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The Magellanic Corona and its Role in the Evolution of the Magellanic Stream

by

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Chapter 5

Simulations of the Magellanic Clouds: A Discussion for the Non-Scientist

My favorite aspect of doing science is talking about it – discussing the nuances of a new publication with my colleagues, giving seminars explaining my research to other physicists and astronomers, or simply talking about black holes with strangers in an elevator. I wrote this chapter in hopes of starting many more of these conversations. It has not only strengthened my love for public science, but allowed me to see my work in a new light with a much broader impact. If we as scientists continue to nestle ourselves in ever more esoteric niches without bringing the public with us or relating our work to other fields, science literacy is bound to wane. I am extremely grateful to Professor Bassam Shakhashiri and the Wisconsin Initiative for Science Literacy for starting this project and to Cayce Osborne and Elizabeth Reynolds for supporting my participation.

Humans have always been gazing at the heavens, trying to understand what's out there. We started closest to home with our own Solar System. Understanding that the Earth and all the other planets orbit the Sun was crucial to finding our place in the universe. With this information, and continually improving telescope technology, we discovered that all the other dots we could see in the night sky were other suns located at incredible distances from Earth. All of these stars comprised our Milky Way galaxy, which, as recently as the 1920s, was thought to contain all the stars in the universe. But in addition to stars, astronomers saw fuzzy patches in the night sky, dubbed "nebulae." By determining the distances to these nebulae, we discovered that the Milky Way was just one of many, many galaxies in the universe (Hubble, 1925).

Even today, there remain many unanswered mysteries of galaxies. Astronomers in the 1990s used the *Hubble Space Telescope* to estimate that there are two trillion galaxies in the observable universe (Siegel, 2022). And each of these galaxies looks different. The huge variety in appearance and morphology of the universe's galaxies showed astronomers that galaxies are not static objects; they grow and evolve. For this to happen, galaxies need to acquire gas, which then compresses and condenses to form stars. However, as stars form, this gas gets used up, so galaxies continually need new gas. The *Hubble Space Telescope* has shown us galaxies across the entire spectrum – from galaxies that ran out of gas and are only made up of old stars, to bright exciting galaxies with stars forming right now. My work aims to understand how these galaxies acquire new gas and evolve into what we see in the night sky today.

In order to learn about how galaxies get their gas, we need to be able to see that gas. When looking up into the night sky with your naked eyes, or perhaps a backyard telescope, we see starlight (emitted from stars, or reflected off of planets and moons). However, advances in telescope technology have given us the ability to look beyond the light that our eyes can see. Various chemical elements can emit light in the ultraviolet, infrared, microwave, or radio wavelengths, imperceptible to the human eye. By building telescopes that can detect these different frequencies of light, we can see more than just the stars; we can see the gas. And while space may look pretty sparse to our naked eyes, it is very much not empty.

If we observe the sky in radio waves, we see something drastically different than the tiny pinpricks of stars that we are used to. Radio waves trace the existence of cold ("neutral") hydrogen gas, and hydrogen is everywhere. Figure 5.1 shows comparisons between an optical photograph as

Figure 5.1: The night sky in optical and radio waves. Three versions of a photograph taken by Colin Legg of the Milky Way disk and Magellanic Clouds. The original (optical) photo is in the top left showing what you would see with your naked eye. The top right photo is what would appear if we could photograph radio waves showing the neutral hydrogen in the sky. The Milky Way disk and Magellanic Clouds are still clearly visible. The bottom photo shows the neutral hydrogen only associated with the Magellanic Clouds. The two galaxies are the bright spots at the top center of the image (LMC on top, SMC below) and the Magellanic Stream extends out towards the right edge of the image. The Leading Arm clumps are to the left of the Magellanic galaxies.

we would see with our naked eyes ("optical," top left) and the neutral hydrogen in the sky traced by radio wave emission (top right). The bright band of stars on the left side of the optical image (top left) is the disk of our Milky Way galaxy. Our disk is also very bright in radio waves (top right) since it is where most of the hydrogen gas resides. We can also see two bright spots at the top center in both images. These are the Large and Small Magellanic Clouds (LMC, above; SMC, below). They are two other galaxies outside the Milky Way. And as we can see from the top right image, they aren't just made up of stars, they have a lot of hydrogen gas as well. If we isolate just the gas associated with the Magellanic Clouds, we are left with the image on the bottom of Figure 5.1. A huge amount of hydrogen is not only overlapping with the stars of these galaxies, but extending out all around them. This extensive network of gas covering the sky is the mystery that I have been trying to explain through this work – the Magellanic Stream.

