Implementation of the radio/jet mode AGN feedback in the AMIGA model

Author: Miquel Colom Bernadich
*Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.**

Advisor: Eduard Salvador Solé

Abstract: In this *Treball de Fi de Grau* the radio/jet mode Active Galactic Nunclei reheating feedback has been implemented in the AMIGA model, a semi-analytic hierarchical model of galaxy formation that works in the ΛCDM cosmology, in order to observe its possible repercussions on the galaxy and black hole mass functions at redshifts $z = 6.3$ and $z = 3.9$ for the cases of radio/jet mode efficiency equal to 0.1 and 1. A significant decrease in the abundance of galaxies of two orders of magnitude ($dex^{-1}Mpc^{-3}$) has been found between between $10^{11}M_{\odot}$ and $10^{12}M_{\odot}$ in the case of efficiency equal to 0.1 at $z = 3.9$, while the case of efficiency equal to 1 showed an unpredicted negative feedback effect.

I. INTRODUCTION

The basics for the modelling of galaxy formation were established as early as in [1] and [2]. Any serious current semi-analytic calculation that pretends to reproduce the characteristics of galaxy population over different times including our local/present neighbourhood is built upon on their initial model. For a detailed description of its implementation in previous works the reader is recommended to consult [3], but here a very brief explanation will be made. In their picture, currently known as the hierarchical model of galaxy formation, hot gas accumulates, cools down and condensates into galaxies at the centre of the potential wells of dark matter haloes, all while these haloes interact hierarchically and fuse together over time.

Following this, the physical phenomenology that rules the processes involved in galaxy formation needs to be implemented both in semi-analytic calculations and hydrodynamic simulations, as it is well explained in works such as those of [4] and [5]. The particular phenomenology that motivates this current work is the quenching of gas cooling due to one of the two reheating feedback processes provoked by the Supermassive Black Holes (SMBH) at the centre of the most massive galaxies, the so-called radio/jet mode Active Galactic Nuclei (AGN) feedback, supported by the observational evidence as shown in [6],[7] and [8], and first considered in [9] and [10]. This work will begin with an overview of the motivations for the reheating feedback processes, a more detailed description of the quasar and radio/jet mode AGN feedbacks and their implementation in the AMIGA model presented in [11] will follow and finally the resulting galaxy and black hole mass functions at redshifts $z = 6.3$ and $z = 3.9$ will be presented.

*Electronic address: mcolombe7@alumnes.ub.edu

II. FEEDBACK PROCESSES

A. The role of feedback

As it is well stated by its name and in the context of galaxy formation, a feedback process is a physical response of the system to other active processes, which is retroactive by nature and can have a great impact on the future of the system. Concretely, the main point of discussion in this work will be the reheating feedbacks, whose physical response is the reheating of the cooling gas which effectively quenches or slows down galaxy growth and star formation.

In [9] and [10] the need for this kind of processes is very well put. The observed luminosity function of galaxies at redshift $z = 0$ decays exponentially at the bright end while it flattens at the faint end. This clearly contradicts the prediction of an implementation of the hierarchical model without any kind of reheating feedback, as it is to be expected that the smallest hot gas haloes cool very rapidly and form many faint galaxies, all while the progressive fusion of dark matter haloes populate the universe with giant and bright galaxies. Furthermore, it also predicts that at our current redshift there are still large reserves of hot gas that should be cooling and accreting onto those giant galaxies, triggering star formation and painting in blue their luminosity. This is wrong too since giant galaxies are actually known for having an old and reddened star population due to the lack of star formation, a deficit that is also attested by X-ray observations that show the absence of significant cooling flows. This illustrates the need for reheating feedback processes that avoid the prediction of excessive cooling, but finding what kind of physical phenomenology is responsible for it is not a trivial task.

One of the first proposed reheating feedbacks mechanisms were the stellar and supernova feedbacks. The idea consists in that, as star formation is triggered due to the accretion of cold gas into the galactic disc of spiral galaxies, part of the energy lost through cooling is returned to the hot halo gas via stellar and supernova winds originating from the recently formed stars. Studies on of this effect were made by [12] and [13], and it has been tested in relevant computations such as those of [14] using the GALFORM simulation or [15], achieving a moderate success. However, despite the fact that these feedbacks correct the luminosity function in a good direction, their response still lacks strength. As a matter of fact, in [16] it was stated that either their efficiency needs to be unrealistically high in order to reproduce observations or that some other kind of reheating feedbacks needed to be considered, such as those coming from the AGN.

