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Review the formation and characteristics of black holes – examining the properties of Sgr A* centered at Milky Way

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Abstract:

The black hole is one of the important celestial bodies in the universe, and understanding its properties is important to help us understand universe and our homeland Milky way. My aims are to explore the properties of center black hole on Milky Way, Sagittarius A (Sgr A*). I first review the properties of black hole in the literature, including the formation of black hole, classification, and observations of black holes. Then, I examine the properties of Sgr A*, exploring its mass-calculation based on observation and properties as supermassive black hole. Through this study, I find that Sgr A* can form from gravitational collapse of a massive cloud of gas and dust, properties and observations like accretion disk, gravitational influence, and gravitational waves it has as a supermassive black hole, and its mass can be calculated from star orbit. In summary, studying the properties of Sgr A* is crucial to understanding our galaxy, and the fundamental nature of the universe.

Keywords: Black hole, Sgr A*

1. Introduction

Black holes are defined as a region of space-time where gravity is so strong that nothing, including light and other electromagnetic waves, has enough energy to escape it. To do some simple research on them, knowledge of basics of Newtonian gravity is crucially needed, and to be specific, it is needed to know stellar evolution, concept of Accretion Disks and so on.

The definition of the problem is how we know black holes(detection) and what we know(properties) about them. In this case, we will learn ways we detect the existence of black holes and ways to find out their mass, as well as properties such as quantity, distribution, unique activities those black holes have.

Then I will present reasons for my research. Objectively, black holes can be a step to understand the astrophysics, having a fundamental understanding universe, which helps us unravel the mysteries of the universe and gain a deeper understanding of its origins, evolution, and structure. Moreover, know more about black holes us know space nearby the earth. For example, if sun will end up a black hole, what properties do the black hole on the center of our Milky Way have, what affections they have on us. Personally, the main reason for my research is curiosity on this invisible, untouchable but extremely disruptive celestial body. Due to its tremendous gravitation, anything, including lights, goes into or near them will never get out of them and become part of their mass, which makes black holes hard to observe. At the same time, inside them, most amazing things happen--time and space no longer exist, travel to the other side of universe becomes possible...This mysterious but fascinating, extremely energetic body really catch my attention, giving me the motivation to learn about what we know about this mystery.

In section 2, I will investigate black holes in several aspects. Firstly, I will figure out their possible formations. Exotic as they are, they must have special formations comparing to other celestial bodies. Secondly, how we detect these black holes. In the case they are invisible, how can we know their existence, in which ways can we see them? Additionally, after we detect them, what differences are shown between different black holes, and why? After I have some understandings on black holes, in section 3, I will discuss the center black hole on Milky Way SgrA*. Firstly, it's possible formation. Then the way to find them as well as calculating its mass. Moreover, several of its properties detected. Finally, I will conclude my findings in section 4.

2. Literature review

In this section, I will review properties of black holes, the formation of the black hole, classification, observations of black holes.

2.1 the formation of black holes

There are many possible pathways to form black holes. I will introduce star collapse, dark matter attraction, density fluctuation and vacuum decay below. Till now, star collapse is the main and only certain way to form black holes among pathways I will talk below, while for the rest ways are still hypothesis.

2.1.1 star collapse

The first pathway is star collapse. Those black holes are formed after stars are run out of fuel and continuously collapse inward, end up in compact dense objects. (Celotti & Sciama, 1999). There are several stages in formation of star collapse black holes. I will introduce from the formation of stars from gas and main sequence of stars, when gravity balance with electrostatic force, to white dwarf stage that electron degeneracy pressure balance with gravity, finally neutron star stage that neutron degeneracy pressure balance with gravity.

Firstly, a big glob of nebulae will collapse to form a star. Because of gravity, a clump of diffusion nebulae that weighed more than Kings quality collapses and form a protostar, whose gravitational potential energy transfers into internal energy then radiates outward in the form of light. The protostar continuously collapses and density of it increases thus the thermal radiation decreases from the outside in. Currently, temperature of the inner star increases, pressure roughly balances the gravity, collapsing nearly stops. When temperature of the core of the star reaches about 80K, nuclear fusion happens, the pressure surges and the star completely reach the hydrostatic balance. In this case, a star forms. After all the H in the core are depleted, white dwarf will form. Core of the star continuously collapses and the temperature of it increases until H in the shell of the star are ignited. So, the shell and the core both radiate outwards, the surface layer of the star is heated and expands outwards. Matters in the star are gradually divided into outer part and inner part. After several circles like this, all H in inner part is depleted and turned into He. If the mass of the star is more than 0.5 M ⊙ , He will be in hydrostatic balance due to high pressure, which means white dwarf forms.