5.1 The Magellanic System

Although faint, the stars in the Magellanic Clouds are visible with the naked eye from the southern hemisphere. There are innumerable references to the Clouds as "fountains" or "pools of water" in the sky from cultures in the southern hemisphere such as the Mapuche in Chile and the Tupi-Guaranis in Brazil (Dennefeld, 2020). From the 16th Century, they were dubbed "Nubecula Minor" and "Nubecula Major" in scientific publications. It wasn't until the end of the 19th Century when the galaxies began to be associated with Ferdinand Magellan's name. This was presumably because they feature prominently in the astronomers' and navigators' writings from his circumnavigation of the globe in 1519 (Dennefeld, 2020).

Today, we know the LMC and the SMC as dwarf galaxies that are currently orbiting the Milky Way. Our Galaxy has many "satellite" galaxies, but the Magellanic Clouds are the two biggest. They are also the only two that still have any gas. Additionally, we know that the Clouds have been experiencing strong gravitational forces. Both of their disks are warped and misshapen (they are both technically classified as "irregular galaxies"). We can also see a bridge of gas and stars extending between the galaxies (D'Onghia and Fox, 2016). All of these observations point to the Clouds most likely having had a collision a few hundred million years ago (very recently on the scale of galaxies!), and possibly more interactions in the past.

In addition to the LMC, SMC, and "Magellanic Bridge" mentioned above, the Magellanic System includes the Magellanic Stream, originally observed in the 1970s. Don Mathewson and collaborators used newly acquired radio telescope data from the Parkes Observatory in Australia to identify a continuous stream of gas trailing behind the Magellanic Clouds (Mathewson et al., 1974). They gave it the name the Magellanic Stream, and in the decades since its discovery we have learned a tremendous amount about it. Improved telescopes have given us incredible, high-resolution images of the hydrogen gas in the Stream (like we can see in Figure 5.1). These observations allow us to map the distribution of cold gas.

We call this cold gas "neutral" because it is comprised of hydrogen atoms that still have their electrons. In its natural state, hydrogen has a proton and an electron, making it electrically neutral. However, if the gas gets hot, these hydrogen atoms are moving much more quickly and colliding into each other with much more energy. These collisions dislodge the electrons, “ionizing” the hydrogen. We can see the (neutral) hydrogen in radio waves because of its electron changing energy levels. Since ionized hydrogen has lost its electrons, we have to detect this hot gas another way.

The technique scientists have used to observe this hot, ionized gas is called “absorption-line spectroscopy” and it has been put to good use in the Magellanic System. While we aren’t able to take a picture of the hot gas like what we see in Figure 5.1 for the cold gas, we can still estimate how much of it there is. And it turns out that this ionized material constitutes the majority of the total mass of the Stream! Andy Fox and collaborators in 2014 found that what we can see in the bottom image in Figure 5.1 is actually just a quarter of the total gas that the Magellanic Clouds are bringing with them (Fox et al., 2014). The hot gas makes up the remaining 75%! As we will see below, this observation was one of the key inspirations for my work.

5.2 Previous Theories

We know a lot about the Magellanic Stream, but one piece of the puzzle that we still haven’t worked out is where it came from. People have been trying to understand the origin of the Magellanic Stream ever since it was first discovered (Fujimoto and Sofue, 1976; Davies and Wright, 1977; Murai and Fujimoto, 1980; Gardiner and Noguchi, 1996; Mastropietro et al., 2005). Some of the best tools we have for this exploration are computer simulations. However, back in the 70s and 80s, computers weren’t nearly powerful enough to simulate the full evolution of the Magellanic Clouds. As computers have improved, our simulations have improved as well. But there have also been a few key observations that have paved the way for us to learn about the history of the Magellanic Clouds.

