\documentclass{aastex63}

%% Define new commands here
\newcommand\latex{La\TeX}
\graphicspath{{./}{figures/}}
\usepackage{graphicx}
\usepackage[most]{tcolorbox}
\usepackage{listings}
\providecommand{\keywords}[1]{\textbf{\textit{Index terms---}} #1}

\begin{document}

\title{The MW-M31 Dark Matter Merger Remnant 3D Distribution\\}

\author{Cassandra Bodin}
\affiliation{University of Arizona}

\keywords{Dark Matter Halo, 3D Distribution, Major Merger, Merger Remnant, Local Group, Milky Way, Andromeda}

%% Start the main body of the article. If no sections in the
%% research note leave the \section call blank to make the title.
%%Introduction
%%Introduction
\section{Introduction}

%%Define the proposed topic:
%%MW/M31 Merger Remnant- Dark Matter Halo Evolution
%%Question: Is the 3D dark matter distribution spheroidal? or elongated like an ellipsoid.

Our universe consists of countless numbers of galaxies, each belonging to different subgroups. Our galaxy, the Milky Way (MW) belongs to a small subsection of galaxies that we call the local group. Within our local group the 3 largest galaxies, or dominant galaxies, are the MW, the Andromeda Galaxy (M31), and the Triangulum galaxy (M33). In 2012, using data from the Hubble Space Telescope, it was discovered that M31 is on a direct collision course for the MW, see Figure 1. The collision is projected to take place in approximately 4 billion years. \cite{Dunbar_2012} Throughout the time of the merger a substantial amount of changes will take place that will shape the evolutionary path of not only the MW but the entire local group. One such change will be the 3D distribution of dark matter. Currently the distribution has two main peaks centered on the MW and on M31. After the merger the two dark matter halos will coalesce, resulting in a single much larger peak in the dark matter distribution.

\begin{figure}[ht!]

\begin{center}
\includegraphics[scale=0.30,angle=0]{CollisionScenario.jpg}
\caption{\label{fig:1}, A depiction of the collisional path of the MW and M31 galaxies. (Credit: NASA; ESA; A. Feild and R. van der Marel, STScI)
\url{https://www.nasa.gov/mission_pages/hubble/science/milky-way-collide.html} }
\end{center}
\end{figure}

%%State why the topic matters to understanding our galaxy:
Understanding the outcomes of this merger is important when it comes to understanding the formation and evolution of galaxies, not just for our own but many others. For example in the early forming stages of the MW there was a major merging event with another galaxy, Gaia-Enceladus. This merger greatly affected the evolution of our galaxy, changing not only the internal structure of the MW but also affecting the dark matter distribution within the galaxy's halo.\cite{Helmi_2018} Because dark matter is the predominant source of mass within our universe, the 3D dark matter distribution within the halo of a galaxy directly links to how that galaxy evolves. The distribution will affect a galaxy's internal evolution. Dark matter halo growth depends on the potential well of the galaxy, thus a larger halo will accrete more gas and will retain more gas in the outflows. As a result of the increase in the amount of gas within the galaxy more new stars will be able to form, increasing the size of the galaxy and causing alterations to the internal structure of the galaxy over time. Another effect of the 3D distribution of dark matter is how that galaxy interacts with other galaxies within the local group through orbital dynamics.\cite{Wechsler_2018} Therefore, being able to predict what will happen to the dark matter after the MW-M31 merger is an important part of being able to predict how our galaxy will evolve after the merger.

%%Overview of current understanding of the topic:

The shape of the dark matter halo after the merger is completely dependent upon the initial conditions of the two galaxies before they merger, specifically in relation to their mass, angular momentum and other orbital properties, and energy of the merger. When analyzing the mass distributions of the halos via simulations Drakos et al .\cite{Drakos_2019} found that low energy mergers resulted in mass moving inwards towards higher density, whereas for high energy mergers the halo was more extended. Therefore if we know the motions of the galaxies before and during the merger we should be able to speculate on the general shape of the dark matter halo, whether it be extended from the merger or not. Based on motions of both the MW and M31's satellites, astronomers have created models for the shapes of the MW and M31's dark matter halos pre-merger. The MW's dark matter halo (see Figure 2) is modeled as a triaxial ellipsoid, or an ellipsoid where the radius along each axis (x,y,z) has different lengths. This discovery was made through the creation of models using the data for tidal debris the Sagittarius Dwarf Galaxy, a satellite of the MW. This data was obtained through digital sky surveys such as Two-Micron All Sky Survey and the Sloan Digital Sky Survey. \cite{Law_2010} Unlike the MW, M31's modeled dark matter halo is a prolate spheroid, or a sphere that is elongated along the z axis, where the x and y axes are equal. This model of M31’s halo was created by Hayashi and Chiba \cite{Hayashi_2014} using nonspherical mass models of M31 and the positions of its satellites, and was compared with cold dark matter models.

