THE DEATH OF STARS - 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:

Martin Rees

Astronomer Royal, Fellow of Trinity College, Cambridge

Carolin Crawford

Emeritus Member of the Institute of Astronomy and Emeritus Fellow of Emmanuel College, University of Cambridge

And

Mark Sullivan

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Transcript:

[Melvyn Bragg] Hello. Across the universe, stars have been dying for billions of years. Some in enormous explosions, some expanding then deflating, and others quietly sputtering out. Those like our own star, the sun, become red giants, sprawling outwards only to collapse into white dwarfs. The massive stars, many times the mass of the sun, burst into supernovas visible in daytime. And every element in our bodies, every planet, was made in one of those stars, either as they burned or as they exploded. With me to discuss the death of stars are

Martin Reese, Astronomer Royal Fellow of Trinity College and Emeritus Professor of Cosmology and Astrophysics at the University of Cambridge,

Mark Sullivan, professor of Astrophysics at the University of Southampton, and

Carolin Crawford, Emeritus Member of the Institute of Astronomy and Emeritus Fellow of Emmanuel College, University of Cambridge.

[Melvyn Bragg] Carolin Crawford, what is a star?

[Carolin Crawford] Stars form from diffuse clouds of gas that are lying in interstellar space between stars. And they form because of gravity. You have all the hydrogen atoms within these clouds start falling together under their mutual self-gravitation. And so parts of the cloud collapse down under gravity to become denser. And as they become denser, they compress, they become hotter. You have a runaway gravitational collapse until a point that portions of those clouds reach temperatures in excess of 15 million degrees, very high densities. And at that point, you can initiate nuclear fusion. And this is a simple idea of what stars are. You need to sustain nuclear fusion to counteract the gravitational attraction. And when you have the two in balance, you have a star. Now, that's a very simplified version of what's going on. Nuclear fusion is when you combine nuclei of elements to form heavy elements. And when you do this, there's a loss of mass which is converted to energy, which provides a thermal pressure, and that is what counteracts the gravity and stalls the gravitational collapse. So, for example, our sun burns hydrogen, turning it to helium in a series of nuclear reactions, where you start off with four protons and you end up with a helium nucleus and some subatomic particles. It releases energy and that holds the star in place. So it exists as a star as long as you have this balance - this quite fragile balance between gravity and thermal pressure at the core. The nuclear fusion doesn't happen throughout the whole star. It can only happen when it's very hot, and that is very dense.

First of all, it needs to be dense so that you have a higher probability of collisions occurring and the reactions taking place. And they need to be hot so all the particles have enough energy to smash into each other. So, like the protons overcome their natural electrical repulsion and still combine. So you only have nuclear fusion going on in the core. So essentially, a star's life - it can exist as a star for as long as it has enough fuel at the right temperature, the right density and the core of the star to stall the gravitational collapse. And it's when it runs out of its fuel at the core, that's when you reach the end of its lifetime and we start going through the death processes.

[Melvyn Bragg] Can I go back to what you said at the very beginning? It came out of clouds. Can you say a bit more about that? Is this what's drifting around in the universe before there's anything there?

[Carolin Crawford] Well, this is even in our current galaxy between stars, it's not truly a vacuum. There's very diffuse clouds of cold hydrogen atoms and molecules. And a lot of this collapsed early on into stars - so when galaxies were young - but there's still star formation going on from these diffuse, interstellar clouds.

[Melvyn Bragg] Why is the mass of a star so important?

[Carolin Crawford] The mass of the star is important because if you have more mass, you've got more gravitational attraction, and so the core of the star gets squeezed more. If you squeeze matter, it heats up and it becomes denser. This means that more massive stars can initiate a more complicated series of nuclear reactions and they can go on and build quite heavy elements at their cores through their lifetimes. And secondly, they have to produce more energy to overcome that greater gravity. And so even though they're more massive to begin with, they actually have shorter lifetimes. It's counterintuitive. But they have to chomp through their fuel supply so furiously that they exhaust it more rapidly. So the mass of the star dictates what happens in the core, what you create in the core, and it also determines the lifetime of the star. So if a star like our sun - we reckon it's about 5 billion (so that's 5000 million years old) - it's depleted about half of its fuel in the core. So we reckon it's about halfway through its lifetime. So stars like the sun have lifetimes of 10 billion years or so. More massive stars, when you get to 10, 20, 30 times the mass of our sun, they have - this is an astronomer speaking when I say - a "short" lifetime. I mean it's only tens or hundreds of millions of years but a lot less than our sun.

[Melvyn Bragg] Martin Rees, this has been alluded to but how will the sun come to an end?

[Martin Rees] Well, as Carolin said, it will run out of hydrogen fuel in its center and it will then go on contracting in its core. But for slightly complicated reasons, that blows off the outer layers. So what will happen is that it'll blow off its outer layers and become a red giant, expanding so it would engulf the inner planets. But then the core will settle down to what's called a white dwarf. This is a dead, dense star, about a million times denser than ordinary stuff, and many white dwarfs we see in our galaxy which are the remnants of stars rather like the sun. And I should mention that, to add to what Carolin said, we can test our theories, not only because we understand the physics, but because we can look at lots of stars. It's rather like if you had never seen a tree before and you wandered around in a forest for a day, you could infer the life cycle of trees, you see saplings and big trees, etc. And so even though our lifetime is minuscule compared to the lifetime of a stable star, we can infer the population and life cycles of stars observationally and the theory does corroborate that fairly well.