Closer to what we want to deal with, AGN feedbacks are associated with the central spheroid of galaxies, hence the name of Active Galactic Nuclei. The SMBH are said to accrete mass whenever there is cold gas present in their respective spheroid, and when this happens their luminosity, emitted mainly in the form of X and gamma rays, can get up to radiation levels of $10^{51} erg/s$, a value even greater than that that of the whole stellar luminosity of the host galaxy. Following the modelling of [17], the bolometric luminosity L_{bol} of an enlightned SMBH is said to be proportional its rate of growth $\dot{M}_{SMBH}$ in the following way:

$$L_{bol} = \epsilon \frac{1}{2} \dot{M}_{SMBH} c^2 \tag{1}$$

Where ϵ is an efficiency constant whose value is to be determined by observations and $\dot{M}_{SMBH}$ is proportional to the presence of cold gas. It is also known that around a 10% of this luminosity is emitted in the form of two opposed jets of relativistic charged particles. Based on their effects and method of reheating, there are two types of AGN reheating feedbacks, the quasar mode and the radio/jet mode.

B. The quasar mode AGN reheating feedback

When SMBH emission happens, part of it remains trapped inside the spheroid of the host galaxy and any cold gas present there gets reheated and then expelled back to the hot gas halo in the form of superwinds in a similar way to that of the stellar feedback, but with a much higher efficiency. This process effectively quenches the cooling flows by mixing with the expelled gas, interrupts star formation due to the expulsion of cold gas and stops further mass accretion on to the SMBH. While it is the most prominent in the aftermath of violent and drastic episodes such as galaxy merger events or disc instabilities, which is when the cold gas has the opportunity to enter the spheroid in large quantities and when the SMBH accrete most of their mass as argued in [18], it can actually happen whenever the right conditions for it are held. This is the quasar mode AGN reheating feedback, and it proves to be critical when following the growth of galaxies as with its implementation the problem of excessive cooling at the bright end of the luminosity function gets mostly solved.

However, the problem of the reddened giant elliptical galaxies with a deficit in cold gas still remains. Since the quasar mode is only active in the presence of cold gas within the spheroid, it is expected for the surrounding hot gas to cool and condensate again after the cold gas has been expelled and those periods activity has passed, thus maintaining a young population of stars. This turns out to be true for spiral galaxies because cold gas accumulates at their disc and extra conditions of instability are needed for the cold gas to reach their bulb, but the cooling flows observed in the elliptical galaxies are far less intense than one would expect. This can be remediated by the introduction of the radio/jet mode AGN reheating feedback process, which inputs energy directly to the hot gas.

C. The radio/jet mode AGN reheating feedback

Due to the surrounding hot gas halo transparency to most most of the SMBH radiation, in the absence of great quantities of cold gas in the spheroid a large fraction of this radiation gets lost on to the extremely diffuse intergalactic medium. However, this is not the case for the relativistic jets which actually collide with the hot gas. Most giant elliptical galaxies are active radio galaxies that emit two opposed jets of relativistic charged particles, and as noted in works such as those of [6],[7] or [8], these jets input their energy directly to the hot gas halo, potentially quenching the cooling flows and cutting of the gas supply for the host galaxy. This is known as the radio/jet mode AGN reheating feedback, which is exclusive from the massive elliptical galaxies and it is called this way thanks to the jet's emission in the radio wavelength, which remains undetectable during the quasar mode when the jets are trapped within the spheroid. It is believed to be the responsible for the reddening of the star population in giant elliptical galaxies since the cooling flows, which are already minimized due to the AGN activity, go to feed the SMBH instead of condensing into stars, and by its own nature it is much less intense and more quiescent than the quasar mode since it requires an equilibrium between the effective cooling rate and the SMBH energy output. For this, it is expected to have a significantly smaller impact on the history of galaxies besides their reddening. As a note, it is possible for these galaxies to accrete cold gas again in the case of a merger or simply if the radio/jet mode output is not strong enough to quench the cooling flows, opening the door to new quasar mode activity.

