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8.02 Electricity and Magnetism, Spring 2002
Transcript – Lecture 36

Today I would like to talk to you about some of the research that I did during my early days at MIT.

It's a long time ago.

I got my Ph.D in the Netherlands on nuclear physics and I came over to MIT in 1966.

I was supposed to be here only for one year.

I had a one-year postdoc position.

But I loved it so much I never left.

I changed fields.

I joined the research group of Professor Bruno Rossi here at MIT, I changed from nuclear physics to x-ray astronomy.

X-ray astronomy speaks for itself.

You're trying to do astronomy in x-rays.

You cannot see any x-rays from the ground because the earth atmosphere absorbs them completely.

So you have to go outside the atmosphere unlike optical astronomy and radio astronomy which you can do from the ground.

When I use the word x-rays I'm thinking of the kind of x-rays that your dentist would be using, medical purposes, about 1 to 50 kilo electron-volts.

And since all of you took 8.02 you should know by now what a kilo electron volt is.

Uh, optical light is 2 electron volts, where x-rays, way more energetic than optical light.

Uh, during the Second World War Wernher von Braun in Peenemunde developed under Hitler Germany destructive rockets.

They were used to destroy the Allies.

To destroy you and me.

And after the war, around 1948, the Americans used these rockets to do science.

They also got Werner von Braun over to this country and for reasons unknown to me he became a hero.

They tried to observe x-rays from the solar system.

And they found indeed that the sun emits x-rays.

The sun is very close.

So you may say well that's not a surprise.

But it's really very unusual because to create x-rays you need extremely high temperatures, which we didn't think existed on the sun.

And if you take the power that the sun puts out in x-rays, this is joules per second now, and you divide that by the power in the optical and the infrared light of the sun, this symbol stands for sun, that ratio is about 10 to the -7.

So you must conclude that the sun emits largely optical light and infrared and that the amount of x-rays is a modest byproduct.

Interesting as it is all by itself.

In 1962 several scientists here in Cambridge, Massachusetts, among them Bruno Rossi and Riccardo Giacconi and Herb Gursky, made an attempt to observe x-rays from stars outside our solar system.

The odds were strongly against them.

The detectors were not sensitive enough.

If you take the sun and you bring the sun to the nearest stars, which is a distance say of 10 light-years, then there would be no hope that you would be able to detect x-rays from an object like the sun.

In fact the detectors were too insensitive by about a factor of one billion.

They tried anyhow and they were successful.

They did indeed find to everyone's surprise and joy, they found x-rays from at least one object outside the solar system.

This object was later called SCO X-1.

SCO stands for the constellation Scorpio in the sky and X for x-rays and 1 for the first source observed in that constellation.

We now know that this object is a faint blue star.

And what is extremely special about the object SCO X-1 is that if you take the ratio x-ray power over optical power then that ratio is about 10 to the 3rd.

Compare that with the sun.

This object, we had no clue what it was in those days, primarily emit x-rays, and the optical emission is a byproduct.

Whereas with the sun it is reversed.

And so the burning question was in those days, what kind of animal is this?

It must be a totally different beast.

Something very different from our sun.

And when I came to MIT in 1966, there were six sources known outside our solar system.

And they were all discovered with rockets.

The rockets in those days could spend about five minutes above the earth atmosphere and they would quickly make a scan over the sky, five minutes, that's all they had.

And I joined the group of uh George Clark, who is still at MIT, uh he was doing x-ray astronomy from very high-flying balloons, very close to the top of the atmosphere, and the advantage of balloons was that you could observe the sky for many, many hours, if you're lucky sometimes even a day or more.

But on the other hand, since there is always a little bit of atmosphere left above you, even though there's very little, there is still some left, the x-rays are absorbed, almost all x-rays below 20 kilo electron-volts would be absorbed, and we would not be able to see them.

But of course the compensation was that we could look at the sky for many, many, many hours.

Nowadays no one is doing these balloon observations anymore.

No more rocket observations.

Everything is done of course from satellites.

So when I came to MIT, together with George Clark, I developed new x-ray detectors for these balloon observations.

Many graduate students were involved.

