8.03SC Physics III: Vibrations and Waves, Fall 2012
Transcript – Lecture 23: Farewell Special, No Formal Materials

PROFESSOR: So today I will talk to you about the research that I was doing in my early days here at MIT, which is a long time ago. I got my Ph.D. In the Netherlands in nuclear physics. And then in the early 1966 I came to MIT, I had a post-doc for one year, I fell in love with MIT, and I never left.

So I changed fields from nuclear physics to X-ray astronomy. X-ray astronomy was a very young field at that time. You can only do X-ray astronomy from above the earth's atmosphere, because the X-rays are completely absorbed by the earth's atmosphere. Unlike radio astronomy and optical astronomy, which you can do from the ground, you have to get above the earth's atmosphere.

So I joined a research group of Professor Bruno Rossi and George Clarke. George is still at MIT. And when I say X-rays, you have to think about the same kinds of X-rays that your dentists are using, one to roughly 50 kilo electron volts. All of you know, I hope, what a kilo electron volt is. Optical light is only two electron volts, so X-rays are substantially more energetic than optical photons.

It was in 1948 that American scientists started to explore the outer space, for which you need rockets. And they used the German rockets which were developed in World War II at Peenemunde by Wernher von Braun. But these were weapons. They were launched from France, from Belgium, and from Holland. And the target was London, they caused a tremendous amount of misery and death as a flying bomb.

And after the war, Wernher von Braun was welcomed into the United States, and for reasons that still puzzle me to date, he even became a hero. Using these rockets, these v-2 rockets leftover from Hitler's Germany, the Americans discovered X-rays from the sun. The sun is very close, so you would say, well it's not too surprising. No, indeed, it's perhaps not too surprising.

And, in fact, the amount of X-rays from the sun is only a minute fraction of the total energy output of the sun. So if we take the power, joules per second, in X-rays, and we divide that by the power in optical light, of which the sun is also ultraviolet and infrared, that's all included. And if you do this for the sun, then you get a number of about 10 to the minus 7. So one-ten millionth of the energy comes out in the form of X-rays.

It's still very puzzling, by the way, why there are so many X-rays, but that's a different story. In 1962 scientists from Cambridge, Professor Rossi, Riccardo Giacconi, Herb Gursky, and Frank Paolini wanted to explore the possibility of whether there were also X-ray sources outside the solar system.

And the odds that they would detect something like that were extremely low, because if you take the sun, and you put the sun at the distance of the nearest stars, there is no hope on earth with the detectors that existed in those days that you would detect the sun. In other words, the detectors, I think I recall, were about one billion times too insensitive to see a solar like object at the distance of the nearest stars.

Yet, they succeeded. In 1962 they reported the first extra solar X-ray source. It was later called Sco X-1. Sco stands for the constellation, X for the fact that it was an X-ray source, and one because it was the first source in the constellation of Scorpius. And we now, it took several more years, that the optical counterpart of this bizarre object is a very famed blue star. It's about the distance of about 1,000 light years.

And what is so unusual about Sco X-1 is that if you take the power in X-rays, and you divide that by the power in optical, and you do for Sco X-1, then you'll find approximately 1,000. Now think about it. The sun, the X-ray emission is a minute fraction of the total emission, one in 10 million. In this case the optical emission is only a very small fraction of the total emissions. It's completely dominated by X-rays.

And Riccardo Giacconi received the Nobel Prize for this two years ago, the Nobel Prize in physics. And so the big question was, what can this be? How is it possible that any object in the universe can do this?

And when I came to MIT in early 1966, about six of these sources were known. They have been found using rockets. These rockets would be launched, spend at most five minutes above the Earth's atmosphere and would reenter. They would make a quick sky scan, and that led to the discovery in '66 of about a total of six of these sources.

So I joined a group of George Clarke, who was preparing to observe X-rays from high flying balloons. The advantage of high flying balloons is that balloons can stay up for hours, in some cases even for days. So we have a huge advantage over the rockets, we have way more time to observe.

But there is a problem, and that is you can never get above the atmosphere, because you are a balloon. So there's always a little bit of residual atmosphere above you. As little as that is, it absorbs most of the X-ray spectrum. In fact it absorbs everything below 20 kilo-electron volts. So, yes, we have way more time, but we were only sensitive to the energy range roughly about 20 kilo-electron volts.

Nowadays, no one flies rockets anymore, no one flies balloons anymore. We do everything from satellites 365 days a year. So I developed and I built, in 1966, X-ray detectors with the help of graduate students, with the help of undergraduate students. It would take about two years, typically, to build such a telescope.

At today's dollars, it would cost about $3 to $4 million to build such a telescope. You need substantial funding, and the weight of the telescope would be 1,000 or 2,000 kilograms. The balloon that we needed, you will see a picture of it, with today's dollars would be about $300,000. And the helium that is needed to inflate the balloon, we would inflate only a small portion of the balloon, was something like $150,000. So this was not really a cheap endeavor.

The diameter of these balloons when they're fully inflated is 500 feet. They're made of polyethylene. And they are extremely thin, because you need low weight balloon, otherwise you can't get very high. In fact the skin is thinner than cigarette paper, 15 microns thin. You can look straight through it.

It's a very risky business, you pay a lot of money, there's no guarantee that it will work. You try your luck, if it doesn't work, tough luck, you get no money back. They can easily get damaged because they're so thin. There's a good probability that you will damage the balloon right at the launch, and you'll see why. It's very difficult to launch these balloons.

But even if the launch is successful, when the balloons go up they go through the tropopause, which is 70,000 to 100,000 feet. The temperature is very low, -70 degrees centigrade. And there are jet winds. So the low temperature makes the polyethylene brittle, and then the jet winds just break the balloon. And when that happens, we do have a parachute. You will see the parachute that is supposed to bring the payload back. But when that balloon bursts, in general, it interferes with the parachute, and the whole thing comes down.

