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Progress Report and Future Work: 2021

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1. BACKGROUND

The star formation process is a complex multiphysics, multiscale, nonlinear problem and is an active area of research in both computational and observational domains (see Krumholz et al. 2014 for an extensive review). The general life cycle of a star forming region is well understood: A giant molecular cloud (GMC) collapses gravitationally, fragmenting into sub-clouds and stellar sub clusters. Stellar feedback then destroys the remaining cold dense gas thereby halting star formation and allowing for the hierarchical assembly of the final star cluster (Figure 1). It is well established that it is specifically massive star feedback that plays a vital role in the star formation process. Their strong stellar winds, ionizing radiation, and supernovae carve away cold gas, shutting down local star formation.

We hypothesize that it is also the timing of massive star formation that greatly affects the star formation and cluster assembly process. Since massive star feedback interactions with natal gas and subsequent cluster formation and assembly is difficult to observe, computational models are necessary to explore such processes. We use Torch, which integrates the magnetohydrodynamic code FLASH into the framework of the N-body and stellar evolution suite AMUSE to create a computational parameter space to test the effects of early forming massive stars.

2. PROGRESS: 2020 - 2021

2.1. *The Effects of Early Massive Star Formation: Gas Expulsion and Cluster Dynamics*

To test our prediction that early forming massive stars will significantly disrupt not only the star formation process but also the hierarchical cluster assembly process, we perform a controlled experiment. From identical initial conditions, we run 4 magnetohydrodynamic (MHD) n-body simulations of a collapsing GMC and follow the gas, individual stars, stellar feedback, and dynamically formed binaries. The first run is the fiducial: we allow stars to form randomly, Poisson sampling from the Kroupa mass distribution. In the other 3 runs, we force the first star to form to be a 50, 70, or 100 $M_\odot$ star. These forced massive stars form about 1 cloud free-fall time (1.8 Myr) earlier than most of the massive stars in the fiducial run. We run the simulations for $\gtrsim 6$ Myr each.

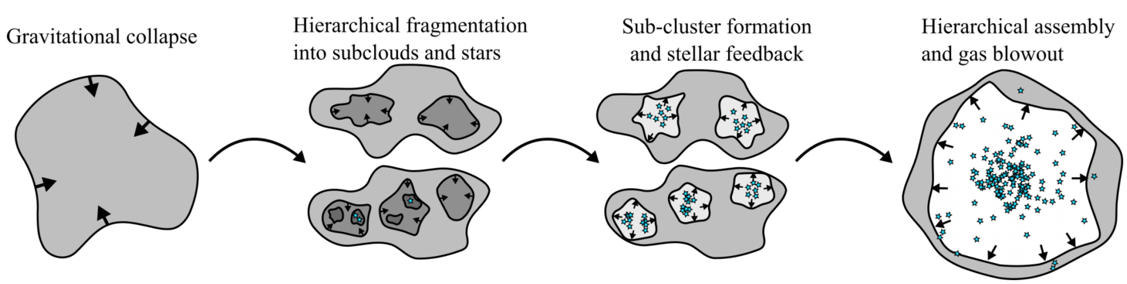

Figure 1. Star formation process: GMC gravitational collapse, formation of subclouds and isolated star forming regions, gas expulsion in sub-clusters by massive stars, hierarchical assembly of stellar sub-clusters in to single massive cluster. This process will take on the order of 10 Myr. Image credit: Grudic et al. 2018

Results - Early forming massive star effects on gas:

- Gas is globally unbound 2 Myr earlier than the fiducial run.
- The forced runs end with more material (stars and gas) removed from the simulation domain. 50% of initial mass remains in fiducial, 40% in the 50 $M_{\odot}$, 10% in 70 and 100 $M_{\odot}$ runs.
- Early forming massive stars suppress the total eligible star forming gas on grid.

Results - Early forming massive star effects on star and cluster formation:

- Limit overall gas accretion rate onto sink particles.
- Similar above point: limit the conversion of gas into stars
- Result in formation of several subclusters of 1000 $M_{\odot}$ or less while the fiducial run results in single dominant cluster of 3300 $M_{\odot}$.
- The sub-clusters are still bound objects, but are less bound than fiducial massive cluster
- The sub-clusters are not bound to the most massive cluster on the grid; they will not combine to form a single massive cluster.

This work expands on the understanding that massive star feedback plays a vital role in the star formation process. We find that early forming massive stars not only expel gas and stifle star formation, they also stifle the hierarchical assembly of sub-clusters into a single young massive cluster. While individually bound stellar associations are still formed, the associations are not bound to one another and will not combine to form a single massive cluster like the one found in the fiducial run.

This work culminated in a presentation I gave at the American Astronomical Society 238th meeting this June. The presentation involved creating a poster which you can see here: AAS iPoster (click me!), and giving a 5 minute presentation on my findings.

2.2. *Star Formation in GMCs in a Galactic Context*

Hui Li of Columbia University has provided me with snapshots of GMCs taken from galaxy simulations. I have begun building a framework within FLASH to convert his output data into initial conditions for Torch runs. Li's data is produced using the MHD code AREPO which operates using a fundamentally different framework and data-structure when compared to FLASH. I use FLASH to read in AREPO's Voronoi mesh data as particles onto the FLASH grid. I then have FLASH refine on the particles, and finally map the particle data (density, temperature, velocity) onto the FLASH grid using a cloud-in-cell method. There is still much work to be done on this front, see Future Work Timeline for more details.