Many undergraduates.

It would take about two years to build a telescope.

To give you a rough idea it would take a million dollars in terms of 1966 dollars, and the weight of such a telescope would be roughly 1000 kilograms.

The balloons in those days would cost about $100,000 to get us up to these high altitudes, and we would need about $80,000 of helium, and you will see some slides of that.

We have to go to altitudes of about 140000 feet.

We had huge balloons for that.

You will see one.

They have diameters of about 600 feet.

And the material was polyethylene.

Extremely thin to make them light-weight so that they can go high.

The thickness of that polyethylene was about half of one-thousandth of an inch.

Which is thinner than the saran wrap that you have in the kitchen.

It is thinner than cigarette paper.

A very risky business to fly these balloons.

No guarantee of course that they would work.

You pay your money.

If they work that's great.

If they don't work that's just tough luck.

There is a good chance that you have a failure when you launch the balloon.

They're very fragile.

There could be damage right at the launch.

But even if they make it up in the atmosphere they have to go through the tropopause, near about a hundred thousand feet where it's very, very cold, the balloons get brittle, and then they can burst.

And that of course would be the end then of that balloon flight.

And that could also be the end of a Ph.D thesis.

Because that all these flights of course were connected with research and therefore with Ph.

D work and so the tension during these early phases of the launch were always extremely high.

Sometimes even unbearable.

So now I would like to show you some slides, which will give you a good idea of what these expeditions were like.

Oh, yeah, a classic problem.

This is nice that these -- ah, now they work.

All right, so if I can have the first slide, you see here Jim and Pat who at the time were undergraduates, they are now both Ph.Ds, and they are working there, very tedious work, trying to put the electronics together.

You may think that science is not very romantic.

But I can assure you it is.

They fell in love.

They married.

They have kids.

And that's the way it sometimes goes in life.

And so here you see the plant in Texas where these huge balloons were made.

Uh, balloons are put together sort of like the -- the way that the tangerine is put together.

At the surface you see these gores of the balloon.

And the sealing of these gores to make up the balloon were -- was only done by women.

Only women were allowed to work there.

Has nothing to do with sex discrimination of any kind.

It just turned out that women were more patient.

They did the work better.

They make way fewer mistakes than men did.

That's the way it goes sometimes in life.

Here you see balloon coming out of the box.

Nicely protected in a plastic cover.

And we also have here cloth on the -- on the grass because the balloon is so thin that it would certainly get damaged if it touches the grass, it's enormously thin.

This was not my balloon.

Uh we were worried that there was something wrong with it.

You can see here the concern.

They thought it was a -- there was a hole in the balloon.

And that if there is a hole in the balloon there's just nothing you can do about it anymore.

You can't patch it because the hole is almost always through many many layers.

What you're looking at here is hundreds of layers of balloon that are folded together.

But as I said, since it wasn't my balloon I wasn't too worried, but of course it's never nice if you see a failure of your colleagues.

Now I bring you to the desert town Alice Springs in Australia.

Right at the heart of Australia.

And now you get a pretty good idea of what it's like.

Here you see the launch truck.

The telescope is there.

And then you see this enormously big balloon.

All of it is empty now and most of this will stay empty.

This is the roller arm which holds this part down.

This is the only part that will be inflated.

And here you see the helium truck.

And here you see the inflation tubes.

And we will let helium in from both sides which will then gradually begin to fill this top part of the balloon.

And you see here the roller arm in detail.

The roller arm is very important because when this part of the balloon is being filled it wants to lift, it wants to go up, and of course you have to keep it down, you have to keep it under control.

And so this roller arm and this -- this car is loaded down with concrete.

It's very heavy.

And then just before the launch this roller arm by command is [fweet] flipped over, and then as you will see later then the balloon will make it up.

And here you see the early part of the inflation.

Helium comes in from both sides.

And so we -- we fly these balloons almost always early morning because then the winds are very calm.

You need extremely reliable winds.

You need to know the direction very well.

And the winds should be no more than something like three or four miles per hour.

If they are stronger you would lose the balloon.

You see here these gores that I mentioned to you earlier.

Where the sun is behind the balloon.