[Melvyn Bragg] I was going to ask that. So you really do know half its life has been spent - the sun?

[Martin Rees] We do. And of course, to digress a bit, if you go back to the 19th century, there was a big puzzle about how stars lasted so long, because Darwin and the geologists already realized that the Earth had been around for at least tens of millions of years. And at that time it was unclear what the source of power was to keep stars shining for even that length. It was a big paradox. And a famous scientist, Lord Kelvin, made a big deal about this and he said it needs some completely unknown source of energy. And it wasn't until the 20th century that nuclear energy was discovered, and that indeed is more than enough - fusing hydogen to helium - to make the sun go on shining for 10 billion years or so. So that solved what was a problem recognized in the 19th century.

[Melvyn Bragg] Is the sun recycled from previous dead stars?

[Martin Rees] Yes, it is, because we believe that the pristine material in the universe was mainly just hydrogen and helium, and all the atmosphere we are made of were not there soon after the Big Bang. They were all made in stars which lived and died before our solar system formed. And this leads to the problem of trying to understand more massive stars which have more complicated lives and give rise to supernovae - which Mark is an expert on. Because these stars, which are heavier than the sun (say ten times as heavy) - they will, as Carolin said, they'll go on contracting when they run out of hydrogen fuel and they get hot enough to turn helium into carbon then carbon into oxygen, and then, eventually, [turn] things into iron and other elements. And so when those big stars face a crisis, they blow off the outer layers which already contain all this mix. And the cloud from which our solar system formed was already contaminated by the debris from earlier generations of massive stars which had lived and died more than say, 5 billion years ago. So we're literally the ashes of those long dead stars, or if we're less romantic, where the nuclear waste from the fuel that kept those old stars shining.

[Melvyn Bragg] And that certainly brings you down to Earth, Martin. So we four around here are inheritors of nuclear waste?

[Martin Rees] Indeed, yes.

[Melvyn Bragg] We are here because of nuclear waste. Well, that's a thought. Mark, Martin mentioned white dwarves. Can you tell us what the Chandrasekhar limit is and how that applies to white dwarves?

[Mark Sullivan] So, the Chandrasekhar limit is the maximum mass that a white dwarf star can have. As has been described already, white dwarf stars are extraordinary objects because they're incredibly dense. So you've taken something of the mass of the sun, say, and compressed it down to something of the volume of the Earth. But nonetheless, all stars have the problem of supporting themselves against gravitational collapse, whether that's a star like our sun, which is burning hydrogen into helium and thus providing lots of thermal pressure to stop collapse, or whether it's a white dwarf star - but it doesn't have any hydrogen to burn because it's an old, dead star fading away. So it has another method to stop itself collapsing, and that is called degeneracy pressure. So, although a white dwarf is very dense, gravity is still trying to pull that white dwarf to be even denser and even denser. And when you get to the densities of a white dwarf, there's a fundamental limit as to how close together you can pack electrons, which are subatomic particles. Now, those electrons can't be in the same place with the same energy in quantum physics. And so as you try to compress them together, that creates an outward pressure that stops the star from collapsing any further. That's called electron degeneracy pressure, and it gives a maximum mass that a white dwarf can have, because when it reaches that Chandrasekhar mass, even that electron degeneracy pressure is no longer sufficient to support the staff from collapse.

[Melvyn Bragg] So we're back to what we said at the beginning by Carolin. There's got to be this balance.

[Mark Sullivan] Yes, exactly. Exactly the same. I mean, in the white dwarf stars, it's a different physical effect than in stars like the sun.

[Melvyn Bragg] What happens to these white dwarves when they explode?

[Mark Sullivan] Yes, so the Chandrasekhar mass sets an upper mass limit to a white dwarf, and if a white dwarf somehow exceeded that mass, that Chandrasekhar mass, it will collapse into a neutron star. Now, this doesn't happen spontaneously to stars, because stars can't magically grow in mass, and a star like our sun will never grow in mass because it lives by itself in space. But most stars in the universe don't live by themselves. They live in what are called binary systems, where you have two stars orbiting each other rather than just a single star like we have as the sun. They're probably born with different masses, and so they evolve at different speeds, and one will become a white dwarf. Now, the physics is a bit complicated, but what can happen is that that white dwarf can steal material from its companion star and so mass gets transferred from the star that might be like our sun onto the surface of the white dwarf. And that can cause the white dwarf to grow in mass. Now, it never quite reaches the Chandrasekhar mass because what happens is as the white dwarf's mass grows larger and larger... The white dwarf is made of carbon; it's made of oxygen; and the temperature and the pressure in the center of that white dwarf star can become so extreme that carbon detonation can occur in the center of the white dwarf. And that is a runaway, thermonuclear reaction that carbon "burns", in astronomer's speak - into more massive elements and in one or 2 seconds, the entirety of the white dwarf star can be disrupted. So you're thinking of something the size of the Earth, the mass of the sun, instantaneously or near instantaneously exploding. And so that's an extremely violent cosmic event. But even something even more remarkable, is that we probably might not know about those types of explosions were it not for the fact that during all that carbon burning in the white dwarf star, luckily for us to observe them, it makes something called nickel 56. Nickel 56 is what's called an iron peak element. So it lives with iron and cobalt on the periodic table and it's radioactive. And so in one of these, thermonuclear explosions, you make vast quantities of this nickel 56. It's radioactive. And over the course of a few weeks, it decays. It gives off gamma rays (which are just electromagnetic radiation) gives off positrons (which are anti-electrons) and they get absorbed in the now rapidly-expanding remnants of the star and they heat the remnants of the star up to be very, very hot - tens of thousands of [degrees] Kelvin - and they make it glow very bright. And that is what we see in a supernova explosion. We see the radioactive aftermath of a white dwarf blowing up. We never see the explosion itself - that lasts about an hour in visible light - but the aftermath we see is the radioactive material decaying.

