Dynamics of black holes in young stellar clusters

Project summary:
Goal is to investigate young massive star cluster models for massive stellar mergers to determine the imprint on black hole spin distribution. The basic idea is that angular momentum from merger injects itself into merger product. In some cases, these merger products may ultimately lead to collapsar-like objects, black holes embedded within thick disks that accrete material and spin up. Depending on the details, these mergers may lead to following implications: 1) some fraction of black holes in clusters will be born with non-zero spins, which has implications for retention following subsequent BBH mergers. 2) Depending on mss growth, these may provide another avenue for growing IMBHs in clusters. 3) These events may produce luminous fast blue optical transients (FBOTs) in young stellar clusters detectable by transient surveys. 4) These objects may produce r-process elements, possibly explaining observed r-process enhancement in some Milky Way globular clusters like M15.

Basic info on the cluster simulations:
To model star clusters, we use the code CMC (which stands for "Cluster Monte Carlo"). You can read more about CMC here: https://arxiv.org/abs/2106.02643. Basically this is an N-body code that solves the gravitational force equations for a system of N particles over time, and also incorporates the stellar evolution of individual stars in the cluster.

We have a list of 10 young star cluster models produced for previous projects. We may eventually run additional models, but these 10 will be good starting place. The main goal initially will be to study the different types of collisions that occur in these young clusters and, ultimately, determine the implications on the black holes that form.

I will send you a zip file with all models necessary to get started. Each of the 10 models is placed in a separate directory, and each directory contains four files with relevant info:

1) **initial.collision.log** — this files lists the time and properties (for example, stellar masses and stellar types) of all collisions that occurred in the simulation.

An example line reads:
```
t=0.000837203 binary-single idm=1066861(mm=21.774)
id1=224615(m1=0.0867749):id2=359198(m2=21.6872) (r=0.938885) typem=1 type1=0
type2=1
```

- "t" is the time of the collision (in code units… more on that later…)
- "idm" is the identification number of the collision product (note collision products are assigned a new ID number). "id1" and "id2" are the ID numbers for the two stars that collide.
- "mm" is the new mass of the collision product and "m1" and "m2" are the mass of the two stars

that collide. Note we assume “sticky sphere” collisions” meaning that M_new = M_1 + M_2.
- “binary-single” means the collision occurred during a binary-single (three bodies total) resonant encounter. You may also see “binary-binary” (a four body encounter) and “single-single” (a two body encounter)
- “r” is the radial location at which the collision occurred in the cluster (in code units)

2) **initial.semergedisrupt.log —** In addition to the interactions listed in the collision.log file, you can also have mergers which occur when two components of a binary star merge together. All of these mergers are listed here. The format of the file is largely similar to the collision.log file. The main difference to note is that unlike collisions, where the collision product is assigned a new ID number, merger products are not assigned a new number (the ID number from one of the two input stars is retained)

3) **initial.bhformation.dat —** Each line of this file tells you information about a black hole when it forms. The total number of lines tells you the total number of BHs that formed throughout the entire simulation.
- “time” tells you time of formation
- “r” is the radial position of BH when it forms
- “binary?” tells you whether or not the BH was a member of a binary system at time of formation
- “ID” is the identification number for the BH
- “zams_m” is the zero age main sequence mass of the star that created the BH (we call this star the BH’s progenitor star).
- “m_progenitor” is the mass of the star just before it collapsed to a BH

4) **initial.conv.sh —** this file contains info required to convert from code units to physical units. For example the lines:
```
# code unit of time (Myr)
timeunitsmyr=1799.12
```

Indicate that in order to convert time in code units to time in Myr, you simply multiply by the factor “1799.12”

There are a number of additional files for each CMC model, but these four are the most important for now just to get started.

——————— FIRST STEPS ——————————

To get started, let’s look at following things. For now, you can just choose any of the 10 models. We will eventually look at all 10, but one is good to start.