2.3. *Other Points of Progress*

- Published co-author: Cournoyer-Cloutier, C., Tran, A., Lewis, S., et al. (2021): Implementing primordial binaries in simulations of star cluster formation with a hybrid MHD and direct N-body method
- Upgraded Torch to python3 and FLASH4.6.2 and latest commit of AMUSE.
- Major fix to Torch: ensured B-fields are initialized properly in FLASH. Past runs had 0 B-field due to field value not being properly set to cell faces rather than cell centers.
- Found and fixed OpenMPI communication error in FLASH causing runs to stall silently.
- Communication with Silvia Toonen (Univ. of Amsterdam) on massive star evolution implementation in SeBa, correcting very massive star stellar evolution behavior (and therefore ionizing and wind outputs in Torch).
- Weekly journal club with torch group; have read 6 papers with them, a great supplement to my normal reading.
- Assisted Joshua Albert (research associate) and Julius Hendrix (MSc student) at Leiden University.

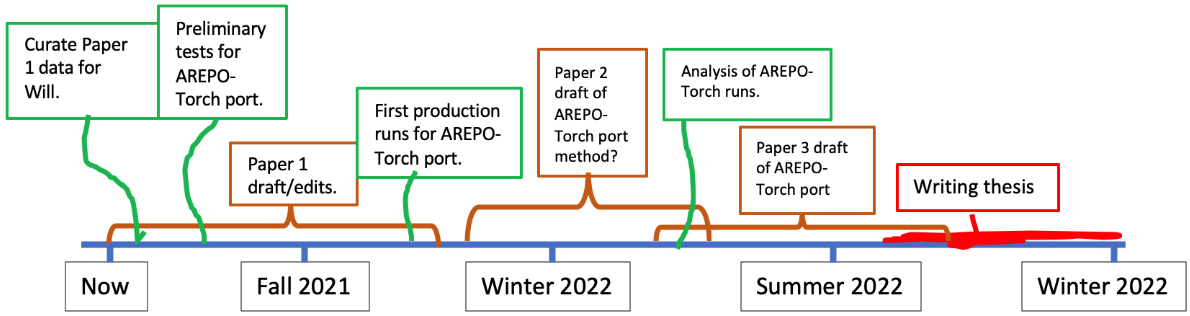

Figure 2. This timeline is aggressive and optimistic, it assumes I complete my Ph.D. by the end of 2022 (5.5 years total). Paper sub-timelines are denoted by brown brackets. The start of the braket indicates when I will begin writing the paper. The end of the bracket indicates when major edits/revisions are (loosely) predicted to be done. Paper 2 is questionable (?) as I would like to discuss its merit and whether it is a worthwhile endeavor with the committee.

3. FUTURE WORK TIMELINE

3.1. *Paper 1*

The Effects of Early Massive Star Formation: Gas Expulsion and Cluster Dynamics will be my first paper. I will have a draft by the end of the summer (September). The paper will consist of the analysis of my production runs presented at AAS 238. I will also expand my analysis by examining simulations that are identical to those previously described, but with no stellar wind feedback. This will allow me to better isolate the effects of early forming massive stars to the combination of ionizing radiation and winds or just ionizing radiation.

My analysis pipeline is robust and can easily be executed on any number of other runs. I have computation time available to finish the no stellar wind feedback runs and sufficient storage space to extract and save the relevant data.

The no wind feedback runs will be complete within the next 2 to 3 weeks. Extraction of their data will take less than 1 week, and writing the paper will likely take 1 to 2 months.

3.2. *Preparing Data for Further Analysis*

Beyond the analysis I have done/am doing for Paper 1 there is significant room to expand upon the simulations. The long-term evolution of the formed star clusters and associations, analysis of cluster structure, and deeper comparisons to observations are all possible and warranted. I will prepare the simulation output for this expanded analysis, curating my analysis pipeline for ease of access. The analysis will likely be performed by Will Farner as a part of his thesis.

3.3. *AREPO to Torch Port*

So far, researchers using Torch have studied star forming from idealized initial conditions: isolated spherical GMCs with a random velocity field applied. In order to model star formation as accurately as possible, we need to model the process on a galactic scale to form GMCs in a realistic galactic environment rather than from idealistic initial conditions. By using GMCs formed in Hui Li's galaxy simulations with Torch, we can develop one of the most accurate pictures of the star formation process ever made. Though I have a good start on this project so far, there are still months of development ahead and more months beyond to allow for simulations to progress. I will have a proof-of-concept simulation (reading in Hui Li's AREPO data and using Torch to evolve the simulation) by the end of the summer. There likely will be many parameters to perfect which may delay the start of production runs by another month or more. This project is an extremely important aspect of my thesis work, and the bulk of my attention will be focused here over the next 1.5 to 2 years.

3.4. *Paper 2, Maybe 3*

The production Torch runs using AREPO data as initial conditions will deserve its own stand-alone paper. The announcement and initial analysis of these runs will constitute Paper 3. There is also the possibility of a short paper detailing the process of converting AREPO output data to FLASH input (Paper 2). No finite mass moving mesh code has ever been ported to FLASH before and the ability to make completely separate code bases and computational methods compatible is an achievement worth noting, though I defer to the opinion of the committee on whether such a publication is warranted or worthwhile.

3.5. *Other Future Items*

- Keep consistent with AAS meetings, present talk at next winter/summer meeting (hopefully in person).
- Other conferences of interest? Focus on networking.
- Public outreach presentations at Philadelphia Academy of Natural Sciences, Franklin Institute, AMNH.