Originally, it was thought that in order to form the Magellanic Stream, the LMC and the SMC must have been orbiting around the Milky Way for most of the age of the universe. However, once we were able to actually measure their velocities, astronomers determined that the Clouds are moving very fast (Kallivayalil et al., 2006). So fast in fact, that they couldn’t have already gone around the Milky Way (Besla et al., 2007). By starting with the Clouds in their present-day positions, with their present-day velocities, we can calculate the gravitational forces on them to trace their positions backwards in time. While this depends on the mass of our Galaxy, and can't account for many of the phenomena that affect the gas, it is a good approximation. This backwards tracing shows us that the most likely scenario is that the LMC and SMC are currently moving away from us after just having approached our Galaxy for the first time (Besla et al., 2007).

The first models of the formation of the Stream in this "first-infall" paradigm were published by Gurtina Besla in 2010 (Besla et al., 2010; Besla et al., 2012). She found that we can still form the Trailing Stream through interactions between the LMC and SMC (instead of through interactions between the LMC and the Milky Way). This model was able to reproduce many of the observed features in the Stream, and was consistent with the very high velocities of the Clouds that we observe today. Figure 5.2 shows a schematic contrasting the original models in which the Clouds orbit the Milky Way multiple times (black dashed line), with the first-infall model where the LMC and SMC have just had their first approach to our Galaxy (black solid line).

However, upon realizing that the Stream is mostly ionized (Fox et al., 2014), this model hit a bit of a rough patch. Not only was there no ionized gas predicted in Gurtina's models (there was no mechanism included to heat up the gas), but there was only a small amount of gas stripped out into the Trailing Stream. Andy Fox's work showed that the total mass in the Magellanic System was four times larger than previously thought. A previous graduate student here at UW–Madison, Stephen Pardy, wrote several papers on the evolution of the Magellanic Clouds exploring this issue. In one published in 2018, he increased the amount of gas the LMC and SMC started with in the simulations in an attempt to explain the massive amount of ionized material (Pardy et al., 2018). However, he was still unable to reconcile these models with the ionized gas observations.

5.3 The Magellanic Corona

Building on the work by Gurtina and Stephen, I began my PhD looking to explain the ionized gas in the Stream. It didn't seem like the ionized gas could come from the disks of the Magellanic Clouds (Stephen's work), so we needed a new source for this material. But are there any other parts of a galaxy that we could consider? That depends on the galaxy's mass.

Determining the total mass of a galaxy is very difficult because galaxies are mostly comprised

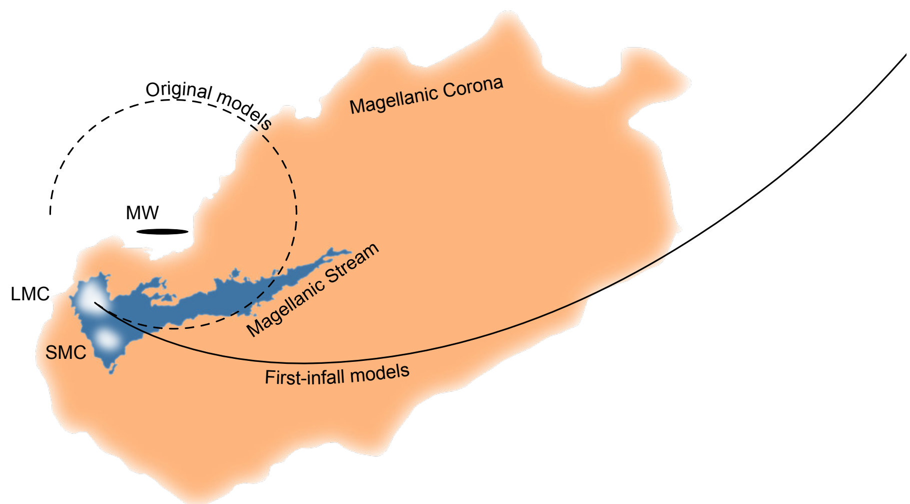

Figure 5.2: First-infall of the Magellanic Clouds. A schematic showing a zoomed-out view of the LMC and SMC relative to the Milky Way (the Milky Way disk is shown edge-on as the black oval labelled MW). The lines show the orbital histories of the Magellanic Clouds contrasting the original, multiple-passage model (dotted line) with the first-passage model (solid line) in which the LMC and SMC have just recently approached the Milky Way. Also shown is a sketch of the cold, neutral Magellanic Stream (blue) trailing behind the Clouds embedded within the massive, ionized Magellanic Corona (orange).