You have a free fall and you lose your payload. And with that, the research balloon burst, and often the Ph.D. thesis also pops, because there are always Ph.D. Students involved in these experiments. So it's very dramatic. If a student has worked two years on these payloads, and then there is a free fall, and you destroy the payload. And it has happened, believe me.

So what I want to show you now is a series of slides to give you an idea of what the balloon launch is like. So if we can make it very dark for this, and we shall turn is off. Then you will see here the first slide. These were two undergraduates of mine, Pat Downey and Jim Valentine. They were working on the electronics. Astrophysics is a very romantic field. They fell in love with each other, they married, they have kids, they are still in touch with me, and Jim got his Ph.D. with me. He stayed with me as a graduate student.

And here you see the plants in Texas where these huge balloons were built. This hallway is 1,000 feet long. The balloons are put together in a way like a tangerine is put together with gores. They're sealed with sealing. And that work was only done by women, it has nothing to do with sex discrimination of any kind. It just turns out that women are more accurate workers when it comes to this than men. They make fewer mistakes, that was the only reason.

You can imagine just a small mistake, and you can have a leak in the balloon, and that's the end of it. So we lay these balloons out on an area, in general, close to an airport. We put cloth on the ground, because the balloon is so thin that if the balloon touches the grass, it would definitely rip. And the balloon is packed in some plastic, you see that. That is the pink sheet that you see, that the balloon is inside. There are hundreds and hundreds of layers of balloon inside there.

It's taken out of the box very slowly, people inspect it, because there's always a possibility that there was some damage during transport. And here I take you now to a desert town in Australia--the heart of Australia, Alice Springs, where you see already the first layout of the balloon. Here is the launch truck. The payload is there, and the balloon is also there. You'll see the parachute shortly. And all of this is empty balloon, and it's only this top part that's going to be inflated.

We launch these balloons typically early morning when the wind is very low. We also need a very consistent wind, you'll see shortly why. The direction of the wind should not change by more than 10 to 20 degrees. If it does, you'll lose the balloon. We need to the winds to push the balloon towards the launch truck. So this is then the launch truck, and there's all this empty balloon. And it will remain empty, because as the balloon rises the gas will expand. And so it is only this part here that will be inflated with helium, you see one inflation tube here.

And so that part wants to go up, and so we have to hold it down, of course. And you do that with a very heavy great tons of concrete. And there is this roller arm that holds the balloon down. And then when the balloon is being launched, we flip this arm up, we do it on radio command, and then the whole thing goes up. This is a very critical part in the launch.

As I said earlier, you want your payload back. The balloons are not allowed to fly over certain areas where there is heavy plane traffic, even though the balloons fly way about the planes. We fly them at 140,000 feet. Airplanes fly only 30,000 feet, but you're not allowed to fly over those lanes. So when you get close to that, you're were forced to terminate that flight. And you do that on radio command.

There are squibs here that break those tables, and then the parachute comes down. And the balloon is so brittle, because it's cold there, that the balloon shatters in pieces and comes down all by itself. And often, or not often, we always find the balloon. Also we terminate the flight, of course, when we get close to water, because we would not be able to recover the payload over water.

So here you see the beginning, we're back in Alice Springs. You see the beginning of the inflation. So here is this roller arm here, and this part is going to be inflated. The helium truck there, we have to truck the helium in from the United States, very time consuming, very expensive, too. It was done by the Air Force for me. They paid for that, it was very nice.

And here you see the typical situation. We fly these early morning when the wind is very calm and very steady. Which, by the way, happens only maybe a few days per month. You can't fly every day. You sometimes wait for a long time for the right conditions, and so you see here the inflation going on. And then the sun is just about to come up.

You see the gore lines here. I mentioned to you that these balloons are put together like a tangerine by the women who seal them with filament tape to give them strength. And you see those gore lines here very clearly. And now the bubble is up, and so the roller arm is right here. Inflation is still going on, you can see that, and the sun is just about to rise. I waited for that moment, I thought it was very romantic, it was just at the moment that the sun comes up, at the apex of the balloon-- terrific.

But my real favorite picture is this one, which I took a little later. Now the sun is a little higher, and the inflation was still going on. This is still Alice Springs. And so you see the inflation tubes, and you look at these gores, this incredible tedious work to seal that polyethylene together with the filament tape, hundreds and hundreds and hundreds of these gores.

And here now we are very close to launch. You see here at the time my graduate student, Jeff McClintock, he's now Dr. McClintock. He's at Harvard. You see here the telescope, and then the empty balloon. And then you see the portion that is being inflated. This part, maybe only 80 feet, and that's enough, that's all you need. You get enough free lift out of that. And then as the balloon rises the gas will expand, and then the balloon will completely inflate.

You see radar reflectors here. It makes it easy for us to track the balloon. And here you see the parachute. There's the point where I told you to do the separation. And Jeffrey was doing some last minute changes. This is very shortly before launch.

And here it goes. This is a moment that your heartbeat easily goes from my normal 60 to 140. This is the moment that if things can go wrong, this is the moment they go wrong. This very thin material is all of the sudden released, the helium wants to go up, and it bounces back against the top of the balloon. You get a mushroom effect, you see that. This is the only helium there is. There's no helium here.

And then this whole thing goes up. The launch truck, the engine is already running. You can see the exhaust. The launch truck has to wait for the balloon to be entirely off the ground, and then the trick is that the launch truck has to maneuver itself to get straight under the balloon. And you'll see why that is necessary. And the wind is blowing the bubble towards the launch truck. And if the direction of the winds change during the last few hours of lay out, then we lose the balloon. And we cannot, because the launch truck cannot meet the location of the balloon at the right moment. And then the balloon is ahead, and then we abort the flight.

You lose all your money, but you don't lose your payload, of course. You will still hold the launch truck. And so here you see a close up of that bubble. It makes a tremendous amount of noise. It's like a storm. Really, it feels like a storm. You can see all this material, 15 microns thin. This beating of this material, it's amazing that some of them actually survive. And so now it's picking up.