Here the bubble is nearly fully inflated now.

Here it's still going on.

Still going on, the inflation.

But we are very close to the end of the inflation.

Here is the roller arm and then in this direction here, 500 feet or so down is the payload with the truck.

We're now very close to a launch.

We're still in Alice Springs.

This is -- was my graduate student Jeff McClintock at the time.

He's now Dr.

McClintock.

Here you see radar reflectors which allows us to follow the balloon -- a radar.

Here you see the telescope hanging on the launch truck.

Here is the roller arm.

All this is empty.

And here you see the parachute.

We have here a connection between the parachute and the bottom of the balloon.

And we can control that on radio command.

We can separate that so that the telescope safely comes back to earth.

At least that's the idea on paper.

And so now you see the release of the bubble.

So the roller arm is up and this bubble now takes off.

This is an incredibly fantastic moment.

This is really butterflies in your stomach and ants in your pants.

This is the moment that balloon can easily fail.

Very thin material, the helium goes up, reflects against the top, is pushed back again, you get this peculiar mushroom shape, it makes an enormous sound like a storm.

The idea now is that this balloon will go higher and higher in the sky.

Will pick up all this empty part.

This is not inflated.

As the balloon goes up in the atmosphere the atmospheric pressure will go down.

And the helium will expand and will fill the balloon.

And the -- the trick now is for this truck to manipulate, to maneuver itself under what we call the bubble.

And therefore the wind has to be in this direction so that the balloon comes to the truck.

And then the truck tries to get straight under the balloon.

And then the payload will be released here.

Here you see a close-up of this mushroom.

You can actually see this reflection of the helium going up and coming back.

You can also see these gores very clearly.

It's tedious work.

By these women who have to seal these balloons.

Enormous amount of labor goes into it.

Amount of helium as I said earlier is about $80,000.

About the same price of the balloon.

And here it goes higher.

We're in Alice Springs.

The cover is falling off.

Balloon is going up.

See the engine is already running.

The truck cannot move yet because if it started to move this part of the balloon would slide over the cloth.

There would be friction and there would be holes in the balloon.

So this truck has to wait until all of this is off the ground.

Going higher.

And I'm now so close to the balloon that I couldn't continue my picture-taking from Alice Springs.

So I will jump back to an earlier flight in the United States.

We flew these balloons in the United States from a town called Palestine, Texas.

And so you will see then the remaining part of the flight from Palestine, Texas.

So the balloon is now completely off the ground.

See a little bit of gas, well it's not so little, but it looks very little compared to the size of this balloon.

You see the parachute here and here then is the connection which on radio command we can separate.

So now this is a very crucial moment.

The person in charge on this launch truck has probably driven the truck to get straight under the balloon.

And when it's straight under there they will allow the payload to go free.

The payload is attached to this truck.

If the balloon is too far ahead and the payload is released it will pendulum into the ground.

And if you release it too early then of course the payload will pendulum back into the launch truck.

Both would be a disaster.

If the pull of the balloon is not enough, for instance if a hole developed during the launch, so if the tension is not strong enough, you would release the payload, it would go bang, back to the ground.

So all these factors have to be taken into account, and then finally the person in charge commits to a launch.

And then there it goes.

All the way empty.

Here you see the helium.

The parachute.

And you see the -- the payload.

And here you see the balloon at 150000 feet, 45 kilometers high in the sky.

The helium has now expanded.

The balloon is fully inflated.

And you can look straight through it.

It's only half of one-thousandth of an inch of polyethylene.

And these are huge ducts which have openings of about ten meters each.

And they are there because the balloon cannot stand any over-pressure.

If there is any over-pressure the balloon would pop and so when the balloon keeps rising and rising and rising when it reaches -- reaches its maximum volume the helium would escape at the bottom.

That's the idea of these ducts.

Here you see George Ricker who was graduate student, my graduate student at the time.

This is in Australia.

He is now Dr.

Ricker.

He's still at MIT.

He's a staff member.

And this is the kind of equipment that we built, at least partially.

And he is checking the early results during the ascent of the balloon.

The balloon will go up with about 1000 feet a minute.