\begin{figure}[ht!]
\begin{center}
\includegraphics[scale=0.20,angle=0]{milky-way-triaxial-dark-halo.jpg}
\caption{\label{fig:2} A depiction of the triaxial shape of the MW halo, colored like a beach ball. The spiral in the center is the galaxy, white axes drawn for reference. Credit: David Law, UCLA \url{https://astronomy.com/news/2010/01/astronomers-map-the-shape-of-galactic-dark-matter} }
\end{center}
\end{figure}

%%What are the open questions in the field: define prolate,oblate,or triaxial halos
%%Prolate- elongated spheroids
%%Oblate- flattened spheroids
%%Triaxial- ellipsoids

One of the main questions regarding the distribution of dark matter post merger, is what the shape of the distribution will be. There are several different possibilities for these shapes, the two main being spheroidal or ellipsoidal. Within these two types of distributions there are other classifications to describe the shape of dark matter halos; prolate, oblate, and triaxial (see Figure 3). Prolate and oblate shapes are both spheroidal in shape, meaning they are both quadric surfaces that can be obtained by rotating an ellipse about one of its principal axes. Prolate describes a sphere that has been elongated into a football like shape. Oblate describes a sphere that has been flattened into a lentil like shape. Both these shapes follow the equation \(\frac{x^2 + y^2}{a^2} +\frac{z^2}{c} = 1\), where a is the semi-axis and is also the equatorial radius of the spheroid, and c is the distance from the center to the edge along the symmetry axis. If $c>a$ then it is a prolate spheroid, if $c<a$ then it is an oblate spheroid, and if $c=a$ it is an exact sphere. The halo would be triaxial if it were ellipsoidal and each of the 3 axes had a different length. This would follow the equation \(\frac{x^2 }{a^2} +\frac{y^2 }{b^2}+\frac{z^2}{c} = 1\), where a is the semi-major axis, b the semi-minor axis and c is the distance from the center to the edge along the symmetry axis; and $a \neq b \neq c$. \cite{Bovy_2017} The MW- M31 merger should result in a dark matter halo with one of these shapes.

\begin{figure}[ht!]
\begin{center}
\includegraphics[scale=0.25,angle=0]{halotypes.png}
\caption{\label{fig:3}A model of the different types of dark matter distributions in galactic halos (prolate,oblate,or triaxial halos) from section 13 of the article Dynamics and Astrophysics of Galaxies,

\url{http://astro.utoronto.ca/~bovy/AST1420/notes/notebooks/III-01.-Triaxial-Mass-Distributions.html} }
\end{center}
\end{figure}

%%This Project
\section{The Project}

%%Specific Questions: Is the 3D dark matter distribution spheroidal, or elongated like an ellipsoid? How does the shape affect future evolution?

In this paper I will be studying how the 3D dark matter halo distribution changes as the MW and M31 galaxies undergo collision and after the merger. Before the merger the MW and M31 dark matter halos are modeled to be roughly spherical for the purposes of the data I will be using. As the galaxies merge the dark matter halos of both galaxies will also collide and the distribution of dark matter around the resulting merger remnant will be different from that of the initial shapes. I will be focusing on finding out what that shape will be, be it a triaxial ellipsoid, an oblate spheroid, or a prolate spheroid. I will be using code to model and plot simulated data of the merger in order to visualize the distribution.

%%What is the open question?
Through the creation of this model I will be able to determine the shape of the 3D dark matter distribution post merger, spheroidal or ellipsoidal, and will be able to postulate how the galaxy and halo will evolve thereafter.

%%Why is this important for understanding galaxy evolution?
This model is special because we know so many of the parameters and kinematics of both the galaxies due to their proximity. By creating this model and understanding the kinematics involved in the merger astronomers will be able to make educated assumptions of how other galaxies will evolve due to collisions. We can take our own galaxy and use it to better understand the universe.

%%Methodology
\section{Methodology}

%%Introduce the Coding Simulations (reference paper \cite{Marel_2012}, explain meaning of N-body simulation)
I will be using the MW-M31 collision data, provided by Professor Gurtina Besla, and code in python to study and model the 3D distribution of dark matter before, after, and during the MW-M31 merger; focusing on the distribution post-merger. The collision data has been used for another paper that analyzes the evolution of the MW, M31, and M33 orbital evolution throughout the merger, as well as the fate of our Sun by Van Der Marel et al. \cite{Marel_2012} The data is

an N-body simulation, meaning a large number of particles of different types were generated around an object, in this case the galaxies, that each interact with each other. Each particle's motion will be affected by the dynamics of every other particle in the system. Thus, the interactions of the particles as they move over time will have to be taken into account throughout the code.

