

A Study on the detection and formation mechanisms of ultra-massive black holes

Hongyu Rao^{1,*}, Zhongqi Wang²

¹Malvern college, Worcester, UK

²Dulwich College Singapore, Singapore

*Corresponding author: rao_hongyu@malverncollege.org.uk

Abstract. With the discovery of Ultra-massive black holes and Super-massive black holes, humans have yet to find out the cause of their formation with modern technology. Based on the analysis, we will look at the detection methods and calculation methods for black holes and their mass. Besides, we will also dive deeper into the actual formation of these Ultra-massive black holes. Taking a closer look at black holes' sizes, there are many black holes between 0.1Ms and up to its maximum 150Ms, but something interesting is that after 150 Ms, we can barely find any black holes bigger than that until we reach black holes with millions of times the mass of our sun. This is quite fascinating, as if the knowledge we have now suggests that bigger black holes are formed through devouring and merging of other black holes. It is simply impossible for some of these black holes to even exist, as looking at the amount of time the universe existed, that is impossible for black holes of this mass to even form. In this paper, the detection method for black holes and black holes' mass and the formation model of ultra-massive black holes will be discussed, which involves concepts like Quasi Stars and Quasi Black holes. These results shed light for us to discover the formation of ultra-massive black holes.

Keywords: Ultra-massive black holes, detection methods, formation of black holes.

1. Introduction

Ultra-Massive black holes are also known as the largest single body in the entire universe. It is stated that Ultra-Massive black holes are formed by merging supermassive black holes, where supermassive black holes are formed by Quasi-black holes [1]. Scholars believe that supermassive black holes are a power source of active galaxy nuclei and quasars, which we are only able to track quasars when they have reached very high redshifts by observation [2]. Supermassive black holes form as early as the early cosmic times, and recent discoveries of quasars support this theory at redshifts supported by supermassive black holes as a power source by the accretion of surrounding gas [3]. Although this is still a theory and no observation has been made, this is the only way to scientifically explain the existence of Ultra-Massive black holes through modelling and calculation. There are two ways for a black hole to form: one is when a star or a galactic nuclei collapse, the other is when a black hole forms at the early stages of the universe, which normally has masses of more than 10^{-5} g. Primordial black holes form when gravitation forces differentiate in different regions. If the average gravitational force is small, the



force will still be large in one region, which will cause the star to collapse due to the expansion velocity and overcoming the star's pressure [4].

Ultra-Massive black holes range between 10 billion M_s to 50 billion M_s , where M_s is the black hole's mass in relation to our sun. Ultra-Massive black holes can be observed in the center of huge elliptical galaxies, and a famous Ultra-Massive black hole is a black hole 3.5 billion light-years away from earth. OJ 287, an Ultra-Massive black hole with a stunning mass of 18 billion M_s , lies in the constellation Cancer. It is red shifting by about 0.306. The black hole is so dense that its gravity engines a quasi-disc, bursting out light about the same amount every single star in the milky way emitted in the last 4300 years, giving the black hole an apparent magnitude of 15.43. This black hole is so massive that a supermassive black hole, with around 40 times the mass of our black hole in the center of the milky way 'Sagittarius a', orbiting it [5].

This black hole was first observed in 1891. Still, no calculations were made until 2004, where a team led by Mauri Valtonen observed and calculated the mass using Einstein's principle of general relativity. The precession of the elliptical orbit was measured with the information about the Quasi outburst. The Schwarzschild Radius of the black hole is around 362AU, and a merge is expected to happen between the black hole OJ 287 and the black hole orbiting it in around 10,000 years [6].

In Detection and calculation methods, we will introduce 2 methods to detect black holes and calculate a Black hole's mass that has a flaw when utilized with black holes that have nothing orbiting around it. Following an example, black hole OJ 287 using the first detection method mentioned, looking at stars motion around the black hole due to gravity. Finally, possibilities and related models of the formation of Ultra-massive black holes.