If all goes well, there's no leak, it will take about two and a half, three hours to make it to altitude.

You see me here sitting on the plane that we used to follow the balloon.

We fly of course at much lower altitudes.

5000, 10000 feet.

We stay as close to the balloon as we possibly can.

It's not always so -- not always easy, certainly not in Australia.

And so we keep an eye on things and if necessary we can terminate the balloon flight by giving a radio command so that the parachute comes down.

Certainly when we get close to the ocean of course that is necessary if you don't want to lose the payload.

The data -- data come back via radio, so we wouldn't lose the -- the data.

You get very sick, by the way in these planes.

If you're sitting for 8 or 10 or 12 hours or longer in these planes as I have, I learned actually a little bit of flying which is quite easy with a plane like this.

Here you see a map of Australia.

Here's Alice Springs.

Uh, we fly probe balloons, weather balloons at 140000 feet every day to find out in what direction the balloon would be drifting.

And we had all reason to believe that the balloon would drift somewhere in this direction.

And we alerted these radar stations.

These circles here are radar stations.

Because there are no airfields here in Australia.

And so we knew we couldn't follow the balloon.

We would probably lose it.

And therefore we alerted these radar stations.

They could tell us then when the balloon was in sight.

And that would allow us then to cut the balloon, cut the payload loose and -- and make the recovery.

Instead, the balloon went straight south.

So the predictions by the weather balloons were not too accurate.

The balloon went straight south.

And here there was sunset and then we don't know too precisely where the balloon was.

Remember this was in the 1970s.

And so we were uncertain.

But here about 26 hours later when we were getting close to Melbourne which we were not allowed to enter the air space here between Sydney and Melbourne we cut the balloon loose.

That means we separate the payload from the balloon.

The balloon is very brittle.

It's extremely cold up there.

The balloon then fractures and comes down in many pieces and if everything worked well then parachute opens and brings the payload safely back to earth.

And then comes the big problem -- how are you going to recover the payload.

You're in the middle of nowhere.

This balloon came down, this payload came down in the desert.

And there are no airports.

At least, the chances are that you are a few hundred miles away from the nearest airport with your payload.

So what you do then is the following.

You try to find a house close to where the payload is located.

We locate the payload.

We see the stuff come down.

Radio beacons on the payload.

And then you fly over that house many, many times in a very obnoxious way.

You make a -- a lot of noise.

You fly over very low.

And so the people who -- whose next neigh- neighbor is probably se- 70 miles away from them know what you're trying to tell them.

You're trying to draw their attention.

And they know what that means is that they want you -- they want you to meet them at the airport.

Whatever airport means.

It's sometimes just a strip in the desert.

You can't land there at night but you can land there during the day.

And so that's exactly what we did.

We drew attention to the house of this guy, Jack.

He was -- he was a complete nut, he was always drunk, was a crazy guy.

And so we went to the airstrip and we waited and indeed after 15 hours he showed up with this truck.

Uh, there is no windshield here in the -- in the truck.

And he used to shoot kangaroos there.

He would go 60 miles per hour on the desert floor and he would -- he would shoot kangaroos.

And he gave me a demonstration.

Uh, he put his dog on the roof.

He would go 60 miles an hour.

And he would slam the brakes.

And then the dog would catapult through the air, the poor dog.

And then all he would say is oh, you can't teach an old dog any new tricks.

And he seemed to enjoy that.

When we go after the payload the plane, the recovery plane, is in the air.

Takes off from that airstrip and we have contact with the recovery plane.

They and only they can see and know where the payload is.

From the ground of course you can't tell.

And so they maneuver you to the payload.

And so of course Jack's help was invaluable.

We needed him.

That was independent from the fact that the man was a little strange.

On these recoveries you encounter many animals.

You see a koala bear here.

In a l- eucalyptus tree.

Very lazy animal.

Unlike most of you.

And then when we came close to the payload there was this animal, a goanna, six-feet tall goanna.

I'll tell you, it scared the hell out of me.

And uh I didn't want to show that to my graduate student who was with me and I said to him look you know these a- these animals are completely harmless, why don't you go first.

This animal was no farther than four feet from the payload.