%%Overview of approach. What are you trying to do?
The code I am creating will model the positions of the dark matter particles at a given snapshot, take those positions and plot them in 3D, and will overplot shapes until a match can be identified. It will utilize other, pre-written programs to pull in the MW-M31 collision data from the specific files I have selected and will find the positions in space of the dark matter halo 'particles' by calculating the center of mass of each particle. In addition to these programs I will write pieces of code that will take in this data and plot it in 3D using a matplotlib subpackage called \lstinline{mpl_toolkits.mplot3D}. This package allows me to not only plot in 3D, but also to choose the type of display for the data, such as contour plots, scatter plots, line plots, surface plots and more. I will also be using this code to plot a wireframe shape over the distribution of particles, in order to fit the shape to the distribution and identify if that shape is a triaxial ellipsoid, oblate spheroid, or prolate spheroid. I will do this for the distributions of dark matter particles for both the MW and M31 pre-merger, as well as, for the combined MW-M31 merger remnant. The final result should look something like the image in Figure 4, which shows the theoretical projected shape of the MW dark matter halo as it is currently, pre merger.

%%Figure (1+)
\begin{figure}[ht!]
\begin{center}
\includegraphics[scale=0.35,angle=0]{mergersnapshot_finalresulthypothesis.png}
\caption{\label{fig:4}This figure is a theoretical prediction of what my resulting plot of the shape of the dark matter halo may look like. The underlying image is a snapshot of the remnant from NASA's Crash of the Titans: Milky Way and Andromeda Collision simulation video at
\url{https://svs.gsfc.nasa.gov/30955}}
\end{center}
\end{figure}

%% Describe the calculations the code will compute. Include all relevant eq. Describe code in Readfile.py, MassProfile.py, and CenterOfMass.py

I will be using pieces of my code in Lab7, which calls in other programs I wrote such as Readfile.py, MassProfile.py, and CenterOfMass.py to process the disk particles throughout the merger and display them in 2D contour plots, to form a basis for my code. Readfile.py is a relatively simple program that reads in the position, velocity, and mass data for a specified file containing a 'snapshot' of the collision data. Having this program allows me to easily read in whatever file I want in a single line of code. It is used in each of the programs I will be using. MassProfile.py creates a series of mass profiles and rotation curves for a selected type of

particle (halo, disk, or bulge). It contains several different types of mass profiles including the Hernquist 1990 Mass Profile and the Mass Enclosed within a radius of each of the particles. The Hernquist Mass Profile contains the most relevant information as it specifically deals with the profile for the dark matter halo. The equation for the Hernquist Mass Profile is \[M_{hern}= \frac{M_{halo}*R^2}{(R+a)^2}\qquad Eq1\]. Where M_{hern} is the Hernquist Mass given in units of $M_\odot\ $, M_{halo} is the mass of the halo particles in $M_\odot\ $, R is the radius, in \si{kpc}, from the center of the galaxy that encloses the particles, and a is the scale length, also in \si{kpc}. The Mass Enclosed functions don’t have any special equations but instead just add up the mass of a particle type that is enclosed within a certain radius.MassProfile.py also used the mass profiles it created to generate rotation curves by calculating the circular velocity using the general equation \[V_{circ}= (\frac{G*M_{encl}}{R})^{1/2}\qquad Eq2\]. Where V_{circ} is the circular velocity in $\frac{km}{s}$, G is the gravitational constant $G=4.498768e-6 kpc^3Gyr^{-2}M_\odot\ ^{-1}$, and M_{encl} is the mass enclosed within a certain radius in $M_\odot\ $. This Program will likely be useful for finding out the values of the mass enclosed within our shape, which is not essential to our goal but is still useful information.
The last program I will be using is the CenterOfMass.py program. This program calculates the center of mass positions (COMP) and velocities (COMV) for each snapshot of the data. It accepts the position data from the designated file and iterates to calculate the COMP for each of the particles relative to each other. Thereafter it calculates similarly the COMV considering the COMP it had just calculated. The COMP is what I will be using to identify where each particle is located in the 3D dark matter distribution. The last piece of my code will be a snippet to draw the shapes in 3D. These shapes will have to be coded in (see Code Snapshot) with arbitrary values for a, b, and c such that they fit the description of each of the shapes (triaxial, oblate, or prolate) and adjusted later to fit over the distribution of dark matter particles.
\begin{tcolorbox}[breakable, enhanced]
Code Snapshot
\begin{verbatim}

```
#set up parameters for the shape we're fitting the 3D distribution to
u=np.linspace(0.0, 2.0*np.pi,60)
v=np.linspace(0.0, np.pi,60)

#shape 1 Triaxial ellipsoid
coef1=(7,5,3)
rx1,ry1,rz1=1/np.sqrt(coef1)
x1= rx1*np.outer(np.cos(u),np.sin(v)) #choose size for x
y1= ry1*np.outer(np.sin(u),np.sin(v)) #choose size for y
z1= rz1*np.outer(np.ones_like(u),np.cos(v)) #choose size for z

#shape 2 Prolate Spheroid
coef2=(10,10,1)
rx2,ry2,rz2=1/np.sqrt(coef2)
x2= rx2*np.outer(np.cos(u),np.sin(v)) #choose size for x
```

```
y2= ry2*np.outer(np.sin(u),np.sin(v)) #choose size for y
z2= rz2*np.outer(np.ones_like(u),np.cos(v)) #choose size for z

#shape 3 Oblate Spheroid
coef3=(3,3,10)
rx3,ry3,rz3=1/np.sqrt(coef3)
x3= rx3*np.outer(np.cos(u),np.sin(v)) #choose size for x
y3= ry3*np.outer(np.sin(u),np.sin(v)) #choose size for y
z3= rz3*np.outer(np.ones_like(u),np.cos(v)) #choose size for z
\end{verbatim}
\end{tcolorbox}
```

