Astrophysics: How and Why Stars Burn

Lecture by Charles W. Cook
November 2, 1958
1 hour, 10 minutes, 13 seconds

Speaker: Charles W. Cook

Transcribed by: Sarah Fuchs

Time	Transcription
00:00	Marian Longstreth: Once again we have come together to meet a leading scientist. It's interesting, isn't it, to explore space in the company of someone who knows something about it? This is the fourth lecture on the series *The Physics of Space*, which The Theatre and Arts Foundation of San Diego County, Convair, General Atomic, and The Scripps Institution of Oceanography have presented to you. Today our speaker is the head of the nuclear physics group at Convair. He obtained his Master's degree in Science and his Ph.D. degree in physics at the California Institute of Technology where he did research on nuclear reactions in stellar interiors. From there, he went on to the Oak Ridge School of Reactor Technology then to the California Research and Development Company, and to North American Aviation before he joined Convair. No doubt when he was a student like you he looked up at the stars and wondered why they were so bright. He found out and he's going to tell us something about astrophysics, how and why stars burn. I take great pleasure in introducing to you, Dr. Charles W. Cook. Dr. Cook.
01:37	Dr. Cook: Today I would like to tell you a few things about stars, a good number of things that I hope that you don't already know. For example, I would like to tell you where they come from, what makes them shine, and what finally happens to them. I would like to begin with a small riddle and see how this riddle actually applies to what I have to say. The riddle is, why are stars like elephants? Why are stars like elephants? As we go along you might try to think and see if you can figure out any relationship between stars and elephants. I will give you one hint, and that is it is not because they are both large. I might also say that this is, the point that I am trying to make is rather a tricky point. It's not something that is very easily seen and so I don't imagine that many of you will be able to see through it but we will explain it at the end. To begin with, you probably already know a good deal about stars. For example, you know that the sun is our closest star. You also know that the sun is very large. For example, if the sun were hollow you could put something like one million of our Earths into the sun. This would give you a rough idea of how big it is. One million of our Earths would fit inside the sun.
03:18	Dr. Cook: The sun also rotates on its axis as does the earth. This is perhaps a fact that not too many of you knew and it also is rotating and this is a very important wheel in trying to figure out where the planetary system came from, but we won't have time to go into that right now. You also know that the sun is very old. In fact, it may be a little bit older than you think. Scientists presently estimate that the age of the sun is four and a half billion years old. And this is quite a long time for a sun to burn, especially when you think that every second the sun is burning four million tons, four million tons of its own material every second is being converted into energy. So when you think that every second four million tons are being burned

and it's been burning for four and a half billion years, you can realize what a tremendous source of power and energy is available in the sun. May I have the first slide, please?

04:45 Dr. Cook: There is of course more to stars and some of their problems than just the sun. And to give you an idea of just where we are located in space, I have here a picture of our galaxy. Now, this galaxy is known as the Milky Way and this is what it would look like if we could get off, way off in space somewhere, and look at it. Looking down from the top, you would see that our solar system, that is the sun and the planets, are located about right here. Way out in one of the spiral arms of our galaxy. Looking from the side, you see that we are, in fact, somewhat near the center. Well, perhaps, just a little bit off the center of the galaxy. So you see that in our own galaxy alone, there are millions and millions of stars and so we have a vast territory to cover besides just talking about our own sun. Thank you. Now the question that I would like to discuss with you today is what makes the stars burn? And I'm going to give an answer to this question right away. Stars burn because of nuclear reactions.

06:13 Dr. Cook: In case you don't get anything else out of the lecture today, I would like everyone to remember that stars burn because of nuclear reactions. What they are, are actually nuclear furnaces. Inside the star, nuclei are being put together into different nuclei and thereby giving up their energy in terms of light and heat. And this is the way that stars burn. So let us now begin by looking at stars and seeing what we can actually find out just by looking through telescopes and see what we can observe. If I may have the next slide, please. One of the things that is very easy to observe about stars is their difference in color and here I have just schematically shown how stars could differ in color. They range from a dull reddish color up to orange, yellow, white, and finally up to blue. The blue stars are the hotter stars and the red stars are the less hot stars. Now in actual practice, of course, we go about determining the color of stars in a slightly more scientific manner than just looking at the color like that and the next slide will give you an idea of how this is done.

