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Transcript – Lecture 35

Today I'd like to talk with you about my early days at MIT and the research that I did here.

This is a long time ago.

I got my Ph.D. in the Netherlands, in nuclear physics, and I came to MIT in January 1966, almost 34 years ago.

And the idea was that I was only going to spend here one year on a postdoc position, but I liked it so much that I never left, and I don't regret it.

I joined the X-ray Astronomy group here of Professor Rossi.

Now, X-ray astronomy has to be done from above the Earth atmosphere or at least near the top of the Earth atmosphere because the X rays are absorbed by air, unlike optical astronomy and radio astronomy, which can be done from the ground.

The kind of X rays that we measure are not unlike those that your dentist is using when he takes an X-ray picture.

The energy range of these X rays is somewhere between one and 30, 40 kilo-electron volts, and if you don't know what a kilo-electron volt is, that's fine, too, but you never express the energy of an X ray in terms of joules, because the number becomes so ridiculously small.

During World War II, under Hitler's Germany, Wernher von Braun developed the V-2 rockets for destructive war purposes.

It was developed in Peenemuende.

And after the war, the Americans used these V-2 rockets for scientific purposes, and the first rocket flights to search for X rays from the Sun took place in 1948.

And X rays were found from the Sun.

That was quite a surprise.

And the power, energy per second that the Sun puts out in X rays divided by the power in optical, which is almost all the radiation of the Sun--

I'll give it the symbol of the Sun--

is approximately 10 to the minus 7, so only one ten-millionth of all the energy comes out in X rays.

So, from an energy point of view, it's very, very little.

It varies a great deal, too.

But it is really very little.

In 1962, scientists here in Cambridge, among them Professor Bruno Rossi, who was a professor at MIT, and Riccardo Giacconi and Herb Gursky--

who were working across the street at American Science and Engineering--

attempted to do an experiment to see whether they could detect X rays from objects outside our solar system.

Now, the odds were very low that they were going to succeed, and the reason is very simple.

If you take the Sun and you move it out to the nearest stars, which is typically ten to a hundred light-years, you wouldn't stand a chance to see X rays.

In fact, the sensitivity of the detectors in these days was too low by at least nine orders of magnitude, a factor of one billion.

To everyone's surprise--

to everyone's, yeah, happy surprise, I should say--

they succeeded, and they discovered an object which was later called Sco X-1.

It's in the constellation Scorpius, "X" stands for X rays, and "1" for the first X-ray source in that constellation.

The total power output of that source was about 10,000 times more than the Sun.

That doesn't make the source so special, because there are many stars in the sky that radiate way more energy than our Sun does, but what's so very special about Sco X-1, that the X-ray power over the optical power for Sco X-1 was approximately 1,000.

In other words, the X rays are the dominant source of energy and the optical is sort of, let's call it a by-product, whereas with the Sun, the optical is the main thing and the X rays is sort of a by-product.

And so the $64 question in those days was, what can these objects be? They must be very different from the Sun, and that's what I want to discuss with you.

When I came to MIT in 1966, there were about six of these X-ray sources known in the sky.

Today there are thousands known, but there were six then.

And they were discovered from rocket flights.

These rockets would be launched, typically from White Sands, and they would spend about five minutes above the Earth atmosphere.

And during those five minutes they scanned the sky, and six sources were discovered.

I joined here the group of Professor George Clark, who is still a professor at MIT.

He was working on observations to be made from very high-flying balloons.

So we would build a telescope, and we would launch it on a balloon, and go near the top of the Earth atmosphere.

It's not as good as a rocket flight which gets completely out of the Earth atmosphere, but the flights on balloons can last way longer than five-minute rocket flights.

We could fly hours and, if we were lucky, even days, but the price we paid for that is that even though there was only very little atmosphere left above us--

about 0.3 percent of the atmosphere was left--

still that caused an effect of the absorption, so we did lose X rays that the rocket flights did not lose.

But we had the great advantage of many, many hours.

To give you a rough idea of what it took in those days--

I worked on this with graduate students and with many undergraduate students--

a telescope in those days, to build it cost typically a million dollars, and it would take us two years to build one.

The balloons that we needed to launch them were about $100,000 in those days, and the helium that we needed to get it up was about $80,000, and the weight of such a payload, of our telescope, was about 1,000 kilograms.

These balloons would go up to 140,000 feet and they were huge--

they were about 500 feet across.

