he did win the Nobel Prize...

[Melvyn Bragg] It was the feathers that got me. Sorry, I interrupted. I interrupted your flow. [laughter]

[14:02]
[Susan Cartwright] Right... so... the bomb idea having obvious drawbacks, he realized that the next most intense source of neutrinos was a nuclear power reactor, that the fission fragments are not stable and they decay by a relative of beta decay and produce vast numbers of anti-neutrinos. So he figured he could use a reactor. He wrote a letter to Enrico Fermi saying that he'd had this idea. He'd previously discussed the bomb idea with Fermi as well, and Fermi wrote a lovely letter back, saying, "I think this is a much better idea. For a start, you'll be able to repeat the experiment." [laughter]

...

[Susan Cartwright] He built what, for the time in the 1950s, when experiments were literally tabletop instruments, he built what was then considered a very large detector. In these days of LHC, large detectors are the size of a small office block. But in those days, his detector was probably the size of this room, not even... maybe the size of this table.

[Melvyn Bragg] It's a perfectly ordinary table.

[Susan Cartwright] ...Yeah, about a cubic meter. You could just about get a person inside it, because one of the things he did when testing it was measure the radioactivity of a person caused by the potassium 40 in your cells. And this was, by the standards of the time, an enormous experiment. He had difficulty persuading people it would work, but that's what you need to detect neutrinos, very large detectors, by the standards of your time.

[Melvyn Bragg] So he was on the track of the neutrinos. But by then, scientists had already worked out, as I understand it, that the sun produced far and away the largest number of neutrinos. Why is that the case?

[Susan Cartwright] Well, the sun, as Frank said, is a nuclear furnace, and the way it generates energy is it converts hydrogen into helium. Now, hydrogen is pure protons. Helium is two protons plus two neutrons. So to convert hydrogen into helium, you must convert two protons into two neutrons. And this is, in fact, exactly the same reaction that Fred Reines used to discover ... the neutrino in the first place...[because] every time you turn a proton into a neutron, you get a neutrino out as a necessary byproduct. And the sun is converting protons into neutrons at the rate of about ten to the power 38 (that's one followed by 38 zeros) every second and every time, a neutrino is spat out. And whereas the light, the energy that is produced in the core of the sun takes about a million years to make it to the surface, because, as we just discussed, neutrinos don't actually notice matter much, the neutrinos get right from the centre to the surface in a couple of seconds - and eight minutes later, they're at your detector.

[Melvyn Bragg] Right. I'm going to pause to try to think on ..that one. Frank Close, we're now moving on to the discovery of the neutrino, which was a quest, and it's begun, [as] David and Susan have [described]. Let's move on into the 1960s, there's a scientist called Ray Davis and he set up this detector that's trying to catch these [neutrinos]. So for the listeners benefit (for mine, if I've got this wrong) please tell us [about this experiment]. This storm of [neutrinos is] coming our way. They interact only with weak energy and there's so many of them that it's only very occasional [that] they do interact. So you don't know they're there unless you have a very elaborate system to catch [them], even though there are billions and billions of them, you have to have an elaborate system to catch just a few of them. So that's the quest, isn't it? Now, Ray Davis has... got a detector, too. So what did he do in the 60s?

[18:03]
[Frank Close] Right, so Ray Davis is trying to detect neutrinos, the little neutrons, the neutrino. What Susan said about the sun, we now know is true, but in fact, we didn't know that years ago. It was just a theory originally that the sun is a fusion reactor producing all of this stuff. And Ray Davis set out an experiment to try and prove it, because if indeed the sun is [a little fusion reactor], then it will be producing neutrinos. The question then is, how do you capture them? And the idea originated with a brilliant Italian called Bruno Pontecovo, who ruined his scientific career by disappearing to the Soviet Union in the 1950s (which is an interesting story in its own right, but not for today) that you could detect neutrinos if you used a lot of chlorine. Because if a neutrino bumped into chlorine, it would turn it into a form of argon, which would be quite easy to detect. And chlorine is cheap - you get it in cleaning fluid. So Ray Davis's idea was to get a lot of cleaning fluid - in fact, it ended up being 400,000 liters of the stuff. So we're no longer talking a cubic meter, we're talking, well, a tank of 400,000 liters of cleaning fluid, which he had to take a mile underground into a disused mine.

[Melvyn Bragg] Why did he do that?