07:52 Dr. Cook: Here we see a prism, which breaks a beam of light up into its component colors so that what we actually do is put a prism at the end of the telescope and look to see what colors we actually get coming out of a star. And a red star, for example, would have a more intense, it would be more intense in the region of the red and this is why it would appear to us with the naked eye as a red star. That is, it would have mostly red light. If a star were blue it would have more of a blue light. There's one thing in particular that I would like to have you notice about this slide and that is that the red light is not bent quite as much as the blue. In other words, in passing through the prism, the blue light is bent much further than the red light. Just as a side light, I would like to show you two examples of how we see this taking place in everyday life. If I may have the next slide, please.

09:12 Dr. Cook: One of the questions that perhaps you wondered about is why the sun is more red in the evening when the sun is setting than it was at midday when the sun was overhead. And the reason is exactly what we saw on the previous slide and this is how it works. When the sun is overhead, the light passing through the atmosphere does not go through a very great amount of atmosphere and so most of the light comes through unscattered. But now when the sun is beginning to set, when it's on the horizon, there it has to go through a much longer path, a much longer path through the atmosphere. Thereby, giving the light rays more of a chance to scatter and if you remember, the red light did not scatter as much as the blue light. So what we see is that the blue light, the blue light has been scattered out and only the red light comes through. Next slide, please. Here's another indication of how we see this taking place every day and that is the formation of rainbows. And I don't want to spend much time on here except to say that the light from the sun comes and is reflected by a drop of water and you will notice that here again that the red is not bent as much as the blue. And in going through the drop of water the light is separated out and you will recall that a rainbow shows the light separated out into different colors. Well, this is the idea that we use to actually tell what color stars are.

11:15 Dr. Cook: Another thing that we can easily observe about a star is its brightness. You all know when you look up into the sky, some stars appear brighter than others and so this is one of the things we can easily tell about stars is how bright they are. Now, this is not, for our purposes, the real thing we are interested in. The real thing is not how bright they appear to be but how bright they actually are. The difference between how bright they appear to be and how bright they actually are, of course, depends on how far away they are. You know that when you drive down the highway that a, and you approach a car, the closer the car is, the brighter its headlights appear, and the farther away the less light, the less bright they appear. So that in order to get the absolute brightness, or actually how bright a star is, we have to know how far away it is. So with these two things, let us see what we can find out. That is we know the color of the star and we know the brightness of the star, now let's see what we can get out of that. If I may have the next slide, please.

12:42 Dr. Cook: Suppose that we look up in the sky and we determine these two quantities, the color of the star and the brightness of the star. And each time we take a star like this we put it on this sort of a graph where the color of it is indicated here. You see the blue, the yellow, and the red. We put it in the proper place along here and also its brightness. We put a dot for each star according to its color and its brightness. Now up at the top, you will see where it says, spectral class. These classes of stars are based on the color. The Class M as you see is a red star, K is an orange, G is a yellow, and so on, ending up with B being a blue star. Now it turns out that the color of a star is also related to its surface temperature and thus corresponding to a blue star we have a surface temperature. It turns out a blue star has a surface temperature of about 36,000 degrees Fahrenheit and so on. So by looking at a star and determining its color or its surface temperature, we can put a point corresponding to its brightness. Now, this is a scale that I don't want to go into necessarily today, but we might just relate things relative to the sun. A sun that is, a star that is brighter than the sun would fall above, up in here, and one that is not as bright as the sun would fall down in this area here.

14:36 Dr. Cook: Now, this sort of a diagram is called a Hertzsprung-Russell Diagram or sometimes it's known simply as an HR diagram. As you see the sun lies in a certain position here. In fact, it's right here and it lies on what we call the main sequence. This band that falls along in here is known as the main sequence and practically all young stars, that is stars that have just recently been formed, lie on the main sequence. Now where they lie on the main sequence, that is, whether they lie up at this end or down at this end depends on how much mass, how much matter is actually in the star at the time it was formed. Stars that are heavier than our sun lie up towards the blue region. Stars that are lighter lie down in the red region. We see that not all the stars lie on the main sequence. In fact, we have white dwarfs. These are the giant stars sometimes called, these over here are called red giants because they are red. These up here are called blue giants. So we see that we can put all the stars that we observe on a graph similar to this.

