ASTR 400B Research Assignment 2

Due: March 20 2025, 5 PM

Outline the scientific motivation for your project, which you will conduct using the simulation of the future fate of the MW-M31-M33 system.

1 The Assignment

Create a 2 page project proposal in LaTeX including an *Introduction* and *Proposal* section, as outlined below.

Your proposal should also include a title and your name as author.

1.1 Introduction

Each of the below points must be a separate paragraph in your introduction. Each paragraph is graded.

1. Par1: Define your proposed topic and how it pertains to Galaxy Evolution. This does NOT mean provide details about the current M33, M31 or MW system. The topic is broader; you should describe this general area of galaxy structure/dynamics and/or evolution.
2. Par2: State why this topic matters to our understanding of galaxy evolution.
3. Par3: Overview our current understanding of the topic in galaxy evolution, broadly.
4. Par4: What are the open questions related to this topic?

You must also:

1. Cite at least 3 journal papers. Use BibTex for formatting citations - if you don't know what this is, come to office hours. Possible papers are listed under each topic below. Note that astrobites often has easier to read articles about journal paper and you can search the website for keywords relevant to your project.
2. Include at least one figure from the above 3+ papers to support one of the 4 paragraphs above.

Note that the simulation details are outlined in van der Marel, Besla +2012, ApJ, 753

Movies of the simulations themselves can be found here: https://hubblesite.org/contents/news-releases/2012/news-2012-20.html

1.2 The Proposal

You must answer each of the below questions as **separate subsections**. Each question is graded.

1. Subsec1: This Proposal. What specific question(s) will you be addressing using the simulation? You only need to pick one - think about how much time you have realistically!

2. Subsec2: Methods. How will you approach the specific question using the simulation data? Define all relevant equations and terms. Here you should outline the codes you'd need to write - each question will need a unique code solution. This can be described in general terms, but all steps need to be outlined (including what particle types/properties will you select and how you will select them, and specify which snapshots will you use).

3. Subsec3: Hypothesis. What is your hypothesis for what you will find? Why do you think this will occur?

In the 2nd subsection (Methods) you must include at least one figure that illustrates your methodology. This can be a diagram.

2 Evaluation of the Assignment

You will be evaluated based on how well you addressed each of the points above. In addition, proper citation and grammar will also count towards your grade. **This assignment is worth 15% of your final grade.**

Submission Instructions:

- The assignment is due on GitHub as a PDF created using LaTeX.
- The assignment should be in a folder called "ResearchAssignments/ResearchAssignment2"
- You must use the journal format for the Astrophysical Journal (ApJ) or Monthly Notices (MNRAS), which are available from the journal websites or on Overleaf.
- The PDF submission should be entitled "LASTNAME_ResearchAssignment2.pdf"
- Please also include the LaTeX file in your submission to Github.

3 Assigned Topics

Under your assigned category, you will find a number of suggestions for how you can direct your research project.

Note, that for all of these topics you will need to identify the relevant particles of the desired galaxy and recenter their positions with respect to the galaxy's center of mass. For this you can use code from the Homeworks.

You may also need to rotate the galaxy/halo particles such that the average angular momentum vector is aligned with the z axis. Lab 7 will provide code and help you learn how to do this.

- Tidal Debris from M33: Stellar Streams of M33 (during and after the MW-M31 merger) TOPIC: Stellar Streams **Alondra, Arthur**

    1. M33's Stream Dynamics - velocity gradients, velocity dispersion within the stream. How do the kinematics evolve throughout the merger or about the merged remnant.
    2. M33's Stream Structure - density gradients along the stream, spatial plots. How well do M33's streams trace the orbit of M33 and how does this behavior evolve and why does this happen? How and when do M33's streams form? What is the distribution of M33's stellar debris in the combined MW+M31 halo?

    You will need to write code to select "stream" stars. These are M33 stars that are no longer bound to M33; they are outside the Jacobi Radius (see Lab 4). So you'll need to write code to compute the Jacobi Radius as a function of time.

