ASTR 400B Research Assignment 2

Due: March 16 2023, 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 should be a separate paragraph in your introduction.

1. Define the Proposed Topic.
2. State why this topic matters to our understanding of galaxy evolution.
3. Overview our current understanding of the topic.
4. What are the open questions in the field?
5. Cite at least 3 journal papers. Use BibTex for formatting citations - if you don't know what this is, come to office hours.
6. Include at least one figure from those papers to motivate your work.

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

Movies of 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.

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

2. How will you approach the specific question using the simulation data? 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.

3. Include at least one figure that illustrates your methodology. This can be a diagram

4. What is your hypothesis of what you will find? Why do you think this will occur?

2 Evaluation of the Assignment

You will be evaluated based on your having addressed each of the points above. In addition, proper citation and grammar will also count towards your grade.

This assignment is worth 20% of your final grade.

Submission Instructions: The assignment is due on GitHub as a PDF created using LaTeX. Please use the journal format for the Astrophysical Journal (ApJ), which is available from their website or on Overleaf. 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. You can decide to answer as many of the suggestions as you want or come up with your own, but do not switch category.

- Tidal Debris from M33: Stellar Streams of M33 (during and after the MW-M31 merger) **Muzoun Alzaabi, Zach Werber, Cyrus Worley**

    1. Write code to select "stream" stars - M33 stars that are outside the Jacobi Radius at any given point in time.
    2. What is the distribution of M33's stellar debris (stellar streams) in the combined MW+M31 halo?
    3. how well do M33's streams trace the orbital path of M33?
    4. how/when do M33's streams form? what is the Jacobi radius and how does this change in time?
    5. Dark Matter Streams: how is the dark matter from M33 distributed in the MW+M31 remnant? Does it contribute to the angular momentum of the halo of the MW+M31 merged halo?

    Relevant papers: Amorisco+2017 MNRAS 464, 2882, Choi+2007, MNRAS 381

- Tidal Evolution of M33's Dark Matter Halo: Mass loss of Dark Matter and changes to internal dark matter profile **Aidan DeBrae**

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

   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 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). 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 is the kinematic evolution of the inner dark matter halo - does the velocity dispersion evolve? Does the halo rotate? (consider phase diagrams)

- Tidal transformation of M33: Evolution of the internal stellar structure of M33 **Matei Corbeanu, Binh Nguyen, Bennett Skinner**

  1. What is the stellar disk density profile as a function of time? Is it fit by a sersic profile for an exponential disk (does that change?); Is there evidence for tidal truncation?
  2. 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 probably want to focus within some radius (e.g. Jacobi radius)
  3. How does the velocity dispersion of the stellar particles evolve?
  4. What is the morphological evolution of the disk (use density contours) ? Edge on: Does it become warped? Does the disk get thicker?
  5. Is M33's disk turning into a spheroidal system? (e.g. more dispersion supported vs. rotation supported and morphologically less like a disk).

  A relevant papers: Lokas+2015 ApJ 810, Semczuk+ 2018, ApJ, 864, Mayer+2001, ApJ, 547

- MW+M31 Stellar Major Merger Remnant: Stellar disk particle distribution/morphology **ASSIGNED: Ezekiel Dong, Surya Suresh**

  1. Identify the snapshots that correspond to the merged system.

2. What is the final stellar density profile for the combined system ? Is it well fit by a sersic profile? Does it agree with predictions for elliptical galaxies?
3. What is the role of "dry" galaxy mergers between spirals in the formation of elliptical galaxies?
4. What is the distribution of stellar particles from M31 vs the MW? Are the profiles different?
5. Is the 3D distribution of stars perfectly spheroidal or better fit by ellipsoids?
6. Do you conclude that "dry" mergers create ellipticals? or is the remnant close to a lenticular/S0 ?

Relevant papers:

Barnes, J. E., Hernquist, L. E.,1992, ApJL, 30, 705

Duc+2013, ASPC, 447

Querejeta + 2015 A&A 573 (connection to S0 galaxies)

Hopkins+2008 ApJS 175

- MW/M31 Galaxy Major Merger Remnant: Stellar disk particle kinematics **Charlie Goldberg, Carl Ingebretsen**

1. Is the stellar MW/M31 merged remnant rotating ? (create a phase diagram: velocity vs radius). Is it a fast or slow rotator?
2. What is the contribution of the MW vs. M31 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 (dwarf vs. globular cluster based on velocity dispersion)
5. Does the remnant sit on the fundamental plane?
6. What is the specific angular momentum of the stellar remnant? does it line up with the dark matter halo specific angular momentum?
7. Look at several snapshots at different points in time after the system has coalesced to see if the results change over time.
8. Can "dry" mergers create ellipticals? or is the remnant closer to a lenticular, (large bulge with rotating disk component) ?
9. Could the major merger remnant be an S0 type galaxy?