2. Detection and Calculation Methods

Contemporarily, there are 2 ways to detect black holes, and the first way is by looking at stars' motion around the black hole due to its gravity. The second way is by detecting the X-ray emitted by the black hole. By looking at the Stars' motion, we can detect a black hole. A good example would be our milky way, where stars can be seen circling a seemingly empty spot, as well as that's where the black hole is. The chart also demonstrates this earlier, showing the stars observed and the black hole itself. Another way of detecting a black hole is through X-ray, where surrounding materials like gas are funneled by gravity into the disc around the black hole, also known as an accretion disc. The molecules in the disc swirl around the black hole extremely fast to the point where they heat up and emit X-rays. An X-ray can then be detected from Earth, pinpointing the position of the black holes. Something worth noting is that we can also physically observe black holes by looking at their accretion disc since they light up after being heated up by their motion. A relevant example will be the black hole picture taken of the Super-black hole Messier 87 back in 2019.

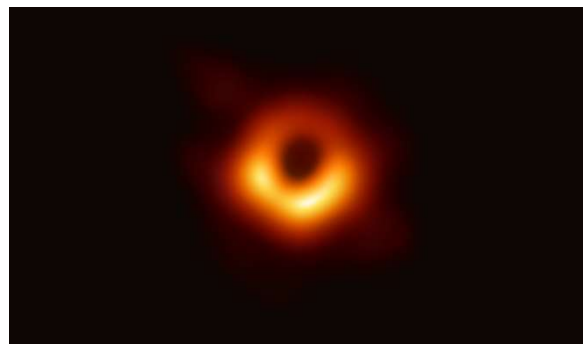


Figure 1. A black hole picture was taken of the super-black hole Messier 87, Apr 10, 2019 [7].

Calculation of a black hole's mass, on the other hand, is fairly straightforward. It involves Kepler's law and another Object that is orbiting the black hole. However, this method does not work for a black

hole with nothing orbiting around it. Although finding a lonely black hole is nearly impossible considering what we have said about the detection of the black hole, considering if there isn't anything orbiting the black hole, the black hole would not be able to reveal its presence in the first place. The first law states that both the star and the black hole move along elliptic orbits around a common point, also known as the centre of mass between the two objects. The third law states that the ratio of the semi-major axis of the orbit to the power of 3 and the orbital time to the power of 2 is constant. The constant is the sum of the two masses times by a numerical factor. Since we can measure the orbital time easily, we can express the average separation of the two objects as a function of the unknown masses. We can also work out the centre of mass, and at each point, the ratio of the distance from the centre of mass to each of the objects is the same as the ratio of their masses. One part that may need to be noticed is the orbital inclination, inferred from the temporal variations in the light curves. Thus, we can calculate the mass of the black hole using the equation under after acquiring all information mentioned.

$$(m_1 + m_2)P^2 = (d_1 + d_2)^3 = R^3 \quad (1)$$

Note that $(d_1 + d_2)$ is the total distance from one of the orbiting objects to the other, where d_1 refers to the distance from object 1 to its centre of mass, and the same applies to d_2 . P in this equation is the orbital period of the object we are observing, and m_1, m_2 each stands for the mass of each object.

3. Detection and calculation of OJ 287

Detection of the black hole OJ 287 is done using the first method we have mentioned, which includes the observation and data acquiring of the stars around this black hole. In 1891, the scientist observed 5 different stars around the black hole, each being Star 4 [4], Star 10, Star 11, Star C1, and Star C2. These stars are taken into this investigation since scientists have noticed them orbiting an area where nothing appears to be there, so data are taken from these stars and calculated, for example, their apparent absolute magnitude, inclination, orbital distance, and orbital period to determine the exact position of the black hole OJ 287 and its existence (as illustrated in Fig. 2).