[14:04]

[Melvyn Bragg] Carolin, can we now look at these massive stars? What tips them towards the end of their lives?

[Carolin Crawford] Massive stars. And here I'm talking...

[Melvyn Bragg] Can you tell the listeners? I mean, these numbers and these things are beyond most of us, frankly. What are you talking about when you say massive star?

[Carolin Crawford] By "massive star" I'm saying something that is say, ten times the mass of our sun, up to about 50 solar masses. That's the kind of mass range I'm talking about. And these will start the same way as stars like the sun and they will burn hydrogen to helium, and helium then goes on to carbon and oxygen. Now, at that point, a solar mass star stops, it becomes an inert white dwarf. But because of the greater weight of the outer layers, a very massive star will keep compressing the core and it can initiate another sequence of reactions. So you have a series of cycles in the core of the star. You deplete one fuel for one set of nuclear reactions. Gravity temporarily wins [and] compresses the core, heats it up, makes it more dense, and suddenly a new set of nuclear reactions are initiated using the products from the previous fusion reactions. And you have these cycles until at the last moment you're burning silicon to iron. And after that iron marks the end point. You can't extract energy from any nuclear fusion reactions with iron because it's the most tightly bound nucleus. The other thing that's interesting is that the star would take a long time to burn hydrogen to helium and helium and so on, but with each set of reactions you're getting less energy out and so it goes through that fuel supply faster. It will burn all the silicon to the core of iron in one of these massive stars in the space of a few days. So at the end it's very rapid and you end up with this iron core. Now, this is where it gets interesting. You can't have any more nuclear reactions, you've still got the gravitational squeezing of that core and it gets squeezed down to phenomenally high densities of over a trillion kilograms per cubic meter, and also temperatures of the order of 10 billion degrees. And it's still an iron core, it gets so hot, is radiating really energetic gamma rays. And the amazing thing is that these energetic photons will then completely undo all those hundreds of millions of years of nuclear fusion by a process called photo disintegration, which literally means the photons disintegrate the iron and other nuclei into their constituent electrons and protons. And all of this happens in a matter of seconds. So by now you've got the core of the star. So originally that iron core would have been about the size of the Earth; it would have had many more masses, solar masses, squeezed into a volume the size of the Earth, about 12,000 km across. And under this pressure it gets compressed down to about ten or 20 km across in a matter of seconds. So this is phenomenally fast shrinkage and you get squeezed down until all those electrons and protons that were created from breaking apart the iron nuclei combine to form neutrons. And like Mark has described with electrons not wanting to be squeezed, you have neutron degeneracy pressure. Neutrons [also] don't like to be compressed. At some point they resist it. And at the point that you've got a ball of almost entirely neutrons, it resists the gravitational squeezing. It's another kind of pressure, but you've got that equilibrium again and you have what's known as a neutron star. So a very different end from a solar-sized star.

[Melvyn Bragg] Martin, is this the way we go to get black holes?

[Martin Rees] Yes, because neutron stars can't exist above a certain mass, just as Mark said that white dwarfs can't be above the so-called Chandrasekhar mass, there's a maximum mass for a neutron star which isn't quite so well known. It's about twice the mass of the sun. So if a neutron star gets above that mass, then it'll compress even further and will become a black hole. It will go on contracting and so, as it were, cut itself off from the rest of the universe, leaving a gravitational imprint frozen in a space is left. It becomes a black hole that things can fall into but not come out.

[Melvyn Bragg] The black hole is a fascinating phrase. We use it for all sorts of things. Can you say a bit more about that?

[Martin Rees] Let me start with neutron stars again, because neutron stars are extraordinary extreme physics. They fascinate physicists because they allow us to study material on the conditions we could never simulate in the lab. And we've learned a lot about physics from them. And we have very good observations of neutron stars because they emit X-rays and gamma rays and more remarkably, they spin round. And because they're so small, they can spin round at as much as a thousand revs per second without flying apart. And what are called pulsars are objects where you see one pulse per orbit. And ever since the late 1960s, when these were discovered, these have been a way in which we can study spinning neutron stars and how they slow down and all that. So they're amazing physics. But a neutron star can't exist above a certain mass. And if you're on the surface of a neutron star and tried to fire rocket, you'd have to fire it about half the speed of light if it was to escape. But black holes are more extreme still because they are objects where the contraction has gone even further and where, as it were, the escape speed has become the speed of light itself, so not even light can escape. And black holes are the endpoint of the most massive stars. And again, they don't emit any light. But again, we can detect them if they are in a binary pair with an ordinary star, as Mark mentioned. And they can then grab some fuel from the companion and as it swirls in to the black hole, this material gets very, very hot and emits powerful radiation. And these are indicators of black holes which are the endpoints of the biggest stars.

[Melvyn Bragg] To secular persons like myself, I'm already dizzy. I'm dizzy with admiration now and just about following. I'm holding on to the table with the tips of my fingernails. Mark, you take a particular interest in supernovas. What would you like to add to what's been said?

