**Slide 1**

Alright, welcome to my talk which I’ve titled “Galactic geometry and the rotation of the milky way. “

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Before we begin, I’ll say some of our goals with this talk and this experiment:

Firstly, to derive for ourselves a curve for the rotational velocity of the Milky way

And Secondly, along the way, we want to compare our results with other predictive models and see what any discrepancies or patterns can tell us about new physical phenomena or what we can confirm for ourselves

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So, to begin, I want to briefly overview the theory of rotation and gravitation.

So I’ll turn your attention to the diagram I’ve created on the right, which shows an object, perhaps a planet, in circular orbit around a more massive, central object.

Essentially, the reason we care about rotation curves is because they can tell us about mass and mass distributions. We can see that immediately by taking what we know from basic classical mechanics, namely Newton’s laws of gravitation and centripetal forces, and combine them to obtain this inverse square root law for the speed of the rotating object. We call this the keplerian prediction because of how it relates to Kepler’s laws.

But we can also consider some imaginary object orbiting inside the central mass. So that would mean it is exposed only to a fraction of the central mass bounded by the orbit, so we can take the mass density of this central object and multiply by the volume the orbit creates to get an effective mass. Substituting this back in to our centripetal force relation gives us this velocity function, which is linear. We’ll call this the solid body prediction for now, because of how it was derived

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Like we saw on the last slide, we have two predicted models—one being this keplerian law (the inverse square root law) and the other being the solid body model (which is the linear function, shown in the gold dotted line.). So these will be our two theoretical models which we may expect to see independently, or perhaps some combination of them when we derive our rotation curve.

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So Now we’ll look at the geometric structure of the milky way. To compute a velocity curve, we’ll need a number of useful kinematic quantities. For this slide, we’ll be referencing my diagram to the right

First of which, when we point the telescope at different galactic objects, we’ll want to know its distance, r, from the center of the galaxy. So if our solar system’s distance to the center of the milky way is roughly 8.5 plus or minus 0.5 kpc, then we can relate the radius we want to our distance by simple trigonometry. So we take the sine of the radian-converted longitudinal angle that our observed object makes with the hypotenuse, and those will be our radii, or the independent variables in the rotation curve.

Next, a crucial concept for this lab is the non-relativistic Doppler effect, which basically states that observes perceive shifted frequencies when the emitted frequency originates from a moving source. I’ve shown the rearranged version of that law, whereby we can simply calculate the velocity of the moving source by considering the difference between this central frequency f0 and the maximally red-shifted frequency.

Then, to get the max radial velocity along our line of sight, we just take the source’s speed and subtract to it this extra term, the velocity of the local standard of rest, which is just to factor out any revolution we as observesr have with respect to the sun.

Finally, combining this max radial velocity with the appropriate component of the speed of our solar system, we get our estimate for the galactic velocity.

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The final piece of our theory is related to how we actually make measurements with our telescope. So it’s well known that traditional optical light gets absorbed a great deal in the interstellar medium by objects like stars and dust. But instead, we can use frequencies in a different range to make measurements, namely in the radio-wave range.

So we known that hydrogen is in abundance in the atmosphere, and hydrogen atoms exhibit a very convenient quantum mechanical property wherein, due to the discretization of angular momentum states, the proton in the nucleus and the electron may occupy either the same spin or opposite spin, which I’ve diagrammed at the bottom. But the Hydrogen atoms can transition from the former to the latter state (which is at a lower energy), and when they do this shift, then according to the Planck relation, the energy emitted is of a frequency of about 1420.4 Megahertz, or about 21 centimeters wavelength. This is the hydrogen spin-flip line, and we use it to measure frequencies in this range in the galaxy to find the Doppler shifts.

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Moving on, I want to show off the experimental apparatus we work with. So on the right you can see an actually picture of the small radio telescope (SRT) on the roof of building 26 (his name is roger), and on the left is a diagram of its structure. So what we have is a parabolic dish that reflects incoming light to this feed horn for internal processing. And while the inner circuitry is fairly complex beyond this simple signal chain, we can at a high level understand this as a telescope which we control using a computer interface to point the antenna at a given orientation, and filter radiowaves in the frequency range around the hydrogen spin-flip line. I’ve included more complex diagrams of the circuitry in my appendixes, but this is sufficient for us for now.

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So now we can start looking at some raw data. So the data we collected was in increments of 5 degrees for longitudinal angles between 0 and 90 degrees in the galactic plane. We pointed the telescope at each of those angles, and measured the frequency spectrum by averaging over 20 scans at each location.