And so my graduate student went first and the amazing thing is during the 10 hours that it took us to recover the payload and put it back on Jack's truck this animal never moved.

It was just sitting there completely still.

This is their way of trying not to be noticed.

And so here you see the payload.

This was Alice, was Jack's wife, this is Tom Brooks, he came from the United States, he was an electronic expert.

And you see here the payload.

It looks heavily damaged but it really isn't.

This is crash pad which protects the payload when it impacts.

And in impact, crash pad worked very well, very little damage to this payload.

And then you come back after several days to Alice Springs.

Alice Springs is a hole in the ground.

Nothing ever happens there.

And so obviously you make it to the front page of the Centralian Advocate.

Perfect balloon launch, thousand watch start of space probe.

They think of this as a space probe, which is fine.

Balloon professor is back in Alice.

They called me there the balloon professor.

I gave -- I gave several talks there for high schools and for, uh, the Rotary Club.

So I was a sort of a local celebrity.

I talked to the news reporter for several hours.

And when you read this story you won't believe the nonsense but that's all a detail of course.

OK, that's enough for the slides for now.

I had si- about 20 successful s- flights.

Between 1966 and 1980.

Many from the United States.

From Canada and also from Australia.

Where that's a s- southern hemisphere which covers part of the sky that we cannot see from the United States.

I had two free falls.

Two of my balloon burst on the way up in the tropopause.

We were unable to separate payload fast enough and then the whole thing, parachute gets entangled.

You get a free fall.

Big hole in the ground and that's the end of the telescope.

And it was.

Twice did I lose the telescope completely.

But I was lucky and I made several interesting discoveries during those successful flights.

We discovered very early on five new x-ray sources.

None of them had ever been seen with the rockets.

And several of these sources, that was the really new thing, were highly variable.

They changed their x-ray intensity on a very short time scale.

We noticed even one source went up by a factor of three in about 10 minutes.

And that of course could not have been discovered with rockets.

Because the rockets were only above the atmosphere for 5 minutes.

They would quickly scan the sky and so there's no way they could discover variability on a time scale of tens of minutes.

But with balloons you can do that.

So it did pay off that we were watching the sky sometimes for 10, 20 hours.

Our -- my longest balloon flight was actually 26 hours.

We also observed x-rays from one source which we named GX 1+4.

Which stands, the 1+4 stands for the position in the sky.

And this showed a periodic signal in x-rays.

About 2.3 minutes periodicity.

At the time we had no clue what that meant but later of course we understood the significance of that.

And you will understand that also very shortly, how significant that was.

So what kind of objects are they?

They are very, very different from the sun.

And we now know what they are.

These objects are binaries.

Binary stars.

One star is not unlike the sun, it's a normal nuclear burning star.

And it is in orbit with a neutron star or in some cases a black hole.

They go around each other.

And if they are close enough together it is possible that the matter of this star is attracted by this neutron star with a larger force than it is attracted by the star itself.

And if that's the case this matter doesn't want to stay here.

But wants to go to the neutron star.

Now of course the matter has angular momentum because they goes around.

So it cannot free fall to the neutron star.

But it would spiral in and slowly make its way to the neutron star.

And we call this an accretion disk.

And we call this the donor, provides the fuel for the transfer of mass onto the neutron star.

And let's assume that the neutron star has a mass capital M and has a radius R.

And let's assume that we dump some matter, little m, onto the neutron star.

Well all of you should remember from 8.01 that you can calculate very easily the speed with which this matter reaches the neutron star.

The kinetic energy, one-half mV squared, must be equal to m M G / R.

We had this equation on the blackboard last lecture when we discussed cosmology.

It was the same equation.

This is the speed with which the matter will fall onto the neutron star.

If this is the mass of the neutron star and this is the radius of the neutron star.

You lose the -- the mass as you always do.

And so you can calculate this speed.

This speed is horrendous because the radius of a neutron star is so ridiculously small.

The mass of a neutron star is very comparable to the mass of the sun.

A little larger.

But not much larger.

But the radius is 100000 times smaller than that of the sun.

It's only 10 kilometers.