So the truck is still waiting. some of that pink material, that cover is falling off. You see that here. And higher, you see the helium. This is only helium here, the rest is all empty. The balloon is now almost off the ground. But I was too close in this case to take more pictures, so now I will move back to the United States, where we used to make these launches from Texas-- Palestine, Texas was where the balloon launching station was.

So I will continue to launch from a different site, also a slightly smaller balloon, but it's the same idea. So you see the balloon is rising, and the launch truck is now definitely moving, trying to maneuver itself straight under the balloon. The balloon now-- you see now the truck managed to get straight under the balloon. If the balloon gets ahead of the truck, and if now you commit yourself to a flight-- that means the payload is attached to the truck. And with radio commands we can snap some wires, and then the payload is released.

If the balloon is ahead of the truck, you pendulum into the ground, and you lose your payload. If, somehow, the person on the launch truck commits too early when the balloon is still behind, then, of course, the pendulum pushes the payload into the truck, and that could also destroy the payload. So it's very critical, this moment is extremely critical, the balloon has to be straight overhead within in a few degrees. And then person who is responsible for this launch must also make sure that there's enough tension in the line, so that the payload will actually go up, rather than go down and plunge to the ground.

In other words, have we perhaps lost helium. And all those decisions have to be made in a matter of seconds, and then when the commitment is made to the launch, then the balloon goes up, and you see that here. The payload has been released from the truck, and this balloon is now going up, typically about 1,000 feet per minute. It takes about two and half hours to go to an altitude of about 140,000 feet.

And then it sometimes happens that the balloon fails. This was a beauty, actually. This was a flight from Texas. You see the telescope, and you see the parachute. All that balloon is empty, and all that will fill up as you will see shortly. It will all filled with helium as the balloon rises.

Then occasionally you see this, and you know that things went wrong. Some hole was torn in the balloon during the launch, and that's then end of it. In this case we did not terminate the balloon on the flight on radio command, so we did not separate here, because we were so close to the ground that would have destroyed the telescope, the parachute would not have opened. We just let the whole thing come down all by itself.

So the balloon, in a way, acted like it like a parachute. It just came down very slowly and very softly. There was no damage on the payload at all. So we could fly it again a few days later. And here you see the balloon at an altitude of 150,000 feet. This is the largest balloon that was ever flown, successfully I should say.

I bought this balloon, it was a 52 million cubic feet balloon. I paid a lot of money for that. Today's money would be, easily, $250,000. And a larger was flown later, but not successful. It was not my own, by the way. So this was the largest ever flown at an altitude of 150,000 feet. And you see straight through the material, it's that thin, 15 microns.

And you see the payload here, even. And this is the parachute. And this from here to here is almost 500 feet. What you also see here I these ducts, we call them ducts. They are huge. They are about the size of this exit hole. They are connected to the balloon up here like the veins going into your heart. And then they go to the bottom of the balloon, and they are just open, openly connected to the atmosphere.

And the reason for that is the balloon is so thin, it cannot stand any overpressure, it will pop. So as the balloon keeps rising and the gas expands, there comes a point that the balloon is fully inflated, and you must get rid of your helium, otherwise the balloon would pop. And then the helium just naturally flows out through these ducts. I think there were five ducts that we have. We see three here. So these openings, these five openings here near the bottom are each about the size of this exit hole.

You see here at the time my graduate student, George Ricker, he's now Dr. Ricker, and he is still at MIT, still very active. A lot of this equipment was built by him and then by other students, graduate students and undergraduate, but also a lot of it was, of course, owned by the balloon launching station. And so we had contact with the telescope. We received the data by radio, we could also command the telescope.

And you see me here sitting on the chase plane. We use a small plane, and we follow the balloon, of course at very modest altitudes. In the United States you hop from an airport to airport, you stay as close to the balloon as you possibly can, and then you terminate it when you have to for reasons that I mentioned-- you get over traffic, air traffic, or you get close to water.

In Australia that is harder, because in Australia you don't have many airports in the desert. You only have some airstrips. It is very, very difficult in Australia to follow the balloon, but we try, and we help from little air strip to the little air strip. But at night you cannot do that, because there's no way you can land in Australia. There are no lights on the airstrips.

So this is the kind of plane that we used, we call it the chase plane, to follow the balloon as it starts drifting away. Here's a map of Australia, one of my many successful flights. This is Alice Springs, a desert town. We launched the days before we think we are going to have our flight. We launch better balloons. We track them by radar. They go to pretty high altitudes, 125,000 feet, which gives us a good idea the direction that the balloon will start moving.

And we had all reasons to believe that it will probably go somewhere in this direction. And so we alerted all these radar stations in Australia that they would pick up our payload, because we have radar reflectors, and they could tell us then where the balloon was. And that, of course, we had to do in Australia, you don't have to do that in the United States for the reason that we cannot follow by airplane here. There's no way that you can land there. So we relied on radar stations to tell us where the balloon was.

Instead, however, the balloon went straight south. So our chase plane was perfect, because this is an area where Australia's reasonably populated. And then when the sun sets we didn't quite know where the balloon was anymore. There was no GPS in those days. So we didn't quite know where the balloon was, but then in the morning we picked it up again. And it's gorgeous to see that balloon in the sky. It's unbelievable. It is way more impressive then Venus now in the morning. It is fabulous. When the sun hits that balloon, you see something that you will never forget in your life.

Hundreds of calls to police stations about reports on UFOs.

[LAUGHTER]

PROFESSOR: Hundreds of them, and I can understand that these people have no idea how far it is away. You can't estimate that it's 150,000 feet. And later, I talked to a pilot which was in one of those small airports. And he said, when I saw this thing I said, I'm going to it. And he says, and I went higher and higher and higher and higher, and I couldn't get there.

And I said, well it was a little higher than you can fly. And he realized that it had to be that far. But of course, he never made that connection. So for him it was really a UFO. And I'm not even sure he believed my story when I told him it was a balloon. So when we were getting close to Melbourne, we had to cut it loose, because this is an area you cannot fly over. It is Sydney here, so this is very heavy air traffic, and so you then terminate the flight.

