MARK HARTMAN: All right, so light as a wave. We have, for so long, been talking about the particle model of light. And we're going to contrast that with the wave model of light because the Doppler effect-- this thing that we're going to learn about-- only shows up when you think about light is a wave.

The model of light as a wave helps us to make interesting and useful predictions. Well, this particle model of light has also helped us to make interesting and useful predictions too. We were able to predict things about measuring luminosity and how luminosity and flux are related because we're thinking of these particles coming out in all directions.

So here's what the particle model of light looked like. Here's our light bulb again. We have particles that are moving outward in straight lines in all directions. They're moving at the same speed. We know that each one of those photons has a different energy. So photons have different energies.

And we experience those different energy photons as different colors. When those photons hit the detector at the back of our eyes, which we call the retina, a signal is transferred up to our brain. And our brain says that looks blue, or that looks red.

Now in this case, in the wave model of light, what we have is here is our light bulb, and we have essentially disturbances in the electromagnetic field that travel outward from this source. So we are going to say we're going to represent that as this. We're going to draw a couple of circles around this object. And these circles are ripples. We're going to look at the surface of water in a minute.

But we're going to say that-- you'll understand this in just a minute-- here, just let me just say so photons have different energy we're going to say here that-- well, this was light is photons that have different energies. In here, light is a traveling disturbance in the electromagnetic field. And the reason we don't spend too long on the wave model of light is because it's not intuitive.

I don't think most people really understand it until they've taken like a second or third college course in physics about it. I, personally, don't really understand it all that well myself. So there's a lot more that goes into this.

You have to understand how magnetism and electricity are related. You have to understand how sources and moving charges produce currents and currents produce magnetic fields. It's not impossible, but it's just a little bit beyond what we want to get into right now. So we're going to simplify it a little bit. But if we have two models that are describing the same phenomenon, describing the same observations that we make, there's got to be correspondence between these two.

There's got to be something that's similar. In this case, our photons are traveling outward in all directions at the same speed. Here we have waves or disturbances in the electromagnetic field that are still traveling outward in all directions at the same speed. And I want everybody to come up and take a look at a couple of things over here.

So can we have the balloons? Oh, you guys are writing. I'll get the balloons. So I want everybody to come to the middle [? Shakib, ?] What's the best way to do this?

Let's each have one of us do these up here. So everybody put their arms out. So what we're doing right now is we're charging up. We are putting extra electrons from our head onto these balloons. Extra charges create an electric field.

The electromagnetic field is electric and magnetic fields. But what is it field? A field is just how you sense or interact with-- ooh, let's see this. Is that working? So if we put this on your arm, what is it that you feel?

AUDIENCE: Tingly.

AUDIENCE: Yeah, it's kind of--

MARK HARTMAN: What does it feel like?

AUDIENCE: Tingly.

MARK HARTMAN: Feels kind of tingly? So why does it feel tingly?

AUDIENCE: Because the hair rises.

MARK HARTMAN: Yeah, so your hair moves around a little bit. And depending on where the charge is, your hairs kind of stand up, and they move towards that charge. It's not that there's one continuous force.

It's not that there's one force between this and your hairs, but it depends on where the balloon is. And you can kind of feel that there's changes when this source moves around. When it's down here, you can feel the-- ooh, it's kind of weird.

So what you're doing is the hairs on your arms are responding to the electric field. They're kind of like being attracted towards it. But when you move around, if you move further away, you can't feel it as much. That's what the idea of a field is.

A field is just describing how does one thing influence another thing, and it's not always the same. It depends on how far away you are. What is this? More? All right.

AUDIENCE: Are you going to shock somebody?

MARK HARTMAN: No, I don't want to shock anybody. But yeah, that does work. So what you're doing-- a field is a way to describe how things interact. It's not that there's one number that can describe this. But if you put it close, then it pulls harder.

If you put it over here. It pulls harder on these hairs, pulls less hard on those hairs. So the idea of a field is just a description of how this object interacts with other objects, and it depends on distance. It depends on where you are. And when you move this around, you can feel the field changing because the amount of pull on each one of these hairs is different.

