Research On Black Holes Influence the Evolution of Galaxies and The Cosmological Simulation

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Abstract. The discovery of the photograph of the black hole is one of the most exciting news recently. In this report, the important factors of black holes will be discussed and summarized, to provide a more complete understanding. It is found that black holes are closely related to galaxy formation, and AGN feedback is used in the research process. Moreover, cosmological simulations such as the IllustrisTNG simulation are useful in researching the properties of the universe, factors such as viscosity, thermal conduction, and dust physics should be considered to build a more accurate model. Various dark matter are also crucial in the simulation models to obtain more convincing results. To simulate the galaxy, methods like N-body simulations and Monte Carlo-based probabilistic scattering are used. The report also suggests that to get more inspiring discoveries in the future, a more accurate simulation model should be introduced.

Keywords: Astrophysics; black hole; cosmological simulation.

1. Introduction

The first image of a supermassive black hole called Sagittarius A* at the center of our galaxy was taken recently. The discovery provided scientists with opportunities to compare the different black holes in our Universe and find out the theory of the evolution of galaxies. Thus, the research on how the supermassive black hole influences the formation of galaxies plays a crucial role in cosmology. According to Black Hole Physics: Basic Concepts and New Developments, a black hole is an area in spacetime where the gravitational fields are so powerful that not even light can escape to infinity [1]. Moreover, it is suggested that there always exists a supermassive black hole in every large galaxy which is quite impressive [2]. There are various ways leading to the black hole formation, one is through the collapse of gas clouds. In the interior area of the galaxy, the gas is gathered by turbulent viscosity or global dynamical instabilities. Another possibility includes the combination of supermassive black hole seeds and the early generation of stars from zero metallicity gas. These various ways promoted the evolvement of supermassive black hole seeds and the formation of galaxies [3]. The black holes continued to grow due to the accretion. It was influenced by the spin of the black hole, which affected the position of the inner radius of the accretion disc, along with the energy that can be extracted from the black hole. Radiatively efficient accretion and high-redshift metal-free halos can also accelerate the rate of accretion, leading to the formation of super-massive black holes [3]. One of the methods of the observation of black holes is by using the Event Horizon Telescope, which is an international collaboration aiming to carry on the consistent long-term progress of improving the capabilities of Very Long Baseline Interferometry (VLBI) at short wavelength [4]. Moreover, black holes can be observed by the Detection of gravitational waves from merging black holes, Stars orbiting Sagittarius A*, Accretion of matter and so on which will not be discussed in this article. In the field of simulation of the Universe, cosmological simulations such as direct N-body simulations, particle-mesh (PM) and hybrid methods, and hydrodynamic codes based on particle and grid-based methods are used widely. Some projects, IllustrisTNG and THESAN project, for instance, provide a large volume of boxes for further research of the scientists by using up-to-date numerical code including thorough physical models and running on supercomputers worldwide [5]. In the scale of the research of the whole universe, the observations and hypotheses suggested about the black holes can provide scientists with a clearer insight into how the galaxy evolved, find out the mystery of expansion of the current Universe, and even predict the future situations of the Universe. Although the research on black holes and galaxy formations is complete and numerous, the supermassive black holes and the simulation of galaxy formation should also be taken into consideration.

Therefore, this paper will discuss how supermassive black holes affect galaxy formation in the form of galaxy simulation, and its role in further studies by summarizing the essays published earlier. The main objective is, by summarising the essential bullet points, to provide a more complete understanding of the galaxy formation, which can also reveal the evolution of the whole universe, originated from the Big Bang.

2. The Role of Black Holes in the Galaxy's Evolution

Through a variety of processes, black holes affect the evolution of galaxies, which has a major impact on galaxy formation. One of the factors is the relationship between bulges within galaxies, which suggests that a core black hole is present in both spiral bulges and ellipticals, and their black hole mass to star mass ratio is the same, usually 0.1%. Moreover, star formation may accelerate or be suppressed as a result of black holes in the bulges returning energy to the surrounding gas in response to gas fueling [6]. Moreover, black hole masses are closely related to the stellar mass and velocity dispersion of the host bulges. This association points to a causal relationship between bulges and black hole formation [7, 8]. One of the understandings of this relationship is that star formation and black hole accretion happen simultaneously because they both use the same gas that gas-rich mergers and disk instabilities bring to the center. When star formation depletes the gas, black hole accretion ceases. Another interpretation is that when the black hole consumes the galaxy's gas, star formation stops [6]. Moreover, by releasing energy to the surrounding gas, black holes can either accelerate or suppress the rate of star formation. This black hole feedback can produce winds that may compress the gas, leading to the acceleration of the black hole formation rate. Occasionally, all the gas in the galaxy can be blown away by the black hole, abruptly terminating both black hole growth and star formation. This quenching process is believed to be important in explaining the major red color in elliptical galaxies [9].