Then comes to neutron star. At about 1wK, helium fusion happens, turning He of inner and part of outer part into C and O, while rest of the outer part continuously expand and ejects matters outwards to become planetary nebula. Then extremely dense inner part is neutron star. If the mass of the star is more than 1.4M ⊙ , the gravity will be bigger than hydrostatic balance pressure and collapses again to become black holes. Fusion of C and O continuously happens and turns them into metals, increases the temperature and finally forms a core of Fe. When the temperature reaches 50wK, photodecomposition of Fe happens and absorbs abundant of heat, which causes core matters collapse to be in neutron degeneracy. At this time, if the core matters weigh more than 30M ⊙ , the pressure from photodecomposition will be greater than neutron degeneracy pressure, the core matters will collapse into black hole. Stars collapsing can explain the birth of a big part of black holes, while for those supermassive black holes, for example, some black holes in the center of some elliptical galaxies, the mechanism can not explain the birth of them. There are responsible ways to explain their formation, like collision and merger of two neutron stars and direct collapse process.

However, I will talk about two exotic and interesting ways to form a type of supermassive black hole--primordial black holes. These two mechanisms both depends on inflation theory (MommyTalk, 2019).

2.1.2 density fluctuations

This kind of black holes form from primordial black hole (PBH) produced through overdensity fluctuations that magnified by inflation in early universe (Hawking, 1971).

In the early universe, distribution of matters were mostly even, while there were still regions that slightly overdense or underdense. At beginning, these density fluctuation can grow freely, characterizing inflation in terms of the Hubble length, when size of these fluctuations were less than the Hubble Length. After inflation begins, Hubble Length shrunk and become smaller than the size of fluctuation, in this case the fluctuation freeze. As inflation ended and hot big bang began, Hubble Length expanded again and density fluctuates, which produce PBH seeds that finally ended up in black holes.

2.1.3 vacuum decay

These black holes formed through extrusion of particles in a low energy vacuum by a high energy vacuum (Deng, 2020). Firstly, high energy vacuum gradually appears from initial low energy vacuum. During the early period of inflation, temperature is very high so vacuum of the whole universe is “false vacuum”, the lowest potential energy of which not equals to zero of the scalar field. When temperature goes down, true vacuums may appear in all corners of universe and rapidly expand because of pressure difference. Then most particles transported from initial vacuum to the new, left low energy ones remain. During process of new vacuum producing, particles will change from one kind of vacuum to the other. However, energy of some particles are too low to realize this, so they just remain in the false vacuum. Finally, PBH formed due to pressure. As space for true vacuum continuously grow, false vacuum space will become smaller and smaller, thus low-energy particles will concentrate more and more until the pressure of them become great enough to balance the pressure of true vacuum, Fermi-balls form. In this case, Yukawa interaction will make these balls collapse and become PBH (linvoshuoyuzhou, 2022; Kawana, K., & Xie, K.-P., 2022).

2.2 classification of black holes

In this section, we introduce the classification of black holes by mass, and review the properties of different types of black holes. We then introduction the method of mass calculation, and finally how to observe the BH.We will introduce three types of black holes classified by their mass, stellar mass black holes, intermediate mass black holes and supermassive black holes , exploring special features of them through observations from specific examples (NASA, 2023).

2.2.1 stellar mass black holes

Stellar mass black holes that have masses between about 4 and 100 solar masses. In this part, I will explore two features about stellar black holes. Firstly, they are the main builders of binary black hole systems. We will see Cygnus X-1 as an example. In addition, we can discover a special activity from a jet ejected by a stellar mass black hole, and here we will particularly look at Galactic micro quasar dubbed GRS 1915+105 (Bowyer et al. 1965).