of invisible "dark matter." We need to look for how galaxies are affecting their environments indirectly. There are many different techniques used to "weigh" the Magellanic Clouds (focusing mostly on the LMC since it is larger). One such method uses the fact that the Clouds just passed their first closest approach to our Galaxy. By Newton's Third Law (for every action, there is an equal and opposite reaction), if the Milky Way is pulling on the LMC, then the LMC is also pulling on the Milky Way. So by looking for signs that the Milky Way has moved, we can measure just how much the LMC was pulling on our Galaxy – giving us an estimate for its mass. This has been done and we do in fact see a shift in the center of the Milky Way's disk when compared to the stars in its outer halo (Petersen and Peñarrubia, 2021). Using this technique and others, scientists have estimated that the LMC's mass is roughly 10% of the mass of the Milky Way.

These estimates now put the mass of the LMC above a special threshold. Small galaxies consist of stars and sometimes gas in their disk, embedded within dark matter. But more massive galaxies can gravitationally hold onto more material. This additional gas gets heated up through repeated collisions and can provide a supporting pressure force due to its increased temperature. Therefore, in addition to the stars and gas in their disk, larger galaxies often are surrounded by a spherical "corona" containing more gas that can slowly feed the disk and fuel continued growth of the galaxy.

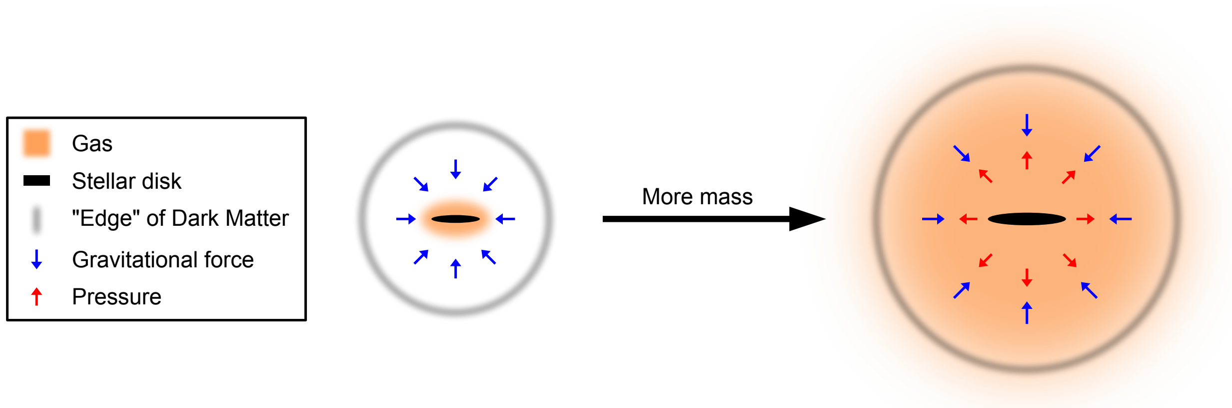

Figure 5.3: Galaxies with coronae. This schematic shows that for low mass galaxies, the gas resides in their disks because it isn't heated sufficiently to provide a supporting pressure force. Whereas in higher mass galaxies, the gas is heated through repeated collisions and fills the volume of space between the disk and the "edge" of the dark matter halo. Gas is shown in orange, the stellar disks are the black ovals, and the extent of the dark matter is shown as a blurred grey line. The blue arrows represent contraction due to gravity, and the red arrow show forces provided by gas pressure.

Figure 5.3 shows the locations of stars and gas relative to the extent of dark matter for low and high mass galaxies. At 10% of the size of the Milky Way, the LMC would be in the category of galaxies with coronae (Jahn et al., 2021). We now have a new possible source of ionized material for the Magellanic Stream – this spherical reservoir of gas around the LMC. We called this reservoir the "Magellanic Corona" and my work was to run simulations of the evolution of the Clouds to determine if this Magellanic Corona could supply enough gas to match the observations.