Relevant papers:

Romanowsky+2003, Science 301, 1696

Cox + 2006, ApJ 650

Querejeta + 2015 A&A 573 (connection to S0 galaxies)

Hopkins+2008 ApJS 175

- MW/M31 Halo Major Merger Remnant: Dark matter halo evolution (density) **Max Cabrera, Peter Hartman, Rianne Kooi, Mika Lambert**

  1. What is the final density profile ? Is it well fit by a Hernquist profile ? Is it more or less concentrated than the MW or M31 before they merged?
  2. Is the 3D dark matter distribution spheroidal? or elongated like an ellipsoid? What do terms like prolate, oblate, or triaxial halos mean? https://astronomy.com/news/2010/01/astronomers-map-the-shape-of-galactic-dark-matter
  3. What are the kinematics of the dark matter halo - is it rotating? what is the dispersion - does the virial theorem give you the right mass?
  4. What is the distribution of dark matter particles from the M31 vs the MW? Are they different?
  5. Where is the "edge" of the merged halo? How might we define this? (What is R200, Rvir, or the splash back radius?)

  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

- MW/M31 Halo Major Merger Remnant: Dark matter halo evolution (kinematics) **Ritvik Basant, Sanvi Khairnar, Jay Motka**

  1. What are the kinematics of the dark matter halo - is it rotating? what is the dispersion - does the virial theorem (or Wolf Mass Estimator) give you the right mass?
  2. Are the kinematic properties of dark matter particles from the M31 vs the MW different?
  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?
  5. what is the energy evolution of the system ? (Jay)

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

- Galaxy Merger Sequence: MW and M31 tidal tail evolution and/or evolution of stellar bar **Avichal Kaul, Aidan Nakhleh**

    1. How can you identify Tidal tails and bridges throughout the MW-M31 interaction sequence?
    2. How can you identify the bar? or pseudo-bulge (disk stars kicked up in the x-shape pattern by the bar) ? How do those structures evolve?
    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?

    Toomre A., Toomre J. 1972, ApJ, 178, 623

    Barnes+2004 MNRAS 350 (model of an example major merger: Mice . Also look up "antennae galaxies")

    Privon+2013, ApJ 771

    Ji et al. 2014 A&A 566

- Galaxy Merger Sequence: Evolution of the MW/M31 Main Stellar Body (Disk, Bulge) throughout the Merger Sequence (prior to final coalescence) **Kush Aggarwal, Gabriel Weible**

1. What is the density profile of the disk/bulge in the remnant? Does it follow a sersic profile? is it more or less concentrated than before the merger?
2. What is the shape of the disk/bulge: bulge - does it look spherical or more ellipsoidal? disk - how do the spiral arms evolve?
3. How does the velocity dispersion of both disks evolve over time? How does the rotation curve evolve over time? What is the ratio Vrot/σ as a function of time?
4. How are galaxy interactions relevant for the star formation histories of galaxies?
5. How do galaxy interactions impact the morphological classification of galaxies?
6. How do galaxy interactions impact the growth of black holes?

Relevant papers:

Brooks & Christensen 2016, ASSL 418

Querejeta + 2015 A&A 573 (connection to S0 galaxies)
Hopkins+2008 ApJS 175

- What is the fate of stars at the Sun's location (8 kpc from center of the Galaxy) - but in M31's or M33's disk? **Olivia Jones, Travis Matlock, Paarth Parab**

1. How will you select particles in M31/M33's disk that are similar to the sun? (e.g. picking star particles in a circular annulus centered at the Sun's location, moving with roughly the right velocity – what is that radius and velocity?)
2. How do the kinematics of the Sun analogs change? (as a function of time or in merged remnant vs. today)
3. How do the positions of the Sun analogs change? (as a function of time or in merged remnant vs. today)
4. Do any become unbound? if so, what percentage?
5. Do any get transferred to or pass through the Milky Way? Or to M33/M31 ? if so, what percentage?

Relevant Paper - van der Marel, Besla+ 2012, simulation paper.

- How to visualize the galaxy merger remnant and/or the fate of stars at the Sun's location (8 kpc from center of the Galaxy) - but in M31's or M33's disk? **Malhar Dave, Ansh Gupta, Rey Squillace**

1. If Sun Particles: How will you select particles in M31/M33's disk that are similar to the sun? (e.g. picking star particles in a circular annulus centered at the Sun's location, moving with roughly the right velocity – what is that radius and velocity?)
2. If Galaxy Components: How might you select the different galaxy components in the merger remnants? Or the M33 stellar streams?

3. What properties of the galaxy components/sun stars will you visualize ? (radial velocities? density?)
4. What kind of viewing orientations could you examine through visualizations? Image of night sky from perspective of particle, or from an outside observer? From another galaxy? From the sun's location (Mollweide Plots) ?
5. Why is it important to develop visualizations of simulation data sets ?
6. What kind of properties could you examine through visualizations? (kinematics)?
7. Are you thinking to make movies? or still shots?
8. What kind of tools do you already know how to use, or what are you planning to learn how to use?

Relevant Papers - van der Marel, Besla+ 2012, simulation paper. Belokurov+2006, ApJ, 642, Martin+2014, ApJ, 787