And as a result of that the speed with which the matter hits the neutron star is about one-third of the speed of light.

When it hits the neutron star this kinetic energy is converted to heat.

It will heat up the surface layers of the neutron star and increases the temperature to about 10 million, 100 million degrees, and at such high temperatures, the star would emit almost all its radiation in x-rays and not in the optical.

Our sun is relatively cold.

It's only 600, 6000 thous degrees.

And so the sun has most of its radiation in the optical but when the temperature becomes 10 million, 100 million degrees, the maximum of the emission is in x-rays.

To give you a little bit respect, a little bit of insight, for this incredible power, for this incredible gravitational pull of the neutron star, because R is so small, if you took a marshmallow and you threw a marshmallow from a large distance onto the surface of a neutron star, at impact the energy that is going to be released is comparable to the energy of an atomic bomb as was thrown on Hiroshima and Nagasaki near the end of the Second World War.

Neutron stars have very strong magnetic fields.

And the matter that flows from the donor onto the neutron star is ionized.

It's plasma.

It's charged.

And as you remember from 8.02, when you have a charged particle in a magnetic field there is the V cross B term.

The V cross B force.

And the V cross B force will then spiral these charged particles around the magnetic field lines and they would end up near the magnetic poles, not unlike the solar wind when it reaches the earth, these charged particles enter the earth atmosphere near the magnetic poles, giving rise to aurora as we discussed earlier.

And so you end up on the neutron star with two hot spots where this matter slams into the neutron star.

At the magnetic poles.

And if the axis of rotation of the neutron star is not the same as the -- [Audience noise] Q: Tall male physicist.

[noise] Hi, Miss Peltier.

[laughter] I remember your name.

[laughter] You were in my 8.01 class.

Q: [unintelligible] Q: [noise] And [unintelligible] physics, is this a physics lecture?

Ask the students.

I don't know.

[laughter] Q: Very handsome and charming.

OK.

[laughter] So are you.

[laughter] Q: [unintelligible] I think you know the answer to that one.

Q: OK, I think we have the right person.

[background noise] Q: We have a song to sing to you.

Q: [unintelligible] [tone] Singing: When I was young I never needed anyone.

But speaking words of wisdom, times have changed.

Singing: Maxwell's equations are too hard for me, so please just help me, help me.

Singing: Help.

I need somebody.

Help.

Not just anybody.

Help.

You know I need someone.

Walter.

Singing: When I was younger, so much younger than today.

I never needed anybody's help in any way.

But now these days are gone, I'm not so self-assured, now I've found my homework's hard, know nothing anymore.

Singing: Help me if you can I'm failing now.

Walter Lewin, can't do physics, I don't know how.

I am on pass-fail, don't let me down.

Singing: Won't you please, please pass me?

When I was dumber, so much dumber than today, I didn't know about Lentz, Maxwell or Faraday.

Singing: But now those days are gone, I'm not so dumb no more.

Thanks to 8.02 and our daring professor.

Help me if you can I'm failing now.

Singing: Walter Lewin, can't do physics, I don't know how.

I am on pass-fail don't let me down.

Singing: Won't you please please pass me.

Walter Lewin, thanks for teaching 8.02.

Now it's summer and we will all miss you.

Singing: You've been crazy and we've all had a good time.

So in your praise the Muses' voices chime.

Singing: Eight days a week.

I love you.

Eight days a week.

Is not enough to show I care.

Singing: Thanks for all you've done, I'll pass somehow.

E and M can't get me down, I know this now.

I'll miss pass-fail next year, this I vow.

Singing: Won't you please please pass me, pass me, pass me, ooh.

I have tears in my eyes.

[applause] So that was very nice.

So now you won't have any time to fill out your evaluation form.

So I was going to talk to you about the -- show you some evidence for these binary systems.

So we have these hot spots on the neutron star and as the neutron star rotates then and the axis of rotation doesn't coincide with the dipole, magnetic dipole axis, you're going to see hot spot, hot spot, hot spot, hot spot, and that explains then the x-ray pulsations.

Uh, you can also see in some cases x-ray eclipses.