[Mark Sullivan] Martin gave an excellent description of neutron stars. There's one other very well, exciting development, I think, in the study of neutron stars and their fate. If you have a binary system, which again is two stars together in space orbiting each other. If they're both neutron stars then something very interesting can happen. Those neutron stars will be orbiting each other and as they do so, because they're very massive and because they're moving very quickly they radiate gravitational wave radiation. Gravitational wave radiation is undulations in the spacetime continuum. So it's not photons that we use for electromagnetic radiation. It's a completely new way of studying objects. And these rotating neutron stars give off a lot of this gravitational wave radiation. As the neutron stars orbit each other the orbit loses energy because the gravitational wave radiation has taken energy away from the system. And the neutron stars get closer and closer and closer together and eventually they merge with each other. Now, that can form a more massive neutron star. That could form a black hole. It depends on the masses of the objects involved. But the other thing it does is when neutron stars touch each other there's a very energetic event and you can get of some very interesting nuclear synthesis which is the formation of more massive elements. And in particular, we think these combining neutron stars are the main sites where heavy elements like strontium or plutonium perhaps even gold or silver these kinds of elements are made in the universe in these neutron stars combining with each other. Now, the interesting thing is that the actual optical emission (in other words if we look with our eyes at the sky of these events) is really faint. There's none of this lovely nickel 56 which is made in the thermonuclear supernovae and which gives us a clue as to where the objects are. They're actually really faint on the sky. And so the best way to find them is using gravitational waves that are very sensitive detectors on the Earth that can sense these very weak gravitational wave passing through the Earth.

[Melvyn Bragg] What happens, Carolin, to all the matter thrown out into the universe by the supernovas? How do they change the galaxy?

[Carolin Crawford] Supernovae particularly are fundamental importance for the host galaxy. First of all, you are blasting a shockwave out through the local medium and we've talked about what happens as the core of the star collapses down to a neutron star or a black hole. What happens to the outer layers of the star is something a bit different because the core collapses down… You know, you've got your iron core [that] collapses down [due to] gravity in less than a second. That kind of leaves the outer layers of the star a little bit behind. They crash down, bounce on the surface of the core and then there's a shock wave that propels all the stellar debris out into space. So this is part of the supernova explosion we've been talking about and it carves out a bubble within the interstellar medium and so you have the shockwaves of the stellar debris. Also the kind of heavy elements that are created within the explosion that Mark was alluding to. And these sweep up the interstellar medium in front of them, and they get thoroughly mixed in. So, again, this is the idea of enrichment. You start off with much more primordial hydrogen and helium gas that gets steadily peppered with all these heavy elements, and there's chemical evolution within the galaxy due to these supernovae. I mean, not everything is recycled in this way. We've told you how much of it is locked into the black holes and the white dwarfs and neutron stars, but a good fraction of the material of those massive stars gets mixed in with the local interstellar medium.

[Melvyn Bragg] And then what?

[Carolin Crawford] Well, and then you may be able to get new star formation being triggered because shock waves will compress the gas clouds. And as we started talking about if you have slightly denser regions of a gas cloud… And we could have a gas cloud that's been sitting out in space for billions of years and hasn't bothered to contract because it's been too hot or is too sparse. If you squeeze that. You make it denser. It's more liable to gravitational collapse and you trigger a next wave of star formation but using gas that has been enriched with all these elements from the cores of stars in the supernova. So we see this: Supernova don't happen in isolated places. We see clusters of young, massive stars, some of which have gone supernova and have triggered new stars forming deep within the clouds surrounding them. So we observe subsequent generations of stars happening within a galaxy.

[Melvyn Bragg] Martin, how is this life cycle linked to the formation of new planets?

[25:55]

[Martin Rees] Well, we've got to go back to when stars form. They form, as Carolin said, from a contracting cloud. And if a contracting cloud has even a tiny little bit of spin, if it's rotating a bit, then as it contracts, then just like the ballerina who pulls in her arms and spins faster, then the contracting cloud will start to spin faster. And what will happen is that it won't all be able to get down to the size of a star. So, when a star forms, because there was this initial spin, or so called angular momentum, in the cloud, the young star is surrounded by a disc, a spinning disk, of dusty gas which carries away most of the spin energy that was in the star. So it'll look like, in a sense, rather like a picture of Saturn, where it's got an object in the center and stuff spinning around it. And that material, the dusty disk, eventually agglomerates - the bits of dust build up to make rocks - and some of this then makes planets. And so we believe that planets form around stars from the disk around the pro-planets which couldn't fall in because they were spinning too fast. And so if this theory is correct, it makes it easy to understand why most stars seem to have planets orbiting them. I mean, it used to be thought that our solar system was very special, to have the Earth and the other familiar planets orbiting the sun. But one of the most exciting advances in astronomy in the last 25 years, especially the last decade, has been realizing that most of the stars you see in the sky are orbited by retinues of planets, just as the sun is orbited by the familiar planets. And this makes the night sky very interesting, because we have to ask, in the planets like the Earth going to be life on them, etc. But it's not surprising that these planets should exist if we accept that the stars formed from a diffuse, big cloud, which contracted and spun up as it contracted and left behind some material which then turned into the planets.

[Melvyn Bragg] Mark, can I pull back to what we were talking about a little earlier? Can we see these stars in the process of dying, these supernovas? What happens when they die?

