Research Project: Simulation of tidally disrupting ex-situ formed globular clusters with the goal of identifying cocoon-like features in their tidal streams

For the first few weeks after beginning my actual research project I read a few papers meant to introduce me to the current state of academic knowledge about tidal streams. This included learning about the following aspects of tidal streams: how they form, why they are useful to study, how we observe them and identify them as being one stellar structure and, finally, how many tidal streams we already know to exist in our galaxy's halo as well as their possible progenitors: either a disrupted globular cluster or a disrupted satellite galaxy of the Milky Way. I learned that studying tidal streams is extremely useful for discovering the history and past evolution of our own galaxy, especially when trying to understand the phase of ex-situ growth in which our galaxy is thought to grow by accreting mass from the disruption of smaller satellite galaxies. My research project found its motivation from a paper (Malhan et al.) that essentially focuses on the discovery of a novel stellar structure made of up widely dispersed stars that surround the thin GD-1 tidal stream, which itself is thought to have formed from GC tidal disruption, this structure is dubbed a "cocoon." The authors of the paper not only establish the existence of this cocoon structure as an entity separate from the thin stream itself but, using simulated streams, they suggest that this cocoon is a product of ex-situ formed GC disruption. The proposed theory of cocoon formation that they put forth is as follows: an ex-situ GC born in the dark matter subhalo of a satellite galaxy orbiting the Milky Way begins tidally disrupting while inside the satellite, as the satellite spirals into the Milky Way due to dynamical friction effects as well as tidally disrupting forces the GC becomes unbound from the satellite and instead becomes bound to the larger MW galaxy while stars are still being tidally disrupted from GC along this new orbit in the MW. Thus, the cocoon is made up of those stars stripped while GC was in the satellite galaxy and the thin tidal stream is made up of those stars stripped after GC is accreted by MW. Since the authors identify this cocoon as being a direct consequence of ex-situ formed GC disruption, they suggest that cocoons can be used as markers to distinguish between tidal streams formed from in-situ vs ex-situ formed GC disruption.

The goal of my research project was to test whether this cocoon-formation theory held up in simulations of ex-situ formed GC tidal streams and whether they contained a cocoon structure that differentiated them from an in-situ formed GC counterpart. Ultimately, determining whether a cocoon was a signature of ex-situ GC disruption could greatly affect how we understand the past evolution of our galaxy. To achieve this goal we chose to investigate those tidal streams formed by the disruption of a GC born in one of the MW's 40 satellite galaxies and see if we could qualitatively establish the presence of a cocoon-like stellar structure surrounding an otherwise thin stream. To set up and execute the simulations we took the following steps:

(1) using the present position of each MW satellite galaxy, integrate its orbit backwards in time inside the MW potential including dynamical friction effects (galpy) - doing so allows us to go back in time and view the inspiral of each satellite galaxy;s orbit in the MW
(2) apply a Hernquist potential to the integrated orbit to model the satellite galaxy as a movingpotential object (galpy) allowing us to model the physical satellite galaxy as it orbits within MW along with its gravitational potential which affects those stars bound to the satellite
(3) initialize a globular cluster with arbitrary mass and size on a circular orbit of 4kpc within the satellite galaxy to simulate the birth of the ex-situ formed GC
(4) simulate the tidal disruption of the satellite galaxy itself by initializing a wrapperpotential object (galpy) which takes in the moving Hernquist potential model of the satellite galaxy (from step 2) and modifies it by decreasing the amplitude of its potential as a function of time beginning at some time (tform) and lasting for some period of time (tsteady) after tform such that: before tform the amplitude is 1 and after tfrom+steady the amplitude is 0 - this wrapperpotential object (galpy) on the orbit of satellite galaxy (from step 1) is used to now model the satellite galaxy as it undergoes tidal disruption
(5) forward integrate the orbits of both: the satellite galaxy inside the MW's potential (including dynamical friction) and the GC inside the potential of both the satellite galaxy [the wrapped Hernquist moving potential which undergoes tidal disruption] and the MW
(6) simulate the tidal disruption of the ex-situ formed GC by doing the following: strip stars along the GC's forward orbit beginning ~5 Gyrs before GC becomes unbound from satellite and ending ~5 Gyrs after becoming bound to MW galaxy, then evolve these stripped stars in the MW + satellite galaxy potential and see where they end up at the end of the GC's orbit - this allows us to view resulting tidal streams (streamtools)
(7) simulate the tidal disruption of the in-situ formed GC corresponding to each ex-situ formed GC: take final position of GC from ex-situ simulations and integrate backwards in the MW potential (galpy) to the same start time as ex-situ GC orbit, then strip stars along the same orbit but now moving forward and evolve them in only the MW potential this time instead of the MW + satellite potential - this is because in-situ formed GCs are born in and only ever orbit the MW galaxy (streamtools) and so are not influenced by potential of satellite galaxy

The tools we employed to do the above steps were the galpy and streamtools packages and a reference is included wherever one of these was used.