So the same idea happens with light. That's an electric field. When you have those bouncing charged particles that are bouncing around that we talked about producing photons, when those move up and down, their charge and they cause a changing field. So everything else around them changes in response to that. And that's what causes these disturbances in the electromagnetic field.

Now we're talking about big disturbances, like moving one or two centimeters, three or four centimeters back and forth, and our hairs can kind of tell the difference. But light is talking about moving up and down really, really fast and moving up and down really, really small amounts, moving those charges. That disturbance travels outward. We just like felt the influence.

Our hairs didn't start moving in response to that necessarily. But let's have everybody come over here. If we have this pan of water that's describing-- if we say this is like the electromagnetic field. If we put a disturbance into it, you can see-- actually, it looks a little bit better if you can see a light. So get so that you can see reflected light in between these things.

So if I put a disturbance or move something around here, you notice what?

AUDIENCE: Ripples.

MARK HARTMAN: Ripples-- right. So the energy of me dipping this into the water is carried outwards in all directions. And if you look what shape are the ripples.

AUDIENCE: Circular.

MARK HARTMAN: They're circular-- right. And they start out small, and they travel outward in all directions. So in the same way that by me dipping this in and out, I'm producing waves in this water, electrons or ions or charged particles are like bouncing around, and they're producing ripples in the electromagnetic field. We think, in our particle model, that each time you have a bounce, you release one photon.

Well, in the wave model of light, when you have that disturbance moving up and down, you're actually sending out these waves or these disturbances in the electromagnetic field. It's not that something actually physically goes outward, but there's a disturbance there. And that disturbance is what travels to us. Now you can't really think of how much of that disturbance do I collect with my detector? You can think of how many photons do I collect with my detector? And that makes sense in terms of counts because you're just saying I got 20 photons, or I got 50 photons. You can't say, well, how much of this wave did I get in my detector?

25.

You could say a number like that. But it's that different models help us to predict different things. And in the case of the particle model, it helped us to figure out flux and luminosity. In the case of the wave model, it's going to help us to figure out what happens when these sources of light are actually moving in one direction or another.

So one observation I want you to make is if I do this, you can see these circles because from the side, if you were to look at the surface of the water, it goes up and down like this. So when you see those circles, that's saying that there's one part of the wave that's up, which we call the crest, and then one part of the wave that's down, which we call the trough. Everybody's heard of the crest and the troughs. In this case, we have circular waves that are traveling out on the surface of a two-dimensional object.

AUDIENCE: [INAUDIBLE].

MARK HARTMAN: Right. So that's the other thing. When you send waves out, they bounce off of stuff in the same way that photons bounce off of stuff. So if we have a source over here, we can watch that source from here, and we see that it bounces out that way. So there's still some of that correspondence between the two. But what you notice here is these circles-- each circle represents the crest of a wave.

So let's all head back to our seats. If I were to draw a wave from the side, I would see-- here was my pencil. If I were to draw it from the side, it would look like that.

Here's the regular surface of the water. This is the crest. That's the trough-- the crest, the trough. And that's what we're seeing from a top view here. So let's write down a couple of these things before we forget them.

The first thing that we want to say is-- oops. So we said wave mild light-- light is a traveling disturbance in the electromagnetic field. So what is a field? A field-- how would you guys describe it?

AUDIENCE: Area surface.

MARK HARTMAN: A what?

AUDIENCE: Area surface

MARK HARTMAN: An area surface?

AUDIENCE: Like a surface of it.

MARK HARTMAN: It's kind of like a surface. In that case, we said that the field would be the surface of the water. Over here, when we put the balloon next to our arms, we said it was a way to describe how one object interacts with another object.

So we're going to say-- let's say how should we say this? Field is a description of how charged particles interact with other matter. And this is going to be the electromagnetic field.

When you have a source that is a charged particle, like we charged up those balloons, the field is a description of how it's going to interact with other stuff. When you hold the balloon farther away, your hairs don't stand up. When you hold the balloon closer, your hairs do stand up. Now this isn't a perfect definition of this, but it's good enough for us to use.

AUDIENCE: [INAUDIBLE].

MARK HARTMAN: Say that again.