1) Make a scatter plot of M_1 versus M_2 for all collisions in the collision.log file. This will tell us the types of collisions that are most common. What is the mean/median mass of stars involved in these collisions? What is mean/median mass ratio of the collisions? What are the typical times of these collisions? Perhaps try color coding the scatter points by the collision time?

2) Make a histogram of mass for all BHs that are formed (you can use the bhformation.dat file for this). We should see some massive BHs with masses larger than 50 Msun. These are pair-instability gap BHs that we know are interesting from LIGO observations!

Those first two plots are just to get us started. We haven't learned anything new yet. These items will be going after some new questions related to your specific project

3) Let's count the total number of BHs that formed from a previous collision. To do this, you will need to cross check the BH ID numbers listed in the bhformation.dat file, with the ID numbers of collision products ("idm" in collision.dat file). What is the fraction of BHs that meet this criteria? My guess is it should be something like 10-50%. Each of these BHs are *potentially* candidates for have high spins due to the previous mergers.

4) Record the mass of all BHs that formed from collisions and make a histogram of the masses. Overplot this histogram with the full BH mass histogram you made in step (2). Are the "collisional" BHs special at all? My guess is that are on average more massive than the overall mass distribution.

5) Repeat steps (3) and (4) for BHs formed from stellar mergers (by cross checking IDs in bhformation.dat file with the IDs in the semergedisrupt.log file). Do more BHs form from mergers or collisions? Are the masses of BHs that form from mergers versus collisions different?

6) Some BHs undergo more than one collision/merger. Often, they may just undergo 2-3, but occasionally, they may undergo up to ten or more. So let's determine the typical number of collisions/merger each of these BH has undergone before forming. My guess is, on average, this number is small (roughly 1-2 collisions/mergers per BH).

6) Find the typical time elapsed between the final collision/merger and the time of BH formation (so "t" in the bhformation.dat file and "t" for the final collision in the collision.log file). My guess is the typical time is quite small (1 Myr or so). Perhaps make a histogram of the typical time between collision and BH formation for all BHs that formed from collisions/mergers

7) Another important item to know is the *type* of stars that collided before the BHs formed. For example, were they main sequence stars? Red giants? Something else? Knowing the type of star will help us determine the features of the collision product (for example what is its radius? Is it rapidly rotating?) CMC keeps track of stellar types using the following identification scheme:

```
STELLAR TYPES (K)
        0 - deeply or fully convective low mass MS star
        1 - Main Sequence star
        2 - Hertzsprung Gap
        3 - First Giant Branch
        4 - Core Helium Burning
        5 - First Asymptotic Giant Branch
        6 - Second Asymptotic Giant Branch
        7 - Main Sequence Naked Helium star
```

```
 8 - Hertzsprung Gap Naked Helium star
 9 - Giant Branch Naked Helium star
10 - Helium White Dwarf
11 - Carbon/Oxygen White Dwarf
12 - Oxygen/Neon White Dwarf
13 - Neutron Star
14 - Black Hole
15 - Massless Supernova
```

All of the collisions that occur in these models at early times (before BH formation starts) should be either type 0/1 (main sequence stars) or giants (types 2-9). If we see anything type 10 or larger, that would be very surprising. Let's try to determine the types of stars that collide and ultimately produce BHs. Are they typical main sequence or giant stars? What is the last collision before BH formation? For instance, if you can state, "X% of BHs are formed from collisions of two main sequence stars, Y% are formed from collisions of two giant stars, and Z% are formed from a main sequence + giant collision" that would be really great!

8) What is the typical location in the cluster of the BHs that formed from collisions? Are they generally found close to the cluster center (maybe… indicating that they are formed dynamically from stars that have mass segregated to center) or are they found further out (indicating they are formed from primordial binary systems)

——————— LATER STEPS (for later in summer) —————————

For the initial analysis above, we will just analyze pre-existing cluster models. Next, we'd like to look at some new models to investigate the effect of various cluster properties on the number of BHs formed through these collisions/mergers.