I will show you pictures of them very shortly.

It was a risky business in that no guarantee of success.

You bought the balloons.

If they worked, so much the better.

If they didn't work, tough luck.

There was just no way that you could recover the money.

They were very thin; the balloons are made of polyethylene, and the thickness of the polyethylene was thinner than cigarette paper, so you can imagine how easy it is to damage them, and if you don't damage them during the launch, it's easy to damage them on the way up, due to the jet stream and the very cold layers of air that you have in the tropopause.

So I would like to show you now some slides, and then we will get back to talking a little bit more about X-ray astronomy.

All right, so let's see what we have first.

You see here two of my undergraduate students.

At the time they were undergraduate students.

Now they are both Ph.D.s, and some of you may think that science doesn't have much romance, but there is a lot.

They married and they have kids.

This is Pat Downey; she's still very important in working with me on PIVoT, and this is Jim Ballantine.

They were working on the electronics, which is an enormously tedious task, to do the wiring of the electronics.

And here you see the plant in Texas where these balloons were built.

These were extremely long halls, as you can imagine.

And here the gores of the balloon, which are like pieces that you see on a tangerine, on the surface of a tangerine, they were sealed together with heat sealers.

And only women were allowed to do this work because it was well known that men are too impatient and make many more mistakes.

And so only women were allowed there.

It was nothing to do with discrimination, but simply because women were better at doing this work.

Here, a balloon comes out of a box.

This is a picture I took in Texas, where we launched balloons from.

It's nicely covered with this pink sheet and we have this huge cloth on the grass because the balloon is so thin that if you would put it on the grass, it would get damaged right away.

I told you, the skin is about...

thinner than cigarette paper, so it's carefully taken out and we inspect it closely.

And in this case, there was some concern that there might be a hole in the balloon.

In fact, there was at least a hole in the pink cover, and so we carefully inspected whether the hole propagated deeper in.

I wasn't too worried, because this was not my balloon, but nevertheless, it's always sad if you see some of your colleagues having a balloon that doesn't get up.

And now I'm taking you to the desert town in Australia, central Australia--

Alice Springs.

I've launched many balloons from Alice Springs.

And now you get a pretty good idea of what the launch is going to be like.

Here is the launch truck, and the telescope is on the launch truck.

And all of this is empty balloon, and here is what we call the roller arm--

it holds the balloon down, and only this part of the balloon is going to be inflated.

Here is the helium truck, and here are the inflation tubes through which we inflate.

The inflation takes place almost always early morning or near sunset in the evening, because that's when the wind is very calm, and we need very calm conditions.

It is this part of the balloon that is going to be inflated, and so there's going to be a huge force, the buoyant force--

I hope you all remember Archimedes' Law--

of several thousands of kilograms' force up.

And so this vehicle here weighs about four or five tons to hold it down.

And when we launch the balloon, we actually release this arm; we flip this arm up.

And so you will see, then, how the balloon will make it on the way up.

So this is Alice Springs, Australia, again.

The Sun is rising, and we started the inflation.

You see here the inflation tubes, and we put the helium in the balloon.

This is the very critical phase of the launch, because if there's a little bit of side wind and the balloon touches the ground, then it's all over.

Then it just gets damaged, and you abort--

you don't even continue.

This is a little later, when the... we call this the bubble.

This is the roller arm here, and this is all this empty balloon in your direction, and this part is only some 80 feet high or so.

And here you see these gores that I told you about earlier.

This is all this tedious work that is done by these women, who seal these gores together, and they all come together here at the apex, in a big aluminum plate.

All right, now you see the situation from the launch truck site.

Here you see the radar reflectors, so we can follow the flight by radar; you see the telescope here--

I won't go into too many details.

This is a ballast box, which contains about 500 pounds of lead shot, which we can drop on radio command.

I believe this was Jeffrey McClintock, who was one of my graduate students at the time.

You see here the parachute.

There's a connection between the parachute and the bottom of the balloon and we can cut that on radio command, and then the telescope, we hope, parachutes safely back to Earth.

And here's all empty balloon, and here is the bubble, that part that was just inflated.

They're still inflating here, but they are already tying off this inflation tube, so we are actually getting very close to a launch.

And here is the moment of launch.

This is a moment that no one will ever forget who watches a balloon launch.

You feel ants in your pants and butterflies in your stomach.

