The Effect of AGN Jets on Galaxy Evolution

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Abstract

This report discusses the influence of active galactic nuclei and their jets on galaxy evolution. Powered by super massive black holes, these active galactic nuclei create and release high-energy jets that heat gas and expel cool gas out of the galaxy influencing the galaxy stellar mass function and overall galaxy evolution. This report will cover the physical background of these active galactic nuclei jets, as well as discuss the simulations that are used to model how the jet impacts gas and galaxies, leading to changes in galaxy evolution and star formation. These models, SAGE and SIMBA, reveal that active galactic nuclei jets are crucial for quenching star formation by fuelling hot gas halos. In this report, the comparisons of these simulations with observational data such as those from MIGHTEE are also summarised. The results reinforce the argument considerably that active galactic nuclei feedback influences galaxy evolution and underpins the need for further observations and more detailed simulations.

1 Introduction

Galaxy evolution is a huge and complex process that occurs over billions of years. This of course implies that there are many factors that will affect it, and in different ways over time. However, at the heart of it are the active galactic nuclei (AGN) and their jets. AGN are among the most energetic and luminous objects in the universe with a super massive black hole (SMBH) at its centre, in some cases these AGN outshine the host galaxy itself. Almost every galaxy contains a black hole at its centre, however, not every galaxy contains an AGN (Robson 1999). Unlike inactive black holes, AGN are fuelled by an influx of gas and dust that forms on the accretion disk around the black hole, this material heats up to extreme temperatures due to friction, rotational forces and the intense gravitational pull from the black hole (Malizia et al. 2020). As this material accumulates on the accretion disk it generates its own magnetic field due to the motion of charged particles within the disk's plasma (Mura et al. 2017). As the material spirals toward the black hole, the magnetic fields get twisted and tangled due to the immense gravitational pull of the black hole, generating a powerful electromagnetic force, which acts as an accelerator for the charged particles, launching them at nearly the speed of light from the poles of the black hole, this type of radiation is called synchrotron radiation (Lovelace 1976). These high-energy jets of relativistic particles extend far beyond their host galaxy, often reaching distances of millions of light-years (Hardcastle and Croston 2020).

AGN can be classified into two groups, jet-mode and radiative-mode AGN, based primarily on the type of emission they produce as well as their energy output (Antonucci 1993). Jet-mode AGN are distinguished by their relativistic jets, which emit strong radio waves due to synchrotron radiation (Hardcastle and Croston 2020). This type of AGN is typically found in massive galaxies with their primary mode of feedback being kinetic, meaning that the relativistic jets transfer their energy into the surrounding gas and dust within the host galaxy (Hardcastle and Croston 2020), regulating star formation and the galaxy stellar mass function (GSMF). The GSMF is a mathematical model that describes how the stellar mass of a galaxy is distributed, similar to how a probability density function describes the distribution of probability (Weaver et al. 2023). This phenomenon plays a crucial role in mass quenching, a process by which massive galaxies stop forming stars (Dubois et al. 2013). On the other hand, radiative-mode AGN produce little to no relativistic jets; they primarily emit electromagnetic radiation that comes from the hot accretion disk. Depending on the conditions in the host galaxy, these radiative-mode AGN can suppress or induce star formation, however, their impact is often localised and less effective at regulating the large-scale galaxy evolution (Mancuso et al. 2017, Smith et al. 2020). Jet-mode AGN are one of the drivers of galaxy evolution, injecting energy from their powerful jets over large distances, quenching their host galaxies over time (Nyland et al. 2018).

In this report, we wish to address the question "How do AGN and their jets influence galaxy evolution?" If models describing galaxy evolution outwith AGN or models describing the role AGN play in our cosmos more broadly are to be designed, it is first necessary to understand and have answers to our question. Refining these models would develop insight into more practical and realistic tasks, such as understanding the future of our own galaxy. We will investigate the prosed question by reviewing the recent literature findings that combine theoretical predictions, observational data, and numerical simulations to study the impact of jet-mode AGN jet feedback on galaxy evolution, star formation and large-scale structure of the universe. By comparing simulation results to real observational data, we will assess the impact and importance of AGN jet feedback in regulating star formation, gas dynamics and black hole growth over time.

2 Simulation Details

A reliable and efficient method for checking our understanding of complex processes are theoretical models of physical processes that are incorporated in simulations (Feynman 1981). If a simulation creates results that matches our observational findings, then it effectively proves that we have a good understanding of the processes involved. AGN and long-term galaxy evolution are areas of active research and our knowledge on the matter is still incomplete. Simulations have been a key method in developing this knowledge, especially as long-term galaxy evolution and AGN cycles happen over hundreds of millions of years (Laursen 2024). This clearly can create difficulties when making observations as we can only glimpse snapshots of galaxy evolution and AGN cycles, however, with the assistance of simulations, it becomes possible to press fast forward on time and check if the results align with our observed snapshots in the sky.