AUDIENCE: [INAUDIBLE].

MARK HARTMAN: OK.

AUDIENCE: [INAUDIBLE].

MARK HARTMAN: So in your physics class, what would you say when somebody says a field?

AUDIENCE: Exactly what that is really [INAUDIBLE] just said.

MARK HARTMAN: OK, one way that we can describe a field for a single-- you can also use this to think about the gravitational field. A gravitational field is the description of how a massive particle, or any mass, interacts with other mass. We had described that, and we said that the force between two masses depends on the product of the masses, as well as the difference-- or I'm sorry-- as well as the distance in between them.

So you can represent a field mathematically, and there is a mathematical description of what all of this looks like or how you could describe it. Oops, where did my notebook go? The other important point is that when you have a source that's moving-- so moving charges. Let's do-- blue's OK?

AUDIENCE: Yeah.

MARK HARTMAN: Let's do moving charges create a disturbance or waves. And we say disturbance. We really mean waves. That's horrible. Creates a disturbance-- that's better-- or waves in the electromagnetic field.

So light is a traveling disturbance, but moving charges or moving charged particles create that disturbance just like my pen created the disturbance on the surface of the water. Except there's a big difference between the waves on the water there, and the light that comes out from a source. Those only traveled outwards in two-dimensions. These waves travel outward in all three dimensions. So towards us, that way, up, down, back in all directions.

OK, so you got that. Now the problem is we need to have a connection between these two models. And right now, how does a photon relate to a wave? Well, we don't really know.

And we also, when we're looking at these waves-- I'm sure everybody has seen this before-- but if you want to measure something about these waves, you can measure a thing called the wavelength. How far is it between one crest and the next crest? How far is it between one trough and the next trough?

So on this diagram, the wavelength is the distance from crest to crest or from trough to trough. Yeah, trough. Well, lots of people farm, but nobody in this room has probably farmed before.

So you maybe not have seen a pig trough but like something that an animal would eat out of. It's a trough. It's a place that goes down, so you can fill in the animal's food. So that's a wavelength.

This distance between here and here is also a wavelength. If we took a picture real quick of when I was dipping the pen in the water, you can take a picture from above, and you could actually measure the wavelength. You can look at the angular size you can convert it into a linear size if you knew how far away it was from the camera. So here's the next part.

The connection between the wave and particle model of light came in the early 1920s with the development of quantum mechanics. So we're going to say that we've already seen that quantum mechanics helps us to understand those electron transitions that we saw in elements or atoms of elements that lead to the peaks that we saw in our supernova remnant spectrum. And we said that quantum mechanics said that those electrons can only be in certain energy levels. Remember, electrons can have energy levels.

Photons just have an amount of energy. Quantum mechanics is the study-- or it's a model of the behavior of really small things. We saw that it tells us about how electrons move, and electrons are tiny. It tells us things about photons, and photons are very tiny. I mean, you really have a size that's just kind of an idea.

So from quantum mechanics, there was a relationship that kind of served as a bridge between the particle model of light and the wave model of light, and that bridge is that the energy of a photon was equal to-- well, let me just say the constant some number-- a constant is like a constant in mathematics-- divided by the wavelength of the wave. So what that means is if we think about things in terms of photons, we have energies of each photon. But if we think of things in terms of the wave model, we don't have any photon energy to measure, but we can measure wavelength. So what this says is if we have a high energy photon, what does that mean about its wavelength?

So what I want you to do, think to yourself, if you had a large energy photon, what would be the wavelength? OK, so Peter and then Steve and then Chris. Peter?

AUDIENCE: High energy the wavelength will be smaller than the low energy would be [INAUDIBLE] wavelength would be longer and [INAUDIBLE].

MARK HARTMAN: OK. Steve?

AUDIENCE: [INAUDIBLE] but it is smaller [INAUDIBLE] smaller wavelength the energy [INAUDIBLE] would be bigger.

MARK HARTMAN: OK, great. Chris?

AUDIENCE: If the wavelength was like two, you have to multiply by the reciprocal [INAUDIBLE] bigger number like [INAUDIBLE]. So it will be bigger.