It is a very tense moment.

If things go wrong, this, in general, is the moment that things go wrong, because when the roller arm is here released, then this enormous amount of free lift, the buoyant force, drives this thing up and you get a bouncing effect.

You get an oscillation of the helium in this upper part--

we call this the mushroom.

And that can already destroy the balloon right away.

The layout is such that we always lay out so that the wind will drive the balloon towards the launch truck.

And you will see later on why that has to be done.

So the launch truck can maneuver itself straight under the balloon, and make sure that the balloon is carrying the telescope before we release the payload.

The payload is now tied to the launch truck.

We have to wait for the whole balloon to be off the ground before the launch truck can actually maneuver itself under the balloon, but you already see that the...

by the exhaust that the engines are already running.

You see a close-up here of this mushroom, and it makes a tremendous amount of noise.

It's really scary.

I'm always surprised, when I see a launch like this, that the balloon, so thin, can actually survive this tormenting launch.

So here it goes higher, comes in this direction, as you see, getting closer and closer to the launch truck, rises higher in the sky and, in this case in Alice Springs, I was so close to the launch that I couldn't follow the bubble going up much further with my camera, so the next picture that you're going to see I took from Palestine, Texas, from which I've flown many balloons.

So it's a different launch, but it is sort of the same stage in the launch that you see here.

Alice Springs was beautiful, by the way, always very nice, clear skies; it's a very fantastic desert there.

It's a wonderful desert town.

It's really in the middle of nowhere.

Okay, so now we're in Texas and you see here the launch truck.

This is the telescope, it was a different telescope.

You see the parachute, and now the trick is for the truck to get under the balloon.

The amount of helium that is in the balloon is only a small fraction of the total volume.

It's just enough for us to get the free lift.

We want to go up at about a thousand feet per minute, and then, since the atmospheric pressure goes down when the balloon goes up, the helium expands and finally fills the entire volume, as you will see.

So now is the moment, this is a crucial moment that the launch truck has actually maneuvered itself straight under the balloon.

And now the person on the launch truck makes sure that there is enough tension in these lines to pick up the telescope.

If the balloon were a little bit too far ahead or too far behind and you released the telescope, then, of course, it would pendulum into the ground and you would lose it, so it's very important that it be done when the balloon is straight overhead.

But that alone is not enough; there must also be enough pull on it so that the telescope doesn't crash to the ground vertically.

And when there is any chance that things go wrong, we just abort the flight, because the telescope is so much more expensive than the balloon, even though the balloon and the helium together is close to a quarter-million dollars.

And here you see it after release: payload, parachute, empty balloon and here, the helium.

And this, from here to here, oh, is about two-thirds of the height of the Empire State Building.

These are huge, huge balloons.

And here you see it at an altitude of 150,000 feet.

This is the largest balloon that was ever flown successfully.

It's still the world record.

It was a balloon with a volume of 52 million cubic feet.

This picture was taken through a telescope.

And you see here the telescope, and you can look straight through the balloon; it's that thin.

From here to here is about 500 feet, almost 600 feet.

All right, here you see my ex-graduate student.

He's now Dr. Ricker, George Ricker.

He's still a staff member at MIT.

This is in Australia.

A lot of this equipment was built by undergraduates and graduate students of mine; a lot of it we borrowed from the balloon launching stations.

And the radio data come in here, and we can command the telescope from here.

We can orient the telescope, we can draw ballast and, very important, we can terminate the flight.

So that we rescue, that we save the telescope when it starts drifting out over the ocean.

Because the balloon starts going with the winds at the altitude of 150,000 feet, and those winds can vary anywhere from 20, 30 miles per hour up to 100 miles per hour.

We try to fly only during the days that the wind is low, and that's the case in the spring, and in the fall, we call that the turnaround.

The winds at these altitudes change twice per year.

They change from about 100 miles per hour to the west, to 100 miles per hour to the east.

It happens in the spring and in the fall, and that's when we try to fly, when the winds are very low, when they are in the process of turning around.

We follow the balloon at low altitude--

5,000, 6,000 feet.

It's a small airplane.

I'm sitting here on the airplane.

This is a typical airplane that we use to hop from airport to airport and stay as close to the balloon as we can, so that we can give the "terminate" command.

And later we can recover the payload, which is an adventure all by itself.

In Australia, that is much harder than in the United States.