There are actually different ways in which the radio/jet mode AGN feedback has been implemented implemented through history. For instance, in [9], a pioneer in implementing this type of feedback in a semi-analytic calculation, it was actually treated as it was feed directly from the hot gas. There, it was considered that the accretion rate of the black hole was proportional to the SMBH mass and the presence of hot gas.

$$\dot{M}_{SMBH} = \epsilon_{radio} M_{SMBH} f_{hot} V_{vir}^3 \tag{2}$$

Being f_{hot} the total fraction of hot gas in the system and V_{vir} its virial velocity, obtained from its temperature. Then, the corresponding fraction of this accretion rate was converted into an energy output that reheats the gas and effectively reduces the cooling rate. A less direct method was implemented in [10], where in stable, quasi-static systems the cooling rate of hot gas was compared with the maximum energy output by the jets, which is just a fraction of the Eddington limit of the SMBH emission L_{Edd}. If the following condition was weld:

$$\dot{M}_{cool} c^2 < \epsilon_{jet} L_{Edd} \tag{3}$$

Then it was considered that gas cooling and star formation is quenched. The results of [9] and [10] clearly suggested that implementing the AGN feedbacks is the way to go since they achieved luminosity functions much closer to the observed ones.

III. THE RADIO/JET MODE AGN FEEDBACK IN THE AMIGA MODEL

A. Motivations for its implementation in the AMIGA model

For a complete and detailed description of the Analytic Model of Intergalactic-medium and GAlaxy (AMIGA) model, the reader is highly encouraged to consult [11]. Here, only its mainline characteristics will be exposed. The AMIGA model is a semi-analytic hierarchical model that works in the frame of ΛCDM cosmology. Instead of using Monte-Carlo simulations or N-body halo merger trees, which are popular among other calculations, it interpolates the typical properties of haloes in a three-dimensional grid of redshift, dark matter mass and age, which allows for an accurate following of the history of mergers. The physical phenomenology is implemented through well defined analytic functions and probability distributions, and at the end the resulting distributions of properties, such as the mass function of the galaxies at a particular redshift, are extracted from the data stored in the grid.

Many processes are taken into account in the AMIGA model, and this includes stellar and AGN feedbacks. More precisely, the quasar mode AGN feedback was the one already implemented before this work. This feedback was considered much more relevant than the radio/jet mode in terms of shaping the galaxy mass function, and the results were already exceptionally good as shown in [19] and Salvador-Solé and Manrique (2018, in progress). However, if the implementation of the radio/jet was to introduce any variation in the mass function, it would show that a more precise modelling of galaxy formation is feasible. Altough little effect is expected, the kit of the question was to see whether an implementation of the radio/jet mode introduces any significant change in the final resulting galaxy and black hole mass functions in a computation that starts at redshift $z = 60$ and ends at redshifts $z = 6.3$ and $z = 3.9$, which is a reasonable time span to see its effects.

B. Implementation of the radio/jet mode AGN feedback

The approach taken for the radio/jet mode in the AMIGA model follows closer the one of [10] than that of [9]. The idea is to consider that a 10% of the total bolometric luminosity of the AGN (namely, an efficiency of 0.1) is spent in relativistic jets that reheat the gas surrounding the central galaxy of a cluster and then see whether if this energy is enough to quench the cooling of the hot gas. What follows now is a qualitative overview on how the code deals with the reheating in the part that involves the radio/jet mode, which can also give some physical insight. It should be remarked that this only applies to the central galaxy of every galaxy cluster.

To begin with, it is considered whether if the reheating coming from other processes such as the quasar mode or the stellar feedbacks is efficient or not. This is decided on the capacity of the hot gas halo to redistribute the energy within itself via mixing with the gas expelled from the spheroid. The reheating coming from these sources is said to be efficient if the reheating rate is smaller than the mixing rate, and if so, it is substracted to the cooling rate. If not, the expelled gas is considered to be lost to to the diffuse intergalactic medium since it is not able to be mixed. Whatever the case, if the particular galaxy is elliptical, it opens the door to reheating due to the relativistic jets, since they input the energy directly the hot gas instead. Then, the radio/jet mode feedback reheating is considered. The maximum power output that a SMBH can produce is at his Eddington limit. The AMIGA model calculates it following [17].