16:19 Dr. Cook: Now what stars do if you look at them over a period of time, you will find that they change their position on a chart such as this. In other words, if we were to look a long time from today, say a billion years or so, we would observe that the sun has moved slightly. It would have a tendency to move up in this direction somewhat. If we look in about five billion years, we will see that the sun is starting to move off over back in this direction towards the red giants. And so what actually happens is this. The stars always start on the main sequence and then they evolve or they move to different positions on this chart. Now what I would like to do is to discuss. Take a star, a star that is just forming, just beginning to burn and we'll go through the reactions that take place and show you where the actual energy comes from for these stars. And then we will come back to this slide and I will show you exactly what it means where the sun will go and what will eventually happen to it. I might give you another hint that out of this, perhaps we will be able to find out why stars are somewhat like elephants. So let us start now with a new star. How is a new star formed? Well, in interstellar space that is between the stars, there exists a gas, a gas cloud if you'd like. The density is very low.

18:26 Dr. Cook: There is perhaps only one particle to a good size suitcase and at sea level here you know there are many billions of billions of stars in a good size suitcase. So this gas is very rare. Its density, if you know, is very low. Now, this gas is composed mostly of hydrogen. I'm sure you've all heard of hydrogen gas. Well, this is exactly what this gas cloud in interstellar space is composed of. That is hydrogen. There is some helium, perhaps as much as 10 percent helium. There's also carbon, oxygen, a few other elements, these in very low abundance.

Now sometimes it's possible in space for this gas to begin to condense. That is it's possible for it to begin to come together to draw closer and closer together and this is due to gravitational attraction. You all know, for example, that when you throw a ball up it comes down. This is simply gravity. Gravity pulls it down. Gravity acts on all the masses in the universe. It has a tendency to pull it together. When you take a gas cloud composed of hydrogen and it begins to condense due to the gravitational attraction, the particles come closer and closer together. As they come closer and closer together, they begin to move faster and faster. Now after this goes on for many, many millions of years, the particles are close enough together and they're moving fast enough so that it's possible to begin nuclear reactions.

20:30 Dr. Cook: That is, it’s possible for this for the star to begin to burn. And as you recall they burn because of nuclear reactions. Now in order for this to happen, the inside has to be very hot and it takes something like a temperature of ten million degrees before these reactions will begin to take place. If you notice here, the surface temperature of most stars is considerably less than that. For our sun, say it’s about 11,000. The interior temperature, that is the temperature at the core of the sun, is more like about ten million degrees or perhaps twenty million. So you can see that there's quite a difference in temperature between the core and the outside surface. So now let's talk about the actual nuclear reactions that take place. If I may have the next slide, please. When the interstellar gas has condensed to the point that nuclear reactions begin, we have this dense sea of hydrogen and the hydrogen is designated here in red, although I would - these are the actual ones that participate in the reactions - but I would also like you to think that all the white ones are also hydrogen. So what happens is that the hydrogens are wandering around in this gas and finally two of them come together, as we have indicated here.

22:25 Dr. Cook: Two of them come together. Two of the hydrogen, two of the nuclei of hydrogen come together. The nucleus is simply the core of the hydrogen atom. Two of the nuclei come together and they form what is called a proton, excuse me a deuteron. Actually, the core of the hydrogen atom is called, when we're talking about nuclear reactions, it's called a proton. So what we have here is two protons coming together to form a deuteron. Now then the deuteron wanders around until it again is bumped by another proton. At this point then another nucleus, a different nucleus is formed, this one is called helium-3. You can see here we have - I think you can see anyway - a little HE with a three superscript. This indicates that, the three indicates that there are in fact three particles in the nucleus. The deuteron has two particles as indicated by the two and of course, the proton is a single particle, it only has one.

23:53 Dr. Cook: Now the reason that people like myself, who are nuclear physicists, are interested in what’s happening in the stars is that many of these reactions that we’re showing here can be studied in a laboratory. In other words, we can simulate, if you will, the conditions inside a star in a laboratory and we can study which of these reactions will go and which ones will not go. Much of this kind of work has been done up at Caltech [California Institute of Technology]. Dr. [William A.] Fowler, Dr. [Charles Christian] Lauritsen, Dr. [Fred] Hoyle was there for a while, Dr. [Geoffrey] Burbidge. These people are very interested in how these reactions take place and I myself have had something to do with finding out how these reactions occur. I might make one special note. A week from Saturday night, a week from this Saturday night, Professor Fowler from Caltech will be on television, Channel 4 at six o'clock, and he will say more about the same sort of thing that I'm telling you today. So if anyone is interested, a week from Saturday night, you will be able to see some of this on television.