And if everything goes well, it comes down on a parachute. And then the balloon cuts brittle, and the balloon comes down as well. Now how do you recover your payload in Australia where the payload comes down somewhere in the desert, maybe 70 miles away from the nearest house, maybe 120 miles away from the nearest air strip? Well what you do is the following-- you try to find a house close to where the payload is.

So you know where the payload is, because your terminated it, you see the parachute come down, you locate it, you put it on the map for this, and so the location so you can find it again later. And then what you do is you find the nearest house. In this case it was the house of Jack. It was 70 miles away from the payload. And you fly over that house obnoxiously low, you make a lot of noise, you make many dives until a person comes out of that house.

[LAUGHTER]

PROFESSOR: And they know what that means, because they've lived there. They know that you want to meet them at the air strip, at the nearest air strip. Once they come out of that house and they wave at you, you just go back to the air strip and you wait. And we did we did, we waited 24 hours, and 24 hours later there was Jack. Jack was this car. Jack is crazy, always drunk, and his profession was to shoot kangaroos.

There is no windshield in this car, and this is a piece of wood, and he would drive 60 miles per hour on the desert floor, and would have his gun on that piece of wood, and he would shoot that way kangaroos.

We are in contact with the plane. The plane talks us to the payload. So we are in contact you with this telephone. Jack had a dog. And he said, I'll show you something. This is a very special dog. And he put the dog on the roof. He started driving 60 miles per hour, and he would slam the brakes. And the dog would catapult through the air, and I felt sick in the stomach. And then he would say, (LOW VOICE) you can't teach an old dog any new tricks.

He must have done it many times with this dog. He was crazy and I think, also, a little cruel, but we got to the payload. In other words, through the telephone with the airplane overhead, he managed to get us there. And here you see-- oh there's a kangaroo, yeah. By the way, on our way to the payload he shot this one.

Because the moment he saw it he said, sorry, you've got to wait. And then he changed direction, and there he went, and he chased it, and he's amazing, you know-- killed it with one shot. I felt sick in the stomach more than once during that recovery. We also encountered somewhere a koala bear, isn't that nice? Wonderful koala bear in a eucalyptus tree.

Ah, and then we got to the payload. And what did I see, six foot iguana, five feet away from the payload, maybe 10 feet. But it was so scarily close, that I-- I don't know, my stomach was turning, and I was my graduate student, Jeffery McClintock, and I said to Jeffrey-- not that I believed it myself-- but I said Jeffrey, this animal is absolutely harmless, why don't you go first? And Jeffrey did go first, and not only that, but these animals don't move, because they think if they don't move that you don't see them.

During the seven hours that it took us to take the payload apart and to put it on Jack's truck, this animal didn't move at all. So I had plenty of time to photograph it.

And here you see the payload. This was Jack's wife, and this person here came with me from United States. He was from the Palestine lunar launching station, a very competent electronic technician. You may think that the payload is heavily damaged, but that's not really truly. We protect it with crash pad, and so when it hits the ground, it may tumble over, but the crash pad, in general, absorbs most of the shock. So there was absolutely no serious damage in this case.

And then you go back to Alice Springs. You must understand that Alice Springs is a hole in the ground, nothing happens there ever. And so there's a big article in the newspaper, it says "Perfect Balloon Launch". And it says "Balloon Professor Back In Town", they called me the balloon professor. I gave talks for high schools and for the Lion Club, your local celebrity. And then when you read this article, your stomach turns. This reporter had no idea.

I explained to him the whole idea about the absorption of the earth's atmosphere. So we had to get very close to the top of the atmosphere. And all he could think of in his article was, the reason why we fly balloons is because that makes the distance between us and the stars a little smaller.

[LAUGHTER]

PROFESSOR: Yeah. All right, that's enough for now. I had about 20 successful flights in the period of 1966 to 1980. And in 1980 I stopped flying balloons, because then the satellites were completely taking over. I'd fly from the United States, from Canada, and many from Australia. Australia has the advantage that you can see the southern hemisphere, which is a totally different part of the sky from the United States.

I had two free falls I already mentioned to you. That happens when there is a balloon burst and then the parachute doesn't open. And twice did I lose my payload. I was lucky though, and I made several interesting discoveries. We discovered, early on, five new X-ray sources which have never been seen from the rockets. And that is perhaps not so surprising. I mentioned the rockets have only five minutes up there, and in five minutes they scan the whole sky.

We had flights of 20 hours. The longest flight I had was 26 hours. And we are very sensitive above 20 kilo-electron volts where the spectrum is very low, very low flux, so the rockets would never observe that, would never detect that, there's not enough time. But we were able to find whole new sources, a whole new class of sources which had a very high energy spectrum. And now, of course, we know many of those. So that was an early conclusion.

And we also discovered the variability in X-rays as we were observing. So we were looking at Sco X-1. I mentioned Sco X-1 earlier. And as we were observing with our balloon payload, we notice that in 10 minutes time, the flux-- the X-ray, the number of X-ray counts per second increased by about a factor of three. And that was a bombshell discovery at the time, because clearly how on earth can an astronomical object change its intensity by a factor of three on a time scale of 10 minutes?

Imagine that the sun would do that. You look at the sun, and all of a sudden 10 minutes later it's three times brighter. That just that doesn't make any sense. But in any case, we now know that X-ray sources do that. That was discovered in one of my early balloon flights. We also discovered a source that we gave a name GX1+4. One plus four makes the connection to where it is located in the sky, and there was a clear hint of periodicity.

We saw the X-ray signal be periodic, the period was about 2.3 minutes. We didn't have a clue what that meant, but now we do. And you will know shortly, also, what that means. So the big problem is, and then remains, what are these X-ray sources. And I think this is a good moment to have a break. You can think about what they may be, and then after the break I will tell you what they are and a little bit more. So we'll have a four minute break. So enjoy yourself, walk around, and stretch your legs.

[SIDE CONVERSATION]

PROFESSOR: Two minutes left in the break.