$$L_{Edd} = \frac{4\pi c G \rho_0 M_{SMBH}}{\sigma C_{Edd} n_0} \tag{4}$$

Where ρ_0 is the mass density surrounding the SMBH, σ the Thomson scattering cross-section, $C_{Edd} \simeq 2$ is related to the Compton cross-section and n_0 is the electron density. The energy output buy the SMBH can be rewritten as:

$$L_{bol} = \frac{1}{2} \dot{M}_{SMBH} V_{last}^2 \tag{5}$$

Being V_{last} the infall terminal velocity of the accreted material. The bolometric luminosity L_{bol} is not allowed to surpass its Eddington limit L_{Edd}. Since L_{Edd} is directly proportional to the SMBH mass, we can expect

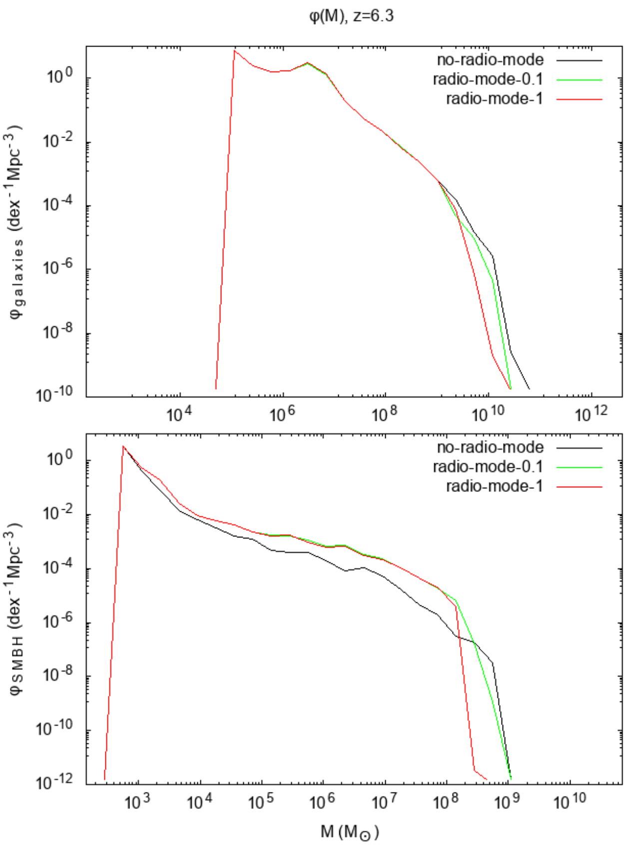

FIG. 1: Graphs of the galaxy and black hole mass functions of the central galaxies and their SMBH at redshift $z = 6.3$ with the radio/jet mode deactivated and with the radio/jet mode activated with efficiencies of 0.1 and 1.

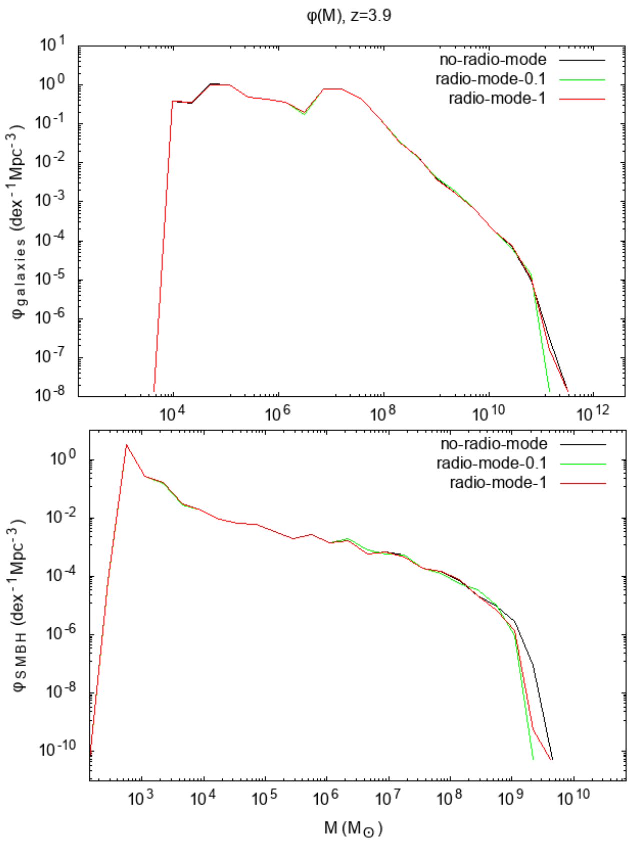

FIG. 2: Graphs of the galaxy and black hole mass functions of the central galaxies and their SMBH at redshift $z = 3.9$ with the radio/jet mode deactivated and with the radio/jet mode activated with efficiencies of 0.1 and 1.