25:26 Dr. Cook: OK, so let's go on with our reactions. We have taken it down now until we have a helium-3 nucleus. Now, this helium-3 nucleus has to wander around in this gas until, as we see here, it can collide with another helium-3. So this means that at this point we no longer can add another proton. Protons are very abundant here. It will be bumping into protons all the time and it turns out that a helium-3 will not react with a proton. And this is one of the things that we studied in the laboratory, whether they will or they will not react. But it turns out it has to wait until it can find another helium-3 to react with before it can go on And you see, to make another helium-3, we have to start with hydrogen over here, come through deuterium, through the helium and finally, we have the two. And they will come together then to form helium-4, or helium-4 is sometimes called an alpha particle.

26:39 Dr. Cook: We see also that after the helium-4 has been manufactured that we have left over two of the protons that we began with. So let us see what the net effect of this is. We see that we started with the hydrogen one, two, three, four, five, six. We put six hydrogens in and we end up with a helium atom and two protons. So the net effect is shown here that actually four of the protons were converted into one helium-4 or an alpha particle. So, this is the chain, the chain of reactions that's occurring in the sun and this is where the sun is deriving its energy. This chain is known as the proton-proton chain. The reason, of course, that it’s known as the photon-proton chain is that the first interaction that takes place is between two protons. As I said, this is the nuclear reaction chain that is producing the energy in our sun. It also is producing most of the energy in stars that are about the same size as our sun. Now as you go to larger stars, and of course there are a large number of stars which are considerably larger than our sun, some of them go up to maybe even fifteen or twenty times the size of our sun, then another reaction is predominant and I don't want to take time to go through a similar chain like this, but I will tell you the name of it. It is known as the carbon-nitrogen cycle. This occurs in stars that are heavier than our sun.

28:41 Dr. Cook: So right now our sun is burning hydrogen and converting it into helium by the PP chain, proton-proton chain. As time goes on now, more and more helium, helium-4, will be found in the center of the sun. And after a long period of time, in fact, the whole center of the sun, the whole core will have been turned into helium. Now it turns out that at this point, the core is not hot enough yet. The temperature is not high enough for the helium, the helium-4 nuclei, to begin to interact and so we do not yet have helium burning. But we still have hydrogen burning occurring in a layer outside of the helium. The helium core is built up and around that there will be a shell or a layer where this reaction is still taking place. As time goes on then this core will be pushed together more and more by the gravitational energy. Actually will be pulled together and the temperature will rise. Now after a considerable amount of time then the core will be hot enough for the helium itself to begin to burn and at this point, the temperature has risen to something like 200 million degrees, 200 million degrees Centigrade, or something like 400 million Fahrenheit. And at this point then we can get helium burning and if I may have the lights, please.

31:00 Dr. Cook: Let's see. Can everyone see this? After we have formed helium in the core and the temperature has risen sufficiently, then we begin to get what is known as helium burning. And this was a very difficult thing for scientists to figure out what actually happened after you did get the helium because it doesn't, helium doesn't like to react with much of anything at all. It's very stable and so this was quite a problem trying to find out what actually happened then after the core had become helium and I think we finally have it figured out now. And this is what it looks like happens, that eventually, you will get enough of the helium built up in the core so that two of them can come together. They will come together and form what is known as beryllium-8. Now, beryllium-8 is very unstable. By unstable I mean that it doesn't like to be beryllium-8 very badly. It would rather be two helium nuclei so that it comes together but it only stays beryllium-8 for a very short period of time. This period of time is so short that we can hardly imagine what it is and in fact, it is something like one 2000th of a millionth of a millionth of a second.

32:45 Dr. Cook: So this is sort of why it was so difficult to figure out this reaction, was because nobody imagined that anything that was as unstable as this could contribute appreciably to the reaction. But this is the way it turns out. In fact, two helium atoms, two helium nuclei come together to form beryllium-8 and in this short period of time, while it's in the form of beryllium-8, another helium nuclei can come along and collide with the beryllium-8 and form then carbon, or carbon-12. Now this reaction, this chain called helium burning was actually predicted by Dr. [Edwin] Salpeter from Cornell University. He said that this, this is the way it has to be and of course, he didn't really know if this was the way it was but he said this is the way I think it is and this is the way it has to be. Then, Dr. Fred Hoyle came along and said well that's all fine and dandy but if it does go that way then this reaction here has to be much more probable. The probability of this reaction taking place has to be much greater than ordinarily, we would think would be possible. And so they set about then in the laboratory to see one, if this reaction was possible and if it is possible if it is much more probable than than you would think.

