SAARIK KALIA: OK. Hi. So my name is Saarik, and I'm going to be talking today about how we can use the 21 centimeter hydrogen line to determine the galactic rotation curve and some of the structure of the Milky Way galaxy.

So first off, why do we care about galactic rotation curves? So basically rotation speed can tell us about mass. We know this from simple Newtonian mechanics. If you have a planet going around a sun, then its velocity is given by this equation, where M here is the mass of the sun.

In our case, since we're working with a galaxy, we have spread out mass. This M is actually going to correspond to basically the mass contained within the orbit. So using a formula like this, given the mass distribution that we see in the Milky Way galaxy, we can guess what kinds of velocities we should see various things rotating at. And we can plot that and we get a curve that looks like this.

But we actually, as we'll see later when we go ahead and observe what velocities stars are really moving at, we'll actually see a huge discrepancy between what we would expect from the visible matter that we can see. And basically the way that we might be able to explain this is possibly there is matter out there that we just can't see. And physicists term this matter as dark matter. So what we're going to be working on in this experiment is trying to be able to actually plot this rotation curve. And in being able to show these discrepancies, this will motivate new physics.

So how are we going to find this rotation curve? So the way we're going to be looking at the velocities of various stars is using the Doppler effect. In our case, this will be a non-relativistic Doppler effect. This is simply just, as an object is moving towards you, the frequencies that it emits are slightly higher than if it were standing still.

So we can look out at the stars. But looking for optical light doesn't work too well because it suffers absorption from other stars or interstellar gas and dust. So instead we prefer something in a slightly lower frequency range around the radio emission range.

Luckily for us, hydrogen actually exhibits an emission in this lower frequency range, particularly, yeah, at this 21 centimeter line. And this occurs as spin flip transition. So when the proton and electron go from being aligned to anti-aligned, that's a slightly lower energy state, and so it releases a little bit of energy. And we can look at that energy coming from the sky. And by seeing how that frequency shifts, we can deduce the velocity that the emitter must have been moving at.

So this is the apparatus we're going to be using for detecting our various emissions. The actual telescope itself is a parabolic dish, which takes an incoming light, reflects it onto this feed horn, and the net signal is fed into this fairly complex circuit. I'll just point out some important things.

The signal comes in, it gets amplified, goes to the bandpass filter. That's just to get rid of any frequencies we absolutely don't care about. And then one important point is that it goes to this image rejection mixer. And what that does is it multiplies the incoming signal by a signal that we manually put in of 1420.4 megahertz. That's the frequency of the 21 centimeter line that we're looking for.

And as you can see from this trigonometric formula, multiplying two signals is actually equivalent to just producing one signal whose frequency is the sum and one who's the difference. And by using the second bandpass filter, we can eliminate the sum and just be left with this signal, which is the difference. And so the reason we do this is just to get a very precise measurement of how off the signal we're seeing is from the 21 centimeter line we would expect from a still observer. And using that we can figure out what velocity the emitter is moving at.

OK, and so in order to turn this into temperatures is what we'll be dealing with. We're going to first have to calibrate this with a noise diode. What this will do is just send a signal to the feed horn that looks like 115 Kelvin blackbody all throughout the sky. And so it uses the signal it sees from this to extrapolate other signals that it will see.

So basically, if later on it sees a signal that's twice as strong as the signal that's on its calibration, at some specific frequency then it says, oh, there must be a 230 Kelvin blackbody at that specific frequency. So at the end we'll be getting some sort of temperature profile as a function of frequency. And we're going to be taking measurements all across the galaxy.

Essentially, our galaxy is mostly shaped in a planar disk, so we'll be just looking within that disk. The galaxy has some central bulge with some spiral arms coming out of it. And our sun is located down here. We will be sweeping from the galactic longitude of zero, which is directed towards the center of the galaxy, out to 180, which is directed away from it, so we'll be looking at the first and second quadrants. As we'll talk about later, these first quadrant measurements will be used to determine the rotation curve and the second quadrant measurements will be used to determine the structures of the galaxy.