[Mark Sullivan] So when they die, the most obvious thing to us on Earth is quite a dramatic optical display in the sky, and this would appear as a new star in the sky. Now, if this supernova were in our galaxy, so quite close to us, we would be able to see it. Well, obviously, we'll be able to see it at night, but if it were bright enough, we'd be able to see it during the daytime as well. So it would appear like a new star in the sky. And of course, we understand what these supernovae are, but you could imagine that our ancestors would have had no idea at all what these objects were - these new stars appear in the sky. And I imagine would have had quite a profound effect on them, given how they would have used the night sky to navigate, and they would have been very familiar with it. There are other ways as well of detecting supernovae. Another interesting way is to use the neutrinos that core collapse supernovae generates. Now, Carolin described the collapse of a massive star when the core gets to iron and can't undergo any more nuclear fusion. And when it collapses, part of the process when the neutrons are formed is to generate a very large number of neutrinos. Neutrinos are very weakly interacting particles. That means they don't stop when they go through matter. Only very small number of them do. Now, remarkably, you can detect neutrinos if you have a very big underground mine, and you fill it with water, and you look for the very rare interactions as the neutrinos interact with the water. There aren't a lot of them, but you can do it. And in 1987, there was a nearby supernova, well, nearby cosmologically speaking, and that generated a vast number of neutrinos, of which a very small number, maybe 10-15, were detected in this neutrino detector. Now, the thing is, these neutrinos are the first signature of the collapse of the iron core. So a long time before any of the light comes out. Well, compared to that many hours or days until the light gets out from the supernova explosion. So the neutrinos act as an early warning system that there's been a core-collapse supernova. And so these days there are all sorts of astronomers around the world who plug into the alerts from these neutrino detectors. And if there is one, they will tell us that our core-collapse supernova is coming and that we should go and look for it.

[28:17]

[Melvyn Bragg] Carolin, what records are held of the first observation of a supernova?

[Carolin Crawford] The supernovae that will have been observed in historical times will, as Mark suggested, had to have been visible with the naked eye in order that they were recorded. And they were recorded because they were of note. This was something that was unexpected in the unchanging heavens. We reckon there is on average about one supernova per century per galaxy. But for all that, there are only perhaps about eight recorded observations of supernova over the years. I mean, the first recorded observation, reliable recorded observation, of a supernova dates from 1006 CE, which is recorded as being 16 times brighter than the planet Venus. So this is one of the ones that Mark is talking about. It was visible during the daytime for about three weeks and would then fade in brightness and still be observable at night. And then 50 years later, you have a recurrence of what's called a "guest" star, which was observed by Chinese and Japanese and Korean and Islamic astronomers. And what is particularly interesting about that one, again, it was visible in the daytime and then faded away to be visible at the night time for a few years. But it's only later that that was identified with a nebula. So about the 1730s, that was the first association of a nebula. So in other words, a supernova remnant - exploded out debris from the star. And we call that the Crab Nebula. It's a very classic case of one of these supernova remnants. There were a couple more that were of note in 1572 and 1602, which were observed by Tycho Brahe and Johannes Kepler, but after that, ever since we've had telescopes, I will say we've been a bit shortchanged in the spectacular outbursts. I mean, astronomers would love one of these to go. We could study them with our modern instrumentation. I think 1987-A has been the best studied supernova, and that's the only one that's been visible with the naked eye since we've had our powerful instrumentation and telescopes.

[Melvyn Bragg] Mark, what are standard candles?

[Mark Sullivan] A standard candle is an object that is of great importance to astronomers because it lets us measure how far away objects are. So measuring distances in astronomy is really difficult. There's no ruler that we can just get out and measure the distance to a nearby object or a nearby star. In our solar system, we can use radar, perhaps, to determine how far away planets are. For very nearby stars, we have techniques like parallax, which is where we can observe the apparent motion of stars on the skies. We rotate around the sun on Earth, and from that, we can do a bit of trigonometry to figure out how far away these [nearby] stars are. But otherwise, distance measurement is very difficult. Now, standard candles are very important because they are objects of known intrinsic brightness. If I can measure on Earth how bright a standard candle appears to me sitting on the Earth, then using the inverse squared law all the light from the standard candle is emitted over the surface of a sphere. As the photons move away from the standard candle, then I can work out how far away it is [from its apparent brightness]. And that is an incredibly useful property in astronomy. Now, there are many types of standard candles, but the type that I study are these thermonuclear supernovae, these explosions of white dwarf stars. Now, the white dwarf star is the object that has this Chandrasekhar mass limit, which tells us the white dwarf cannot be more massive than the Chandrasekhar mass. And when it blows up, it makes all of this nickel 56. But because we know how much mass there was in the beginning, that means pretty much the same amount of nickel 56 is made each time. And that means these thermonuclear supernovae are pretty much the same brightness every time. And they're incredibly bright. They outshine entire galaxies, and you can see them billions and billions of light years away. And that means they're an exceptional measure of distance in the universe. So there were pioneering studies in the 1990s trying to find all of these distant some of these distant supernovae and to map out the large scale geometry of the universe. And when they did that, they had a very, very surprising result. And what they discovered was that the universe was expanding, but it was doing so at an ever faster rate. And that was totally unexpected. And it's almost as if there were some, and I use the term kind of crudely and loosely, some antigravity effects pushing the universe apart. And so these days, that mysterious substance is labeled dark energy, and we don't know what it is, and it makes 70% of the universe, and you can use as many techniques to study it. But these thermonuclear supernovae, are a particular direct way of studying this dark energy that permeates our universe.