If the neutron star as seen from the earth hides behind the donor star, which is much bigger, then all the x-rays are absorbed and so the x-rays stop completely.

You go into an x-ray eclipse and a few hours later you come out of the x-ray eclipse again.

And that's what I would like to show you the evidence for, which came in the early seventies.

With the satellite Uhuru, the first slide is the basic idea.

No, that was right, uh John, John, go back to that picture, yeah, so you see here this is of course a sketch, this is not the real thing.

Here you see a star.

Not unlike the sun.

And then here you see the neutron star.

In some cases a black hole.

And then the matter is being sucked off this star because the gravitational force in this direction is larger.

Forms the accretion disk and ends up on the neutron star.

And the next slide is then the discovery of the early -- convincing discovery of a pulsating system.

The rotation of the neutron star.

This time scale here is about one-and-a-quarter second.

And the data are here, this is the data, unfortunately in this publication this -- this very bold line dominates almost the data, but the idea being very clear that the x-ray signal, this is the strength of the x-ray signal, this is time, one-and-a-quarter seconds, is oscillating one-and-a-quarter second periods.

And that's the rotation of the neutron star.

And the next slide shows you of the same object, it's called Hercules X-1.

You see on a very different time scale this is days.

You see that the x-ray eclipses, that the x-rays disappear completely when the neutron star goes behind the donor.

And the orbital period is 1.7 days.

The x-rays disappear completely.

And so this picture is well-established.

It's beyond a shadow of a doubt we do know what these objects are.

But no one is flying balloons anymore, I make all my reserv- o- observations nowadays from satellites using European satellites, Japanese satellites and American observatories.

Lately we have the Rossi timing explorer in orbit and also Chandra which is the biggest thing in town.

Now between 1975 and 1979 we were so fortunate here at MIT that we had our own private x-ray observatory.

It was called SAS-3.

It was an all-MIT operation.

We maneuvered it from my building, Center for Space Research, Building 37, 24 hours a day, 365 days per year.

It was at that time that Josh Grindlay and John Heise had discovered using a Dutch satellite, believe it or not -- they had discovered that some of these x-ray sources showed sudden x-ray bursts.

The x-ray intensity would rise in about a few seconds, would become 10, 20, 30 times stronger, and then over a time scale of maybe a few minutes, the x-ray intensity would peter out again.

And we had this SAS-3 observatory which ideally suited to do research in these x-ray bursts.

And we discovered within two years 8 new burst sources.

And I think it's fair to say that it's largely due to our observational work and also to the theoretical work by Professor Joss who was at MIT and still is at MIT that we now understand what these x-ray bursts are.

They are huge nuclear bomb explosions on the surface of a neutron star.

The matter that falls onto the neutron star is largely hydrogen and helium.

Because that's the matter of this star.

And the density and the temperature on the surface of the neutron star is so high that you get nuclear reactions.

And 3 helium-4 nuclei can fuse to carbon-12.

And then energy is released.

And this nuclear reaction is very unstable, is extremely sensitive to the temperature.

If the temperature goes up, the reaction rate is higher, more energy is released.

Temperature goes up.

When the temperature goes up the reaction rate goes up and so on, more energy is released.

And the whole thing gets out of hand.

You get a thermonuclear runaway, as we call it.

You see a thermonuclear flash.

A gigantic bomb explosion on the surface of the neutron star.

These bomb explosions are about 18 orders of magnitude more powerful than the most powerful hydrogen bombs that we can build on earth.

So this -- this layer, this fresh accreted layer, goes up in one huge bomb explosion and then new material is accreted and a few hours later you will see another bomb explosion.

So you can see several of these x-rays bursts per day.

The optical counterparts of these stars, these binary systems, are very faint, but you can see them from the -- the ground with optical observatories from the ground.

And we had reasons to believe at the time that simultaneously with an x-ray burst you might actually observe an optical burst.

And I'll give you the reasons why we believed that.

You see here the neutron star and you see the accretion disk.

And let us assume that there is an x-ray burst going on now.

These red wiggles is x-rays from the x-ray burst.

The earth is in this direction.

So these x-rays reach the earth first.

But there are x-rays which go in this direction.