3. The Role of Black Holes in Star Formation

Star formation is also an essential requirement for the evolution of galaxies. Active galactic nuclei (AGNs), which are small, incredibly bright areas in the center of galaxies that can emit significant amounts of energy throughout the electromagnetic spectrum, and are driven by accretion onto supermassive black holes, play an important role in controlling the rate of star formation in the galaxies they inhabit through a mechanism called AGN feedback. This feedback may be generated by adding momentum and energy to the gas in galaxies, which affect star formation. AGNs emit either mechanical or radiative energy, and their different modes are linked to various Eddington ratios [10]. Eddington ratio is a parameter that relates the AGN bolometric luminosity to the Eddington luminosity, and the Eddington luminosity refers to the equilibrium between the outward radiation pressure produced by an object's luminosity and the gravitational force dragging an object inward, such as a star or black hole [11]. In particular, radiative AGNs have a significant influence on star formation, particularly in the early cosmic era, since radiative feedback can drive nuclear and large-scale outflows in galaxies. This emphasizes the significance of multi-scattering of infrared photons for effective momentum coupling between radiation and gas. Furthermore, radiative feedback can influence the disc's overall gas composition and star formation characteristics by heating and rarefying dense gas, which can have an impact on the galaxy's densest star-forming areas [12]. Jet feedback, depending on mechanical energy, can accelerate tiny areas of dense gas and drive rapid nuclear outflows, which can cause localized bursts of star formation. By removing the densest regions of the cold interstellar medium (ISM) in galaxies, jets can effectively percolate through it, heating and pressurizing the gas at wider radii and perhaps lowering global star formation. Furthermore, jet-to-individual ISM clump interactions can happen in galaxies and affect star formation. Jet feedback has the potential to initiate secondary gas inflows that maintain gas accretion rates and supply fuel for fresh AGN activity events on short timescales [12].

4. The Cosmological Simulation In The Evolution Of Galaxies

The simulation of the evolution of the galaxy can give a deeper interpretation of how the black holes affect the process. Important physical processes in galaxy formation models are viscosity, thermal conduction, and dust physics. Viscosity plays a significant role in determining how baryonic matter behaves in simulations [13]. Baryonic effects change the distribution of cold dark matter (CDM) in haloes, which has a large impact on dark matter distribution in simulations and plays a significant role in shaping dark matter profiles [14]. Although thermal conduction is a physical effect that is frequently disregarded in cosmological simulations of galaxy formation, the thermodynamic parameters of galaxy clusters can be influenced by thermal conduction in their hot plasmas. One of its effects is that, by reducing the temperature substructure in the intracluster medium (ICM), thermal conduction tends to make the gas more isothermal. The intracluster medium is the superheated plasma that permeates a galaxy cluster. This smoothing effect is especially noticeable in the temperature maps of the simulated clusters; in comparison to simulations without conduction, the presence of conduction results in a more near-isothermal zone at the center and somewhat hotter outside sections [15]. The other factor is the dust physics. Since dust physics contributes so little to the interstellar medium's mass budget, it has also historically been disregarded in simulations of galaxy formation. However, dust affects radiation processing and thermochemistry, which is vital to the evolution of the interstellar medium. As a result, basic dust models have been incorporated into recent galaxy formation simulations to monitor the creation, expansion, and disintegration of dust in the interstellar medium [13].

The dark matter component in cosmological simulations of galaxy formation is also an essential element to be considered. Usually, it is modeled using a variety of techniques, taking into account alternate dark matter models such as fuzzy dark matter, warm dark matter (WDM), and self-interacting dark matter. An ultralight bosonic scalar field is taken into consideration in the fuzzy dark matter situation, which forms a cosmic Bose-Einstein condensate with macroscopic quantum features suppressing small-scale structures [13]. An extremely low mass scalar field, usually in the range of 10^{-22}eV to 10^{-18}eV, is referred to as an ultralight bosonic scalar field, and the term cosmic Bose-Einstein condensate refers to a theoretical idea that compares the expansion of a positively curved Friedmann-Robertson-Walker (FRW) cosmology with ideal fluid matter sources to the dynamics of a harmonically confined, quasi-two-dimensional Bose-Einstein condensate [16, 17]. Both of the two concepts will not be specifically discussed.

Simulations with warm dark matter models use adjusted initial circumstances because of the high-k cut-off in the early power spectrum, which reduces small-scale power and impacts halo formation. This decrease in small-scale power can affect the overall halo mass function and suppress the production of low-mass halos, which can affect the structure formation process. Furthermore, exponential suppression is observed at the high-mass end of the halo mass function, underscoring the significance of the high-k cut-off on halo formation [13].

Quantifying self-interactions in terms of cross-section per unit particle mass is a key component of self-interacting dark matter models. To represent particle interactions, simulations employ the N-body technique in conjunction with a local Monte Carlo-based probabilistic scattering method. The N-body simulations entail simulating a system of particles' interactions with one another through gravitational pull or other forces. In addition to gravity, these simulations account for other physical components like quantum physics and thermodynamics to give a more complete picture of the system. Based on theoretical models and empirical data, the simulations constrain the interaction strengths and aid in the estimation of the overall cross-section for particle scattering.