%%Describe the plots you will create. One can use code from the class the other has to be your own code
In order to visualize the 3D distribution of dark matter, my code must output a series of plots. The first set of plots will depict the dark matter distribution of the MW and M31 before the merger. This set of plots was generated to test if the code is working. The data we were given assumes that initially the dark matter halos are roughly spherical, so the distribution in this plot should be spherical. The next plots were the distributions during the merger. I added these plots in order to better visualize what was happening between the beginning of the merger and the end. The next part of the code will output the dark matter distribution of both the MW and M31 after the merger on the same graph. For each of these plots I added a section of code that will make the background black, \lstinline{ax.set_facecolor('black')}, and I made the stars either white (for the MW) and light blue (for M31). I also added another snippet of code that can allow you to change the orientation of the 3D plot, so you can view the distribution from above, below, at an angle and face on using \lstinline{ax.view_init(A,B)} where A and B are angles of rotation. All of these additions were made to better be able to visualize and analyze the distribution. After creating all of these plots I will overplot the shape options and adjust the parameters (see Code Snapshot) to fit the shape of the distribution. Once I find which one fits the best, I will find my final result on which shape the 3D dark matter halo distribution follows.

%%What is your hypothesis on what you'll find? Why?
Based upon the current models of the shapes of the halos of MW, as triaxial \cite{Law_2010}, and M31, as prolate \cite{Hayashi_2014}, thus I would hypothesize that the resultant merger halo will be a triaxial ellipsoid. Assuming that the dark matter halos of each galaxy do not completely change during the merger, then the combined halo of the remnant could theoretically be similar to the shape if you added both of the halos together. Adding a prolate object to a triaxial object would result in a triaxial object. However, the simulation data assumes that both the MW and the M31 halos are roughly spherical, which will alter the shape of the post-merger halo. Even though, as a result, the shape might be a little harder to distinguish I still would hypothesize that it still would be a triaxial ellipsoid, though it will probably be relatively close to spherical with only slight variations in a, b, and c. I would hypothesize this because the MW has already undergone a merging event with Gaia-Enceladus \cite{Helmi_2018}, and thus its dark

matter distribution is the result of a merger already. Therefore, it is very likely that the result of another merger will be a triaxial ellipsoid as well.

%%Cited Journal Papers (3+)
%%\cite{Dunbar_2012} #NASA Hubble Space Discovery of collision M31-MW
%%\cite{Helmi_2018} #Gaia-Enceladus MW merger
%%\cite{Wechsler_2018} #dark matter halo- galaxy evolution
%%\cite{Drakos_2019} #current understanding of DM Halo predictions
%%\cite{Law_2010} #Astronomers map DM, triaxial MW halo
%%\cite{Hayashi_2014} #prolate halo of M31
%%\cite{Bovy_2017} #prolate,oblate,or triaxial halos

%%Other citations that might possibly be useful later
%%\cite{Cox_2008} #collision MW-Andromeda
%%\cite{Dubinski_2008} #visualizing N body systems, DM for MW-M31 and local group vs Virgo
%%\cite{Garner_2017} #shining light on DM
%%\cite{Hayashi_2014} #prolate halo of M31
%%\cite{Hoffman_2007} # future of local structures DM and DE
%%\cite{Marel_2012} # MW M31 M33 evolution, merger, fate of sun

\begin{thebibliography}{}

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\bibitem{Helmi_2018} Helmi, Amina and Babusiaux, Carine and Koppelman, Helmer H. and Massari, Davide and Veljanoski, Jovan and Brown, Anthony G. A.\ 2018, Nature, 563,7729, 85–88

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