They are absorbed by the disk.

And then the disk heats up.

To 30, 40 thousand degrees.

And starts to emit optical light.

Some of that optical light will go in the direction of the earth.

And so what this means now is that there is a delay between these x-rays, these -- this optical light and these x-rays.

Because look.

This path length is longer to us than this path length.

And therefore we were hoping not only to be able to see an optical flash, which would mean the x-ray heating of the disk with the optical light from the disk, but we were al- also hoping to see the delay.

If you can measure the delay, if you see a one-second delay, it would mean that this geometry was roughly one light-second from here to here.

And so we were very ambitious.

We organized a worldwide campaign in the summer of 1977.

With SAS-3 we were going to observe one particular x-ray burst source in the sky for two weeks on.

And we were asking observers from the ground, optical, radio, infrared observers, to keep an eye on that object and also observe that, all the time, as long as they could.

17 countries contributed.

44 observatories contributed.

Participated.

And during these two weeks we saw 110 x-rays bursts from this object with SAS-3, none was -- were observed in the optical, none were observed in the radio.

In 1987 we tried it again and we were successful.

This was a collaboration with Joss Grindlay who was at the time at Harvard and my graduate student Jeff McClintock who was at that time already Dr.

McClintock.

He also was at Harvard and he still is there.

It was a smashing success.

We made it to the cover of Nature, which is a rather prestigious scientific journal.

It was covered by the New York Times and by many newspapers in the world.

So we were the first to be able to detect simultaneously an x-ray burst and an optical burst from this binary system.

Uh, the data that I want to show you are not the 1978 data.

But they are data from a year later because they have better quality.

We learned how to do it of course.

These are the x-ray data not from SAS-3.

Because SAS-3 was no longer in orbit in 1979, this was a Japanese satellite, Hakucho.

And so here you see the times in seconds, and here you see the x-ray intensity and you see here the x-ray burst as we observed it with the Japanese observatory Hakucho.

And here you see the optical data which were taken by my friend and colleague Holger Pedersen.

He used a European southern observatory in -- in Chile.

And he observed clearly an optical flash.

This is the intensity of the light before the x-ray burst and then you see an incredible increase and then you see a decay.

I have plotted these so that they both have the same height.

That of course is artificial.

But it makes it easier to compare the two.

And so now comes the acid test.

If now I put one on top of another then you see very clearly that as we expected all along that the optical signal is indeed delayed relative to the x-ray signal.

And you can now do the measurement that we hoped we could do.

You shift one curve on top of another and if you shift it by about two seconds then they're almost carbon copies of each other.

And so we succeeded then for the first time to measure the geometry of the accretion disk around these neutron stars.

They have radii of very roughly 2 light-seconds.

Light had to travel 2 seconds more, first x-rays, x-ray heating and then the optical.

2 light-seconds is about twice the distance from the earth to the moon.

So these systems are amazingly compact, very small indeed.

Needless to say that during the past term I haven't been able to do any research, no science at all, 8.02 has swallowed up everything that I had to offer and more.

And I think you should feel sorry for my graduate students.

And I think you have all the right to feel guilty as well.

Uh, you were on my mind all the time and not only at MIT but also at home, in my living room, my kitchen, when I took showers, and even very often appeared in my dreams.

Believe me, it was hell for my -- for my significant other, who is in the audience, Susan, it wasn't very nice for her.

Frankly, my life will change after today.

I make myself no illusion however.

Most of you will quickly forget all four Maxwell's equations and you will forget all about induction and about nonconservative fields.

I hope for you though that it will not be before next week.

But surely when you will see a rainbow you won't be able to resist to check that the red is on the outside and the blue is on the inside.

It is a disease for which there is no cure.

And if you carry your personal polarizers with you, then you will want to verify that indeed the bows are strongly polarized, and if you do that I'll be very proud of you.

And if that's all you will ever remember of 8.02, long after you have forgotten all about Ampere, Gauss, Faraday, and Maxwell, long after you don't even remember how to spell their names, if that's all you will ever remember, I will have achieved something that has enriched your life, and you will remember me.

And I hope those will be happy memories.

Thank you for attending my lecture.