34:32 Dr. Cook: Now it turns out that it was fairly easy to show that if it is possible, then it is much more probable than you would think. This may sound a little backwards to you but it was fairly easily shown that it would be very probable if it were possible. But the real catch was showing that it was - that it was possible. And here is a reaction that I have actually worked on myself. I worked with Dr. Fowler, Professor Fowler, from Caltech on this and by a rather complicated experiment, we were, in fact, able to show that this reaction is possible and it was shown before that it is also more probable than you would think. So it appears that this reaction actually does take place in stars and we have shown this in the laboratory. I might go on to say that at the present time, Jack Young and myself are setting up an experiment out at the new laboratory at General Atomic to check some more nuclear reactions that are thought to take place in stars. We're just about ready to begin those experiments now. If there are any of you that are interested in actually seeing how some of these things are done in the laboratory, I'm sure that we could arrange a tour out to General Atomic so you could see exactly what we do to find out about these reactions.

36:14 Dr. Cook: So, now we have gone a little further. We have produced helium in the core, to begin with, and then we have shown how we can produce carbon-12. And from here on then there are several more reactions that take place, they get considerably more complicated. But the energy is continually derived from this type, from these type of reactions, and eventually, what you get I have tried to to indicate schematically on another drawing here. I don't know whether you can see this too well or not but what I have tried to indicate is this, that when the star was first formed, you recall we were burning hydrogen in the central region. Then when the core became hot enough and dense enough, we started the helium burning and this shows the helium burning and it also shows the shell around where the hydrogen burning is still taking place. Now as we go on then actually carbon-12 then unites with another helium nuclei and we form oxygen-16. So this shows that in the core then a new nuclei is being formed and here is the helium burning and here is the hydrogen burning. And this goes on and eventually we build up a whole layer, a whole shell-type layer system in the star where each one of these designates that a different nuclear reaction is taking place.

38:00 Dr. Cook: Eventually these reactions will go on until we get only iron. Iron will be in the core and there will be other ones distributed throughout the shell. This is sometimes called the onion skin method of representing how stars burn. So now we have seen some of the nuclear reactions that actually do take place in stars and I think now it might be well if we were to go back to the Hertzsprung-Russell Diagram and see what is actually happening to the star. May I have the slide again, please? Well, this is a shame. We will never be able to actually see why stars are like elephants then but perhaps I can tell you. As you recall the sun was burning on the main sequence and as I indicated that as it continued to burn it would rise a little bit, from the main sequence and why don't I draw this? Oops, I thought I had backed it. Why don't I draw this on the board? As I indicated, the sun is something like four and a half billion years old.

39:52 Dr. Cook: Can I have some other lights, please? Well, let me say a few words, in the meantime. After the sun has burned about another five billion years or so, in other words, when it gets to be about twice as old as it is now it will begin to move off of the main sequence in the direction that I indicated before. And it will begin to move up into the region of the red giant stars. If you recall from the diagram, the slide that we had, the red giant stars were up in the upper right-hand corner. And so then let me draw this here. Let us suppose that this is the main sequence and that our sun is sitting about here. Now after another five billion years or so, it will begin to move off in a direction like this and it will continue to move up into the region of the red giants that's supposed to be RG for red giants - into this region here. If you recall, we have the surface temperature which was increasing in this direction. In other words, the red giants have a low surface temperature.

41:37 Dr. Cook: So what has happened to this star is that the outer part of the star has expanded very greatly. It will be much larger when it gets to this region than it was when it was down in this region and this is, well perhaps you won't agree with me but I was going to say that this is very important to us because what, although it is 5 million years from now when this happens, the sun will have grown to a size that is probably two or three hundred times as big as it is now. This means that it will have engulfed the planets of Mercury and Venus and perhaps even the Earth. So by the time our sun has evolved up to this region, the Earth will probably be - a-ha - will probably be completely vaporized. But life on Earth won't last quite that long because by the time the star has, by the time the sun has evolved just a little ways up on the main sequence, the average temperature on the Earth will have raised to something like that of boiling water and so life at that point will no longer be present on the Earth. And the, yeah life will not be present on the Earth anymore and the sun will have to continue its evolution without any life on Earth, which of course will not matter a bit to the sun.