    Relevant papers: Amorisco+2017 MNRAS 464 2882,
    Choi+2007 MNRAS 381,
    Malhan+2018 MNRAS 481,
    Vasiliev+2021 MNRAS 501 (tidal tails as probes of complex dark matter halos),
    Shipp+2023 ApJ 949 44.

    Stellar Halos: Bullock and Johnston 2005 ApJ 635,
    Bekki and Peng 2006 MNRAS 370,
    Pulsoni+2021 A&A 647,
    Paez-Dong+2022 MNRAS 510

- Tidal Transformation of Satellites (M33 Dark Matter Halo Structure). TOPIC: Mass loss of Dark Matter and changes to the internal dark matter profile of halos **Nicolas, Colin Weber, Virginia**

    1. What is the debate in the literature about the inner dark matter density profiles? Consider:

        Core/Cusp Debate: De Blok+2010 Advances in Astronomy

        Too Big to Fail: Boylan-Kolchin+2011, MNRAS 415

        Bullock & Boylan-Kolchin 2017, AR&A Review, 55

2. What is the time evolution of the inner dark matter density profile of M33? Does it become more or less concentrated with time? Is it well fit by a Hernquist profile? What might it mean if there is or isn't evolution?
3. Can you see a truncation in the Dark matter density profile (e.g. is there a sharp cut off)? If it exists, how does it compare with the analytic Jacobi radius (Lab 4) at that snapshot?
4. What is the 3D shape of the dark matter distribution of M33 - how does this change with time? Is it elongated/ellipsoid or spherical? (use contour fitting - Lab 7). What do terms like prolate, oblate, or triaxial halos mean? https://astronomy.com/news/2010/01/astronomers-map-the-shape-of-galactic-dark-matter
5. What happens to the dark matter outside the Jacobi Radius (Lab 4)? Are there dark matter streams?

Relevant papers:
Frenk & White 2012 Annalen der Physik 524, 507 Review article
Garavito-Camargo + 2021 ApJ 919 (Halo shape of LMC owing to tidal field of MW),
Hai-Feng Wang+2022 ApJL 940 L3,
Chiang+2024 arxiv:2411.03192 .

- Tidal Transformation of Satellites (M33 Dark Matter Halo Kinematics). TOPIC: Mass loss of Dark Matter and changes to the internal dark matter kinematics of halos **Tugg**

  What is the kinematic evolution of the inner dark matter halo of M33 (i.e. dark matter within the Jacobi radius - you will need to define this as a function of time).

  1. How does the average velocity dispersion within the half mass radius evolve?
  2. Does the virial theorem (or Wolf Mass Estimator; see Lab 5) give you the right mass?
  3. How does the angular momentum evolve? Does the halo rotate?

  Relevant papers:
  Wolf Mass: Wolf+2010 MNRAS 406,
  Dubinski+1992 ApJ 401,
  Frenk & White 2012 Annalen der Physik 524, 507 Review article,
  Abadi + MNRAS, 2010 407,
  Drakos + MNRAS 2019a, 487, 993,
  Drakos + MNRAS 2019b, 487, 1008,
  Garavito-Camargo+2019 ApJ 884,
  Wang+2022 ApJL 940 L3,
  Spin: Bullock + 2001 ApJ 555
  Stewart+2013 ApJ 769

- Tidal Transformation of Satellites (M33: Stellar Structure): TOPIC: Evolution of the internal stellar structure of galaxies owing to tides from a massive host. **Animesh, Colin Miller**

You will need to define the Jacobi Radius (Lab 4) as a function of time to define the main body of M33.

