Joseph Zeron is a Physics major at the University of Memphis, graduating in the spring of 2025. Joseph plans to pursue a Ph.D. in Astronomy to continue learning about the complicated mechanism that governs our intricate universe. He was originally from Honduras. He migrated to the U.S. in hopes of getting a better life. His interest in astronomy revolves around Black Holes. He first became interested in these celestial objects when he saw a video about them in high school. Their sheer scale helped him see that there was so much more out there. In the summer of 2023, Joseph participated in an NSF-funded research project involving Black Holes. Thanks to the NSF and mentoring from Dr. Ben Keller, he learned a lot about Black Holes and how to perform research. With help from Dr. Keller, he made a manuscript detailing his work and submitted it to the University of Memphis' Undergraduate Research Journal: *QuaesitUM*. Joseph is very thankful for the opportunity to be part of this research and share it with others.

Joseph Zeron

AGN Feedback in Galaxy Formation

Faculty Sponsor
Dr. Ben Keller

Abstract

In this paper, we look at the impact of Active Galactic Nucleus (AGN) feedback driven by Supermassive Black Holes (SMBH) on the evolution of a Milky Way-like Galaxy. We do this by running the simulation jsAGN2 (joseph AGN 2), using the Smooth Particles Hydrodynamics code ChaNGa, and comparing it to the simulation MUGS2 (McMaster Unbiased Galaxy Simulations 2). However, the MUGS2 simulation includes only Supernovae feedback, while our simulation also includes AGN feedback. This allows us to look at the effects of SMBHs on the evolution of a Milky Way-like galaxy. We observed how the star formation rate was affected by both forms of feedback and compared the gas properties in these simulations.

Introduction

Galaxies are enormous collections of gas, stars, and planets all held together by gravity. They formed over cosmic time through gravitational collapse (Ryden & Gunn). Within these galaxies, rotating clouds of gas dynamically collapse to form stars (Shu et al.). Gas can be further accreted from the Circumgalactic Medium (CGM), which serves as fuel for star formation (SF) (Tumlinson).

If left alone, all this gas would collapse. So, there must be a process through which SF is regulated (Gabor J; White & Frenk). Many forms of feedback aid in the process of limiting SF. Stars themselves are one of them; through stellar winds, ionization, radiation, and Supernovae (SNe), gas is pushed away from star-forming regions in turn reducing the efficiency of cooling and SF of the galaxy (Muratov; White & Frenk). AGN feedback from Supermassive Black holes also contributes through radiation, winds, and gas-ejecting jets (Fabian).

Black Holes inhabit most galaxies and have an inherent relationship with the characteristics of their host galaxies, like luminosity (Kormendy and Richstone) and mass (Marconi and Hunt). In this paper, we analyze how AGN feedback from SMBHs interacts with gas and regulates the growth of its host galaxy. We do this by looking at the largest halo of our simulation jsAGN2 and comparing it to the largest halo in the simulation MUGS2. By implementing this feedback from AGN, we expect the SF to be reduced (Fabian; McNamara).

Methods

Our simulation is run using the N-body + SPH (Smoothed Particle Hydrodynamics) code ChaNGa (Charm N-body GrAvity solver) (Menon et al.). This code can make cosmological simulations with galaxies that interact with each other, and isolated systems. Many of the physics modules used in ChaNGa were originally used in its well-established predecessor, the SPH code GASOLINE (Wadsley et al.)—the code used by the MUGS2 simulation. Some of those physical modules include gas cooling, a cosmic UV background, and SF and SNe feedback. Both simulations use a Barnes-Hut algorithm to calculate the gravitational force exerted on a body.

For the formation of SMBH, an improved Bondi-Hoyle method for the accretion and dynamical friction of SMBHs was implemented. The SMBHs form from Population III stars, which are the stars that were formed in the early stages of the universe when the gas had low metallicity and low fragmentation rates (Bond; Omukai & Nishi). For the seeds of SMBHs to form they must follow these physical criteria:

- Low mass fraction of metals
- Density fifteen times that of the SF threshold
- Temperatures between 9500 K and 10000 K

This allows the gas to collapse quickly and cool relatively slowly (Tremmel). This makes it possible for stars with masses greater than 260 Msol to form, which is the threshold to create a black hole of 100 Msol. (Bond). The AGN feedback used in our code is based on the Keller 2014 Super Bubble model. For the initial conditions, we will use a SMBH initial mass of $1*10^6$ Msol. The SMBHs will achieve this mass by gaining it from the surrounding gas. The simulation is run on 280 nodes on the High-Performance Computing (HPC) supercomputer at the University of Memphis. The simulation is run from $z = 99$ to $z = 0$.