Out of the 40 satellite galaxies of the MW which were integrated backwards to show the inspiral of their orbits in the MW, only 14 satellites spiralled in close enough to be tidally disrupted (approximately 50kpc from galactic center, which is where most of the GCs in the galaxy's stellar halo reside) in a reasonable amount of time (~10 Gyr or less in the future). So, already many of the satellite galaxies were excluded from the tidal stripping simulations after step (1) simply because they didn't orbit close enough to the galactic center which, in turn, meant that any GC bound to such a satellite would not experience enough tidal disruption to form tidal streams. After removing these satellites, the remaining 14 satellite galaxies were used to complete steps (2) through (7). Out of these 14 satellite galaxies for which GC disruption was simulated, all the tidal streams formed displayed some feature in their ex-situ simulations that was absent in their corresponding in-situ simulations. Out of these 14 satellite galaxy simulations, about 10 or so actually resulted in the expected cocoon-like feature surrounding a thin stream. To test whether or not this observed cocoon-like feature was really a result of those stars stripped pre-accretion, (as the paper suggests in its proposed cocoon-formation theory) we created two functions: test_stream and test_cocoon which were meant to separate those stars stripped before the GC became unbound from the satellite from those stars stripped after and plot them on 2 separate figures to spatially (in R vs z) show how the cocoon structure differed from the thin stream. When these test functions were run on those 10 simulations they matched our expectations, allowing us to be quite confident that a cocoon-like feature was truly present in the ex-situ GC tidal streams.

To conclude, based on the results of our ex-situ GC tidal streams we are pretty confident that the formation of cocoons is a direct result of the tidal disruption of ex-situ formed GCs and that these cocoons may, with future work, be used to distinguish the ex-situ from in-situ GC populations in our MW galaxy's stellar halo based on the tidal streams they form.

Reflecting on my project:

Throughout the course of this research project I improved my problem-solving and critical thinking skills as I wrote code to run the simulations and encountered many bugs along the way, some small and easy to fix while others required me to revise whole functions. Moreover, I also learned how to communicate my thoughts, issues and results better whether it was through: video-conference meetings with my supervisor to discuss the progress of my project, presentations to both the research group I was a part of with grad students and professors or to fellow SURP students in the form of 5 minute primers on the basics of mt project. As well, I found the SURP midterm presentation and final poster presentation both to be very useful in taking a step back from the specifics of my work and envisioning my research as a part of the larger research area that is the study of galaxy formation and evolution. Moreover, I learned a great deal about the kind of research that is currently being done at University of Toronto by attending the SURP-organized Astro 101 lectures and became aware of useful tools about academic research in general through the Professional Development workshops. All these experiences together contributed to helping me gain a more holistic understanding of academic research and what it entails for the individual, group and even university undertaking it. I feel much more confident in my ability to take on further research projects, communicate my findings and envision my future in academica because of this experience.

Some of the most challenging parts of this project included:

- Learning to use galpy to handle those parts of my project related with gravitational potentials and orbital dynamics
    - Initializing a GC in a satellite galaxy by doing a change of coordinates
    - Deciding which satellites had reasonable enough orbits to be used for ex-situ GC disruption simulations
    - Using trial and error to figure out which tform gave the least eccentric, and most ideal orbit for the GC when modifying the potential model of the satellite galaxy
- Learning to use streamtools to model tidal streams and figuring out which potential to use for calculating tidal radius and which potential to evolve the stripped stars in
    - Understanding how streamspraydf works (what arguments it takes in)
    - Learning to plot the actual tidal streams: involved plotting the stripped stars themselves along with the most recent part of the progenitor GC's orbit
    - Using the time since stripped to separate out those stars that form the cocoon (stars stripped pre-accretion) from those forming the thin stream (stripped post-accretion) and plotting both separately to compare

Facing the above challenges definitely made me more confident in my ability to learn about unfamiliar code just from documentation and then use it to achieve a certain purpose.

In terms of the project itself, I think future work on this project should include: varying the GC mass and size as well as the size and mass of the potential model for the satellite galaxy itself to increase the number of satellite galaxy orbits that can be used for ex-situ simulations and, thus, increase the sample size so that we can determine, more conclusively, whether cocoons are true signatures of ex-situ GC streams. In addition, I think implementing a more rigorous and quantitatively definitive criteria for establishing the presence of a cocoon would also allow us to report a level of confidence for cocoon existence as well as an associated uncertainty. From there we could possibly begin analyzing tidal streams we actually observe in our galaxy's halo and apply what we've learned from simulations to gain greater insight into the past of our galaxy.