5.3.1 Ionized Gas Results

Based on my simulations, the Magellanic Corona can provide the ionized gas that we see around the Magellanic System today. As the LMC and SMC dance around each other, they strip cold gas out of their disks into the Magellanic Stream just as figure skaters spin around each other and fling their partners out into tremendous jumps. That is the same as Gurtina Besla's model, however now all of this is happening while they are embedded within the Magellanic Corona. So once the Magellanic System approaches the Milky Way, the Magellanic Corona forms a cocoon around the Clouds and the Stream, enveloping the stripped gas with ionized material (see Figure 5.2). The distribution and the total mass of the ionized gas in my simulations agree with the observational predictions from Andy Fox (Fox et al., 2014), and we still see the cold Stream consistent with the radio maps in Figure 5.1. Figure 5.2 shows the cold Stream in blue, embedded within the

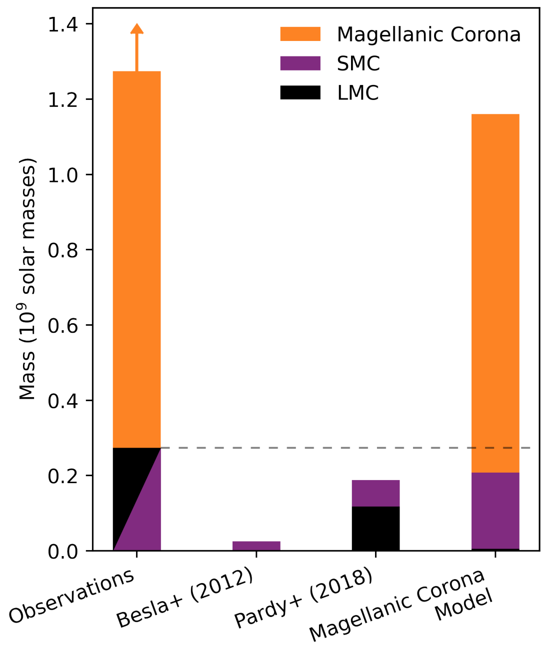

Figure 5.4: Stream mass for different models. Each column represents a different model and the height of the bars show the total mass in each of the components. Black and purple are contributions from gas originally from the LMC and SMC, respectively (the cold, neutral gas). Orange is hot, ionized gas from the Magellanic Corona. The left-most bar are the observed values for the gas in the Stream from Brüns et al. (2005), the next two bars are the results of simulations performed by Gurtina Besla and Stephen Pardy (Besla et al., 2012; Pardy et al., 2018), and the right-most bar summarizes the results from my work showing that the Magellanic Corona can provide the ionized mass in the Stream in agreement with the observations.

Magellanic Corona shown in orange. The Corona has been warped and shaped as it approached the Milky Way and matches what we see in the sky today. Figure 5.4 shows the observed gas mass in the Trailing Stream (left bar) compared with three different models: the original first-infall model from Gurtina Besla, the modified model from Stephen Pardy trying to strip more gas out of the Clouds, and my new model in which the Magellanic Corona provides the ionized gas in agreement with the observations.

So what's still missing from this new model? Well, the inclusion of the Magellanic Corona means that the positions of the Magellanic Clouds in the past aren't quite the same anymore. We're not only trying to find out where the Stream came from, we also want to know how exactly the Magellanic Clouds approached the Milky Way, i.e. what were their orbits in the past? Gurtina found an orbit for the Clouds that matched up the positions and velocities of the LMC and SMC in the simulation with their observations. But once we change what the galaxies look like (add in the Magellanic Corona), we change the gravitational and gas pressure forces that the galaxies feel, so that orbit doesn't work anymore. The main problem with my first model was that my simulated Magellanic Clouds didn't match up with their observed counterparts today.

5.4 Magellanic Orbits

The SMC is orbiting around the LMC while both galaxies are embedded within the Magellanic Corona. So now the SMC has to push through this additional gas as it moves around the LMC.

Instead of biking on a nice clear day, imagine you are the SMC and now you have to bike through a strong headwind. You won't get nearly as far as you would have on the clear day because the wind is working against you. This is what's happening to the SMC as it tries to push through the Magellanic Corona. This additional drag force (called "ram pressure") causes the SMC to lose energy and eventually fall onto the LMC and merge with it. While this will happen in the future, as we observe them today, the Magellanic Clouds are still separated. So in order for the LMC and SMC to match their present-day positions in the sky, we need the Clouds to be interacting for a shorter amount of time.