[Frank Close] Because he wanted to shield his experiment from cosmic rays. I mean, we're being bombarded from outer space all the time by cosmic rays, which hit the atmosphere and make showers of particles. And if they pass through your detector, you might mistake one of them for one of these rare neutrinos. So go deep underground, where all the cosmic rays have been absorbed away, and if you're lucky, what's left will be neutrinos from the sun. So he had all this cleaning fluid shipped across the States on railroad cars. It took them about five weeks to unload the cars, ship them all down to the bottom, put it all in the tank, and then he had the thing there and you wait. And occasionally, in theory, a neutrino from the sun will bump into a chlorine atom in your big tank. And every month or so, you purge out the tank and hope to find one or two atoms of argon to prove that you've done it.

[Melvyn Bragg] Just a sec. That sentence alone... "Every now and then you purge out the tank to find one or two atoms of argon, and you've done it.""That for most of us, needs a little bit more explanation.

[Frank Close] Right...in fact, nobody believed he could do it. Yes, you've got this huge tank of chlorine, and you're trying to find one or two atoms of something else, argon, that's been made.

[Melvyn Bragg] How do you go about it? ...

[Frank Close] ...The argon gives off ...radioactivity, so ...for a radio chemist like Davis, it was straightforward [to measure]. For me as a theorist, it's a miracle. [laughter] And indeed, he found so few [argon atoms] that for years, people didn't believe he could do the experiment at all. He had to convince people he could even do it, let alone that his results that he was getting were real. Now over to Dave to explain how he really does it.

[Melvyn Bragg] David?

[David Wark] Well, I don't want to wax poetic on the subject of detecting a few atoms too long...We did a very similar experiment subsequently, where we detected a few atoms of radioactive germanium in a tank of 60 tons of metallic gallium. Basically, you take advantage of the fact that ....when one of these atoms decays, it has a very particular signature. It emits a very particular energy electron, and you can purify... It's a trick of the chemistry. It turns out [that] it's easy to purify these things down to extreme levels of purity. So you can put them in very, very tiny detectors, which have very little background radiation. You can actually find a few atoms. And this has been confirmed experimentally now that using radioactive sources that produce enough neutrinos that you can actually detect them.

[Melvyn Bragg] So what did Ray Davis get out of what was called the Homestake Experiment a mile beneath the earth with this cleaning fluid?

[22:14]
[David Wark] Well, he started counting his neutrinos, or rather, he started counting his atoms of radioactive argon. And over time, it became clear there weren't enough. And there was something like a quarter to a third the number that was expected.

[Melvyn Bragg] Who'd expected?

[David Wark] Well, when you mention Ray, you have to mention John Bahcall [who] was a theorist who was a postdoc at Caltech at the time and later became a long serving professor in Princeton, who did the very tedious calculations of... exactly how many neutrinos you would expect to come from the core of the sun. The actual detail of it is a bit complicated, because it's not a single nuclear reaction in the core of the sun. There are many different nuclear reactions and they produce neutrinos of different energies. So it's a very complicated calculation to know exactly how many neutrinos Ray should observe. And when he did these calculations, he consistently got numbers three [or] four times higher than what Ray saw. And as Frank says, at first, people simply suspected that Ray had done the experiment wrong. But Ray's ...nothing if not patient, and he eventually convinced pretty much everyone that it looked like he had done things properly. Then they just suspected that John had calculated things wrong. In particular, the Davis experiment sees very high energy solar neutrinos and the calculations are particularly difficult with those. So, at the time, people just assumed that John had got his calculation wrong...

[Frank Close] Just to cut in on Dave who is an experimentalist. To be fair, it was the theorists, like myself, who said, Ray Davis is doing his experiment wrong. And the experimentalists said, Bachall can't do the calculations. [laughter]

[Melvyn Bragg] Now then, Susan Cartwright, so there's more experiments being set up before we bring this part together - more experiments to count these solar neutrinos. What were they and what did they find?