The SAGE simulation in Raouf et al. 2017 can develop our understanding of the effects of AGN on galaxy evolution by including the relativistic jets emitted by radio AGN. Semi-analytic models (Raouf et al. 2017) treat jet energy as a function of black hole mass and accretion rate, showing that powerful jets can suppress cooling flows and quench galaxies. These models like SAGE (Raouf et al. 2017) use cosmological scaling relations and empirical jet power prescriptions to estimate the impact of AGN feedback on gas cooling and star formation, calibrated against X-ray observations of galaxy clusters. These observables include the GSMF, net cooling rate-temperature relation, and the AGN radio luminosity function (RLF). This is necessary for SAGE so that the simulation produces a galaxy population like our real Universe. Properties such as the GSMF are incredibly useful in astrophysics, and for semi-analytic models it can be a very practical parameter (Weigel, Schawinski, and Bruderer 2016). It is also a good indicator for the accuracy of any predictions made by the simulation. If the final GSMF is similar to our observations, it means that the distribution of mass throughout the simulated galaxy is realistic. The net cooling rate-temperature relation is particularly important; this describes how radio jets from AGN can heat up the intra-cluster matter (ICM, matter within a galaxy cluster) which affects the cooling process and plays a role in the wider evolution of a galaxy cluster

(Fiore et al. 2017). The 1.4GHz AGN RLF used in Raouf et al. 2017 is a statistical representation of the number density of radio sources as a function of luminosity (Tucci and Toffolatti 2020). This simulation can track the physical properties of the jets and successfully model the gas cooling-heating cycle, which highlights to us how important this factor is for star formation impacting the life and death of galaxies. Modelling hot gas distributions helps us understand how AGN feedback regulates star formation. The gas cooling-heating cycle is a process where hot gas in the ICM as described previously cools by X-ray emission and flows into the centre of a galaxy (Fabian 1994). This cool gas collapses and fuels the AGN causing it to heat the gas back up (Mittal et al. 2009).

A recent development is the SIMBA simulation (Thomas et al. 2021). SIMBA is based on the MUFASA simulation used in Davé, Thompson, and Hopkins 2016 with the two main adjustments being AGN feedback was added and improved modelling of black hole growth. SIMBA employs a hydrodynamic solver (Thomas et al. 2021) to simulate AGN jets and multi-phase gas, offering a more detailed view of how different accretion modes affect the circumgalactic medium (CGM). SIMBA (Thomas et al. 2021) expands on SAGE by coupling AGN feedback with hydrodynamics, tracking gas density, temperature, and velocity in real-time. Including torque-limited accretion improves our understanding of how angular momentum loss affects black hole growth, influencing the timing and strength of feedback (Thomas et al. 2021). By incorporating torque-limited accretion, SIMBA improves predictions of AGN feedback strength and quenching timescales.

Predictions and results of a simulation, when matched with real-life observations suggest that the simulated physics for AGN and jets (in this case) are correct. For example in SAGE the AGN RLF simulated follows very closely the observed RLF in Best and Heckman 2012 in the redshift interval $z = 0$ to $z = 1$. The relationship between the jet power and the 1.4GHz radio luminosity function predicted in SAGE is in agreement with results seen in Cavagnolo et al. 2010. Both of these agreements indicate that the models used are reliable and correctly describe how an AGN interacts with its surroundings. In this context, the jet power is defined as the total kinetic power of both radio jets (Raouf et al. 2017). The shortcomings of a simulation are not useless results. A disagreement in simulated models and real observations still provides insight into the mechanisms affecting AGN. An example of this in SAGE is the distribution of the stellar mass-radio luminosity relation for jet-mode and radiative-mode AGN (Raouf et al. 2017). SAGE agrees with Best and Heckman 2012 for jet-mode AGN however it underestimates the stellar-mass for radiative-mode AGN. It states in Raouf et al. 2017 that the free parameters (used for calibration) can be chosen for better agreement with radiative-mode AGN, however since it can't be chosen for both this suggests that our models are missing key details preventing us from simulating both accurately at the same time. SIMBA, just as SAGE did, correctly simulated the RLF observed in Mauch and Sadler 2007. This will be expanded on in Section 3, however it again articulates how an agreement with observations indicates that the models used are correct.