MARK HARTMAN: OK, so you're saying if we took this wavelength and then put it up on this side, that wavelength times energy is just some number. So if wavelength gets smaller, energy has to get bigger to multiply to give us the same number. That's actually good. That's three different ways of looking at this idea. Let's see if it actually plays out in what we see.

Do these people have it right or were they crazy? So if we look at our chart of the different telescopes that we were looking at and then what is the energy of photons? We said that visible light has like two to three electron volts of energy per photon. I'm sorry. Yeah, visible light and then x-ray had about 1,000 to 100,000 electron volts per photon. But we saw that as the energy goes up, what happened to the wavelength of light?

AUDIENCE: It gets smaller.

MARK HARTMAN: As energy goes up, the wavelength gets small. Gamma rays-- or gamma ray light, I'm sorry-- has high energy photons, which you can think of as waves with really, really short wavelength. And just like Peter said, if you make the energy-- or I'm sorry. If you make the wavelength really long like here is five billion nanometers, which is about a meter-- maybe a half a meter, then the radio light has photons. Or you can think of it as having photons with very, very low energy-- less than a millionth of an electron volt.

If I rewrite this and actually put in the numbers, when you get is the energy of a photon is equal to this number h times c over wavelength, which lots of people write as this Greek letter lambada. So this is how you say that. You say L-A-M-B-D-A. Lambada-- can everybody say that?

AUDIENCE: Lambda

MARK HARTMAN: Lambda or lambda. That's a Greek letter, and that stands for the wavelength. So wavelength equals lambda.

Oh, wow, OK. So this number h is a constant called Planck's constant. Planck was the name of the guy who figured this out or who came up with this idea.

C is just the speed of light. So this is speed of light. This is Planck's constant. Yeah, a question?

AUDIENCE: Is this like c [INAUDIBLE]?

MARK HARTMAN: Say that again.

AUDIENCE: C equals m over v.

MARK HARTMAN: C equals m over v?

AUDIENCE: [INAUDIBLE].

MARK HARTMAN: OK, so there's another equation that just describes waves. That is, the speed of a wave is equal to the frequency times the wavelength. That's the one.

This is a description of just waves. And it says that if you know how fast they're going, that is equal to the wavelength times the frequency, which is how many waves per second do you have. So this is just for waves only.

We don't actually have to worry about this because for light-- light waves or light particles-- always have the same speed. It's always the speed of light. So I'm going to go ahead and take that off just, so we don't get confused. You don't have to worry about working with that.

I'm just going to give this to you. We're not actually going to use it, unless you really want to. But this number h times c-- you can turn into the value. I mean, if you actually calculate what it is.

It's 1,240 electron volts times nanometers because most of the time, wavelength is measured in nanometers. The wavelength of these light waves is about 10 to the minus ninth, as large as one meter. So they're really, really small.

So this is our bridge that gets us back and forth. So if we have long wavelength, that means we have-- we can think of a long wavelength light wave as having a low energy photon. And if we have a short wavelength, then we can think of the energy of the photon as being very large.

AUDIENCE: [INAUDIBLE]?

MARK HARTMAN: Say it again.

AUDIENCE: [INAUDIBLE]?

MARK HARTMAN: Yeah, this is Planck's constant, P-L-A-N-C-K. Max Planck or Max Plunk, if you pronounce it the right way. Yeah, you don't have to know exactly what that is.

But what you do need to understand is longer wavelength means or larger wavelength smaller or higher energy, smaller wavelength, larger energy.

AUDIENCE: What's the unit of wavelength?

MARK HARTMAN: The unit of wavelength. Let's take a look. If we want our energies to come out in electron volts, we need to have a unit of wavelength be nanometers. And this is for wavelength in nanometers. All right-- [INAUDIBLE] this together with what we learned before.

If you had a source that was emitting light and that source was emitting light at a certain-- it was emitting photons of only one color. It was emitting photons. Energy of the photon emitted is equal to let's say 2.5 electron volts.

If that source was moving toward you, what would be the energy of the observed photon? If that source was moving away from you, what would be the energy of the observed photon? And if that source is moving perpendicular to you, what would be the energy of that observed photon?