2.2.1 .1 builders of binary black hole systems

One special thing about stellar black holes is that a big part of binary black hole systems made by them (Abbott, B. P. el.al, 2017). Actually, it cannot be assured due to limited information we got, but there are still powerful supportive evidences, as when scientists use numerical simulations that involve stellar evolution and population dynamics to study the formation and evolution of black holes, some the results show that most binary black hole systems consist of stellar-mass black holes, also, concluded from observed results in LIGO and Virgo, in the binary black hole model, black holes with lower mass (stellar mass) are more common. In this case, I believe this conclusion is reliable. Cygnus X-1 is a good example for binary stellar black holes. Now we will have a look at observations from Cygnus X-1, how they declare there is a binary black holes exist and these black holes are stellar black holes.

Light variation behavior and different time scales and periodicity detected are two of the main clues to show the existence of binary black holes. Fast-changing light we can observe from Cygnus X-1 may indicates the presence of binary black holes. Cygnus X-1 exhibits irregular, rapid, and violent light changes over multiple wavelength ranges. This unusual light variation indicates the presence of multiple objects interacting, possibly because of the interaction between the two black holes. Also, as evidence for black holes existence, we observed two distinct time scales and periods in Cygnus X-1. One time scale is about 6.5 days, and the other is about 155 days. This bicyclical behavior is often closely associated with binary black hole systems or companion star interactions.

There are reasons for we to conclude that these black holes are in stellar mass, and I will mention peak luminosity as evidence. Cygnus X-1's peak luminosity at the time of the burst is relatively low, usually at a fraction of the Eddington limit. This suggests that the black hole's mass matches the stellar mass threshold.

2.2.1 .2 jet launched activity

Another special feature of stellar black holes is that there might be jet launched activity by a stellar mass black hole, and our example here is galactic microquasar dubbed (a kind of stellar mass black holes) GRS 1915+105. QPO signal we detected from GRS 1915+105 may indicates the presence of jet launched activity of stellar black holes. China's massive five-hundred-meter Aperture Spherical Radio Telescope (FAST) to reveal a quasi-periodic oscillation (QPO) signal in the radio band of a stellar-mass black hole, with a rough period of 0.2 seconds and a frequency of about 5 Hertz. As a phenomenon that astronomers use to understand how star systems like black holes work, at the same time radio emission usually can be used to probes the jet launched from the disk and the black hole, these QPO signals could be seen as the first evidence of jet activity from a stellar-mass black hole. Possibly it can be caused by a misalignment between a black hole's spin axis and its accretion disk. This is a natural consequence of the drag of space-time in the vicinity of a rapidly spinning stellar-mass black hole.

2.2.2 intermediate-mass black hole

One most prominent feature of Intermediate-mass black hole is their mystery. Till now, we have not been able to definitively confirm the existence of Intermediate-mass black holes. Although there is some observational data and indirect evidence to support their existence, there is still a lack of direct, definitive observational evidence to confirm the existence of Intermediate-mass black holes. Here I will explore the reason why these black holes are difficult to observe compared to the other two types, as well as possible formation of these black holes.

2.2.2 .1 difficult to observe

There are several reasons for hard detection, and I will talk about two of them, the rarity of intermediate-mass black holes and existence of potential sources of confusion.

The first reason for these black holes are hard to observe is their rarity, and I will take ESO 243-49 HLX-1as an example.Compared to stellar mass black holes and supermassive black holes, intermediate-mass black holes are generally considered to be relatively rare. This means that there are relatively few opportunities for discovery and research in astronomy, leading to our not enough understanding of the process of formation and evolution of intermediate-mass black holes. This, in turn, makes detection more difficult. Looking at ESO 243-49 HLX-1, as one of the most likely candidates for intermediate-mass black holes found so far, it is in the galaxy ESO 243-49 and is thought to have the characteristics of an intermediate-mass black hole. However, such candidates are very rare, with only a handful of similar candidates found in the entire sky.