The trouble is, we can't simply calculate where the Magellanic Clouds were 5 billion years ago. Based on their positions and velocities today, their masses, and the mass of the Milky Way, we can estimate where they might have been by working our way backwards. But the effects of ram pressure, and the actual stripping of the material out into the Stream are incredibly difficult to calculate in reverse. So using a combination of this "backwards integration" and trial and error, I explored possible alternate orbits for the Magellanic Clouds.

After 134 attempts, we were successful in finding an orbital history for the Clouds consistent with their present-day positions and velocities while including the Magellanic Corona. This history involves two interactions over 3.5 billion years (compared with four interactions over 7 billion years in the previous model; Besla et al. 2012), and we still reproduce the cold and hot gas. The results from this simulation are shown in Figure 5.5. Panel a shows positions of the Clouds (white circles) and the Magellanic Stream gas (purple shading) with respect to the Milky Way (grey oval). This is a similar perspective as in Figure 5.2 (Cartesian coordinates). The past orbits of the LMC and SMC are shown by solid and dashed lines in Panel a and the inset. Panel a also shows the gas density at two times in the past in greyscale. Panel b shows the separation between the Magellanic Clouds over time for our new orbits (solid line) and the previous history (dashed line, Besla et al. 2012). This plot shows that our model has two interactions between the Clouds (the two low points), while the previous model had four.

The most interesting result from this work was the position of the Magellanic Stream gas with respect to the Milky Way. Figure 5.5a (and the zoomed in panel) show the gas getting very close to our Galaxy's disk, closer even than the LMC and SMC themselves. Gurtina's previous model predicted that the gas in the Stream should be much farther away than the Clouds, so our

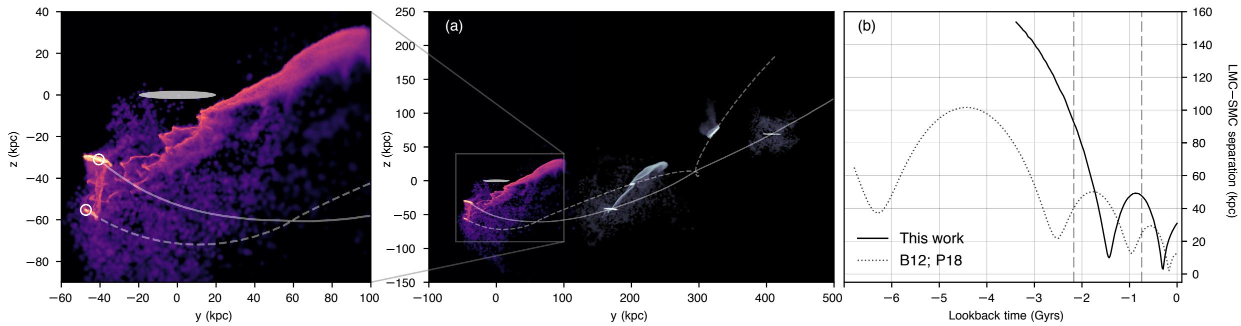

Figure 5.5: The new orbital history for the Magellanic Clouds. This figure shows our simulated Stream relative to the position of the Milky Way (shown as a grey oval). The left panel is a zoomed-in region of Panel (a) which shows the formation of the Stream at the present day (in color) and at two times in the past (750 million years ago, and 2.2 billion years ago). These times are also shown as vertical dashed lines in Panel (b) which shows the separation between the Clouds throughout their interaction history. The solid line is the current model, and the dotted line shows Gurtina Besla's original first-infall model (Besla et al., 2012).

results prompt quite a shift in our understanding of the Magellanic Stream. Interestingly, there are no observational estimates of the distance to the gas in the Stream. Astronomers have devised ingenious methods for determining the distance to astronomical objects. However, all of these techniques rely on stars. Since there are no stars in the Magellanic Stream (it's all gas), we have no way of knowing its distance.

