```
\documentclass{aastex63}

%% Define new commands here
\newcommand\latex{La\TeX}
\graphicspath{{./}{figures/}}
\usepackage{graphicx}

\begin{document}

\title{ASTR400B Research Assignment 2: Project Proposal\\}

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

%% 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.
The collision is projected to take place in approximately 4 billion years. \cite{Dunbar_2012}
During the time of the merger a substantial amount of changes will take place within our galaxy
that will shape the evolutionary path of the MW. One such change is the 3D distribution of dark
matter within the halo of the merger remnant.

\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:
Knowing 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. It affects both its internal evolution and its interactions with other galaxies within the local group. \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 and 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}

%%Proposal
\section{Proposal}

%%Specific Questions: Is the 3D dark matter distribution spheroidal, or elongated like an ellipsoid? How does the shape affect future evolution?
I will be using the MW-M31 collision data, provided by Professor Gurtina Besla, and code in python to model the 3D distribution of dark matter for the remnant of the merger. Through the

creation of this model I will be able to determine the shape of the distribution post merger, spheroidal or ellipsoidal, and will be able to postulate how the galaxy and halo will evolve thereafter.

%%How will you approach the problem using the simulation data? (general coding plan)
I will modify the plotting code I wrote in Lab7 to create 3D plots of the dark matter halo, which will use other programs I wrote such as Readfile.py, MassProfile.py, and CenterOfMass.py to process the merger data. Readfile.py reads in the position, velocity, and mass data for each snapshot in the collision data. MassProfile.py creates a series of mass profiles and rotation curves for each type of the ‘particles’. The particle we will be using is particle 1, which corresponds to the halo of each galaxy. In this program I will most likely use a Hernquist mass profile to model the halo. The last program, CenterOfMass.py calculates the center of mass positions and velocities for each snapshot of the data. This will allow me to relatively accurately calculate where each of the dark matter particles will be located during and after the merger. By calling in each of these programs, my final plotting code will be able to plot the dark matter halo of the remnant. From there I will code in an overplot of the different shapes (prolate, oblate, and triaxial) onto the remnant halo plot and adjust the parameters until one of the shapes best fits the 3D dark matter distribution.

%%Figure (1+)
\begin{figure}[ht!]
\begin{center}
\includegraphics[scale=0.25,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}

%%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}, I 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. Another possible argument is that 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}{}

\bibitem{Dunbar_2012} Dunbar, Brian and Garner, Robert \ 2012, NASA

\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

\bibitem{Wechsler_2018} Wechsler, Risa H. and Tinker, Jeremy L.\ 2016, Annual Review of Astronomy and Astrophysics, 56, 1, 435-487

\bibitem{Drakos_2019} Drakos, Nicole E. and Taylor, James E. and Berrouet, Anael and Robotham, Aaron S.~G. and Power, Chris \ 2019, mnras, 487,1,993-1007

\bibitem{Law_2010} Law, David \ 2010, Astronomy.com

\bibitem{Hayashi_2014} Hayashi, Kohei and Chiba, Masashi \ 2014, APJ,789,1,62

\bibitem{Bovy_2017} Bovy, Jo \ 2017, Dynamics and Astrophysics of Galaxies, 13

%%other citations that I may use later
%%\bibitem{Cox_2008} Cox, T. J. and Loeb, Abraham \ 2008, Monthly Notices of the Royal Astronomical Society, 386, 1, 461–474
%%\bibitem{Dubinski_2008} Dubinski, John \ 2008, New Journal Physics, 10,112,125002

%%\bibitem{Garner_2017} Garner, Rob \ 2017, NASA
%%\bibitem{Hoffman_2007} Hoffman, Yehuda and Lahav, Ofer and Yepes, Gustavo and Dover, Yaniv \ 2007, Journal of Cosmology and Astroparticle Physics, 2007,10,16
%%\bibitem{Marel_2012} Marel, Roeland P. Van Der and Besla, Gurtina and Cox, T. J. and Sohn, Sangmo Tony and Anderson, Jay \ 2012, APJ, 753,1,9

\end{thebibliography}

\end{document}

Bibtex file

@misc{Bovy_2017,
author={Bovy, Jo},
title={Gravitation in elliptical galaxies and dark matter halos¶},
year={2017},

url={http://astro.utoronto.ca/~bovy/AST1420/notes/notebooks/III-01.-Triaxial-Mass-Distributions.html},
journal={Dynamics and Astrophysics of Galaxies},
publisher={University of Toronto},
}

@article{Cox_2008,
title={The collision between the Milky Way and Andromeda},
volume={386},
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url={http://dx.doi.org/10.1111/j.1365-2966.2008.13048.x},
DOI={10.1111/j.1365-2966.2008.13048.x},
number={1},
journal={Monthly Notices of the Royal Astronomical Society},
publisher={Oxford University Press (OUP)},
author={Cox, T. J. and Loeb, Abraham},
year={2008},
month={May},
pages={461–474}
}

@article{Drakos_2019,
author = {Drakos, Nicole E. and Taylor, James E. and Berrouet, Anael and Robotham, Aaron S.~G. and Power, Chris},
title = "{Major mergers between dark matter haloes - I. Predictions for size, shape, and spin}",
journal = {\mnras},
keywords = {methods: numerical, galaxies: haloes, dark matter, cosmology: theory, Astrophysics - Astrophysics of Galaxies, Astrophysics - Cosmology and Nongalactic Astrophysics},
year = {2019},
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pages = {993-1007},
doi = {10.1093/mnras/stz1306},
archivePrefix = {arXiv},