Another reason I will talk about is existence of potential sources of confusion, here I will take ULX (Super Giant X-ray Source) as example for intense radiation confusion, and N6946-BH1 as an example for stellar clusters confusion.When detecting intermediate-mass black holes, we often face the challenge of similar features to other celestial bodies. There are two confusions exists. Firstly, intermediate-mass stars in stellar clusters may exhibit behavior like intermediate-mass black holes, making it difficult to distinguish them from true intermediate-mass black holes. In addition, there are similar challenges in active galactic nuclei. Active galactic nuclei produce intense radiation and have high-speed accretion disks, which can lead to misjudgments about the intermediate-mass black holes that may be present at their centers.

2.2.3 supermassive black holes

2.2.3 .1 location

One most significant feature of supermassive black holes is they mostly locate in the center of galaxies. For example, using the European Southern Observatory's Auxiliary Telescope (VLTI) in Chile and the Event Horizon Telescope Network, scientists were able to observe the supermassive black hole at the center of the Milky Way. These observations make use of the velocity distribution of stars in the galaxy, as well as measurements of near infrared and radio radiation used to detect the presence of supermassive black holes.

2.2.3 .2 galactic evolution

Supermassive black holes always influence how galaxies evolve. They affect the movement of stars, control the shape of the galaxy, and even impact the birth of new stars. For example, the supermassive black hole at the heart of Messier 87 (M87) significantly influences the galaxy's evolution. Through the formation of colossal jets of particles, gravitational interactions with stars, and the presence of an accretion disk emitting powerful radiation, M87's black hole shapes the dynamics and structure of the galaxy.

2.3 Observation

There are three ways to detect black holes, their gravitational influence and accretion disk phenomenon, while I will also introduce a less common way, gravitational waves detection.

2.3.1 gravitational influence

Black holes are always orbited by objects. Due to gravitational influence, black holes can attract gas clouds, stars or even galaxies to orbit around them. For example, at the center of the Milky Way, we see an empty spot where all of the stars are circling around as if they were orbiting a really dense mass. That's where the black hole is (NASA, 2011).

2.3.2 accretion disk

We can detect lights from black holes when things fall into them. Accretion disk phenomenon occurs when the matter falling into the black hole. As matter falls in, it settles in a disk around the black hole that can get very hot. Some of the energy liberated from falling in is turned into light, which we can then see, for example, in X-rays (NASA, 2011).

2.3.3 gravitational waves

Binary black holes can be detected via gravitational waves which is results from its inward spiral and merger of. For example, gravitational wave GW150926, detected by the LIGO detectors in Hanford, Washington state, and Livingston, Louisiana, USA, at 09:50:45 UTC on 14 September 2015, states the existence a pair of black holes located mainly in the Southern Celestial Hemisphere,[2]: 7 : fig 4 in the rough direction of (but much farther than) the Magellanic Clouds (Abbott el al. 2017).

3. Discussion

The Milky Way is a barred spiral galaxy, home to our solar system, with a vast structure containing billions of stars, planets, and various celestial objects. It has a central supermassive black hole, Sagittarius A* (Sgr A*), at its core. I find it exciting to explore Sgr A*, firstly because it's our neighbour -- Sgr A* is relatively close to earth compared to other supermassive black holes, making it relatively easy for detailed observation and study. Moreover, Sgr A* holds clues to the history of our galaxy. Studying its properties is like flipping through the pages of a cosmic history book, offering glimpses into the ancient processes that shaped the Milky Way.

3.1 available observations of Sgr A*

3.1.1 the first photo of Sgr A*

This is a picture of Sgr A* (ApJL, 2022) as shown in Figure 1, also a groundbreaking image that marks a pivotal moment in astrophysics, as for the first time, the mysterious and unacquainted celestial body-- black hold, is presented in a picture, a such straight forward way. From the figure, one can see a donut structure, bright ring around a spot of darkness. The dark spot is believed as a shadow of a black hole, that provides the direct evidence of the existence of black hole. From this imaging, we learn not only about our galaxy but also about how gas acts around black holes more generally, confirming models made back here on Earth. Figure 2 shows the orbital of stars (Eisenhauer et al., 2005) surrounding the center Sgr A*. One of the brightest star is called S2, also known as S0–2 which can be used to calculated the mass of Sgr A*. The orbiting period is about 16 years, and the semi-major axis of the orbits about 970 AU.For following discussion, I will use these images to help explanation.