[24:13]
[Susan Cartwright] Well, there were a number of different experiments. As Dave said, the problem with Ray's experiment was that it was only sensitive to neutrinos that were emitted by a small side branch of the sun's output. And those people who were convinced that John Bahcall had got his sums wrong were not claiming that he'd got the vast majority of the sun's energy production wrong. They were just saying that this small side branch, instead of being 1% of the sun's output, was maybe a quarter of a percent of the sun's output. So it was a small byproduct. So there were two issues that were addressed by the next generation of experiments. One was that this idea of producing a few atoms of radioactive argon, flushing them out of the tank and counting them, doesn't actually prove you're detecting neutrinos from the sun at all, because you have no direction sensitivity, and you don't even know exactly when those argon atoms were produced. So, if you were a real skeptic, you could claim that, in fact, Ray Davis had detected no solar neutrinos. He was detecting some form of background that we hadn't thought of. So what you want is something that can tell you where the neutrinos came from, and that something is called the Cherenkov effect. Now, I'm going to give you a nasty shock. Everybody knows that nothing can travel faster than light. It's not true! Nothing can travel faster than the speed of light in the vacuum of space. But when light travels through a transparent medium, like water or your glasses or my contact lenses, then it is slowed down. And that's how your glasses focus and correct your sight problems. [But] the particles are not slowed down [in a medium]. So light in water is traveling only about three quarters of the magic speed limit, whereas a particle traveling at 99% of that speed limit is still traveling at 99% of that speed limit in water, which is faster than the speed of light in water. And when an aircraft travels

faster than the speed of sound, you get a sonic boom. When a particle traveling in water travels faster than the speed of light in water, you get a "light boom" - you get a cone of blue light and that is called Cherenkov radiation, after Pavel Cherenkov. And you can detect that blue light and because it's a cone that goes forward at 40 degrees from the path of the particle, you can therefore find out where the particle was coming from and an experiment down a mine in Japan called Kamiokande, which was actually designed to look for the decay of the proton (but that's another program) was able to detect neutrinos from the sun when they reacted in its water tank and made electrons that travel faster than the speed of light in water. And for the first time, they were able to prove that the neutrinos that they detected were actually coming from the sun. They could take a photograph of the sun in neutrinos.

[Frank Close] A "neutrinograph" of the sun...

[Susan Cartwright] A neutrinograph of the sun... exactly!

[Melvyn Bragg] So we know where they're coming from. But, David Wark, we've been talking about neutrino as if it's one thing, but a development was that... there were three types of neutrinos... You call them three flavors. I can't understand why you call them three flavors, but that's up to you. Can you tell us about these three flavors?

[27:58]
[David Wark] Yeah, we've been talking about the electron, but in fact, we now know that the electron has two Heavier cousins, one we call the muon and one we call the tau. And these particles, the muon and the tau, are pretty much just like electrons, except they're more massive. They're heavy, and because they're heavy, they decay, because there are lighter things they can decay to. So the neutrinos emitted, say, by the reactors that have been detected are electron-type neutrinos. And the neutrinos emitted from the fusion reactions in the core of the sun are also electron-type neutrinos, or they should be. However, along with the muon and the tau "leptons", the things that are like electrons but are heavier, there are also more neutrinos. There's a neutrino that goes with a muon, which we call the muon neutrino, and a muon that goes with the tau, which we call the tau neutrino. And these extra neutrinos are not emitted by the sort of reactions that we've talked about up to now, but they can be observed via the weak interaction, because if a [mu-neutrino] interacts, it produces a muon, which you can see, and it has different properties from an electron, so you can tell them apart. And if a [tau-neutrino] interacts, produces a tau. So we have these three different flavors of neutrino, which makes the whole situation more complicated.

[Melvyn Bragg] So we're drawing to a particular conclusion of this episode, aren't we, Frank Close? There are now three flavors, and they're distinct. And where does that take us?

[Frank Close] Well, the processes in the sun are making just one type of these, the electron type of neutrino. And Ray Davis' experiment has been set up to detect the electron type of neutrino. And John Bahcall's calculation says he should have been finding more. And so there's a shortfall of electron-type neutrinos. Now, the irony is that the realization that there are more than one type of neutrino was around for 10-15 years before this was all sorted out. And Pontecorvo, again of all people, had come up with an idea that if there's more than one type of neutrino, it is possible that in the 150 million km journey from the sun to here, what started out as the electron type had sort-of changed its spots in a strange way and turned into a muon type or a tau type, or maybe it stayed the same. And by the time you got here, everything had sort-of evened out, so that only one third remained electron types and the other two thirds Davis was blind to. And that would explain why there was a shortfall. Now, the great irony of these things is that nobody took any notice of this, not least in part because he'd written this in Russian in a Russian journal and it wasn't translated for a couple of years and so on. But the real problem was that the laws of physics said "that could not happen", because everybody knew that neutrinos travel at the speed of light without any mass. And it turns out that Pontecorvo's idea won't work if neutrinos have no mass. We now know that neutrinos do have a mass, and that Pontecorvo's idea is right, and that in that 150 million kilometer journey, the neutrinos are changing from one type to another. It's called oscillating.