1. What is the stellar disk density profile as a function of time? Is it fit by a sersic profile (Lab 6) for an exponential disk (does that change?); Is there evidence for tidal truncation? [recall sersic profiles for disks and ellipticals are different!]
2. What is the morphological evolution of the disk (use density contours; Lab 7) ? Face On: How do the spiral arms evolve? What is the pitch angle? Edge on: Does the disk become warped (if so, when/why)? Does the disk get thicker (how does the scale height evolve)?
3. What is the mass loss rate of M33? (how does the Jacobi Radius evolve - Lab 4).

Relevant papers:
Lokas+2015 ApJ 810,
Pardy+2016 ApJ 827,
Semczuk+ 2018, ApJ, 864,
Mayer+2001, ApJ, 547,
Varela-Lavin+2023 MNRAS 523

- Tidal Transformation of Satellites (M33: Stellar Kinematics). TOPIC: Evolution of the internal stellar kinematics of galaxies owing to tides from a massive host. **Kris**

  1. How does M33's stellar rotation curve evolve? You can plot this analytically from the mass enclosed, and also using phase diagrams (Velocity vs distance). You'll need to focus within some radius (e.g. Jacobi radius)
  2. How does the velocity dispersion of the stellar particles evolve?
  3. Is M33's disk turning into a spheroidal system? (e.g. more dispersion supported vs. rotation supported and morphologically less like a disk).

  Relevant papers:
  Lokas+2015 ApJ 810,
  Pardy+2016 ApJ 827,
  Semczuk+ 2018, ApJ, 864,
  Mayer+2001, ApJ, 547,
  Varela-Lavin+2023 MNRAS 523

- MW+M31 Stellar Major Merger Remnant Morphology. TOPIC: The evolution of stellar disk/bulge morphology owing to a major merger.

  You will need to identify the simulation snapshots that correspond to the merged system. You may also need to combine the MW and M31 particles together, or the disk + bulge particles (look up concatenation of arrays).

  General question: What is the role of "dry" galaxy mergers between spirals in the formation of elliptical galaxies?

1. Stellar Density Profile of the Merged Bulges and Disks **Nikhil, Laura**. How well is the remnant described as a classical elliptical galaxy based on its surface density profile? What is the best fit sersic profile?
2. Shape of the Stellar Remnant **Hanga, Jessica**: Is the 3D structure of the remnant a spheroid or does it have some elongation/triaxiality? What is the classical Hubble classification of the remnant (E0, E7, SO; fit ellipses) ? How does the shape vary as a function of radius? Is there substructure in the remnant - i.e. tidal tails?
3. Properties of Bulge Particles vs. Disk Particles within the remnant **Ellen**: What is the contribution of the bulge vs. disk to the density profile/shape/velocity dispersion/angular momentum of the remnant? What component is rotating (if any)?

Relevant papers:
Barnes, J. E., Hernquist, L. E.,1992, ApJL, 30, 705
Lotz+2008 MNRAS 391
Duc+2013, ASPC, 447
Querejeta + 2015 A&A 573 (connection to S0 galaxies)
Hopkins+2008 ApJS 175
Eliche-Moral+2018 A&A 617

- MW/M31 Galaxy Major Merger Remnant Kinematics. TOPIC: Stellar disk/bulge kinematics after a major merger **Suhani, Hina, Aleksandar**

  You will need to identify the simulation snapshots that correspond to the merged system. You will also need to figure out how to combine the MW and M31 particles (disk and bulge) together (look up concatenation of arrays).

  1. Is the stellar MW/M31 merged remnant rotating ? (create a phase diagram: velocity vs radius; Lab 7). Is it a fast or slow rotator (Lecture 16; V/σ)? What is the evolution of the rotation curve ("observed" and mass-derived)
  2. What is the contribution of the MW vs. M31 stellar particles to the kinematics of the remnant?
  3. What is the velocity dispersion of the remnant as a function of radius?
  4. Does the virial theorem work to return the total mass (stars + dark matter) of the remnant? Recall Lab 5.
  5. Does the stellar remnant fit on the fundamental plane (Lecture 13)?
  6. Look at several snapshots at different points in time after the system has merged to see if the results change over time.
  7. Can"dry" mergers create ellipticals? or is the remnant closer to a lenticular/S0, (large dispersion supported bulge with rotating disk component) ?