[33:14]

[Melvyn Bragg] Martin, when all the stars die - this is about stars dying - what will things look like?

[Martin Rees] Well, to follow up with what Mark said, we do think that the universe, the most likely long range forecast is it'll go and expand forever, getting ever colder, ever emptier. And that's because the observations of these distant supernovae tell us about the speed of different distances and therefore, at different times in the past, because the further away we look, the further back we look in the past and that's the evidence that the expansion is speeding up, not slowing down. And so if we were to come back in, say, 100 billion years, that's ten times longer than the present age of the universe more or less, we would find that most stars would have died out. There would be lots of white dwarfs - the remnants of stars like the sun. There will be lots of neutron stars and black holes. There will be some very faint stars because the very small stars weighing about a 10th as much as the sun, called M-dwarf stars; they burn their fuel so slowly they'd still be around. There'll be a few dim stars there and there'd be occasional flashes caused by things like neutron stars merging, etc. But the universe will get sort-of ever colder and ever emptier and, in fact, all that would be left within view would be the remnants of our galaxy and the Andromeda galaxy, the nearest big neighbor, and a few smaller galaxies around them. All the more distant universe which astronomers like Mark studied, galaxies far away; they would all have expanded their distance from us and, in effect, disappeared over a sort of horizon and so we just wouldn't see them at all. They'd be too faint, rather like an inside-out black hole as it were. But in this case, they will have moved so far away that we can't see them anymore. And so the long range forecast is a very cold and very empty universe.

[Melvyn Bragg] Carolin, would you like to come in here?

[Carolin Crawford] I would just like to return just for a minute to something Martin was telling us about how planets are formed around proto-stars within these clouds that perhaps were triggered by star formation for supernovae. It's worth actually mentioning the very first planets found around another star were found around a neutron star; were found around a pulsar. And if you stop and think about this, this is incredible. This means that it had to be maybe a pre-existing planetary system around that star that survived this colossal supernova explosion that created the neutron star. And that is quite intriguing. This is fairly small, rocky planets two or three times the mass of the Earth and quite tight orbits around their star. And you can speculate that maybe they were once giant planets like Jupiter that had the outer gassy layers blasted off and you're left with the rocky core. Or maybe those planets were stolen from another star that got too close; maybe they didn't originate with a neutron star. Or maybe they formed after the supernova explosion from some of the leftover material and perhaps if the supernova was caused by accretion from matter from another star. So we have yet to work out really where these exoplanets came from and how they can exist around pulsars.

[Melvyn Bragg] Mark we are towards the end now. What would you most like to know about death of stars that you don't know at the moment?

[Mark Sullivan] I'm very excited about a new big telescope observatory that's being built that will help uncover some of the answers to some of the biggest mysteries in supernova explosions. I think it's worth just stepping back a little and making the point that a lot of science is international, particularly in astronomy. We depend on international collaborations to do cutting edge science. Most of our observatories as scientists, are located, well, in very nice places to go and visit and observe in, the top of dormant volcanoes in the middle of the Pacific or mountain rages in Chile. And in Chile at the moment, there's a new telescope under construction. It's called the Vera Rubin Observatory, and it's named after a famous astronomer who found the first good evidence for dark matter by examining the rotation curves of galaxies, how galaxies rotate. Now that the observatory is going to run a big all-sky survey, all sky that's visible from Chile anyway, called the Legacy Survey of Space and Time. And it is going to observe the night sky for ten years and it will do the entire sky every three days. And what that will give us is millions and millions of supernova explosions, none of them in our galaxy, I'm sure, all in other galaxies, all very distant. I think that will unlock many of the mysteries around dark energy that I talked about, helping us constrain various different models of dark energy. I think it will help us understand how supernovae explode. And I think most exciting of all, it will probably uncover completely new ways to blow stars up.

[Melvyn Bragg] Martin?

[Martin Rees] Well, I agree with Mark, but there's another big telescope being built in Chile, which is the European Extremely Large Telescope. They're not very imaginative in the nomenclature, but this is a telescope being built on the ground which has a mirror 39 meters across, not one big sheet of glass, but a mosaic of 800 bits of glass. And this will also be able to observe very distant objects - they can collect lots of light - and this would include looking at galaxies just forming, but also perhaps being able to detect some of the planets orbiting other stars. And we ought to mention, of course, also in space, the James Webb telescope, which was launched about Christmas time last year and is going to start observations. And that's got a six and a half meter diameter mirror. But in space it has an advantage, and that's going to be looking in the infrared at very very istant galaxies where the light, owing to the red shift, is shifted to infrared. So that's going to tell us again about what the galaxies were like when they were very young, which would gather lots and lots of data, which would clarify all the things that are still mysterious. And that's the way science goes, of course, you settle some problems, but they bring in to focus a new set of mysteries.

[Melvyn Bragg] Well, thank you all very much, Martin Rees, Carolin Crawford and Mark Sullivan and to our studio engineer Duncan Hannan.

And the In Our Time podcast gets some extra time now with a few minutes of bonus material from Melvin and his guests.

[Melvyn Bragg] That was terrific. Now then, I think the best way we kick it off is by saying, what did you not say you'd like to have said? Starting with you, Carolin.