```
    eprint = {1811.12839},
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    adsnote = {Provided by the SAO/NASA Astrophysics Data System}
}

@article{Dubinski_2008,
	doi = {10.1088/1367-2630/10/12/125002},
	url = {https://doi.org/10.1088%2F1367-2630%2F10%2F12%2F125002},
	year = {2008},
	month = {dec},
	publisher = {{IOP} Publishing},
	volume = {10},
	number = {12},
	pages = {125002},
	author = {Dubinski, John},
	title = {Visualizing {astrophysicalN}-body systems},
	journal = {New Journal of Physics},
}

@misc{Dunbar_2012,
    title={NASA's Hubble Shows Milky Way is Destined for Head-On Collision},
    url={https://www.nasa.gov/mission_pages/hubble/science/milky-way-collide.html},
    journal={NASA},
    publisher={NASA},
    author={Dunbar, Brian and Garner, Robert},
    year={2012},
    month={May}
}

@misc{Garner_2017,
    title={Discoveries - Highlights},
    url={https://www.nasa.gov/content/discoveries-highlights-shining-a-light-on-dark-matter},
    journal={NASA},
    publisher={NASA},
    author={Garner, Rob},
    year={2017},
    month={Feb}
}

@article{Hayashi_2014,
    title={THE PROLATE DARK MATTER HALO OF THE ANDROMEDA GALAXY},
    volume={789},
```

ISSN={1538-4357},
url={http://dx.doi.org/10.1088/0004-637X/789/1/62},
DOI={10.1088/0004-637x/789/1/62},
number={1},
journal={The Astrophysical Journal},
publisher={IOP Publishing},
author={Hayashi, Kohei and Chiba, Masashi},
year={2014},
month={Jun},
pages={62}
}

@article{Helmi_2018,
author={Helmi, Amina and Babusiaux, Carine and Koppelman, Helmer H. and Massari, Davide and Veljanoski, Jovan and Brown, Anthony G. A.},
title={The merger that led to the formation of the Milky Way's inner stellar halo and thick disk},
year={2018},
month={Oct},
volume={563},
number={7729},
pages={85–88},
ISSN={1476-4687},
journal={Nature},
publisher={Springer Science and Business Media LLC},
doi={10.1038/s41586-018-0625-x},
adsurl={http://dx.doi.org/10.1038/s41586-018-0625-x},
}

@article{Hoffman_2007,
doi = {10.1088/1475-7516/2007/10/016},
url = {https://doi.org/10.1088%2F1475-7516%2F2007%2F10%2F016},
year = {2007},
month = {oct},
publisher = {{IOP} Publishing},
volume = {2007},
number = {10},
pages = {016--016},
author = {Hoffman, Yehuda and Lahav, Ofer and Yepes, Gustavo and Dover, Yaniv},
title = {The future of the local large scale structure: the roles of dark matter and dark energy},
journal = {Journal of Cosmology and Astroparticle Physics},
}

```
@ARTICLE{Law_2010,
   author= {Law, David},
   title= "{Astronomers map the shape of galactic dark matter}",
   journal = {Astronomy.com},
   year= {2010},
   month= {jan},
   archivePrefix = {arXiv},
   adsurl
={https://astronomy.com/news/2010/01/astronomers-map-the-shape-of-galactic-dark-matter},
}

@article{Marel_2012,
   author={Marel, Roeland P. Van Der and Besla, Gurtina and Cox, T. J. and Sohn, Sangmo
Tony and Anderson, Jay},
   title={The M31 Velocity Vector. Iii. Future Milky Way M31–M33 Orbital Evolution, Merging,
And Fate Of The Sun},
   journal = {\apj}
   year={2012},
   month={Aug},
   volume={753},
   number={1},
   pages={9},
   doi={10.1088/0004-637x/753/1/9},
   archivePrefix = {arXiv},
   adsurl ={https://iopscience.iop.org/article/10.1088/0004-637X/753/1/9},
}


@article{Wechsler_2018,
   author = {Wechsler, Risa H. and Tinker, Jeremy L.},
   title = {The Connection Between Galaxies and Their Dark Matter Halos},
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   year = {2018},
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}
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