This was El Paso, but in Australia, there are no airports in the desert, and so that is way harder to hop from place to place.

I'm taking you to Australia now, here is Alice Springs.

And when we launched this flight, the days before, we had balloons, weather balloons, test balloons, which we drove up to 140,000, 150,000 feet, and then we probed the winds at that altitude.

And the people who did that give us good reasons to believe that the balloon would either go sort of in this direction or maybe here, but in any case, it would go north-northwest.

And so we alerted all these radar stations in Australia to look out for the balloon--

that we have radar reflectors, so they could give us an early warning, because between here and here, there are really no airports.

So if we follow this by airplane, you can land during the day at some air strips, but really, there are really no runways, so that's pretty dangerous.

At night, you couldn't land here.

And so we were hoping that these radar stations would give us an early alert and tell us where the balloon is.

What happened, however, the balloon went straight down.

And then it was sunset, so we don't know exactly where the balloon is at sunset.

We can't see it, but we have radio contact with it and so we were flying close to it.

And then at sunrise we picked it up, we could see it, and then here, when it was getting close to forbidden zone--

because there is commercial flights here--

we cut it down, so we gave the radio command which separates the parachute from the balloon.

The balloon is very brittle--

it's very cold there.

The balloon shatters, breaks in pieces, comes down and, if everything goes well, then the parachute brings the telescope safely back to Earth.

This is the person that we contacted during that flight.

You try to draw the attention of local people, and you do that by flying with your airplane low over their house.

This person lived in the desert, and his nearest neighbor was from 70 miles away from him.

He was crazy, he was always drunk...

[students laugh]

he was shooting kangaroos in the desert.

There is no windshield here.

He would drive 60 miles an hour, and then he would chase these kangaroos and shoot them.

And he had a crazy game which I didn't like at all.

He would put the dog on the roof--

and he gave me a demonstration once; I was with him in this truck--

and he would drive 60 miles per hour, would slam the brakes, and the dog would catapult through the air, and then he would say, "You can't teach an old dog any new tricks." We encountered wonderful animals during recovery: koala bear, quiet, peaceful, very lazy, unlike most 8.01 students.

[students laugh]

And then, when we got closer to payload--

it took us a day and a half to get to the payload--

there was this nasty iguana, he was about six feet long.

And let me tell you, I was really scared.

It scared the hell out of me.

But of course I didn't want to show that, so I said to my graduate student, "There's no problem, these animals are harmless; you go first."

[laughter]

And he did, and it turns out they are harmless, and during the entire four hours that it took us to recover the payload and get it on Jack's truck, this animal was just sitting still, didn't move at all.

That is his way of thinking that we don't see him, then.

Beautiful animals, these iguanas.

The aborigines eat them, it's very precious food, by the way.

So here you see Don Brooks, who was an American who came with me.

He was an electronic expert, and this is Alice, which was the wife of Jack.

You see the payload here, tumbled over, but it's in good condition.

The crash pad is there purposely to protect against the impact, to get a lower deceleration, and, of course, it's okay that that cardboard crash pad is destroyed--

that's the whole idea.

And then when you come back a few days later in Alice Springs, it's... nothing happens, ever, in Alice Springs.

I mean, it's completely a hole in the ground.

So this front-page news, "Perfect Balloon Launch" and "1,000 watch the start of a space probe"--

they called it a space probe.

I had a long interview with this news reporter, and I told him that the reason why we have to go high is because of the absorption of the X rays in the Earth atmosphere, but the article didn't get that across.

They said, "They fly balloons because then they're closer to the stars." Well, I suppose that is close enough, but it really missed the issue of the absorption of the X rays, which of course... that's the reason why we have to go up, not because we want to get closer to the stars.

Okay, so now I'll go back to the blackboard, if I can find my way.

So between 1966 and roughly late '70s, I had about 20 successful flights from the United States, from Canada, and many from Australia.

Now, we also had some problems, we had some bad luck.

Twice during my flights, the balloons popped.

70,000 feet, there is the tropopause; it's very cold, -70 degrees.

There are jet winds and they beat on the balloon, and then the balloon can burst.

And when that happens, we don't have enough time to terminate the flight--

we can't separate the parachute from the balloon; it happens all of a sudden--

and then, in general, the parachute gets entangled and then you get a free fall.

So the payload is entirely destroyed, and that happened twice.

But we were lucky enough that at several occasions we made some interesting discoveries.