This means that we have relied on simulations and models to predict how far away the gas in the Stream should be. However, because we predict the gas in the Stream to be so much closer, we may be able to use indirect methods to estimate its distance observationally. In ongoing work, we are looking for stars with known distances that overlap with the Stream on the sky. By using absorption-line spectroscopy (as we did to find the hot gas in the Stream), we can see if the Magellanic Stream is in front of or behind those stars. This would only be possible if the Stream is nearby, so it hasn't been tested before. Hopefully we will be able to learn about the distance to the gas in the Stream which would help us confirm or reject different models in the future.

5.5 Future Directions

Over the course of my PhD, we have developed a new picture for where the Magellanic Stream came from. My research began with unexpected observations of hot gas leading to the discovery of the Magellanic Corona, and moved to exploring the implications of this Corona on the history of the Magellanic Clouds. However, we still have much to do. Looking to the future, I am working on making my simulations more robust. By making them more realistic, I will be able to better compare with the available data to see where my models succeed and where they require improvement. One key area which I will be focusing on is in the calculations for the hot vs cold gas. Previously, we used rough assumptions to separate the neutral and ionized components of the Stream. In my new models, I hope to be able to use the simulation code to directly estimate the temperatures and ionization states of each particle.

This work has not only given us a more complete picture of the Magellanic System today, but it has given us crucial insight into what the Magellanic Clouds looked like in the past. In other simulations, we have seen LMC-like galaxies and we can consider their properties throughout the evolution of the universe, but my work has given us strong constraints on the properties of the real LMC. My simulations have shown that the LMC should have had a Magellanic Corona of gas before it approached the Milky Way. This gives us important information about the evolution and growth of dwarf galaxies of that size.

Furthermore, by understanding the distance to the Magellanic gas, we will have a better idea of how it will affect the Milky Way in the future. One way in which galaxies grow and acquire new gas to form stars is through merger events in which multiple galaxies come together and coalesce. Right here in our very own Milky Way, we have an exciting merger event ongoing with the Magellanic Clouds. By understanding what will happen to this gas, we can learn about how galaxies could refuel their gas supply and continue growing and forming stars.

References

Besla, G., et al. 2010, *ApJ*, 721, L97–L101, 10.1088/2041-8205/721/2/L97.

Besla, G., et al. 2007, *ApJ*, 668, 949–967, 10.1086/521385.

Besla, G., et al. 2012, *MNRAS*, 421, 2109–2138, 10.1111/j.1365-2966.2012.20466.x.

Brüns, C., et al. 2005, *A&A*, 432, 45–67, 10.1051/0004-6361:20040321.

D'Onghia, E. and Fox, A. J. 2016, *ARA&A*, 54, 363–400, 10.1146/annurev-astro-081915-023251.

Davies, R. D. and Wright, A. E. 1977, *MNRAS*, 180, 71–88, 10.1093/mnras/180.2.71.

Dennefeld, M. 2020, *The Messenger*, 181, 37–42, 10.18727/0722-6691/5210.

Fox, A. J., et al. 2014, *ApJ*, 787, 147, 10.1088/0004-637X/787/2/147.

Fujimoto, M. and Sofue, Y. 1976, *A&A*, 47, 263–291.

Gardiner, L. T. and Noguchi, M. 1996, *MNRAS*, 278, 191–208, 10.1093/mnras/278.1.191.

Hubble, E. P. 1925, *The Observatory*, 48, 139–142.

Jahn, E. D., et al. 2021, *arXiv e-prints*, arXiv:2106.03861.

Kallivayalil, N., et al. 2006, *ApJ*, 638, 772–785, 10.1086/498972.

Mastropietro, C., et al. 2005, *MNRAS*, 363, 509–520, 10.1111/j.1365-2966.2005.09435.x.

Mathewson, D. S., Cleary, M. N., and Murray, J. D. 1974, *ApJ*, 190, 291–296, 10.1086/152875.

Murai, T. and Fujimoto, M. 1980, *PASJ*, 32, 581–603.

Pardy, S. A., D'Onghia, E., and Fox, A. J. 2018, *ApJ*, 857, 101, 10.3847/1538-4357/aab95b.

Petersen, M. S. and Peñarrubia, J. 2021, *Nature Astronomy*, 5, 251–255, 10.1038/s41550-020-01254-3.

Siegel, E. 2022 , bigthink.com/starts-with-a-bang/how-many-galaxies/. Accessed 14/4/2023.