So here you’re seeing two such examples of those scans; on the left you see 60 degrees and on the right you see 85 degrees. On the x-axis we have our frequency bins, a total of 148 bins of width about 7 kilohertz. And on the y-axis, you have the relative intensity (or temperature) that the SRT measures ine ach bin in units of kelvin. So these raw spectra give us some information, but in order to proceed with the analysis I choose to fit the data to a linear function, in order to construct a background model that can be subtracted from these raw spectra to obtain more meaningful signals. So in red, you can see on top of the data points the best fit linear background functions in each case.

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Like I said, we take the background models we fit and subtract them from the raw data to get these new spectra. Our x axis is the same frequency bins, but now on the y axis we have the relative background-subtracted intensity spectrum as scanned. We see some interesting peaks in the spectra, and to determine what those are I fit each of these new spectra to a functional which is comprised of the sum of four Gaussian functions and a constant offset.

So in green, you’re seeing the best fit functional over the data. Now remember that we need to determine the maximally red-shifted frequency, so in order to do that I take the smallest mean-fit parameter, I.e. the smallest frequency center of the four gaussians, and call that the maximally red-shifted frequency, since subtracting that from the 21cm line frequency will give the largest shift.

So in red, you can see each of those max red-shifted frequencies labeled on the plots.

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Now, with the data we have, we’re actually able to compute the velocity curve! So for each of our longitudinal angles, we compute the corresponding radii, and that’s what you see on the x-axis in kiloparsecs. Now on the y axis you have the rotational velocity of the milky way at the various points away from its center.

As for the figure on the right, we have the comparison between the two theoretical models we started out with. So curve A is, once again, the Keplerian prediction and curve B is the approximately linear prediction. You can see that above r0 there’s a large discrepancy between the two curves. The first time physicists observed this, they posited that the curve’s behavior at longer distances was indicative that there was some undetected mass distribution present, hence the name dark matter. So for that reason, I’ll now refer to the linear solid-body model as the ‘dark matter model.’

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So now we can fit our data to the two models. So the plot you’re looking at is once again the calculated experimental velocity curve data points in blue, where the error bars horizontally and vertically are primarily from propagating the uncertainties in the solar system distance to the galactic center and the solar system’s speed, respectively. So there’s the data, superimposed above which you now see the purple dotted line representing the best fit to the linear dark-matter model, and the green solid line is the best fit to the keplerian model. As a reminder, you can see both functions on the left of the plot.

Now you’re also seeing this gray dotted line, which I;ve added because you’ll notice that I’m only performing these fits for the data points above 6 kiloparsecs. The reason I do this is because the radius of the Milk Way bulge is in fact about 6 kiloparsecs, and I wish to study the rotation curve law outside of this region of concentrated mass to get a more clear comparison between the models.

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Now moving ahead one slide, I’ve provided a zoomed in version of the previous plot, where you can see both model fits and the data above 6 kpc more clearly. And amazingly enough, computing the chi-squared from each fit shows that our dark matter model minimizes the chi-squared for the data by about 10 times that of the keplerian model.

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So looking at our results again, we find a chisquared value for the keplerian mode fit to be about 21.3, and the dark matter model fit has a chi squared of about one-tenth the keplerian’s which is around 2.12. So indeed for these data the dark matter model provides us with a much better prediction.

Briefly discussing some sources of error throughout this experiment: first statistical; when I collected data I didn’t scan each galactic longitude as frequently as each of the other data points in some cases leading to higher standard errors on some of the data points than others. Also, as always more data can always help mitigate some of the flucutations we see and there are, at times, varios extra noise sources in the galactic plane that interfere with some of the scans.

As for some systematic errors, the telescope has a harder time with some of the lower-longitude scans at the times we performed them due to the fact that they were often at the boundary if not just beyond the SRT’s field of view. Also the fit function that I described for the new background-subtracted frequency spectra was determined primarily by inspection and not motivated by a theory. Finally some of the days during which we gathered data varied fairly significantly in weather, which may have interfered with the SRT device.

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To conclude, some of the things we managed to do were derive a rotation curve for the milky way and indeed confirm that the dark matter prediction is valid and desvribed the observed data much better than the classical keplerian model. We also hence showed that the 21cm SRT technique is very useful for studying the milky way.

As for where this can go, we can use these data and methods to probe galactic regions for a better understanding of the dark-matter (or other) mass density. And we could also go further and derive the spiral arm structure of the milky way in the future.

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Finally some acknowledgements. I want to thank my lab partner Luke for all of his collaboration, as well as the wonderful 8.13 staff for all of their help and guidance, as well as MIT for providing the equipment and laboratories.

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Thanks so much!