[SIDE CONVERSATION]

PROFESSOR: OK then, [WHISTLE] the last time you hear the whistle. What are these sources? These are binary systems. Here is a star, just a normal star burning nuclear fuel. And it is in orbit it with another star, which is either a neutron star or which is a black hole, and it's a binary system. They go around each other like this. And there is somewhere a point between these two stars, while the gravitational pull in one direction is the same as the gravitational pull in the other direction.

We call that the inner Lagrangian point. There's also such a point between the earth and the moon. It's very close to the moon, but there is such a point. And if that point is inside that star-- so when the gravitational pull in this direction is the same as the gravitational pull in the direction of the neutron star-- if it's inside that star, then the matter will flow towards the neutron star, because that's energetically more favorable.

And so since the whole thing is rotating, it cannot radially do that, and so it spirals in through an accretion disc, and then it ultimately ends up on the neutron star. This star is called donor, the name speaks for itself. This disc is called then the accretion disc. And this object is called the accretor.

Now let us assume that this is a neutron star. It can be a black hole, but let's assume it's a neutron star, and that this is the neutron star. And the neutron star has a mass, m, and has a radius, R.

And I take a little bit of matter, just a test particle from a large distance, a little test particle, and I dump that onto the neutron star, and I want to know what is the speed with which it reaches the surface of the neutron star. All of you should be able to do that in 30 seconds-- well not all of you, but most of you. Right, Emma?

All of you who have had 8.01 can obviously do this. It is a matter of conversion, of gravitational potential energy to kinetic energy. And so I can write that down blindly, even if you wake me up at 3 o'clock at night. 1/2 mv squared, m being this mass, v being the speed as it hits the neutron star. It's then mMG divided by r. Not r squared, but r. It is gravitational potential energy converted to kinetic energy. And the little mass never enters into the equation.

If you take for the mass of the neutron star the mass of the sun, but in reality they're probably a little larger, but take the mass of the neutron star. And you take for the radius of the neutron star 10 kilometers, which is enormously small, that is 100,000 times smaller than the radius of the sun. If you do that, you get an enormously high speed of about 1/3 of the speed of light. So that matter hits the neutron star is about 1/3 the speed of light, 100,000 kilometers per second.

And if enough matter is transferred onto the surface of the neutron star, this kinetic energy, of course, is all converted to heat. You get an enormously high temperature, 10 million, 100 million degrees, and that high temperature the radiation that comes out, electromagnetic radiation, is almost all in X-rays. And that is what really is the X-ray source.

If you take a marshmallow, and you throw a marshmallow from a large distance on a neutron star, when it hits the surface the energy that is released, that means the explosion that is caused by the impact is comparable to the energy levels released when the atomic bomb was thrown on Hiroshima at the end of the WWII.

So the X-ray source that we saw from Sco X-1 is really the neutron star. That's where the X-rays come from. And the optical emission comes from the donor, and also some of it comes from the accretion disc, itself. And so when you take this ratio the way I did it for this system, this is really what comes from one of the two objects, and this is what comes from the object. So that's why you get such an absurd ratio. It is not just one object, but it's a binary system.

Neutron stars are formed in a supernova explosion when a star burns its nuclear fuel like our sun. Then there is a heat source, which is the nuclear furnace inside burning hydrogen and burning helium, nuclear fusion. So you have heat production here, and that obviously will make the star grow bigger-- it expands the star at a heat source.

And then there is, of course gravity, which holds the star together. And there's always that equilibrium between gravity and the pressure due to the heat that, the term is then the final size of the star. There's an equilibrium situation. But when all the nuclear fuel has been exhausted-- there comes a time that the nuclear fuel is just gone-- then you get an implosion, because gravity takes over, so the red goes away. But the green always is there. Gravity is very patient, and ultimately gravity takes a chance, and it pulls the whole thing together. And that's a supernova explosion.

We have about one of those every hundred years in our own galaxy. They're extremely rare. Our sun will actually not undergo a supernova explosion. So our sun will not become a neutron star. Stars have to be at least 10 times the mass of the sun-- 10 to 20 times the mass of the sun-- for a neutron star to be formed, or a black hole for that matter.

But our sun will also die at some point when the nuclear fuel has been used up. That's going to happen about five billion years from now, so you don't have to worry yet. In five billion years, the sun will become a white dwarf. It will become the size of the earth, very small. And before that it will actually first become very large, and it will swallow up the earth. It will swallow up Venus, and all kinds of misery, so you don't have to worry about that either.

When a neutron star is formed, the magnetic fields of the star before it became a neutron star may have been very modest. But in the formation of a neutron star, that magnetic field goes up staggeringly. And that has to do with 8.02. If you make a very naive calculation, you get the right answer, maybe for the wrong reasons.

And the very naive calculation is then the following-- if you have a star which has a magnetic dipole field, and you shrink the star, say, by a factor of a million in terms of radius, then the surface area goes down by a factor of 10 to the 12th. But the magnetic dipole field doesn't change, and so at the surface of that new star you get a magnetic dipole field which is about 12 orders of magnitude higher than what you had originally when we star as this big.

So that very naive back on the envelope calculation tells you then that the magnetic field would increase by a factor of 10 to the 12th-- by twelve orders of magnitude. So we have strong magnetic fields, that's 8.02.

And then we have 8.01 which says, yeah, but you cannot shrink a star without speeding it up. There is this idea of conservation of angular momentum. i omega is conserved, i being the moment of inertia. And so if you make the radius of the star 100,000 times smaller, then the moment of inertia, which goes always with r squared, right? I hope you remember that. Yeah, you do?

OK, 100,000 times smaller radius means that the moment of inertia goes down by a factor of 10 to the 10. And that means that omega goes up by 10 to the 10, because i omega remains constant. So this star spins up by a factor 10 billion. So we have a strong magnetic field, the neutron star is spinning like crazy.

And then there's something else. And that is if you have here that neutron star, and here you have this magnetic field-- this magnetic dipole field, which is enormously strong, then there's matter that comes from the side, from the accretor. And that wants to fall onto this neutron star. That matter is highly ionized, because it's hot. But ionized matter cannot just go through like this, because there's 8.02.