3 Influence of AGN on Galaxy Evolution

Hot gas distributions play a critical role in galaxy evolution by influencing star formation and the growth of massive systems. The two studies reviewed (Raouf et al. 2017; Thomas et al. 2021) focus on how energy from AGN jets impacts the CGM, affecting gas cooling and star formation. Raouf et al. 2017 uses SAGE (a semi-analytic model) to track AGN-driven heating, while Thomas et al. 2021 uses SIMBA hydrodynamic simulations with a detailed black hole accretion model. Both studies find that AGN feedback suppresses star formation by either heating or expelling cold gas, particularly in massive galaxies.

AGN jets create empty regions of space, shocks, and uneven heating in the CGM, leading to long-term suppression of star formation. This prevents cold gas from replenishing, with the persistence of hot gas halos depending on jet power, black hole accretion rates, and halo mass (mass of outer galactic regions mostly composed of dark matter, but also gas and stars) (Raouf et al. 2017; Thomas et al. 2021). Raouf et al. 2017 describes how jet-mode AGN heat the CGM through Bondi accretion, a model describing how a black hole accretes hot gas and grows in consequence. All the hot gas surrounding the SMBH and below the *Bondi radius* moves slow enough to be pulled inward by gravity. The *Bondi accretion rate* $\dot{M}_{\mathrm{Bondi}}$ is given by:

$$\dot{M}_{\mathrm{Bondi}} = \frac{2.5\pi G^2 M_{\mathrm{BH}}^2 \rho}{c_s^3}, \tag{1}$$

where M_{BH}, ρ and c_s are the mass of the black hole, the density of the surrounding gas and its sound speed, respectively. This equation can be modified to contain parameters obtainable by models like SAGE, making it extremely useful for predicting AGN-driven heating (Raouf et al. 2017). Radiative-mode AGN, on the other hand, undergo episodic feedback driven by gravitational torque-limited accretion. This describes black hole growth from cold gas that keeps losing angular momentum due to gravitational interactions, usually provoked by mergers or galactic encounters, spiral arm instabilities or bars or disk asymmetries (Thomas et al. 2021). These mechanisms ultimately describe how energy is deposited into hot gas reservoirs, affecting the efficiency of galaxy quenching (Raouf et al. 2017; Thomas et al. 2021).

From a galactic point of view, stars form when dense regions of gas collapse under gravity (Madau 2014). The distribution and behaviour of cold gas (usually found in radiative-mode AGN) in interstellar medium (ISM) is the main reason regions with high stellar formation rate (SFR) exist (Hardcastle and Croston 2020). AGN feedback can sometimes heat or push cold gas out of the galaxy (especially in massive galaxies), reducing the SFR and inducing galaxy quenching (Raouf et al. 2017; Sabater et al. 2019). On the other hand, gas-abundant mergers often trigger intense starbursts (Davé, Thompson, and Hopkins 2016).

The evolution of massive galaxies is closely linked to hot gas distributions. AGN feedback regulates the GSMF and cosmic star formation history. Without AGN feedback, excessive star formation would lead to an overabundance of massive galaxies, conflicting with observations (Raouf et al. 2017; Cavagnolo et al. 2010). By injecting energy into the CGM, AGN jets reduce gas accretion and decrease the number of high-mass star-forming galaxies at low redshifts. Sabater et al. 2019 further shows that jet-mode AGN dominate in the most massive systems, where long-term heating is most effective, while radiative-mode AGN are found in younger, star-forming galaxies. The decline in star formation rates in massive galaxies over time, driven by AGN feedback, is observed in both simulations and real data (Sabater et al. 2019; Hardcastle and Croston 2020). The mass of the roughly spherical region surrounding the main visible regions of a galaxy (the disk and bulge), also called the *halo mass*, is an important variable in the transition from star-forming to quenched galaxies, with large systems maintaining hot gas halos that prevent cold gas from fuelling new star formation.

These simulations rely on advanced computational techniques and observational data. As explained in Section 2, both models align well with observational data, reinforcing their accuracy. Thomas et al. 2021 shows how SIMBA captures the relative abundance of radiative-mode AGN and jet-mode AGN at different redshifts. This suggests that the simulated feedback mechanisms reflect real AGN behaviour. Additionally, the predicted distribution of quenched galaxies matches observations (Raouf et al. 2017; Thomas et al. 2021) showing declining star formation rates in massive systems over time. X-ray studies confirm the presence of empty space regions and shock fronts in galaxy clusters, consistent with AGN-driven heating (Thomas et al. 2021). Radio surveys also identify extended jet structures that match simulated AGN outflow structures, supporting the role of jet-mode AGN in long-term galaxy quenching (Hardcastle and Croston 2020). This agreement strengthens the conclusion that AGN feedback is a key driver of galaxy evolution, shaping the thermal properties of hot gas and regulating star formation.