Results

Once our simulation is over, we proceed with the analysis. **Figure 1** shows a density slice of the biggest halo on our last snapshot, viewed face-on. In **Figure 2** we can see the same snapshot viewed from the side, which offers us a different point of view of where the SMBHs are located. We can see that we were able to form a disk galaxy with SMBHs orbiting it. The arrows represent the velocity vectors. However, none of the SMBHs reached the center of the galaxy. With dynamical friction which occurs both due to large and small-scale perturbations, we expected the SMBH to be forced towards the center of the galaxy (Chandrasekhar). However, this was not the case because the dynamical friction used in this simulation was designed to allow for wide orbits generated from mergers. Another point that helps us further understand this is that some of the SMBHs are moving at speeds around 200 km/s, which helps visualize that some of them have noticeably larger orbits.

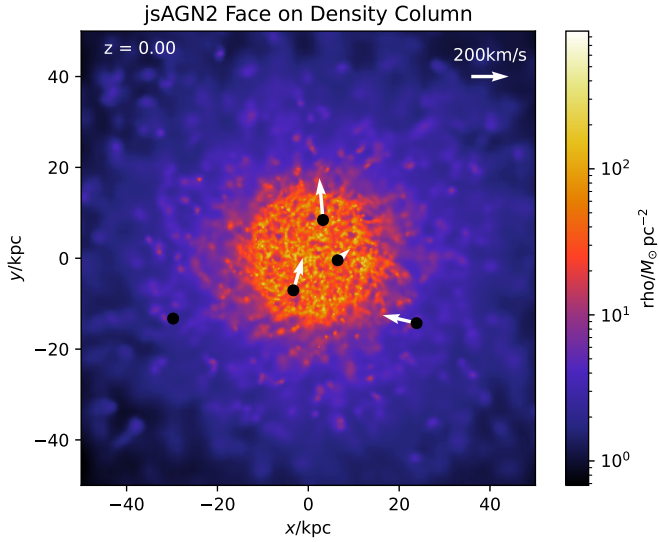

Figure 1. Face-on Density Column

Figure 1 shows the gas column density of a snapshot from the simulation jsAGN2. In the graph, there are five SMBHs, each with their velocity vector. The legend shows an example of a vector that represents 200 km/s. This helps give an idea of how fast each SMBH is moving. Interestingly all the black holes are orbiting the halo, but none are in the exact center.

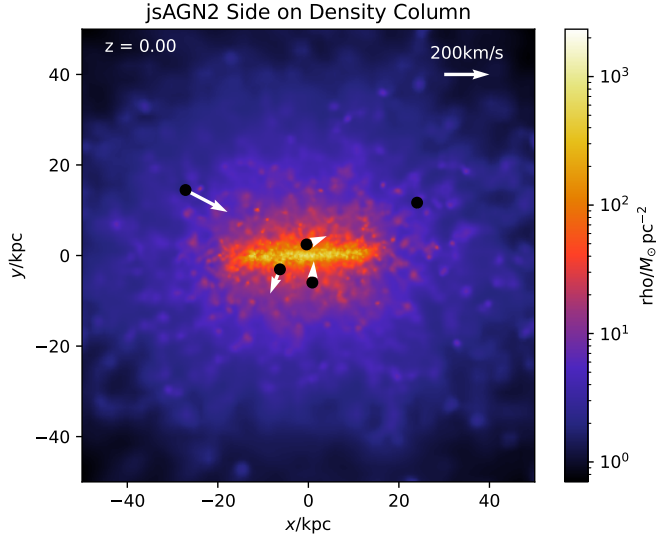

Figure 2. Side-on Density Column

Figure 2 is also a column density plot. However, this plot shows the same halo, as seen in **Figure 1**, but viewed edge-on, which offers another view of the position of the SMBHs. This allows us to see that some of the SMBHs are further from the center than they appeared to be.