And 8.02 says that the force on a charged particle, q, is q times v cross B. This is the famous Lorentz Force. And so you cannot cross these field lines as a cross product between the velocity and B, and so there is a problem. And what happens now-- the same thing happens, by the way, with the earth's magnetosphere-- that as the matter gets close enough to this neutron star, it begins to spiral around the field lines that it can do, and then it ends up on the magnetic poles. And so most of the matter then ends up here and ends up there.

And so you get onto the neutron star two hot spots. They may be no larger then maybe a few kilometers in size, not even that. They may be as small as a soccer field. So that means you have two hot spots. Now imagine that I'm a neutron star, and that here is one hotspot and there is another hot spot, for these are my magnetic poles, but this happens to be my axis of rotation.

So we rotate like this, and you will see a strong X-ray signal, now you see less, now you see another strong X-ray signal, and now you see another strong X-ray signal. So now you will see pulsations. So now you expect that the X-ray intensity varies because you were looking at these hot spots, these magnetic poles. And then there is, of course, the possibility in these binary systems as seen from the earth, it may be that when they go around each other, that the neutron star hides behind the donor star. And when that happens, the X-rays from the neutron star are completely absorbed, because the donor star absorbs the X-rays.

So then you don't see X-rays, and that's called an X-ray eclipse. And all of that has been observed, and I will show you the evidence for that, so that you can fully appreciate what's going on here. So let me then go back to the slides. Make it dark, and I'll show you the idea of a binary system. So this is, of course, just an artist's conception.

You see on the left side the donor, and then you see here the location of the neutron star, or in some cases a black hole. And then the inner Lagrangian point is apparently inside this star, and so the matter will flow, it makes an accretion disk, and gradually finds its way, and then the energy is released the way that we discussed. Gravitational potential energy is converted to kinetic energy.

This data is from one of the early X-ray satellites called the Uhuru-- data from 1971. Horizontally is time-- this is 1 and 1/4 second, so that gives you an idea of the time scale. And this is the X-ray intensity, how many X-rays per unit time were observed. And the actual data are the very faint lines in the back. And they immediately noticed the pulsations, and so then they did a fit to the data, and they came up with this shape.

And they, unfortunately, made that very bold, and so you can hardly see the data anymore. But in any case, it is very clear that you have here the cycle of the rotating neutron star, and the neutron star in this case goes around-- spins around in 1.24 seconds. So from here to here is 1.24 seconds. This object is called Hercules X-1.

Spinning like crazy, think about the sun. The sun rotates about its own axis in 25 days. You can't see that very well, because nothing to recognize on the sun, but it goes around in 25 days. This one goes around this neutron star in 1.24 seconds.

Here we see data from the same source, but on a very different time scale. From here to here is 1.7 days. And I show you this so that you can see the eclipses that I mentioned, the X-ray eclipses. It's a very different time scale. You can't see the pulsations anymore. And so we see that every 1.7 days, a neutron star hides behind a donor, and is invisible until it emerges again on the other side, and then the X-rays come back up again, and this is another set of data. So this is many, many days of data.

And today, we see the overpowering evidence for these objects being binary systems, the eclipses, you see the pulsations, and what more do you want? I am no longer flying balloons these days. Clearly, satellites have taken over. I've flown [INAUDIBLE] observing every conceivable X-ray observatory that you can think of, EXOSAT was a European satellite, ROSAT, the Japanese satellites, Hakucho, Ginga. Tenma was also a Japanese satellite. Rossi X-ray Timing Explorer, which is still up and running. Chandra, it's the big thing in town nowadays. I make observations with Chandra. Newton, XMM-Newton, very important observatory also in orbit-- European observatory.

So I've been doing satellite work for most of my time here at MIT. And in the period 1975 to '79, we at MIT had our own small little X-ray observatory. It was called SAS3, Small Astronomical Satellite number 3. We were running it from my building, the Center for Space Research. George Clark was the principal investigator. 24 hours a day, data coming in, 365 days a year. Compare that with a five minute rocket flight, and it was a 20-hour balloon flight.

It was at that time that an astronomical satellite, which I think it was a Dutch satellite, it was called the Astronomical Madeleine Satellite, it was a collaboration with the United States, that they discovered a phenomenon which we now call X-ray bursts. The person who discovered it was Josh Grindlay, who was at Harvard, and John Heiser, at that time was in Utrecht, the Netherlands.

What they noticed is that when they look at some of these X-ray sources, at one in particular, they all of a sudden in a matter of a few seconds see the X-ray intensity go up by a factor of 10 or 20. It's very bright, and then a few minutes later, it's back to normal. That's referred to nowadays as X-ray bursts. And with SAS3, with our spacecraft, we were ideally suited to search for these X-ray bursts, even much more so than the Netherlands satellites. Our system was perfect. We never thought of that when we designed it, but it just turned out to be perfect.

And in the first two years, we discovered eight new burst sources, and is largely due to those observations, and also due to the theoretical work by Professor Paul Joss, who is still at MIT, that we now know what causes these crazy X-ray bursts. These X-ray bursts are huge nuclear bomb explosions on the surface of the neutron star. What happens is the following.

You got accretion onto the neutron star, and the matter that comes from the donor is largely hydrogen, maybe a little bit of helium, largely hydrogen, and maybe some helium, just like our sun. And so that matter falls onto the neutron star, and it releases then the X-rays, due to what we just discussed, the gravitational potential energy is converted to kinetic energy, but nevertheless, it's still hydrogen as it reaches here, and so it forms a layer onto the neutron star, and the densities are high and the temperature is high, and there's a thermonuclear reaction and it turns the hydrogen into helium.

And then when the temperatures are even higher and the densities are just right, the helium starts to go into a nuclear reaction and forms carbon-12. And that is a very peculiar reaction. You need three helium nuclei, helium-4, and they merge then to carbon-12 and you get energy. This reaction rate is enormously sensitive to the temperature. I forgot the exact number, but I recall something like that it's proportional to the temperature to the power 30, temperature in degrees Kelvin to the power 30.