So in this case, this source is emitting light. We're thinking about it. We're looking at it in terms of the wave model of light. I want you to think about, well, now, what if it was a particle model of light?

So with your groups, for just a minute or so, think about if a source was emitting only 2.5 electron volt light, that's a yellow. And a flat spectrum-- it was only emitting yellow light. If it was moving towards you, what would be the energy of the photons that you would collect? Would it be yellow?

Would it be exactly 2.5 electron volts? Would it be bigger? Would it be smaller or what?

So I think with your group? If the energy of the emitted photon was 2 and 1/2 electron volts, if that source is moving towards us, what energy of photon do we observe, Jalen?

AUDIENCE: We would like see green or blue.

MARK HARTMAN: OK.

AUDIENCE: The lower the wavelength, [INAUDIBLE] have to get higher-energy protons.

MARK HARTMAN: To lower the wavelength of the light, the higher the observed energy of the photon. So the energy of the observed photon is going to be greater than 2.5 electron volts, which we see as not yellow. So let's say emitted photon is yellow.

Here we're going to see it as blue or something that's green or blue-- green or blue. What about when the source is moving away from the observer? Chris is raising his hand.

AUDIENCE: I was stretching.

MARK HARTMAN: Looked like you were raising your hand-- same thing.

AUDIENCE: It would be less.

MARK HARTMAN: OK, what would be less?

AUDIENCE: The one we would see.

MARK HARTMAN: The energy of the observed photon would be--

AUDIENCE: It would be less than 2.5.

MARK HARTMAN: --less than 2.5 electron volts. What would we interpret that as? What color?

AUDIENCE: Pink.

MARK HARTMAN: If it's yellow, it would be more like maybe orange or red. OK, what about in the last case? Jalen, you want to go again?

AUDIENCE: It would be the same as the stationary. It would be yellow.

MARK HARTMAN: OK

AUDIENCE: Well, near.

MARK HARTMAN: It would be near. It would be close. So it would be about 2.5 electron volts-- so still yellow. So hang on.

Here's our object. It's moving away fast. So it looks like-- whoops. Somebody throw me a marker, please.

So if it's moving away fast-- oh, that's horrible. If it's moving away fast-- again, horrible. These are all still circles. They're not ovals, which is what I'm having trouble with.

If they're moving away fast and you're over here, you're going to measure this distance as your wavelength. So you're saying that's really wide. So what is different about when you're moving away slow?

AUDIENCE: It produces like a yellowish orange.

MARK HARTMAN: Well, let's not get to that just yet. So that's fast. What does it look like when it's slow but still moving away from you?

AUDIENCE: [INAUDIBLE] but they're not as wide as [INAUDIBLE].

MARK HARTMAN: They're not as wide as when it's going fast. But how do they compare to when it was stationary?

AUDIENCE: It was even [INAUDIBLE].

MARK HARTMAN: Go ahead and finish.

AUDIENCE: Well, they weren't moving at all [INAUDIBLE].

MARK HARTMAN: OK. Lauren?

AUDIENCE: They have shorter wavelengths than if it was stationary, I think. If it was moving from you.

MARK HARTMAN: It's moving slow. It's going to be this. You're still over here.

AUDIENCE: Yeah, so you'd have-- oh, never mind. I just screwed something [INAUDIBLE] no.

MARK HARTMAN: That's slow. This is stationary. They're all perfectly evenly spaced.

AUDIENCE: So there'd be larger wavelengths for the slower one. But [INAUDIBLE]-- I don't know.

MARK HARTMAN: So here. Let's go back what Jalen said. Somebody give me another marker, please. Maybe a staff person.

Oh, no, I can't tell which one it is. OK, so in this case-- oh, good marker choice. So that's like dripping off the wall.

So in this case, our observed wavelength was much, much longer than our emitted wavelength. Here this is our emitted wavelength. Here we're still moving away but slow. Here we're moving away fast.

My diagrams get worse the further into the day we get. So is this wavelength here-- this is lambda observed. This is lambda observed slow. That's lambda observed fast.

How does this wavelength compare to the emitted wavelength? Is it the same? Is it larger? Is it smaller?