We confirmed that SMBHs were formed, now we want to know what their effects are. To do that we look at the star formation history. **Figure 3** shows the star formation rate over time, and it compares the MUGS2 simulation with jsAGN2. We can see that SF is limited by AGN feedback. While in the initial stages of the galaxy, the star formation rate remained similar in both simulations, after 10 Gyr the star formation rate of jsAGN2 subsides and a lower rate is reached by the end. However, that is not the only thing of importance. Throughout the graph, you can see that jsAGN2 has less burstiness than MUGS2. This refers to the sudden peaks in star formation rate that we see throughout MUGS2 history. The star formation history indicates that AGN feedback somewhat suppresses late-time star formation.

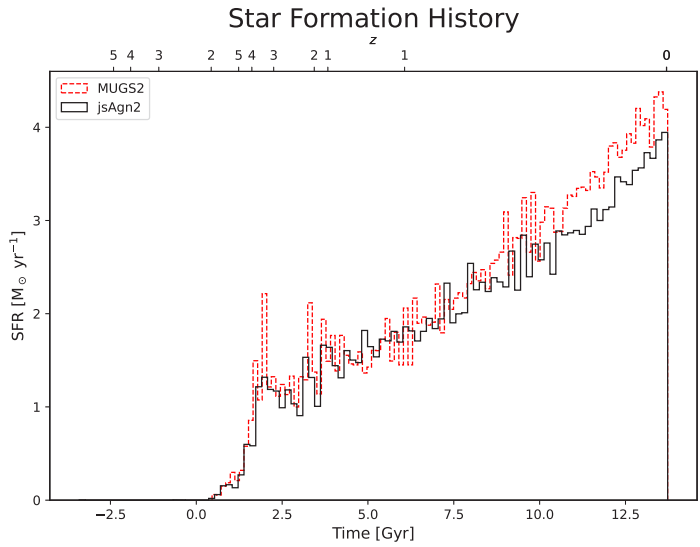

Figure 3. Star Formation History

Figure 3 shows the star formation rate over time in billion years of the simulations MUGS2 and jsAGN2. This graph plots the star formation history of both simulations on top of each other to compare how the implementation of SMBH reduces star formation. The graph shows that the presence of SMBHs regulates the rate and burstiness of the star formation.

To understand why this happened to the SF, the first thing we look at is the gas present. In Figure 4 we plotted the gas, stellar, and total mass of the largest halo in both simulations. We can immediately notice that the gas mass of jsAGN2 is lower than MUGS2 throughout the halo's history. The stellar mass, while not as much, also saw a slight decrease. Yet the total mass of both simulations is almost identical. This is because of Dark Matter (DM) particles, DM particles are unaffected by SNe and AGN feedback. SNe and AGN interact with gas particles by heating them and increasing pressure, this change in pressure causes gas particles to push each other out of the inner CGM. However, DM particles are not affected by electromagnetic forces. So, they do not heat up. Thus, they were not pushed around as much as gas particles; considering that DM particles constitute around 81% of the halo mass, it makes sense that it remained similar in both simulations.

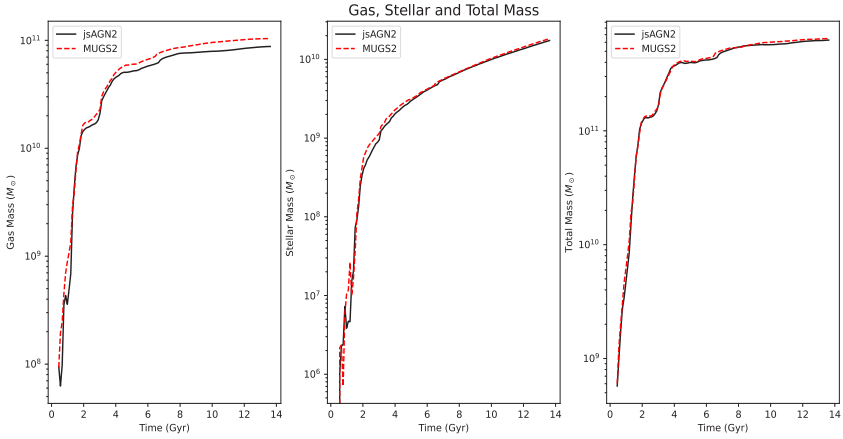

Figure 4. Gas, Stellar, and Total Mass

Figure 4 plots the gas mass, stellar mass, and total mass over time of jsAGN2 and MUGS2. We can see that the gas mass was the most affected by SMBHs. The stellar mass was also affected but to a lesser extent. Due to DM the total mass saw little to no change overall.