[Melvyn Bragg] Susan Cartwright, so we're on the way to solving the solar neutrino problem at this stage

[31:22]
[Susan Cartwright] At this stage, we are indeed. The original argument of the problem was either there is something wrong with the sun or with Bahcall's calculations, or there is something wrong with Davis's experiment, or there is something wrong with the assumptions about the neutrino. At this point, there is more than one experiment confirming the solar neutrino deficit. So we can absolve Davis's experiment of blame. And Bahcall's calculations have been checked by looking at the interior of the sun, as revealed by a science called helioseismology, basically "sunquakes". So the only thing that can be wrong is that there is something wrong with the [old theory of the] neutrino. And the framework of what are called neutrino oscillations, the changing of neutrinos from one type to another, could provide a solution. So what you need in order to solve the solar neutrino mystery is an experiment that can detect neutrinos from the sun, whatever flavour they come in and this is an experiment that took place in Canada, which Dave was part of. So I think he should take on this story from there.

[32:43]
[David Wark] Yeah, as Susan said, ...the difficulty is detecting the neutrinos that aren't electron neutrinos. The problem is these neutrinos coming from the sun don't have enough energy to make a mu or a tau. So you can't observe the sort of reactions we've been talking about up to now. They just don't happen. And so instead, you have to build a detector that can see a much subtler type of reaction, a much harder-to-observe type of reaction [the understanding of which] had come along in the meantime, something called a "neutral current". It's another type of weak interaction which nobody even knew existed when this story started. And so myself and 400 of my closest friends (actually, I joined after it was already well on the way, although I was then part of it for 20 years, which gives you some sort of feeling for how long these things take) built a detector called the Sudbury Neutrino Observatory. It consisted of 1000 tons of heavy water in an acrylic bubble 12 meters in diameter suspended inside a giant soccer ball, 17-meter soccer ball, on which were mounted 10,000 very sensitive light detectors, all of which was 2 km underground in a nickel mine in lovely Creighton, Ontario. And using this device, we could independently measure the type of reactions we still talked about at the start, which told us the number of electron neutrinos. And we could see another reaction which broke the deuteron up, and we could detect that.

And using that, we could count the total neutrino flux. And what we saw was that the total neutrino flux, the sum of the nu-mu's [muon neutrinos] and the nu-tau's [tauon neutrions] and the nu-e's [electron neutrinos] was exactly what John Bahcall had been saying it was all along.

[Melvyn Bragg] For how many years had he been in the doghouse for? ... I hope he was alive when ...

[David Wark] Yes

[Melvyn Bragg] Thank goodness for that!

[David Wark] Oh, there's a lovely story about that... In fact, one of the great pleasures of my scientific career was when we gave the first talks announcing these results. I had a slide and it simply said, John Bahcall was right all along. And when we finished the talk, I went back to my office and emailed it to John. And John later said in the New York Times, and then subsequently in an interview that was shown on the BBC in fact, that he felt like a criminal who had been convicted of a heinous crime he didn't commit and then 30 years later, DNA evidence is found that absolves him of all guilt. He said he felt like dancing. And if you knew, John, that was a hard thing to picture. But no, it was a tremendous feeling of satisfaction to have resolved this tremendous problem but [it] also opened up neutrino oscillations, this whole new phenomenon of nature for study.

[Melvyn Bragg] So, Frank Close, that study is the [neutrino] branch of astronomy, isn't it, really? And we have - what's... this neutrino telescope look like?

[35:52]
[Frank Close] Well, that's probably in its simplest form is the thing that Susan was telling us about, that when a neutrino hits in water by emitting this Cherenkov light, you can tell where the neutrino came from. So you can see its direction, you can measure its energy, and you can tell the time that it hits. So from that, you can work out, did it come from the sun or did it come from someplace else? So that's the basic idea. The most exciting thing, perhaps, really, to add to this story, though, is that in 1987, the only other astronomical object ever detected in neutrinos was seen, and that was a supernova. The only supernova that has happened in our lifetime took place in 1987. In fact, it didn't - it took place 170,000 years ago in the large Magellanic Cloud.... A supernova is a star that's collapsed. And the theory was that when it collapses, it produces neutrons and neutrinos. And the theory said that although a supernova shines brighter than an entire galaxy to your eyes and can even be visible in daylight ... 99% of the energies in neutrinos! I mean, that's vast! So 170,000 years ago, a star collapses in the large magellanic cloud, and neutrinos set out traveling across space at almost the speed of light. And I'm not sure quite what we were doing here in the BBC 170,000 years ago or what was going on anywhere, but these neutrons are flying across and 169,000 years of traveling later, we've got to the Norman conquest and... 169,950 years later, Pauli comes up with the idea that maybe there's things called "neutrinos" and still this wave of neutrinos from the supernova is traveling on. And after 169,998 years, totally by chance, the Japanese and some others have got this big tank of water deep underground, which is now a neutrino telescope, beginning to work. And at breakfast time, in English time, through my cornflakes, ... passed this little wave of