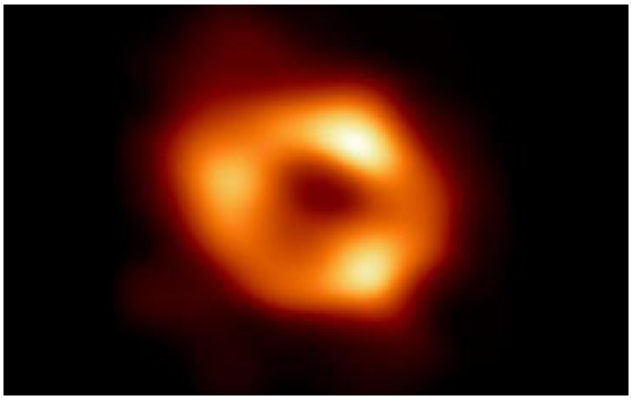

Figure 1. the photo of Sgr A*.

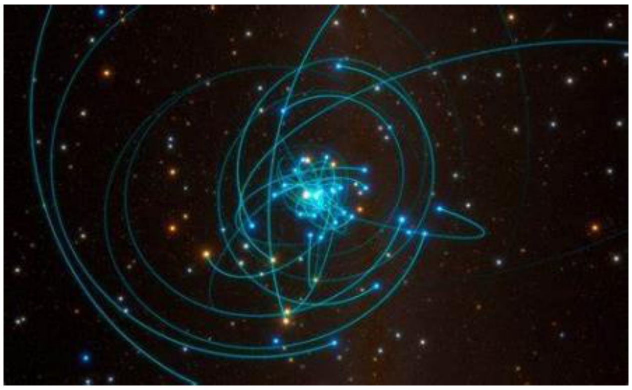

Figure 2. Trace of orbiting stars and galaxies around Sgr A*.

3.1.2 accretion disk

Observations with the Chandra X-ray Observatory have revealed the presence of an extensive hot gas corona around Sgr A*-- the “orange glowing donuts” in the photo presented (as shown in Figure 1), this corona is believed to be related to the processes occurring in the accretion disk.

3.1.3 gravitational waves

Till now, we haven’t found direct detections of gravitational waves emanating from Sgr A*, while the dense environment around the supermassive black hole, which includes potential encounters between compact objects like neutron stars or stellar-mass black holes, are generating detectable gravitational wave signals. The scientific community continues to monitor the galactic center region, including Sgr A*, for potential gravitational wave events. Advanced detectors, upgrades to existing facilities, and new observatories are being developed to enhance sensitivity and broaden the range of detectable signals.

3.1.4 gravitational influence

As shown in the Figure 2, stars and galaxies are orbiting around Sgr A*, known as gravitational influence, a very distinct feature of supermassive black holes. To be specific, The Keck Observatory in Hawaii, among other telescopes, has been instrumental in tracking the orbits of individual stars, such as S0-2 and S0-102, as they revolve around Sgr A*. What’s more, these observations have allowed astronomers to precisely measure the mass and gravitational pull of the black hole. This mass-calculation way will be used in next section specifically.

3.2 black hole mass calculation method

We can calculate their mass through our observations on stars surrounded or reverberation mapping.

3.2.1 star orbit

Actually, we can measure the mass by tracking how stars orbit the center of the galaxy and then determine how massive the black hole needs to be to keep them move in this way. However, we are only able to use this technique for very nearby black holes. Most black holes are too far away for telescopes to be able to image the orbits of these stars, so the method introduce below appear to be more practical.

3.2.2 reverberation mapping

Now I will emphatically introduce reverberation mapping, which we use time delay of light emitted to calculate the radius of orbit, then relates the kinetic energy of a system to its gravitational potential energy to find out the mass. Firstly, we calculate time delay to find out the radius of circular cloud. When black holes pull matters into them, there are often flares emitted from the accretion disk. Some of this light goes directly to an observer while some of it gets reflected off the clouds before coming to us. We can measure the time delay between when we first see the flare and when we see the light reflected from the cloud. This period is the time for lights to travel for the length of cloud radius, so we can calculate the radius by r=c ($=3*10^8$)

*t. Of course, reality isn't that simple. There are complicated factors need to be considered on this process: lights from flares travel in all directions, which causes broad response; time needed to observe light from far away; time interval for occurrence of flares and so on.