So when this reaction starts, energy is released so the temperature goes up. When the temperature goes up, the reaction rate goes up, and when the reaction rate goes up, the temperature goes up, and that's what you call a runaway. You get a runaway process, and we call that then a thermonuclear flash. So the whole system gets completely out of hand, and you get a thermonuclear bomb explosion on the surface of the neutron star, which gives the immediate increase, then, in your X-ray signal.

If you wait a few hours, then you build up a new layer of hydrogen, and that goes to helium and you get another X-ray burst. So when you look at these sources, you may see one every hour, one every two hours, or sometimes a few per day. These bomb explosions are about 18 orders of magnitude more powerful than the hydrogen bomb that we can make on Earth.

So the optical counterparts of these X-ray binaries are rather faint. You see the donor, I mentioned that to you in the optical from the ground, and you see the accretion disc, and the X-rays then come from the neutron star. But you can see from the ground, with an optical telescope, you can see the optical counterpart. And we had reasons to believe that if there is an X-ray burst, that somehow it should be followed by an optical burst.

And I can explain that to you best by showing you a transparency. When the X-ray burst occurs, the X-rays go off in all directions. So here you see the neutron star and you see there the accretion disc, and when the X-ray bomb takes place, you see the direction to the earth-- this is the direction to earth, that's where you happen to be, and so you see the immediate increase in X-rays, but the X-rays also go in this direction. And then they hit the accretion disc, and they get absorbed by the accretion disc, and they heat up the accretion disc.

They can heat the accretion disc locally up to maybe 30,000 degrees, much higher temperature than is normally had, and so the accretion disc now begins to radiate an optical light, at least more likely than it did before. And then when this becomes a source of optical light, it goes in all directions, the optical light, and some of it goes in the direction of the earth.

And so the net result is that you first see the X-ray source, and then a little later the X-ray burst, and then a little later, you will see the optical burst, because there is extra travel time from here to there that may take a second, and then there is extra travel time from here to here, it may take another second. And so don't be surprised that the optical flash, the optical burst then, comes a little later.

But if you can measure that delay, then you have succeeded in getting a reasonable idea of the size of these accretion discs. Because if the delay is 10 seconds, then you would know roughly that the radius of these accretion discs might be 5/6 light seconds, but if the delay is only two seconds, that tells you, then, that this distance is probably only one light second. You have to add, of course, this extra distance.

So this was for us a reason to start a worldwide campaign in the summer of 1977. We committed SAS3 to observing one and only one of these stars, binary systems, and we asked everyone in the world who had a telescope, optical telescope, radio telescope, infrared telescope, to watch the optical counterpart. And then we would tell them later when the X-ray bursts were observed, and they would look at the data to see whether there was any change in the optical light from that star.

And I remember that in the summer of 1977, there were 17 countries that contributed. 44 observatories contributed. We saw 110 X-ray bursts from this source, and not a single observatory saw an optical increase or in the radio or in the infrared. So we decided we need larger telescopes, because we were not going to give up. So we tried it again in 1978, and then we succeed. It was a collaboration with Josh Grindlay from Harvard, and also Jeff McClintock, my ex-graduate student, who was also at Harvard at the time.

We succeeded. We saw an optical burst a little bit after we saw an X-ray burst. It was a smashing success. And we made it to the cover page of Nature, which is a very prestigious scientific journal. It was covered in the New York Times, the usual thing, Boston Globe, and even more.

I want to show you an X-ray burst and an optical burst, but not the data from 1978. I have data of much higher quality which we got in 1979, a year later. We pursued this research very heavily. We worked with Holga Patterson, who was in Chile, the European Southern Observatory, and with my collaborator Jan van Paradijs. We often went there and we made the optical observations. By that time, SAS3 was no longer functioning, so we had the Japanese satellite Hakucho looking at the particular object that we were interested in.

And I want to show you first the X-ray burst that was observed by Hakucho. Here is the X-ray burst. You see the time scale. The rise of this burst is unusually slow, that's just the way it is, happens occasionally. This rise takes about five or six seconds, normally it goes up in one or two seconds, but nothing I can do about that. So you see here the data before the burst, so that's the accretion, that is the X-rays that come available because of the matter falling onto the neutron star, and there you see the thermonuclear bomb explosion, and then afterwards here, there's still a little bit afterglow but it settles very quickly to the pre-burst level.

And then Holga Patterson in Chile came up with this optical burst. You'd think it's almost like a carbon copy. And I've plotted it for you in a way that the peak at the same height, that is just an artificial way, but I can scale that, of course. And if now I put the X-ray data on top of the optical data, then what do you see, that indeed, there is a delay. The optical data are a little bit later than the X-ray data, and all you actually have to do is just slide it by two seconds, and they almost become carbon copies of each other.

And so indeed, we succeeded. We were the first to measure the size, the rough size, of the accretion disc at the point where the X-rays were absorbed and then convert it to optical, which then was seen by the earth. And we concluded that the accretion disc was something like one light second in radius, which is about the distance from earth to moon, one light second.

GUEST SPEAKER: Is there a Professor Lewin anywhere?

PROFESSOR: Oh my goodness. I recognize you. What are you coming here for?

GUEST SPEAKER: Well, we came to visit.

PROFESSOR: Not without-- I'm getting flowers?

GUEST SPEAKER: Yes, of course.

PROFESSOR: Oh my goodness. What have I done to deserve them?

GUEST SPEAKER: I don't know. Has he done anything good recently, guys?

[APPLAUSE]

PROFESSOR: Wow. I recognize some of you. This is fantastic.

[SINGING A CAPELLA] Last day of class, am I going to pass? These rays are really quite frightening. They sometimes reflect, they sometimes transmit. Oh, they do both a bit. Transmission lines, wave guides and more, how does a thin film work anyway? Rectangular splits, what do I see? Diffracted intensity.