for the radio/jet mode to be relevant only at the highest masses, where SMBH have a large range of possible powers of emission. And finally, trough an iterative process, the program calculates the reheating rate $0.1L_{bol}$ compatible with the cooling rate and the SMBH energy output, which basically means that the remaining effective cooling rate has to be the exact same one which induces the SMBH emission that quenches it in the first place. If the program doesn't find a solution due to the cooling being too strong, the radio/jet mode is also considered ineffective and the cooling rate is not modified.

It should be remarked that the efficiency of the radio/jet mode is actually a free parameter that can be changed at will if required, that is, to any desired %.

IV. RESULTS

In figures FIG. 1 and FIG. 2, the resulting mass functions after the implementation of the radio/jet mode are shown. Before discussing them, it is important to clarify that the case with efficiency equal to 1 is entirely hypothetical and lacks any kind of observational evidence. However, it will be used to illustrate what would happen in the extreme that all the luminosity of the SMBH was to be spent reheating the hot gas or, to a greater extend, to see what would happen if the relativistic jets were to carry a greater fraction of the luminosity of the SMBH.

To begin with, focusing the study only in the orthodox case with an efficiency of 0.1, a clear drop in the abundance of massive galaxies and SMBH in respect to the case with no radio/jet mode can be seen at $z = 6.3$ and $z = 3.9$. In both resdshifts the SMBH clearly accumulate at lower masses, indicating that the radio/jet mode has impeded them to grow as large as they would in the case where it remained deactivated. In the end, however, the overall effect on galaxy mass function is pretty weak and it only has major repercussions in the masses between $10^{11}M_\odot$ and $10^{12}M_\odot$, leaving the rest of the function pretty much invariant except for small protuberances where the population actually increases, probably due to the fact that more galaxies retain a smaller size, and showing that most of the quenching of cooling had already bee done by the quasar mode and other reheating feedbacks.

The case with and efficiency of 1 gets a bit more complicated. At $z = 6.3$ it comes across as an exaggeration of the case with an efficiency of 0.1, but then at $z = 3.9$ a negative feedback result leaves the galaxy mass function closer to the case with no radio/jet mode is appreciated. This may certainly come as shocking news, but it can actually explained by the fact that since the radio/jet mode is so effective in this case that, as seen in FIG. 1, many high mass SMBH do not form, which means that they are in general less massive and thus their Eddington limit is smaller. This leads to an underperfomance of the radio/jet mode at latter redshifts and to the cases with efficiencies of 0.1 and 1 interchanging their roles, resulting the efficiency of 0.1 in a much more effective quenching of cooling.

V. DISCUSSION AND CONCLUSIONS

In this work, the radio/jet mode AGN feedback has been added to the already implemented quasar mode AGN reheating feedback in the AMIGA model, a semi-analytic hierarchical model of galaxy formation that works in the frame of ΛCDM cosmology. It has been found that it only has a relevant contribution in the high range of the galactic mass function in the case of an efficiency of 0.1 from $10^{11} M_\odot$ to $10^{12} M_\odot$ at redshift $z = 3.9$. This was an expected result, since the radio/jet mode is a quiescent process that is active only in giant elliptical galaxies and with far less power than the quasar mode.

An interesting feature of the implementation has been the discovery of a negative feedback effect that palliates the quenching of cooling in the case of efficiency equal to 1, probably due to the an overperformance at early stages that reduces too much the size of SMBH and leads then to an underperformance at more recent redshifts.

The modelling of galaxy formation gains in physical significance every time new feature such as this is added. Further observations and creativity will allow for the implementation of even more process and for a more precise testing of semi-analytic models. In the meantime, deeper insights on the consequences of the implementation of the radio/jet mode could be achieved by, for example, running the AMIGA model up to redshifts closer to $z = 0$ or exploring its consequences in other results of the computation such as the luminosity or color functions.

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