AUDIENCE: Smaller.

AUDIENCE: Larger.

MARK HARTMAN: What do you think, Chris? You saw it.

AUDIENCE: I think it's larger.

MARK HARTMAN: So this is still larger. Lambda observed slow-- is still greater than the emitted wavelength, but it's not quite as big as that one.

So how could you say all of this in a sentence? What does speed have to do with what happens to your wavelength? Peter?

AUDIENCE: The faster an object travels, the larger the wavelength.

MARK HARTMAN: The faster an object travels, the larger the wavelengths. Well, what if what if my object was traveling this way towards me?

AUDIENCE: [INAUDIBLE] coming towards you, it depends. The faster it goes, the shorter the wavelength. [INAUDIBLE] slow, fast-- kind of medium [INAUDIBLE] it will still have a shorter wavelength, but it would be small as the one [INAUDIBLE].

MARK HARTMAN: OK, so Steve? That's good.

AUDIENCE: [INAUDIBLE].

MARK HARTMAN: OK, so if you're going fast away from an observer, the wavelengths get long. The faster you go, the longer, they get. If you're going towards an observer, the faster you go, the shorter they get. So scientists write this relationship as lambda observed minus lambda emitted over-- let's just make sure we do this right, and then we'll stop for today because we're already way late.

Peter, is it over lambada emitted or over lambada observed? I think it's over lambada emitted. Yeah, so this relationship says that the difference between these two, which is really the shift that you're getting-- is it getting wider? Is it getting narrower? --is equal to the velocity that it's moving divided by the speed of light. Oops, I suppose I could do this-- sorry.

AUDIENCE: I have a question.

MARK HARTMAN: Yeah.

AUDIENCE: If you do that right, [INAUDIBLE] cancel out?

MARK HARTMAN: Oh, wouldn't the thing that made it in the bottom cancel out? It would if this was a multiplication sign. This is a subtraction. So this is the change in wavelength. So in this case, let's check this out. Here we said that lambda observed was less than lambda emitted.

So this number is less than this number. So what do we get on top? A negative number. In that case, if we divide that by the lambda emitted, we get a negative velocity, which we kind of just choose which way is negative and which way is positive.

Negative velocity says the source is moving towards you. Now, well, let's look at the one that's moving away that we were just talking about. If the source is moving away from you, the observed wavelength is longer. So this number is bigger. So bigger number minus a smaller number is a positive number.

So a positive velocity is moving away from you-- away from the origin. That's why we call it positive. But if we move away faster, what does that do to our observed wavelength?

AUDIENCE: It changes.

MARK HARTMAN: Say that again.

AUDIENCE: It changes.

MARK HARTMAN: How does it change if the source moves away faster?

AUDIENCE: [INAUDIBLE].

MARK HARTMAN: OK, the wavelength that we observe-- the wavelength we received-- is even bigger. So this number up here gets even bigger, and that's reflected by saying it's a higher velocity. It's moving away faster.

OK last thing for the day, and then we're going to finish up. Astronomers call this measurement this value right here is called redshift. It is a quantity called redshift, and you represent it as the letter Z. Why would they call this redshift?

AUDIENCE: Because the [INAUDIBLE].

MARK HARTMAN: Because what?

AUDIENCE: Because the core of the particle itself [INAUDIBLE] moving away [INAUDIBLE] moving towards you, it emits different kind of light?

MARK HARTMAN: As the source is moving away from you or towards you, it doesn't always emit the same color. If it's moving towards you, it will be shifted toward the blue end of the spectrum. It will be shifted towards shorter wavelengths, higher energies.

And it's moving faster, it'll be shifted to even faster energies-- or I'm sorry-- even higher energies. It will be shifted toward the blue. If this number is negative, it's a negative redshift.

So the light that we see is shifted towards higher energies-- bluer energies. If the source is moving away from us, then this number gets larger, and it's a redshift. What happens to the energy of the photons that are emitted?

AUDIENCE: Gets red.

AUDIENCE: Goes toward the red.

MARK HARTMAN: It goes toward the red. They don't turn red. They just become smaller energy, longer wavelength.