I start to get the gist, you put your right hand like this, E crossed with B and you're all set. Lewin's a superstar, you made us come so far, we're traveling at the speed of light. Ten years from now, we'll still be here, trying to finish our PhD. We'll say to ourselves, why are we here? 8.03 rocked back in sophomore year. [INAUDIBLE], is it elliptical or linear? Dipole antennas and radiation, what's going on in the far field?

I start to get the gist, you put your right hand like this, E crossed with B and you're all set. Lewin's a superstar, you made us come so far, we're traveling at the speed of light. I start to get the gist, you put your right hand like this, E crossed with B and you're all set. Lewin's a superstar, you made us come so far, we're traveling at the speed of light.

Sorry, girl, but you just failed on that test your ass got nailed, but Walter Lewin is there, he'll work with you because he cares. Now you're dominating class, fifth week flag can kiss my ass, waves and media are no prob, now I'll definitely get that job. Last day of class, am I going to pass? These waves are really quite frightening. We are in love, haven't you heard? Walter Lewin rocks my world.

I start to get the gist, you put your right hand like this, E crossed with B and you're all set. Lewin's a superstar, you made us come so far, we're traveling at the speed of light. I start to get the gist, you put your right hand like this, E crossed with B and you're all set. Lewin's a superstar, you made us come so far, we're traveling at the speed of light.

PROFESSOR: Thank you very much.

[APPLAUSE]

SINGER: Thank you so much.

PROFESSOR: I'm very impressed. Thank you very much, and I gather that the text, which I couldn't always follow, was very much connected to my X-ray binaries. So in that sense, I appreciate it double. Thank you very much. Let me thank you, because I recall you from-- you were in my class last year, right?

SINGER: Yes.

PROFESSOR: Well, I don't know whether there's much time left for you now to fill out the evaluation forms, but that's a problem that you have. The orbital motion of neutron stars and the donor stars give rise to Doppler shifts, which is something that we covered in 8.03. So we have a rotating neutron star which pulsations, it's a clock, the case of Hercules X-1, 1.24 seconds.

And when that clock moves to you, the period is smaller, blue shift. And when it moves away from you, the period is longer, red shift. And you can measure that. You can actually see, as the neutron star goes around, and if it comes toward the earth, that you see a different period than when it goes away from you.

And then of course, you have the donor itself. The donor is an optical spectrum, and you see absorption lines in the spectrum which come from the atmosphere of the donor, and then you see the shift of the absorption lines of the donor. And you worked on a particular case of Hercules X-1, you perhaps remember that in your problem set, whereby we used the Doppler shift of the donor to calculate the mass of the accretor.

And that turned out to be a black hole. That was the first X-ray binary that was discovered in 1972, by Murdin, Webster and by Bolton. A 5.6 day orbital period, and they derived from the Doppler shift that the black hole was something like 15 solar masses. So this has led to a whole new industry of mass determinations of neutron stars and black holes.

And then there is Fourier analysis, which we covered very heavily, or at least sufficiently, I hope, in 8.03, which plays a central role in uncovering these periods. Radio people, X-ray people, optical people, they all Fourier analyze their data. The fastest rotating neutron star that is a single radio pulsar, it's not in a binary system, it has a period of 1.5 milliseconds. Imagine. It goes around more than 650 times per second.

Think about if you were at the equator of that neutron star, you go around more than 650 times per second, you would have a speed of 40,000 kilometers per second, 14% of the speed of light. And it just so happens that only a few days ago, four days ago, an announcement was made that an X-ray pulsar in a binary system was found with a spin period of the neutron star of 1.7 milliseconds. All of this could not have been done without Fourier analysis. This was in a binary system with an orbital period of 2 and 1/2 hours.

We've now come to the end of 8.03. Needless to say that it has swallowed me up completely. I lost 10 pounds. And it has also taken a lot out of Markos, whose dedication was fabulous.

[APPLAUSE]

You should feel sorry for my graduate students and my post-docs, who didn't get to see much of me. I'm not saying that you should feel guilty, but perhaps you should. You were on my mind all the time, and not only at MIT but also at home, in the living room, in the kitchen, in the shower, and even in my dreams. It was a very difficult time for my significant other, Susan, who is here, and Susan at times said to me, it was pure hell. Did you forget, Susan?

SUSAN: Yeah.

PROFESSOR: Good. So life will become normal again, but I think I will miss you. And of course, I make myself no illusions. You will quickly forget most of what we covered in 8.03. Maxwell's equations, Fresnel equations, Rayleigh scattering, the Larmar equation, and even the resonance frequencies of sound in a closed box, all of that will fade away in a matter of months. I just hope for you that it doesn't fade away before next week.

But surely, from now on when you will see a rainbow, you will check that the red is outside. You will look for the primary, you will look for the secondary, you will look for the bright light inside the primary. You can't help it. It's a disease. It is a disease that no one can cure anymore. It will be with you for the rest of your life, and I take full responsibility for it. You cannot resist when you see a rainbow to make those checks, even if you try.

I will be very proud of you when you use your personal polarizers, which I'm sure you will carry with you, because you have one now, to check that the bow indeed is polarized. And occasionally, don't forget the blue sky 90 degrees away from the sun is also 100% polarized. And those who do not have your knowledge will enjoy the rainbows, of course. They will see the pretty colors. But you will now see so much more than just the pretty colors. It's like with art. Knowledge only adds. Knowledge never subtracts.

And if that is all you will ever remember of 8.03, I will have achieved something that has enriched your life, and you will remember me, and I hope those memories will be happy ones. I have immensely enjoyed this term, and thank you for being such great students, and thank you for coming to my lectures even when we had no mini quizzes, like today. Thank you.

[APPLAUSE]

Thank you very much. There is still the 10 minutes left for your evaluation forms. They're there, and they're also in the back. And we will collect them, and Maria will come and pick them up. Thank you, Steve.

AUDIENCE: I enjoyed every one of them.

PROFESSOR: But you've seen some of this already when I--

AUDIENCE: Some of it, like today. But I've been at all your classes the whole time. I learned a lot.