These findings provide a clear picture of how hot gas distributions influence galaxy evolution through AGN feedback. By modelling the interaction between AGN jets and the CGM (SAGE models the jets directly, while SIMBA models their feedback, as stated in Section 2), the simulations show that hot gas halos sustain long-term quenching and control the properties of massive galaxies (Raouf et al. 2017). The combination of semi-analytic models and hydrodynamic simulations captures both large-scale trends and detailed physical processes. Observational evidence strongly supports AGN feedback as a crucial regulator of cosmic star formation history, validating theoretical models that link hot gas distributions to star formation suppression. Future work will refine these simulations by incorporating higher-resolution modelling and improved prescriptions for black hole accretion and jet formation, further enhancing our understanding of AGN-driven galaxy evolution (Hardcastle and Croston 2020; Sabater et al. 2019).

4 In the Future/Improvements

It has been shown that there is a wide range of accurate simulations modelling the behaviour of AGN in the near universe which have strong backing at low redshifts. However, at high redshifts, there is no coherent connection between AGN activity and star formation. This is a significant shortcoming, as high-redshift galaxies make up a large fraction of the universe.

A recent development in the data available on AGN is the MIGHTEE survey, published in Hale et al. 2022, which covers a well-documented area of the sky spanning 20 square degrees, gathering measurements to look deeper into this region with the backing of previous observations. These observations have been used to test the precision of SIMBA simulated results, which are strongly paired (Whittam 2022).

The MIGHTEE survey extends the reach of the previous data at z>1 by a factor of ~20 due to its increased depth and area. This dramatic increase means that we will accurately measure the evolution of such sources to z~2, testing the key ingredient of galaxy evolution simulations (Jarvis et al. 2016).

The difference in extending the depth of the observations from z = 0.5 to z = 1 is equivalent to looking back in time ~3Gyrs. Another ~2.5Gyrs in time is reached when redshift values are extended from 1 to 2. This is because the galaxies most distant from us recede the quickest away from us. The farther away we look also corresponds to the more distant in time we are looking back. Having data on the important features of AGN at this distance is key to painting a bigger picture of the long-term evolution of galaxies with respect to the AGN environment. It is also known that star formation peaked around z~2 (Madau 2014) and regressed into the current epoch; therefore, this is a key area to investigate.

Another key feature of the MIGHTEE survey is the homogeneous 21 cm HI absorption and emission from AGN across the radio luminosity function, which will allow exploration of the link between AGN behavior and neutral gas of galaxies, giving insight into AGN origin and influence on the host galaxy (Heywood et al. 2024).

As well as new satellite surveys, there have also been improvements to semi-analytic models used in simulation. Expanding on the theoretical models in SAGE, a recent version of DARK SAGE tracks the metallicity and mass of gas reservoirs and stellar components of galaxies, with further separation of discs into age bins. This allows DARK SAGE to make predictions of galaxy structure that could previously only be matched by hydrodynamic simulations (Stevens et al. 2024). These age bins unlock the capability to reconstruct the formation history of each disc and bulge component of a galaxy from an individual output, allowing them to be compared to recent observation.

5 Conclusion

From the discussions presented above it is clear that AGN play a role in galaxy evolution, particularly through the effects of their jets that influence star formation and gas dynamics. These jets, found in jet-mode AGN, primarily affect galaxy evolution through kinetic feedback that has been investigated to great lengths through comparing simulations with observations. The jets heat gas and eject gas out of the galaxy in shocks which supplies a hot gas halo and prevents cold gas from being replaced thus quenching star formation.

The simulations, SAGE and SIMBA, are two different types of simulations. SAGE is a semi-analytic model that was calibrated against free parameters such as the GSMF and the AGN RLF. SIMBA is a hydrodynamical simulation that offers a more detailed view of AGN and their affects more broadly. These simulations have proved themselves to be a reliable test of models after having predictions confirmed from new information obtained from surveys such as the MIGHTEE survey. SAGE's and SIMBA's data for the RLF closely aligns with results seen in other studies for specific redshift intervals. Thus by modelling AGN and their jets in simulations it clearly suggests that the feedback created by AGN has large repercussions affecting the host galaxy's evolution as well as neighbouring galaxies in the galaxy cluster. The agreements discussed between observations and simulations make an irrefutable argument that AGN play a major role in galaxy evolution. More detailed simulations, such as DARK SAGE, and higher resolution observations are required to complete our understanding of the effects of AGN and their jets on galaxy evolution, such as the formation of jets and a more detailed model of black hole accretion.

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