[Carolin Crawford] We've talked about seeing the deaths of stars from their supernova, very massive stars, core collapsing, producing supernova, and these wonderful new generation of telescopes with automatic data processing that will pick up these changes. One challenge would be, is whether there are stars that reach the end point of their lives and collapse down without producing a supernova, and how we might find those without the supernova explosion. Now, theoretically it's possible, but the only way you'd find them is by actually seeing stars disappear. So rather than stars brighten and appear, you might be looking for stars that disappear from galaxies. And possibly that's something else that might come out that it's difficult to quantify because we don't know how common that is or whether it even occurs. But it's a possibility that is one of these new results that might come up from the studies that Mark is talking about.

[Mark Sullivan] Yeah, I agree with that. That would be very exciting.

[Melvyn Bragg] Martin, who would you credit most for the major advances in what you've been talking about?

[43:32]

[Martin Rees] Well, I think it depends on how far back we go. I think the first people who realized that stars made the same stuff as the Earth were those in the second half of 19th century who took spectra and showed that there were particular colors that were prominent in the light of stars, showing that they were made of the same stuff as the Earth. And that led to the idea that we could do physics on the stars. And that was a whole lot of people. But I think the idea that the elements, that we are made of, were all synthesized in stars; the key person was Fred Hoyle, who wrote a paper in 1946 with this idea. And then there was a big paper about ten years later, in the late 1950s, written by Fred Hoyle, along with three other people, Geoffry and Margaret Burbidge, a famous astronomical couple, and Willie Fowler who was a nuclear scientist in California. And they wrote this very long paper codifying all the nuclear processes which would occur at different stages in the heavy stars, which Carolin mentioned, which have this sort of onion-skin structure with the hotter inner layers processed up to the Arctic table. And this classic paper written by these four people, it's often called BBFH, after the four authors. This really set the scene, and it's been obviously refined by work in the last 50 or 60 years. And I think they deserve the credit for this remarkable discovery that we are literally made of the ashes of long dead stars. And there have been some puzzles because you want to understand the ratio. While some are common, some are rare, and as Mark mentioned, one of the issues was where gold came from. And it seems that gold comes in a rather exotic way from these neutron stars in a special phenomenon. But I would say that Fred Hoyle and his collaborators really had the basic idea. But of course, testing it has been a collective enterprise and we now have much better theories and we could do computer calculations and all the rest of it.

[Melvyn Bragg] Is it accidental that there are some massive stars and some very small stars?

[Carolin Crawford] It's to do a lot with the conditions - the initial cloud collapse and how the cloud fragments and how much mass is available. So there are stars of all kinds of masses, from ones that are sub-solar, right up to about 50 solar masses are quite common, and there may even be stars that are greater mass than that. But usually between about 0.8 solar masses up to say 50 solar masses is the range we have the stars.

[Melvyn Bragg] So, what you're saying suggests that planets will ceaselessly, be reformed, reinvented.

[Martin Rees] Well, new stars will form new planets and so if we look around a star that's younger, it may still have planets around it. But of course we can then say two things. We can say firstly that if planets form around a big massive star, there'll be not much chance of life evolving; there'll be enough time before the star ran out fuel and exploded. So we would expect that the planets which are most likely to be habitable are those around stars which are like the sun in the sense that they have a lifetime of billions of years giving as much time as we had here on Earth to evolve from a simple life to the biosphere of which we are a part. But of course this is another subject. But it's one of the most fascinating subjects in astronomy, of course, to ask whether these planets which are habitable, in the sense that they contain all the basic ingredients of life, are actually inhabited by any kind of life. We just don't know because I like to say that biology is a much harder subject than physics and although we can understand the physics of exotic things like neutron stars and gravitational waves and all that, we don't understand how life began. So we don't understand how we got from complex chemistry of a kind that we do observe in interstellar flows to the first replicating metabolizing things we call alive. That's one of the big mysteries for the 21st century astronomers to solve.

[Melvyn Bragg] You want to say something more..?

[Martin Rees] Well, I think if there was more time I'd like to have said a bit more about the history really, because astronomy is, I like to say, the oldest science except for medicine and the first that did more good than harm. So it goes back a long time. But it wasn't until about 200 or 250 years ago that people realized that the stars spangled across the vault of heaven were really other suns. They didn't realize how far they were away until they had parallax evidence. And then they realized that if they were that far away they had to be as bright as the sun. And so they then realized that the stars were other suns. But it wasn't until 1850 that they realized that they were made of the same stuff as we have on the Earth. I didn't mention that in the program. And that was by taking spectra of the light from the prism and picking out the characteristic light like yellow from sodium and things like that and realizing that the sun and the other stars contain these elements. So I think that was important. But it was really nuclear physics which had to come along to understand the star's long lifetime. And then, of course, Einstein's theory had to come along in order for us to understand the death of stars except for the ones that settle down quietly as white dwarves.