43:19 Dr. Cook: Now as the sun – we have seen it the sun has evolved first up a little ways and then out into the red giant region. Now when it gets to this point, up to this point, it has been burning hydrogen, the first reaction that we had on the board. It has been burning hydrogen all this way and it's also been growing bigger. And so it has moved. If we looked at different times, we would see that it would have a different position on this diagram. Then as time goes on we would suddenly see that it started to change its direction. Instead of moving up this direction, it will have started to streak down across in this direction. And I say streak because even though we're talking about ten million years or so it is still much shorter than the original ten billion or so, that the sun spent down in this, this little region here.

44:21 Dr. Cook: What happens to make the sun change its course is that it has a mild explosion in the core. This explosion is triggered off by the fact that we have, we don't anymore, don't have it anymore but by the fact that we have started to burn the helium. Once the helium starts to burn we have an explosion in the core. This is called popping the core. And it doesn't change it much except it changes its path of evolution and so then the sun will go rather rapidly. It will be found in the different positions here. In this region, we find it's not indicated here but we find a lot of what are known as variable stars. Now variable stars are variable. They change their brightness and they change their size as you look at them over a period of perhaps a few days or perhaps a few weeks. You can actually see the difference in the size of the star and more likely in the brightness of the star. The sun will eventually evolve through a region here where it will oscillate if you will. It will become bigger and smaller and brighter and less bright.

45:54 Dr. Cook: As we go on then, the star is now streaking over in this direction and eventually then the last part of its evolution will take it down as it goes across here, you see. The surface temperature is increasing and as you notice by my poster there, as we build up the different layers, the actually, the actual burning of the star was taking place closer to the surface. Therefore, as this happens you would expect that its surface temperature would rise and so we would expect that the star would take off in this direction and in such a manner to increase its surface temperature. Now eventually the star will run out of nuclear reactions, that is all the fuel, so to speak, will have been burned up. The star will have been converted mostly to iron and at that point, it cannot derive any more energy and it will start to cool off.

47:00 Dr. Cook: And in fact, it will cool off and it will come down into the white dwarf area and now we are finally to the point where I can tell you why stars are like elephants. Perhaps you heard the story that for a given herd of elephants, they always go to a common place to die. And people have always been looking for these places because, at the point where all the elephants have died, there must be a vast fortune of elephant tusks. So as elephants go to a common place to die, so do the stars. The stars start out on the main sequence, they evolve up to the red giants, come across here, and eventually, they end up in the white dwarf region to die. After they reached this region, they are cooling down, contracting, and eventually, they will just fade away.

48:13 Dr. Cook: So we have traced a star, from its beginning, all the way through its sequence, to the end. And I would like to say perhaps, oh spend another one or two minutes, telling you that it appears likely that most stars don't give up the fight.

They don't go calmly to their death in the white dwarf region, but rather they put up a rather good fight before they do and this gives rise to what is commonly known as novae and supernovae. Now the novae, the word is derived from the Latin. In fact, I believe it's novae, if I remember my Latin. It doesn’t appear likely right now. But anyway, it comes from the Latin and the word means new. And so what probably prompted people to name these novae was the fact that these stars suddenly become much brighter than they have been in the past so that ordinarily, where ordinarily you would not see a star when it reached the point in its cycle that it became a novae, it would suddenly appear and hence the name new was was attached to these stars.

49:56 Dr. Cook: Now what actually happens for a novae is that after the star has built up the layer system, it has the hydrogen in the outer layers and it turns out that the hydrogen simply cannot burn well there. And what happens is that you get an explosion and suddenly the whole outside part of the star explodes and it essentially blows itself apart. And where before we had that the star popped its core, now you might say that it has popped its lid and it actually blows itself apart. But the amazing part of it is that although it does blow itself apart, it doesn't blow itself completely apart. It just sort of expands a bit and it turns out that the gravitational attraction is strong enough such that it's pulled back together again. After it's pulled back together again the same conditions can arise and it pops its lid again. And this goes on and it will probably go on for our sun for something like a thousand times or so. That this star will explode and then come together and explode again.

51:23 Dr. Cook: Now this is the way that stars about the same size as our sun will behave. But when you get to slightly larger stars, stars that are about beginning at one and a half times as large as our sun, we will have a slightly different thing taking place and this is, is what is called the supernovae. As the name implies these are much greater explosions than the novae. And just to give you an indication, a novae is something like when it takes place it’s something like 100,000 times as bright as it was before the explosion. And in a supernovae, you get something like about another 2000 times as big. So you can see that where you ordinarily couldn't see a star before when it suddenly explodes it will be much easier to see. Anyway, in the case of the supernovae then because there is more mass, this is the bigger stars, when it explodes it blows itself completely apart and the gases go completely off.