This shows that the absence of gas could be why SF was affected by the SMBHs. To confirm this, we have a closer look at the mass and temperature of both simulations' halos. **Figure 5** shows the radial profiles of the mass and temperature of the gas around the halo radius. If you look at the gas mass around 20 to 100 kpcs from the center of the halo, you notice a significant decrease in jsAGN2 compared to MUGS2. Another

interesting thing to notice is that the gas temperature is higher in jsAGN2. This is because of the gas ejected from the halo, the cooling efficiency was reduced resulting in longer cooling times and higher temperatures.

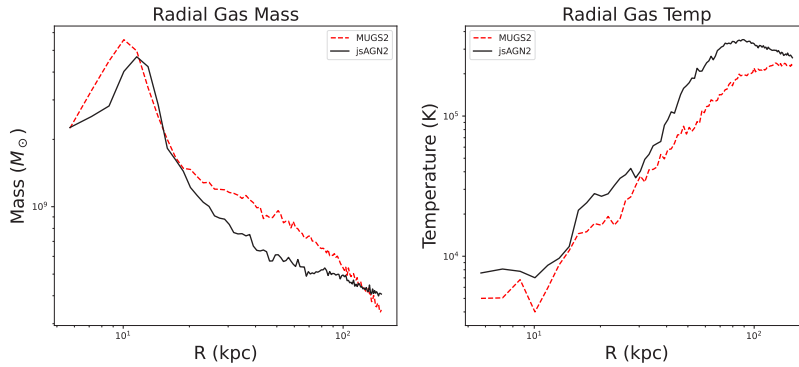

Figure 5. Radial Mass and Temp

Figure 5 gives us a closer look at the state of gas in both simulations. We can see that SMBHs resulted in a decrease in gas mass in the disk and the CGM. This decrease also seems to correlate with an increase in temperature, which can be attributed to longer cooling times due to lower densities.

This effect in the halo's gas mass is caused by AGN jets displacing large amounts of gas from the inner CGM through jets. The CGM is a source of fuel for a galaxy's star formation, so less fuel means fewer stars being formed. If we look at **Table 1**, we can see the gas, stellar, and total mass of the halo at the end of the simulation. By the end of the simulation, jsAGN2 had 16% less gas mass than MUGS2. It also had a lower stellar mass and total mass. The table also contains the SMBHs mass, which amounted to a total of $1.349*10^7$ Msol. This shows that the SMBHs ejected the gas rather than accreting it, because the total gas mass lost was around sixteen billion Msol and the total mass of the SMBHs is not nearly enough to account for all the missing gas mass.

Halo Final Masses				
Name	**Gas mass (Msol)**	**Stellar Mass (Msol)**	**Total mass (Msol)**	**Total SMBH Mass (Msol)**
MUGS2	$1.04*10^{11}$	$1.86*10^{10}$	$6.49*10^{11}$	0
jsAGN2	$8.77*10^{10}$	$1.77*10^{10}$	$6.27*10^{11}$	$1.349*10^{7}$

Table 1. Halo Final Masses

In **Table 1** here, we can see the different masses of the halo when the simulation concluded at z = 0. The gas mass has the biggest change, decreasing by 16% in jsAGN2. The stellar mass was also affected along with the total mass. We also have the total mass of the SMBHs, which if you compare it to the gas mass lost proves that the gas was ejected and not accreted; because of how small the total mass of the SMBHs is compared to the gas mass lost.

Conclusion

In this paper, we delve into the mechanisms that limit the SF of a galaxy. We compared two of those mechanisms, SNe and AGN feedback. We did this by running the simulation jsAGN2 using the N-body + SPH code ChaNGa, with feedback from SNe and AGN, and compared it to the previously run simulation MUGS2; which used the code GASOLINE with feedback from SNe only.

We found that AGN feedback noticeably reduces the SFR and burstiness of the simulation. To understand why this happened we looked at the gas in the largest halo of both simulations. We found that throughout the halo history, the gas mass was reduced. This also affected the stellar mass. However, the total mass was unaffected due to DM particles. We then proceeded to analyze the radial profiles of the halo's gas. We discovered that jets, caused by AGN feedback, ejected the gas out of the inner CGM of the halo resulting in lower densities that caused higher temperatures due to longer cooling times. This work is the first of what we are hoping to be a continuing effort to improve our techniques of galaxy simulation, which will aid in our understanding of how galaxies grow and develop.

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