Then we will measure the orbiting velocity of the cloud, mainly through relating change in wavelength and velocity of the source. As Doppler effect states, the wavelength of the emitted light can change if the source emitting the light is moving away from us or towards us. If the light source is moving towards us, we say it is blue-shifted and the wavelength decreases. If it is moving away from us, we say it is redshifted and the wavelength increases. In this case, we record the wavelength of lights emitted and use Doppler principle to find out the velocity.

Assumes the system is in virial equilibrium, now that we have the radius of the clouds (R) and their orbital velocity (v) we can determine the black hole mass using this simple equation $M = f R v^2/G$.

3.3 mass calculation of Sgr A*

3.3.1 gravitational influence

Here I will use orbital stars around Sgr A* to calculate the mass of Sgr A*, and the details are presented as followings:

Firstly, we will use telescopes to track the orbit of a star orbiting around Sgr A*. Select a star with a known orbit around Sgr A*. for example, star is S0-2. Use high-resolution telescopes like the Keck Observatory or the Very Large Telescope (VLT) to observe the star over an extended period (Do et al.,2019). Then, they measure the star's position accurately over time. This involves determining its celestial coordinates (right ascension and declination) at different points in its orbit.

Velocity Measurements: Analyze the apparent motion of the star across the sky. The track or path traced by the star provides information about its angular motion. Then, determine the parallax of the star. Parallax is the apparent shift in the position of a star when observed from different points in Earth's orbit. The parallax angle is inversely proportional to the distance to the star.

Combine the apparent motion and parallax measurements to calculate the transverse velocity of the star. (The transverse velocity is the component of the star's velocity perpendicular to the line of sight.)

The transverse velocity (Vt) can be calculated using the formula:

$Vt=\mu*d$

where μ is the apparent motion in arcseconds per year, and d is the distance to the star in parsecs.In this way, we know orbital period (T) and the semi-major axis (a) .

Then, it can calculate the mass of the center body-- Sgr A*.Apply Kepler's laws of planetary motion to the observed orbit. Kepler's laws relate the orbital parameters (like semi-major axis and orbital period) to the mass of the central object, in this case, Sgr A*.

We can use the third law of Kepler, relates the orbital period (T) and the semi-major axis (a) to the mass of the central object (M) using the equation,

$M=4\pi^2a^3 /GT^2$,

where G is the gravitational constant. We can get the mass of Sgr A* is 4.1±0.6 million solar masses.

3.3.2 reverberation mapping

Reverberation mapping isn't an appropriate way for Sgr A* mass-calculation. Reverberation mapping is typically applied to objects with bright, active cores, such as active galactic nuclei. Sgr A*, being relatively dim, primarily emits radiation from an accretion disk and surrounding stars. Consequently, the techniques of reverberation mapping are not applicable in this environment.

3.4 properties and potential formation mechanism of Sgr A*

As shown in previous subsection that we can obtain the mass of of Sgr A*, 4.1±0.6 million solar masses. Sgr A* is a supermassive black hole and has a lot properties supermassive black holes owned. Moreover, as the most of black holes, Sgr A* influences galactic evolution surround it. It can be observed an verify through several phenomena. The orbits of stars near Sgr A*. They are profoundly affected by its immense gravitational pull and be made to move differently. Additionally, the presence of an accretion disk around Sgr A* contributes to the emission of radio and X-ray signals, indicating active processes near the black hole. This radiation interacts with surrounding material, influencing the galactic environment. The specific formation mechanism of Sagittarius A* (Sgr A*), the supermassive black hole at the center of the Milky Way, is still a subject of ongoing research and debate. While still, many reasonable theories are offered. Here, I will briefly discuss and summary the formation scenarios of Sgr A*.

As shown in the literature review, the possible formation scenarios of the black hole include star collapse, density fluctuation, and vacuum decay. According to observations, one proposed main scenario of Sgr A*, involves the collapse of a massive gas cloud. In this model, a large cloud of gas collapses under its own gravity, forming a dense and compact region known as a protostar. As more material accretes onto the protostar, it can continue to grow in mass. If the mass accumulation surpasses a critical limit, the protostar may eventually collapse into a black hole. In the case of supermassive black holes, the process likely involves the repeated merging of smaller black holes and the accretion of mass from surrounding gas and stars. Over billions of years, these black holes merge and grow, creating a supermassive black hole at the center of a galaxy. The precise details of this process are still a subject of ongoing research and observation.