  Relevant papers:
  Romanowsky+2003, Science 301, 1696

Cox + 2006, ApJ 650
Naab+2014 MNRAS 444
Querejeta + 2015 A&A 573 (connection to S0 galaxies)
Taranu+2015 ApJ 803
Hopkins+2008 ApJS 175

- MW/M31 Halo Major Merger Remnant Structure. TOPIC: Dark matter halo (density or halo shape) after a major merger

  You will need to identify the simulation snapshots that correspond to the merged system. You will also need to figure out how to combine the MW and M31 dark matter particles together (look up concatenation of arrays).

  1. Density Profile of the Merged Dark Matter Remnant **Alessandro, Zach, Maritza**. What is the density profile of the combined MW + M31 halo? How does this compare to the original profile of each galaxy halo? How does this compare to a Hernquist profile or other dark matter profile (e.g. NFW, Isothermal Sphere)?
  2. Shape of the Dark Matter Distribution of the remnant.**Ethan, Chip, Abhinav** Is the shape of the combined halo Triaxial? Oblate? Prolate? Does it evolve in time? What do terms like prolate, oblate, or triaxial halos mean? (you can fit ellipses in different spatial planes) https://astronomy.com/news/2010/
  3. What is the contribution of the MW vs. M31 halo particles to the density profile/shape/or kinematics of the merged remnant? **Coco, Catherine, Eason** Does the contribution from each galaxy have the same spatial orientation/angular momentum direction?

  Question relevant to all the above: Where is the "edge" of the merged halo? How might we define this? (What is R200, Rvir, or the splash back radius? Lecture 10)

  Relevant Papers:
  Frenk & White 2012 Annalen der Physik 524, 507 Review article
  Abadi + MNRAS, 2010 407
  Drakos + MNRAS, 2019a, 487, 993
  Drakos + MNRAS, 2019b, 487, 1008
  Prada+2019 MNRAS 490
  Chua+2019 MNRAS 484, 476-493

- MW/M31 Halo Major Merger Remnant Kinematics. TOPIC: Kinematic evolution of Dark matter halos after a major merger **Laine, Aaron**

  You will need to identify the simulation snapshots that correspond to the merged system. You will also need to figure out how to combine the MW and M31 dark matter particles together (look up concatenation of arrays).

  1. What are the kinematics of the merged MW+M31 dark matter halo - is it rotating? How does this relate to teh spin of the halo?

2. What is the velocity dispersion profile? Does the virial theorem (or Wolf Mass Estimator; Lab 4) give you the right mass? (using dispersion within half mass radius)
3. What is the average specific angular momentum? Is it the same or different than the halos of either galaxy before they merged.
4. What is the escape speed of the remnant as a function of radius?

Relevant Papers:
Dubinski+1992 ApJ 401
Frenk & White 2012 Annalen der Physik 524, 507 Review article
Abadi + MNRAS, 2010 407
Drakos + MNRAS, 2019a, 487, 993
Drakos + MNRAS, 2019b, 487, 1008
Garavito-Camargo+2019 ApJ 884
Spin: Bullock + 2001 ApJ 555 Stewart+2013 ApJ 769
Wolf Mass: Wolf+2010, MNRAS 406

- Galaxy Merger Sequence of the MW and/or M31 Stellar Disks and Bulges. TOPIC: galaxy evolution through tidal interactions

  - Rotation Curves **Isabella, Colton**: how does the "observed" and mass-derived rotation curve of each galaxy evolve (disk, bulge) ? ("observed" meaning plot the simulated disk particle line of sight velocity field edge on; See Lab 7).
  - Velocity Dispersion **Matan**: how does the velocity dispersion of each galaxy evolve (bulge/disk) throughout the interaction ? Is the disk being "heated" vertically? Can you compare this vertical velocity dispersion to that of the present day/observed MW or M31 (Lecture 7)? What is the ratio Vrot/σ as a function of time?
  - How does the stellar (surface) density profile of each galaxy evolve (disk and/or bulge) **Ava, Matthew**? i.e. Sersic profiles, disk warps, exponential density profiles? (Lab 6). How do the spiral arms evolve? What is the pitch angle? How do galaxy interactions impact the morphological classification of galaxies?
  - How do the bars within both galaxies evolve (Lab 7, contours) **Christian**? What happens to those bars after the merger?