52:45 Dr. Cook: And if I may have the last slide now I can show you the remains of one such explosion. This is now known as the Crab Nebula and this was a supernova, novea explosion back in the year 1054, 1054 AD. It was recorded rather accurately by the, by the Chinese and what we actually see, or should be seeing, is that the gas is being blown apart still from the terrific explosion. Somewhere left in the center there will be what is left in the star, the core of the star, and it will then eventually go as all stars do and become a white dwarf and so die. So now we have traced through the whole stellar pattern from the beginning, from interstellar gas, and incidentally, the gas that's dispersed here will eventually become part of the interstellar gas and it will probably again condense into another star. So we've taken it from the beginning through the end and also found out that this will supply some gas for the beginning again and this is now a good time to stop. Thank you.

54:05 [audience applause]

54:20 Dr. Cook: Thank you.

54:22 Marian Longstreth: Thank you so much, Dr. Cook. Would you have time to answer a few questions that the students would like to ask you?

54:26 Dr. Cook: Certainly

54:27 Marian Longstreth: [unclear] If so, would you raise your hand and stand up? Questions? Over here first and then you. Would you please stand up [unclear]?

54:40 Speaker 1: How soon will life cease on the Earth?

54:45 Marian Longstreth: I'm afraid we can't hear you. Will you repeat it into the microphone so that everyone can hear it?

54:56 Dr. Cook: The question is how long will it be before life ceases to exist on Earth? According to the method that I have outlined here, which perhaps not everyone will agree with. But anyway, the time that it looks like from this point of view, is something like about five billion one hundred million years. That is the point at which you will recall that the average temperature on the Earth has risen to something like that of boiling water. So long enough that we don't have to worry about it from this point of view.

55:43 Marian Longstreth: [Unclear] here and then we'll come back to you.

55:49 Speaker 2: What are the rest of the reactions– I mean after carbon-12 combines with hydrogen-4, oxygen-16, what are the rest of the chain to iron?

56:03 Marian Longstreth: Can you repeat the question?

56:05 Dr. Cook: Well, the question is what are the nuclear reactions that take place after the helium burning, after the helium has been converted to carbon-12, what reactions take place then? As I indicated the first reaction that takes place is that carbon-12 combines with a helium-4 to make oxygen-16. Oxygen-16 then combines again with helium-4 and this time I believe it makes neon-20. Neon-20 then combines with another one and this makes I think magnesium-24 and at this point then you start a whole new process and this is called the alpha process. I really don't have time to go into all of them now, in fact, I probably couldn't even if I wanted to. But you do get the alpha process after this. This is part of the helium burning. The stage that I gave you before was the first part where you get carbon-12. These reactions then complete the helium burning. The next phase is what is called the alpha process and after this then you get a very complicated process which is called the E process. I'm afraid I really don't have time to go any further than this, but if we could look at those, that would tell you the whole story.

57:39 Speaker 3: What elements are left after the star after it's fallen?

57:44 Dr. Cook: What elements are left in the star after it has fallen? You mean after it becomes a white dwarf? Is this the question? I believe that everything will finally boil down to iron. And so I believe this is correct that in the final analysis when the star is all done, there will be a small core of iron left. I would like to elaborate on this point one bit, and that is in the last slide, you notice that I indicated that the gases were dispersed into space and perhaps that new stars could be formed. It appears that our star or that our sun is what we call a third-generation star. In other words, the material that we have now in the solar system and in our sun is on its third time around. In other words, it's been in two stars that have already blown up, and that it is now on its third time around.

58:56 Speaker 4: Since Earth is only so many years old, how do you know all this stuff about the stars?

59:06 Dr. Cook: [laughing] The gentleman would like to know since the Earth is only also four and a half billion years old, how do we know what has taken place in stars before? This is a rather difficult question and one could spend a lot of time telling about how you actually do find out what has taken place before. Most of it is done in the following way. You come up with an idea of what you think has taken place and from this idea then you are able to say that if my idea is correct then certain things, there will be certain things about the stars that we can observe today and thus check whether our ideas are in fact correct. And this is usually the way that is, is done. And so most of these things are in fact theories and they are being checked as fast as we can get the experimental information. So that I believe the answer to your question is that we have guessed the way it should be and we are trying to check it.