[Mark Sullivan] Well, one other thing that we haven't talked about which I find quite interesting is what would happen if there were a supernova nearby to the Earth as has almost certainly happened during the Earth's history. And so if there were a supernova within, say, 20 or 30 light years of the Earth I'm afraid to say it would have a rather catastrophic effect on the Earth. So if there are supernova; now we have nothing to fear from the light from the supernova and we have nothing to fear from what we call the ejecta of the supernova which is all the material thrown off. But in the supernova explosion you can get particles accelerated to very high velocities or very high energy. These are called cosmic rays. And when they hit the Earth they would interact with the ozone layer in our atmosphere and they would strip the ozone layer from the atmosphere of the Earth and that would allow the UV radiation, the ultraviolet radiation from our sun, to penetrate the atmosphere and have a very harmful effect on life on Earth. And in fact, although it's not my field, I understand that this nearby effect of a nearby supernova is possibly one of the triggers for mass extinction events that we see in the geological record of the Earth. And there's some really interesting work going on which is trying to correlate these periods of mass extinction with the deposit of particularly long-lived radioactive isotopes in the Earth's crust and to see if there's any correlation because what we would expect is the cosmic rays will come first and remove the ozone. And the effect of the ultraviolet light would be to, you know, distort the DNA and eventually kill things on Earth. And then the ejecta of the supernova would follow and deposit radioactive isotopes. And if you could match the two together, then you could probably find evidence that there had been nearby supernova explosions which have been responsible for some extinction events on Earth.

[Martin Rees] Just a footnote to that. The energy in the form of ordinary photons, ordinary light, that's in the center of a supernova diffuse out and takes weeks to escape. But if the star is spinning, then it'll be an oblate spheroid; it'll have a minor axis along the spin axis. And so the easy way out is for the radiation not to diffuse through, but to find the shortest escape route, which is along the spin axis. And I mention this because gamma-ray bursts are objects I've worked on a lot myself, and these are when a supernova occurs. But because the initial star was sort of flattened, there was an easy escape route, and all the energy escapes in jets along the spin axis. And so instead of it diffusing out over a period of weeks, as it does in supernovae, it comes out in a few seconds. And these objects called gamma ray bursts, which last a few seconds, are the most powerful objects in the universe in the sense that for those few seconds, they're putting out more power than all the stars we can see in all the galaxies. They're extremely powerful because the energy is coming out in a narrow beam and just a few seconds. So these are, again, extreme phenomena which are special kind of supernovae. So I just put in that plug for the interest in gamma-ray bursts.

[Mark Sullivan] I think that's interesting - that the field can have so many different effects on so many different things: formation of the elements, ...can affect life on Earth,... you can use it to study dark energy. I think its wonderful.

[Martin Rees] It's very cross-disciplinary. You have to understand all these things. And of course, if you do discover life elsewhere, then we have to learn some biology.

[Melvyn Bragg] You don't say "there's bound to be", but "in nearsest [estimate] there's bound to be" life somewhere else?

[Martin Rees] Well, I wouldn't say that. It could be unique because we don't understand the actual process of forming the first life. Darwin told us what happens to get from simple life to complex life, but we don't understand but...

[Melvyn Bragg] We don't understand how simple life came about?

[Martin Rees] ...how it came about? Yes, but I think there's hope in two ways. First, serious people are now thinking about this problem. It used to be put in the sort of too difficult box where people didn't think it was worth thinking about it even. But now serious people are working on it. But of course, more important, if we could find evidence for life in another second place, that would make a big difference. There are two things that could happen. One would be that we can get a spectrum of the light from a planet around another star, which tells us what's made out of oxygen - is there chlorophyll there as it would be if it was covered with vegetation or something like that. But also in our solar system, because Mars, of course, people are probing Mars, and there might be some big bacteria there. But most interesting are the moons of Jupiter and Saturn. There is Enceladus, which is a moon of Saturn, which has ice over an ocean, and

Europa, a moon of Jupiter like that. And under those thickness of ice there could be some life. And so there are ideas to send robots to actually investigate there, because there's water and the temperature may be alright, so there could be life there. And the reason that'd be so important is that if we could find evidence for life on a moon of Saturn or Jupiter, it would have to have originated independently of Earth. And so if life originates twice within our single solar system, that says it's not a rare fluke, and therefore it almost certainly exists in a billion places in the galaxy, and that will be a really momentous discovery. I emphasize this rather than Mars, because if we detect evidence for life on Mars, then it's certainly possible for life to get from Mars to the Earth or vice versa on meteorites, because there are some Martian meteorites that landed on the Earth, so it wouldn't be clinching that it was independent. Whereas if we find life so far away that it couldn't plausibly have got from the Earth or vice versa, that would indicate two independent origins in one solar system. And that would mean therefore in our galaxy where there are a billion planetary systems, that it must be teeming with life. And that would be a really great discovery.

[Carolin Crawford] Just to revert back to the death of stars. Mark was talking about stars within our galaxy. One of the interesting things to speculate about is which of our nearby stars, hopefully not within 30 light years or so, which of the stars we see in our night sky, some of these giant stars is the one that's most likely to be supernova next, and we've got several candidates. There are massive stars which are 20-30 times the mass of our sun. Betelgeuse is one large red giant [and] there's a star on the southern side called Eta Carinae, where they're already in fairly volatile states; they're varying in brightness, they've got clouds of billowing gas and dust around them, they're very active. There's something to do with the end of their lives. The problem is, a star that's about to undergo core collapse actually doesn't look very different from one that is several millions of years ahead of it. So when I say these two are good candidates for going supernova soon, it could be next year, it could be a hundred thousand years time. So it's a bit of a guessing game. Yes, we're likely to have a nearby supernova, hopefully not too near, but which of these red giants that we see in our light sky is going to be the one is anybody's guess at the minute.

[Melvyn Bragg] Okay, well, thank you all very much indeed.

In Our Time with Melvin Bragg is produced by Simon Tillotson.