For Kyle's future reference, consider varying the following parameters:
- rv1 vs rv2
- Primordial mass segregation vs no primordial mass segregation
- High versus low massive star binary fraction
- Radii truncation on/off
- Intrinsic spin up parameters? e.g., some accretion efficiency parameter?

That would potentially give us 16-32 models depending on how many parameters we vary.

Several of these we already have with our previous simulations (catalog models and original collision paper). A few of these we will need to re-run or use Elena's new models.

For now, let's just get Josiah set up with decent set of models, and start sorting through the data.

If we have time later in summer, we can also start analyzing the STARFORGE simulations. Basically then everything in project will fall under umbrella of growing black holes in young massive star clusters.

Reading Material :
(no need to read all of these word for word! Just sending a list of relevant stuff for you reference)

- New CMC code website: https://clustermontecarlo.github.io/CMC-COSMIC/intro/index.html
- New CMC code paper: https://arxiv.org/abs/2106.02643
- CMC model catalog: https://ui.adsabs.harvard.edu/abs/2020ApJS..247...48K/abstract
- Massive BH formation in clusters: https://ui.adsabs.harvard.edu/abs/2020ApJ...903...45K/abstract
- Effect of high mass binary fraction on massive BH formation : https://ui.adsabs.harvard.edu/abs/2021ApJ...908L..29G/abstract
- LIGO black hole populations paper: https://ui.adsabs.harvard.edu/abs/2020arXiv201014527A/abstract
- Basics of collapsars: https://ui.adsabs.harvard.edu/abs/2019Natur.569..241S/abstract
- EM transient signature of stellar collisions: https://ui.adsabs.harvard.edu/abs/2017ApJ...835..282M/abstract
- Pair instability supernova/gamma ray bursts: https://ui.adsabs.harvard.edu/abs/2001ApJ...550..372F/abstract

Model paths (for Kyle's reference):

(1) Old models from collision project (start with just these for now)

rv1z0.002rg20N8e6 with primordial mass segregation
```
/projects/b1095/kylekremer/cmc/COSMIC_CMC_3/rundir/
rv1rg20z0.002N8e5_primMS_alpha1_0
/projects/b1095/kylekremer/cmc/COSMIC_CMC_3/rundir/
rv1rg20z0.002N8e5_primMS_alpha1_1
/projects/b1095/kylekremer/cmc/COSMIC_CMC_3/rundir/
rv1rg20z0.002N8e5_primMS_alpha1_2
```

rv1z0.002rg20N8e6 w/o primordial mass segregation
```
projects/b1095/kylekremer/cmc/COSMIC_CMC_3/rundir/
rv1rg20z0.002N8e5_alpha1_fb0_0
kylekremer/cmc/COSMIC_CMC_3/rundir/
rv1rg20z0.002N8e5_alpha1_fb0_1
kylekremer/cmc/COSMIC_CMC_3/rundir/
rv1rg20z0.002N8e5_alpha1_fb0_2
```

rv0.75z0.002rg20N8e6 w/o primordial mass segregation
```
kylekremer/cmc/COSMIC_CMC_3/rundir/
```

```
rv0.75rg20z0.002N8e5_alpha1_fb0_0
kylekremer/cmc/COSMIC_CMC_3/rundir/
rv0.75rg20z0.002N8e5_alpha1_fb0_1
kylekremer/cmc/COSMIC_CMC_3/rundir/
rv0.75rg20z0.002N8e5_alpha1_fb0_2
```

rv0.75z0.002rg20N8e6 w/ primordial mass segregation

```
kylekremer/cmc/COSMIC_CMC_3/rundir/
rv0.75rg20z0.002N8e5_primMS_alpha1_0
kylekremer/cmc/COSMIC_CMC_3/rundir/
rv0.75rg20z0.002N8e5_primMS_alpha1_1
kylekremer/cmc/COSMIC_CMC_3/rundir/
rv0.75rg20z0.002N8e5_primMS_alpha1_2
```

(2) Newer models from Elena with updated radii prescription (for later)

`/projects/b1095/egp8636/IMF_HMBF/CMC-COSMIC/rundir/`