Moreover, N-body simulations can be employed to investigate matter excitation behavior in models with a running cosmic vacuum, which could allow self-interacting dark matter and provide fresh insights into small-scale cosmology [18]. By taking into account the probabilistic character of particle scattering events, one may simulate the dynamics of the system and describe particle interactions using a local Monte Carlo-based probabilistic scattering approach. This method makes it possible to calculate scattering probabilities depending on the characteristics of the particles involved by modeling particle interactions as localized, probabilistic events that happen in space and time. One can watch the paths of the particles as they interact with one another and mimic the scattering processes by generating random numbers using Monte Carlo methods. This approach offers an effective tool for researching particle interactions in complicated systems, and it can be especially helpful in examining self-interacting dark matter, in which the behavior of the system is largely determined by the interactions between the particles [18].

5. The Supermassive Black Holes and Galaxy Evolution In Illustristng Simulation

The IllustrisTNG project is an ongoing series of large, cosmological magnetohydrodynamical simulations of galaxy formation [19]. The evolution of supermassive black holes in cosmological simulations is modelled using sub-resolution models that calculate the accretion rate from gas parameters at resolved scales [8]. The accretion rate in these models is calculated using the Bondi-Hoyle formula, where the mass accretion rate is determined by the square of the mass of the black hole. Since larger densities are obtained at higher resolutions, which result in faster growth at higher resolutions, the projected mass growth rate for supermassive black holes increases with resolution. However, self-regulation processes defined by global halo and galaxy features eventually limit the divergent behavior of black hole masses in simulations with varying resolutions, causing the black hole masses to converge to a common final value. The black hole masses that contribute to the high brightness end of the quasar luminosity function are impacted by this resolution dependence. The quasar luminosity function provides information about the instantaneous state of accretion of supermassive black holes and primarily focuses on the most luminous black holes [20].

Moreover, the relationship between black hole mass and other parameters like stellar mass and star formation efficiency is examined within the framework of IllustrisTNG simulations. There is less scatter in the simulation predictions compared to observations, indicating that the black hole mass-stellar mass relation correlates well with observational data. In addition, in comparison to the data, the simulation predicts a smaller scatter in the mass over the stellar mass fraction, suggesting that observational biases may be the cause of the discrepancy. Black holes expand according to their mass; for all masses, the kinetic mode is subdominant, while accretion in the thermal mode dominates mass growth for the majority of black hole masses. The growth in the thermal mode is suppressed for supermassive black holes that are more massive than a threshold, which results in a shift towards the kinetic mode and increases the significance of mergers for mass growth. For supermassive black holes with masses less than 109 $M_\odot$, the accretion rate in the kinetic mode is still very low, indicating that the quasar luminosity function may not be greatly affected by AGN in the kinetic mode [20].

In conclusion, a thorough framework for researching galaxy formation physics has been made available by the IllustrisTNG simulations, which have also created new opportunities for studying the evolution of supermassive black holes, galaxy quenching, and the interaction of various feedback mechanisms in determining the properties of galaxies over cosmic time.

6. Conclusion

In summary of the comments in the main body, black holes play a significant role in the evolution of galaxies through various processes, including the relationship between bulges within galaxies and their black hole mass-to-star mass ratio. Star formation can be accelerated or suppressed by black holes returning energy to the surrounding gas in response to gas fueling.

AGNs play a crucial role in controlling the rate of star formation in galaxies through AGN feedback. AGNs emit mechanical or radiative energy, and their modes are linked to various Eddington ratios. Radiant AGNs have a significant influence on star formation, as they can drive nuclear and large-scale outflows in galaxies. Jet feedback, based on mechanical energy, can accelerate tiny areas of dense gas and drive rapid nuclear outflows, causing localized bursts of star formation.

Cosmological simulations play a crucial role in understanding the evolution of galaxies, focusing on factors such as viscosity, thermal conduction, and dust physics. Viscosity affects the distribution of CDM in haloes. Thermal conduction can influence the thermodynamic parameters of galaxy clusters. Dust physics is vital to radiation processing and thermochemistry. Dark matter is another essential element in cosmological simulations, with techniques such as fuzzy dark matter, warm dark matter, and self-interacting dark matter. Self-interacting dark matter models use the N-body technique and local Monte Carlo-based probabilistic scattering methods to represent particle interactions and estimate the overall cross-section for particle scattering.

The IllustrisTNG project is an ongoing series of large cosmological magnetohydrodynamical simulations of galaxy formation. The accretion rate in these models is calculated using the Bondi-Hoyle formula, which determines the mass accretion rate by the square of the black hole's mass.

The report summarizes the factors that are important in finding out the relationship between black holes and galaxy evolution. It provides a more complete insight into the complex definitions and concepts, aiming to help readers fully understand the knowledge in the field of astrophysics.

However, since the report is simply a summary of the other research, it does not consider any real data during the research. Moreover, the range of knowledge introduced in the report is quite limited and requires further readings of the related papers to get a deeper understanding of the knowledge. In future studies, more accurate galaxy simulations should be invented to offer a more complete model of the universe and more opportunities for scientists to do further research.

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