During the early years of X-ray astronomy, we discovered five new X-ray sources, so we doubled the number of sources that were known from rocket flights before us.

And some of these sources that we saw from balloons were highly variable.

We noticed an X-ray flare; the X-ray intensity went up by a factor of three or four on as little time as ten minutes.

And that was completely new in those days, and that could not have been discovered from rockets, because the rockets themselves are only five minutes above the Earth atmosphere, and they're not looking at one source all the time.

They are scanning the sky, because their objective was to find as many X-ray sources as they could.

But we were up sometimes 26 hours, so we had plenty of time to look at one portion of the sky for a long time, for hours on, and so it was not an accident that we discovered these flaring events which lasted up to ten minutes and longer.

We also discovered an object which we called "gx1+4"--

the number has to do with where it is in the sky--

and we noticed, much to our surprise, that the X rays seemed to fluctuate in a periodic fashion, 2.3 minutes.

At the time, we had no clue what that meant, but later, as you will see very shortly, it became clear that that was the rotation period of a neutron star.

So the big question was, in the early days: What are these objects? And this is something that we have discussed in 8.01 and I will go over it very briefly again, but we discussed it and you even had some homework problems on it.

These objects are X-ray binaries, whereby one object is very compact--

which could be a neutron star, or in some cases even a black hole--

and the other object, the other star, is a normal nuclear burning star, something like our Sun.

And they are very close together.

They are so close together that the matter, which is here, is attracted by the neutron star stronger than it is attracted by the star itself, and so it starts to find its way to the neutron star.

This is a binary system, so they go around each other.

This matter cannot just go in radially, but it would spiral in slowly and find its way to the neutron star.

Strangely enough that we still don't understand how it makes it, but it does make it, ultimately, to the neutron star, and this is, then, what we call the accretion disk.

This is the accretor and this is the donor.

The donor provides the fuel that finds its way to the neutron star.

And if you take a little bit, mass m, and you drop that on a neutron star--

and a neutron star has mass capital M, say, and radius capital R--

then the kinetic energy that is released at impact is something that all of you should be able to do next Monday.

That is the following: mMG divided by R equals one-half mV squared.

This is the gravitational potential energy that becomes available if an object of mass little m crashes onto the star.

The surface of the star has a radius capital R; the mass of the star is capital M.

And that is converted to kinetic energy, which is one-half mV squared, so this is the speed at impact.

Of course, it's always independent of little m, and so you can calculate that speed and that speed is horrendous for a neutron star, the reason being that the radius of the neutron star is so absurdly small; it's only ten kilometers.

It is roughly 100,000 times smaller than the radius of our Sun.

The mass of the neutron star is comparable to that of our Sun--

a little larger, but it's comparable.

But it is the radius which is so small, and that's why you get a speed at impact which is about one-third of the speed of light.

And this kinetic energy is converted to heat--

for the same reason that when we drop something here on the floor, that the kinetic energy ultimately goes into heat--

and so it heats up the surface layers of the neutron star, and the temperature becomes horrendously high, ten to the seven, ten to the eighth degrees--

10 million, 100 million degrees--

and at that very high temperature, almost all the energy, almost all electromagnetic radiation comes out in the form of X rays.

The Sun has a temperature of only 6,000 degrees; most of it comes out in the form of optical light, but when you go to 10 million degrees, that's no longer the case.

The spectrum shifts in favor of the X rays.

The amount of energy that is released is horrendous.

To give you some feeling for that, if you take a marshmallow and you throw a marshmallow from a large distance onto a neutron star, then the energy that is released, which is this energy, is comparable to the energy that was released of the atomic bomb that was thrown on Hiroshima and Nagasaki.

So that tells you something about the enormous gravitational forces that are at work on the surface of a neutron star.

We know now what these systems are; the evidence is overwhelming.

We have observed the rotation of the neutron stars.

The 2.3 minutes that we found, we now know is the rotation of the neutron star.

These neutron stars have a strong magnetic field, and the matter that accretes onto the neutron star reaches the magnetic poles.

In 8.02 you will see...

you will learn why this plasma, which is highly ionized, why that cannot just reach the neutron star anywhere, but it is forced to only enter the neutron star near the magnetic poles, and if the neutron star rotates, then the magnetic poles can rotate like this.

And when you are on Earth, you see X rays, X rays, X rays, no X rays, X rays and so you see pulsations.