1:00:28 Dr. Cook: Of course, there is one other point and I might say this, that as we look out into the stars, it takes a certain amount of time for the light to reach us from these stars. I forget exactly. I think the speed of light is something like 186,000 miles a second or so. And it turns out that if you look at the stars and galaxies that are as far away as we can see them with our present telescopes that we can look back in time something like two billion years. So that in this way, we can also tell something about what happened quite a few years ago. Now it will be very interesting when we get to the point that we can look back just a few billion years further because certain theories of how the whole universe started, say that it started with a huge explosion back sometime in the past, and this time is usually estimated at somewhere four and seven billions years. Now if we get to the point where we can look out that far in space, it will be very interesting to see what we see. If we see nothing, then perhaps it did start with a big explosion and nothing has actually gone out that far yet. On the other hand, if we do see things still out that far away this would be an indication that perhaps some other method triggered the whole thing off.

1:02:20 Speaker 5: What happens [unclear] during the radioactive [unclear]?

1:02:28 Dr. Cook: I'm sorry, I can't hear.

1:02:31 Speaker 5: What happens during the disintegration, the disintegration of radioactive elements when it gets down to [unclear]?

1:02:41 Dr. Cook: The question is, I believe, what happens to a radioactive - radioactive what? Element? When it gets down to the last atom? Is that right? In other words, let me rephrase the question in such a way that I think that maybe I can give an answer and that is if you have some radioactive material and this is decaying by radioactivity, what happens when you get down to the last atom that hasn't decayed? I think this is, and I think the answer to this is that it will decay [audience laughter]. Perhaps I don't understand the question.

1:03:46 Speaker 5: [unclear]

1:03:50 Dr. Cook: I'm sorry. How is it? It will divide itself as all the others have done. What happens is that if you have a number of radioactive, a radioactive batch of material then you look at the nuclei that have decayed by whatever process you have. And so as you look perhaps this one will decay into its products and eventually they will decay away and when you will get down to the last one it too will simply decay.

1:04:37 Speaker 5: [unclear]

1:04:48 Dr. Cook: Perhaps what you are saying is that I mean the point that's bothering you is that if you begin, you have a certain amount of material. If you look at a time later that is equal to its half-life, you will find that you will only have half of that material left and this goes on. Well, I believe the answer is still the same that as time goes on, more and more of it will have disappeared and eventually the last one will decay as all the others did.

1:05:30 Marian Longstreth: [Unclear] Will you stand up, please?

1:05:32 Speaker 6: If iron is [unclear].

1:05:38 Dr. Cook: It turns out that iron is not the heaviest element that is possible. The important point here is that iron is the most tightly bound and this is a considerably different thing. I don't know off hand how I can indicate it very clearly to you but let me try by drawing a valley, something like this and let me put iron down here and something like uranium up here and perhaps hydrogen here. This then indicating, let's say, the degree of stability of different nuclei. And this is rather dramatically shown I believe, for example, in the case of an ordinary fission bomb. In a fission bomb, you derive the energy from splitting uranium. You split it into two components. Each of the components lie down in here. Let's see, is that possible? Probably they lie one here and one here. I don't recall off hand, but anyway it breaks up into two particles, each of which are more tightly bound than the uranium. So this is, it shows that it in fact goes towards iron at the breakup, the most stable is towards iron, and on the other side we have fusion, a hydrogen bomb if you will. This effect combines things together, two hydrogens for example and they will lie in here again heading towards iron. And so the point is that iron is the most stable and that is where you will end up. It is not the heaviest.

1:07:45 Speaker 7: First of all, how can you tell what generation stars are? I thought that you said [unclear] first-generation gas stars iron. How would they be enough hydrogen second generation of stars via the third generation of stars? Finally, how many generations are there?

1:08:10 Dr. Cook: The last part I can't answer. I don't know how many generations there are.

1:08:14 Marian Longstreth: Repeat the question.

1:08:16 Dr. Cook: Ah. I'm sorry the question was in brief if I can remember it is that how do we know in fact that the sun is a third-generation star? The answer to this question I believe is that as you build up the elements in the star, as you recall, we build up quite a layer of them, and then they explode. You then have in this gas, a different distribution of the elements that have already been built up. If you do this several times, then the distribution will again be considerably different. So if you look at the sun and in fact, at our Earth and meteorites you'd like to do it, and determine the relative abundances of the elements that we have, you can work back and figure out how many generations, how many different generations of stars it had to go through to give us the relative abundances that we actually observe here on the Earth and in meteorites.

1:09:37 Marian Longstreth: Thank you so much, Dr. Cook. I'm sure that the students [unclear]