neutrinos from that supernova which also swept through the tanks there. And about a couple of dozen of these neutrinos bumped into atoms of water in the tanks and revealed themselves. And this is remarkable when you think about this, that the rate that these things detected neutrinos from the sun is like a few a day. And here you've detected a couple of dozen in a few seconds that have been traveling for 170,000 years. That alone gives you an idea of how much power took place in the supernova explosion.

[Melvyn Bragg] Well, throughout this program, I'm exhausted trying to make sense of these numbers, but you're ploughing on. No, you're going on, I'm sort-of ploughing on here. So what are we learning from this neutrino astronomy, Susan?

[38:42]
[Susan Cartwright] Well, from supernova 1987a, where there must have been at least 20 papers generated for every neutrino that Kamiokande and IMB saw. We learned that the energy does indeed go into neutrinos because in order to detect a couple of dozen from a supernova 170,000 light years away, you can calculate back as to how many must have been emitted by that supernova. And that turns out to be, within the experimental errors, precisely the number that you would expect to be emitted when a supernova explodes. So that detection, minor though it was, a couple of dozen neutrinos, already confirmed much of our theory about how massive star supernovae happen. The astronomical community is feeling very shortchanged on the supernova front. In the late 16th century, there were two naked-eye supernovae only 30 years apart, Tico Brahes in 1572 and Johannes Kepler's in 1604. And there hasn't been one that we saw in our galaxy since that time. So there were two 30 years apart, cunningly timed just before the invention of the telescope, and none in the 400 years of astronomical history since that time. So they're really hoping for another one. If we had a supernova go off anywhere in our galaxy (which is only about a quarter as far away, even at the far reaches, as the Large Magalanic cloud) with the neutrino detectors we have now, thousands of neutrinos will be detected.

[Melvyn Bragg] David Wark, what's the latest neutrino experiment going on again? We're in Japan, aren't we?

[40:33]
[David Wark] Yeah. We're building experiments all over the world now, and Susan and I are involved in one in Japan to try to probe this phenomenon of neutrino oscillations. It's potentially a hint to one of the biggest unsolved mysteries in fundamental physics, which is, where did the matter in the universe come from? We started with a big bang, which is essentially energy and radiation, and as that cools, it produces matter. But according to the known laws of physics, it should have produced almost identical quantities of matter and antimatter. But we don't live in a universe that looks like that. We live in a universe that has matter in it. So if the known laws of physics won't produce more matter than antimatter, there must be unknown laws of physics. And neutrino oscillations is a possible place where you could look for that. So what we're trying to do is build an experiment where we can measure these neutrino oscillations with incredible precision, and then compare the oscillations of neutrinos and anti-neutrinos and see if they're the same. And we suspect they won't be, but we'll have to see. So we've built an experiment in Japan called T2K. We make a beam of neutrinos on the east coast of Japan, a place called J-PARC, by using a big particle accelerator.

Then we fire that beam of neutrinos for 300 km underneath Japan to a huge detector ...near the west coast of Japan, which is Kamiokande's bigger offspring, which is called Super-Kamiokande -- 50,000 tons of water. And by firing these neutrinos under Japan, we look for a tiny branch of neutrino oscillations, which we think will open up the route to doing experiments to look for the difference in oscillation between matter and antimatter.

[Melvyn Bragg] Finally, Frank, for listeners, what is this going to lead to? Not necessarily in a utilitarian sense, but we've gone fast down the track since the 1930s.

[42:28]
[Frank Close] Well, one possibility is that we might discover why we live in a universe dominated by matter and not antimatter. Of course, the real excitement is "we don't know" that's the excitement of science - But that's also a bit of a flip answer. I think what we have already learned is, by using neutrinos, we have looked inside the sun, we have looked inside a supernova. And I think John Bahcall is the guy who really had the nice statement. He said, "the history of astronomy shows it's very likely that what you discover will not be what you were looking for".

[Melvyn Bragg] Thank you very much, Susan Cartwright, David Wark and Frank Close.
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