OK, so as we mentioned before, given a frequency, we can turn that into a velocity using our Doppler shift via this formula. This 120. 4-- or 1420.4 megahertz is just the emission, the frequency of the 21 centimeter line. This right here is just the speed of light. And then we have this VLSR. This is just our velocity with respect to the sun just to factor out any revolution that we have around the sun. So this V observed is actually the velocity with respect to the sun, not with respect us.

And so now we can use this velocity using various trig formulas, Law of Sines. We can relate the velocity we observed to the actual velocity of the star in question. And note here we have to use this critical assumption that the stars move in circular orbits, which is fairly close to accurate. But using this assumption allows us to say that the velocity of this star is at a right angle with its radius. And then if we know the radius at which the star lies, then we can use this formula to relate the velocity we see with the velocity of the star.

And here we're going to be taking R naught, which is the distance from us to the center of the sun, to be a 8.5 kiloparsecs and theta naught, which is our speed within the galaxy, to be 220 kilometers per second. These numbers are not too well known, but these will be the values we'll be using. And the literature will compare again, so we'll be using the same values.

Right, and so this formula is all well and good if we actually know what radius this star is at. But, a priori, we don't know that. So the trick we're going to be using here is actually just to consider the maximum velocity that we see. And the maximum velocity will occur at the minimum radius. And that's simply given by this R naught sine L.

And so if we specifically consider that minimum radius, then this formula allows us to relate that maximum velocity to the velocity of the star in question. Note, however, that this only works for longitudes less than 90. That's in the first quadrant I was talking about before. And that's simply because, if you're looking at stars which are further away from the center of the galaxy, then they're all just going to get further and further away. There's not going to be any minimum radius.

Right, so we wanted to determine this maximum velocity that's equivalent to determining a minimum frequency. So how are we actually going to get that minimum frequency? So as we said before, we have this temperature spectrum as a function of frequency. We're going to start off by trimming off the edges. There's just a very quick falloff just from the bandpass filter there, so we have to get rid of those. And at each given longitude, we take about 40 trials and we average that into one the temperature spectrum.

So this is what our spectrum looks like. We're going to fit the first few bins to a linear background. And we can see that the background fit is quite good for these initial points. You'll notice here we have this annoying little peak here. This actually shows up in most of our plots. This is probably because of just some constant source that's creating noise. So when we fit this background, we just ignore those points in particular. But for the rest of the points, the fit is quite good.

Then we're going to find the first point, which exceeds this background by some fixed amount one Kelvin. And we say that that is going to be our minimum emission frequency. So in this case, this is 1420.4494 megahertz. And we can estimate the error on this method by basically fudging this 35 number, so see what happens if we use the first 20 bins versus what happens when we use the first 50 instead.

And so the number we get out of it will shift a little bit up or a little bit down. In this case, it shifted one bin up and two bins down. And so that gives us an error on what this kind of method will give for a minimum emission frequency. And by default, if shifting around this 35 number doesn't change anything, then we'll just say that the error is just the bin with itself.

Great. So using that minimum mission frequency, we can find a velocity as per the formulas I had a few slides ago. And we can also get the radius simply as a function of the galactic longitude. And we can plot it out. And we'll get a curve that looks something like this.

So this red curve that I'm plotting here is a curve I found in the literature from a paper by Clemens. He fit a piecewise polynomial to his observed data, and so we're comparing it to that. We see actually that the later values, the higher radii actually agree quite well with the literature. We see a little more disagreement with the lower values. This can be for possibly a few reasons.

One could be you might have seen in that plot I had before that the temperature starts to rise much slower, and so it's harder to find an emission frequency. For these higher values, there's a much sharper jump. Secondly, the actual frequencies that you need to move these points up to this line tend to be outside of our frequency window or where that annoying little noise was, so that's just somewhat of a limitation of the apparatus. And then the third is the circular orbit assumption. For smaller angles this assumption becomes more critical, and so even a small shift in angle can make a much bigger difference.