Another two possible scenarios density fluctuation, and vacuum decay might be difficult to explain. The formation of a supermassive black hole like Sgr A* from density fluctuations in the early universe is a complex process that involves a combination of gravitational collapse, accretion, and the merging of smaller black holes. However, there are challenges in explaining the formation of supermassive black holes solely through the direct collapse of high-density fluctuations. Similarly, the concept of vacuum decay is related to quantum field theory and the stability of the vacuum state in particle physics. It involves the idea that the universe might exist in a metastable state, and under certain conditions, it could transition to a more stable state. While this idea is fascinating and has been explored in theoretical physics, it's not directly applicable to the formation of supermassive black holes like Sgr A* at the center of galaxies.

Conclusion

This research is all about unraveling the mysteries of black holes, with special focus on our Milky Way's own black hole—SgrA*—to enhance our understanding. When it comes to the content, we're diving deep into the characteristics of black holes, exploring what makes them stand out, understanding the processes that lead to their formation, and examining the methods we use to observe them. This exploration is essentially a journey to become more acquainted with the black hole at the center of our cosmic neighborhood—the Milky Way.

Looking forward, one of the potential avenues for further exploration lies in the structural intricacies of black holes. According to my project findings, our current understanding of the structure of black holes is predominantly theoretical, and even at that level, certain aspects remain veiled in uncertainty. This opens a vast landscape for future developments and research endeavors, paving the way for deeper insights into the structural dynamics of these celestial enigmas.

The intention is to make this information accessible to individuals, like me, who may not be well-versed in intricate mathematical concepts. By presenting a simplified depiction of black holes, this research aims to provide a user-friendly entry point for high school students and the public. The objective is to strike a balance between depth and accessibility, tailoring the information to align with the mindset of those seeking an introductory understanding of these cosmic wonders. Considering my position as a regular high school student without a strong background in advanced mathematics, delving into the complexities of intricate black hole research is a bit out of reach. So, the overarching principle guiding this research is to maintain simplicity and ensure a clear grasp of the fundamental aspects of black holes.

Review

In this research endeavor, I set out to unravel the intricacies of black holes, with a particular emphasis on our very own Milky Way's black hole, Sgr A*. The primary goal was to cultivate a deeper understanding of this celestial phenomenon by exploring its fundamental properties. As I delved into the content, the exploration took me through the basics of black holes, probing into their distinctive characteristics, the mechanisms governing their formation, and the methodologies employed in their observation. This journey served as a gateway to familiarize myself with the enigmatic black hole at the heart of our cosmic neighborhood—the Milky Way.

These above are satisfying achievements. However, there are also disappointing parts.

The most significant limitation is my lack of knowledge needed. As an ordinary high school student, my venture into the complexities of advanced mathematics and theoretical physics posed a considerable challenge. The lack of a solid foundation in modern physics, including concepts like relativity, became a significant limitation. This gap in knowledge hindered my ability to grasp a crucial and fascinating facet of black hole research—the inner workings of these cosmic entities.

Moreover, one of the most glaring constraints I encountered during this exploration was the constraint of time. The process of crafting the essay turned out to be more demanding than initially anticipated. Striking a balance between the rigorous demands of the project and my existing commitments proved to be a delicate task. With an already packed schedule, I found myself compelled to streamline the essay's complexity and length to meet the project's objectives.

Reflecting on this experience, a key takeaway is the importance of judiciously managing time and carefully selecting topics. In future endeavors, I intend to choose subjects that not only capture my interest but also align more seamlessly with the comprehension level of a high school student. This strategic decision, coupled with enhanced time management skills, will undoubtedly contribute to a more successful and fulfilling research experience.

Throughout the course of this project, I acquired valuable insights into the techniques of academic writing, honed my skills in resource exploration, and developed proficiency in synthesizing information. Additionally, the need for careful consideration before embarking on a research project became a pivotal lesson. This newfound awareness will undoubtedly inform my decision-making process in future academic pursuits.

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