And so these pulsations have been seen from many neutron stars now, from many of these binary systems.

It's very clear that it's a binary system.

If you are in the plane or near the plane of the orbits of the two stars, then the neutron star can go behind the donor, and then you don't see any X rays, because the X rays are then absorbed by the donor.

And then you see an X-ray eclipse, so the X rays vanish.

So you would see the pulsations, strong X-ray signal, and all of a sudden, boom--

it's gone.

And then a few hours later, it starts up again when the neutron star reappears, reemerges from the donor star.

So that picture is all very clear, but I do want to show you at least a sketch of what we think such a system would look like, which is just the next slide, and maybe the person in the booth...

Oh, I can do it from here.

So this is what it sort of looks like.

You see the donor there on the left, and you see here the neutron star, or it could be a black hole--

that's sort of the same idea, you would not be able to tell--

and you see how the matter swirls in.

Of course this is a not a real picture, this is a sketch made by an illustrator.

We know hundreds of these systems in our own galaxy, and, of course, there are many in other galaxies as well.

I discussed with you in 8.01 that if you measure the Doppler shifts of these stars--

and if you are lucky, you get the Doppler shift both from the pulsations of the neutron star and from the optical lines in the donor--

that you can even find the mass of both the star here and the star there.

And if the mass becomes horrendously high, as in some cases, then you have to conclude that you are dealing with a black hole.

And you had a problem on section...

in one of your homework assignments.

I'm no longer flying balloons, because all the work that I do nowadays is done, of course, from satellites.

You get 365 days per year data, you are always above the Earth atmosphere, so that's clearly the way to go.

And I have used European satellites, Japanese satellites, and nowadays I am using the Rossi X-ray Timing Explorer, which is an American satellite, and Chandra, which was launched early this year, which is the biggest thing in town.

In 1975, here at MIT we had our own satellite, called SAS-3.

And we operated SAS-3 from the Center for Space Research, which is Building 37, where my office is, 365 days per year, 24 hours per day.

And in '75, Josh Grindley, from Harvard, and John Heise in Utrecht, the Netherlands, discovered something which we call an X-ray burst.

And an X-ray burst is a phenomenon that you see the X-ray signal become very strong all of a sudden.

In about one second, it becomes ten times stronger, maybe 20 times stronger than it was before the burst, and it peters out on a time scale of about a minute or so.

And we were very lucky at the time, 1976, with SAS-3, that we could do research on these X-ray bursts and within a year or two, we discovered eight more of these burst sources.

And it is largely through that work--

that observational work that took place--

and through the work, theoretical work by Professor Paul Joss, who is still at MIT--

that we now know what causes these X-ray bursts.

They are nuclear bomb explosions on the surface of neutron stars.

What happens is that on the surface of the neutron star, the matter that accretes--

which is largely hydrogen and helium from the donor--

becomes very hot, it becomes very dense, and at that high temperature and at very high densities, you get thermonuclear fusion.

And a reaction that can take place is that three helium nuclei--

helium-4--

fuse to form carbon-12, and when that happens, energy is released, thermonuclear energy is released.

This reaction is extremely sensitive to temperature.

When energy is released, the temperature goes up.

When the temperature goes up, the reaction rate goes up, then the temperature goes up, then the reaction rate goes up even further, and the whole thing gets out of hand and that's why it is a thermonuclear explosion.

We call it a thermonuclear flash, so it is an uncontrolled, runaway process.

And the bomb explosion that occurs on the surface of the neutron star would be a billion times a billion--

a billion times a billion, ten to the 18 times more powerful than hydrogen bombs that we can make here on Earth.

We speculated early on that when you see an X-ray burst in the sky, that you may be able to see also an optical flash in the sky.

The donor stars and the accretion disk emit optical light.

It's very faint, there are very faint sources, but you can see them from the ground with your optical telescopes.

And we had reasons to believe that we might see an optical flash when an X-ray burst occurs, and I'll tell you why we believed that was the case.

If you have here a neutron star and here you have the accretion disk, and if the bomb explosion occurs--

these red wiggles are the X rays--

then the stuff that goes straight to the Earth you will see.

But there are other X rays which go in this direction, and the heat of the disk...

we call it X-ray heating.

And the disk locally would get a temperature of maybe 30,000, 40,000 degrees and brightens in optical.