So we see, if we look just at the later points, we actually get a pretty decent chi squared of 13.4. So, yeah, this agrees fairly well with the literature. So then there's one more thing that we want to try to look at using this 21 centimeter line, and that's going to be the galactic structure of the Milky Way.

As we talked about before, we know that the Milky Way has spiral arms, so we're going to try to see if we can look out and find those structures. So in order to do this, we specifically need to assume some sort of galactic rotation curve, so we're going to be working with the one that we found in Clemens. And using the formulas before, we can use this given curve to solve for a specific R given any observed velocity.

So now we can associate radii with all the velocities that we see. And, of course, this is just the radius from the center of the galaxy. What we actually want is the distance from us in order to be able to plot this, so we can make that quick change here.

And now note that this only really works for galactic longitudes greater than 90. Those are things in the second quadrant simply because, if we look inwards to the first quadrant, there are two possible solutions. Along the same line of sight you can find two different points that have the same distance from the center. And again, we're going to fit these to a linear background now with 25 initial bins and 10 final bins. And we're going to say the temperature above the background multiplied by the distance from us squared, this is just because of an inverse square power law, we're going to say that that gives us a relative measure of how much hydrogen must be there and, as a result, how much emission that we're seeing.

So we can use these methods and plot out of a big plot of what the second quadrant of the Milky Way galaxy looks like. So you can see here, there are two spiral arms we can see, one much closer to us and then one forming out around here. Those actually correspond fairly well with this Perseus arm here and then the outer arm further out here. You might notice that, as we get up to higher longitudes, the points start to become larger. Here the points denote the strength, yeah, the relative amount of hydrogen that we would see in a region out there based on the temperature of the background.

And so you might see here that, as we get out to higher longitudes, we start to see it blow up a little bit. We don't believe that this is a physical consequence, that this is actually physical. This is more just a limitation of the apparatus.

So in conclusion, we were able to use this 21 centimeter technique to derive the rotation curve of the Milky Way, and we saw pretty good agreement with the literature for large radii. In particular, we saw there was a constant velocity function as we went out to higher radii, and that disagrees with the theoretical prediction. And so this really necessitates some sort of dark matter, which can compensate for the discrepancy. We were also able to see some of the Milky Way structure by looking at the exterior points. And in particular, we saw two spiral arms in that second quadrant.

And finally I would like to thank my partner, Toby, for all his help throughout this semester and on this particular experiment, some last minute data collection. I'd like to thank the 8.13 staff for all their help throughout and instruction and then MIT for offering this course. OK.

PROFESSOR: Questions?

SAARIK KALIA: Yeah?

AUDIENCE: You mentioned that you fit your background to a linear fit.

SAARIK KALIA: All right.

AUDIENCE: Why do you expect the background to go up as you go in frequency? It seems like, at least [INAUDIBLE], it would just stay constant across all the planes.

SAARIK KALIA: So I think this is essentially because of the-- you would expect the temperature that you see from a blackbody to go like Planck's Law or his formula, right, the blackbody spectrum formula. But essentially what we're doing is we're zooming in on a very, very small part of that, specifically around one frequency. And so in that region, it's linear.

AUDIENCE: OK.

SAARIK KALIA: So this is why we're expecting some sort of linear background.

AUDIENCE: OK.

PROFESSOR: Good questions?

SAARIK KALIA: Yeah.

AUDIENCE: What uncertainty do you find in your temperature counts? Or is there uncertainty?

SAARIK KALIA: So for the rotation curve, the uncertainty in the-- I mean, yeah, I guess there should be some like Poisson uncertainty in the temperature counts. For the rotation curve, that's not as important because what we care about is the frequency at which it occurs. I guess for the galactic structure, you really could put some uncertainty on that and it would just be squared of n Poisson uncertainty.

PROFESSOR: OK. And no other questions? Thank the speaker again.