Relevant papers:
Brooks & Christensen 2016, ASSL 418
Querejeta + 2015 A&A 573 (connection to S0 galaxies)
Kannan+2015 MNRAS 452
Pardy+2016 ApJ 827
Hopkins+2008 ApJS 175
Torrey+2012 Apj, 746 (mixing during mergers)
Bars: Rathore+2024 ApJ 978

- MW and M31 tidal tail evolution. TOPIC: Mass loss and tidal debris during the Galaxy Merger Sequence. **Peter**

    1. What is the evolution of stellar debris in tidal tails and bridges throughout the merger (Density gradients/asymmetry/velocity dispersion/morphology)?
    2. How can you identify Tidal tails and bridges throughout the MW-M31 interaction sequence?
    3. Where do the tidal tails come from? Can you select the tail and trace them back to the undisturbed systems?
    4. What are the kinematics of the tidal tails over time? Do they change in velocity dispersion and energy?
    5. What is the morphological change of the tidal tails over time? Do they grow in size?
    6. Are the tidal tails unbound? Do the tails return to their original galaxies?
    7. How long lived are the tidal tails? For how long might we observe the system with extended tails? What does this mean for our ability to identify merging galaxies?
    8. What is the mass transfer between the two galaxies? Do they exchange material? If so, where does this exchanged material end up? Does it rotate in the plane of the disk? What is the mass exchange between the MW nad M31 over time?
    9. What is the structure of the tidal tails? Are there any clumps or is it smooth?

    Relevant Papers
    Toomre A., Toomre J. 1972, ApJ, 178, 623
    Barnes+2004 MNRAS 350 (model of an example major merger: Mice. Also look up "antennae galaxies")
    Mihos+2004 IAU Symposium 217
    Privon+2013, ApJ 771
    Ji et al. 2014 A&A 566

- Why do Galaxies Merge? Modeling Dynamical Friction **Thomas**

    1. What is dynamical friction? What is the analytic form? (Lab 9)
    2. How does this analytic calculation compare with the merger timescale of the MW-M31 merger? (Lab 9)
    3. How does the angular momentum of the merging systems evolve? How does the energy of the system change? As the orbit decays, where does the orbital energy go?
    4. Can you identify the dark matter wakes of M33 in the simulation ? You will need to use the highest resolution version of the simulation.

    Relevant Papers:
    Foote+2023, ApJ 954, 163
    Garavito-Camargo + 2019, 884

- Exploring the Galaxy-Halo Connection of the MW-M31 Merger Remnant TOPIC: How do galaxies and dark matter halos evolve together through mergers? Swapnaneel, Ben, Savannah

    1. How does the net angular momentum vector of the merged remnant halo compare to that of the stellar remnant? Is it aligned? How does this evolve? How does the alignment depend on radius ?
    2. Is the dark matter halo prograde or retrograde to the disk ? Does it depend on the radius ?
    3. What fraction of the angular momentum is in the disk and halo prior and post merger ?
    4. Is the net angular momentum (disk + halo) conserved prior and post merger ?
    5. Does the merged remnant follow the Stellar Mass-Halo Mass relation? (Lab 5)

Relevant Papers:
Drakos 2019a MNRAS 487 (993),
Chua+2019 MNRAS 484 (476-493),
Prada+2019 MNRAS 490,
Baptista+2023 ApJ 958