So we expected that we should see that effect, that effect of X-ray heating.

But our goal was even more ambitious.

You see, the optical light that comes from here must be delayed than the X rays that go straight to the Earth, because first the X rays travel in this direction, and then the optical light goes in this direction.

So if I put my pencil here, this is the extra path that the electromagnetic radiation is going, and that takes time.

And if that takes one second, then that means this distance is one light-second.

If it takes 20 seconds, this distance is 20 light-seconds.

So our goal was to actually measure, for the first time, the dimensions of the inner part in the accretion disk.

And so we organized a worldwide campaign in 1977.

17 countries were contributing, 44 observatories, and we told them that we were going to look at a particular star in the sky, a very faint star, which was this X-ray binary system.

We would record with SAS-3 the X-ray burst, and we wanted them to record--

in the radio, in the infrared, wherever possible, in the optical--

whether they would see a change in the appearance, in the optical or in the radio appearance.

In the summer of 1977, we saw 110 bursts from a particular burst source.

None of them were seen in the optical or in the radio--

zero results.

We did it again in 1978 and then we succeeded.

This was in collaboration with Josh Grindley from Harvard, Jeffrey McClintock, who was my ex-graduate student--

he is now also at Harvard--

and my good friend Jan van Paradis from the University in Amsterdam, who worked with me at the time here at MIT.

This was a splashing result--

simultaneous observation of an optical flash with an X-ray flash--

and it was on the cover sheet of Nature, which is a very prestigious journal in which people publish, so we were extremely happy.

I do want to show you the simultaneous events but not the 1978 event, but I'll show you one that is more impressive that my colleague Holger Pedersen observed a year later, when he did the optical work from Chile.

This is that observatory that I mentioned to you earlier.

I have been there many times myself.

It's in La Silla, 2,400 meters above the ground.

This is where the atmospheric pressure is only three-quarters of an atmosphere, and where you can't boil a soft-boiled egg because the temperature of boiling water is only 92 degrees.

Okay, here is the optical flash that Holger observed, and we were looking with the Japanese satellite, which was called Hakucho.

SAS-3 I think was no longer operating at the time.

You see here the time of the optical signal, so this is the strength of the system in quiescence and then the X-ray burst occurs, and we see here clearly an optical flash, and here you see the X rays from Hakucho.

They look very similar, but now comes the interesting part.

Of course, I have scaled them up here on the view-graph so that they have the same height.

That's just artificial, of course.

But now comes the interesting part.

If I overlay them, then look at the blue line, which is the optical--

it's clearly delayed relative to the X rays, and that was our goal.

And this was really a very clean observation, cleaner than our 1978 observations, and if you move the optical back--

or the X-ray forward, whichever you want--

by about two seconds, then they almost exactly overlap.

And so this was conclusive evidence that the dimensions of the disk, of the accretion disk around these neutron stars, had typical dimension of about two light-seconds, of that order.

We suspected that, for other reasons, but nevertheless, this was the conclusive evidence.

The bad news is that during my past term that I was lecturing 8.01, I have been able to do nothing but 8.01--

no research at all.

And I think you have all the right to feel guilty about this.

[class laughs]

Very guilty.

Now, the good news is that I enjoyed it, and whether you like it or not, you were on my mind almost all the time, day and night.

I had even nightmares about it, and a typical nightmare that I would have is the following.

I would come into 26.100, but I lost my lecture notes and I couldn't find them and I was completely ill-prepared, but I would start my lectures anyhow, and you would start laughing at me and I would wake up in sweat.

I don't think we need Freud to explain that dream.

Now, I have enormously enjoyed lecturing 8.01, and in a way, you have touched my life and I trust that I, too, have touched your life.

Now, I make myself no illusions.

I am sure that you will very soon forget Kepler's Third Law, although I hope it won't be before Monday, when we have the final.

[class laughs]

And you will probably also forget how to properly apply the conservation of angular momentum.

But perhaps you will always remember from my lectures that physics can be very exciting and beautiful and it's everywhere around us, all the time, if only you have learned to see it and appreciate the beauty.

And surely, when you go on your first monkey hunt, wearing your own safari hat, or when you will orbit the Earth and you want to throw a ham sandwich to your friend, you may be thinking of me.

And I hope those will be happy memories.

I wish all of you the very best, and I thank you for attending my lectures.

[class applauds]

LEWIN: Thank you.