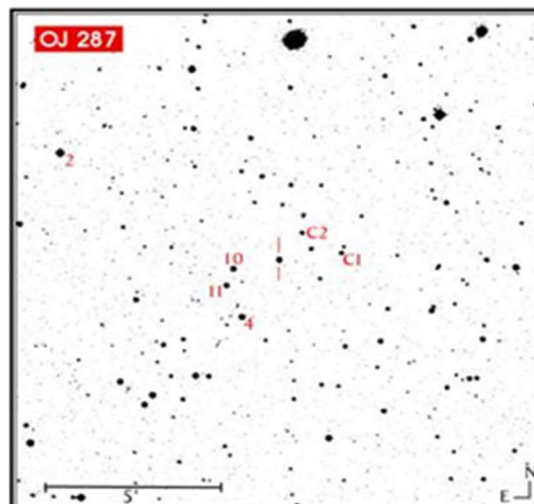


Figure 2. Finding chart and comparison stars calibration [8]

According to the results, OJ 287, which is in the centre of this chart field, also emits light. This is attributed to the accretion disc, also called the quasi disc with black holes this massive emitting light and radiation. OJ 287, in this case, consumes the particles and elements around itself, but some gasses are not drawn into the event horizon. Instead, they start orbiting the black hole at an extremely fast speed, heating and lighting up, cause a burst of light and x-ray. Despite this black hole can be seen due to its quasi disc and giving us an apparent magnitude, it is still better that we only recognize the black hole's

existence after taking in data of the stars orbiting it since there are a lot of objects within the cosmos that can light up and emits radiation. The chart of the data taken at the end goes by the following Table. 1.

Table. 1 Optical-near-IR photometry of comparison stars [8].

Star	U	B	V	R	I	J	H	K
4	15.49	15.01	14.18	13.74	13.28	12.647	12.206	12.114
10	15.00	15.01	14.60	14.34	14.03	13.612	13.325	13.256
11	15.39	15.47	14.94	14.65	14.32	13.889	13.568	13.521
C1	15.88	15.5	15.08	...	14.377	13.782
C2	16.12	15.66	15.21	14.474	14.045	14.023

Out of these 5 planets, close observation was made on Stars 4, 10 and 11 since they are much closer to the black hole compared to star C1, C2, where all three Stars mentioned before has an orbital radius of less than 15 AU compared to the other two where one has an orbital radius of 15.88 AU. The other has an orbital radius of 16.12 AU. Star 4 was then taken to calculate the mass of OJ 287 since although it only has an absolute magnitude of 14.18, it's got the smallest inclination of only 13.28.

Despite us mentioning a method to calculate the mass of a black hole, the mass calculated for black hole OJ 287 uses the general rule of relativity in 2008 during the calculation led by Mauri Valtonen. The timing of the outburst of the two black holes allowed the precession of the companion orbit to be measured, which allows the mass of the central black hole to be calculated using Einstein's General Rule of Relativity. Interestingly, the timing of the outburst also provides a test of the black hole's no-hair theorem, which has been consistent so far with the results.

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi}{c^4}T_{\mu\nu} \quad (2)$$

The first part of the equation $R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R$ describe the mathematical expression of the curvature of time and space, wherein this equation $R_{\mu\nu}$ is the ricci tensor R is the scale of the curvature and $g_{\mu\nu}$ is the matric on space-time. The second part of the equation $\frac{8\pi G}{c^4}T_{\mu\nu}$ described the energy and mass also momentum since what we have studied about special relativity shows that mass and energy are the two sides of the same coin, it shows that mass is not the only source of gravity. Still, it's more about the energy around an object in general, this is shown by the symbol $T_{\mu\nu}$. After this calculation, Mauri Valtonen's group came out with an unimaginable number for humans at that time, where the black hole has a stunning 18.35 billion M_s with a radius of 362 AU. Till this day, this is the biggest black hole human has yet to discover.

4. Formation of Ultra-massive black holes

With everything that has already been said, a question is raised amongst many, since the time that the universe has existed simply does not allow the formation of black holes with such size, how are Ultra-massive black holes formed? First, let's look at the formation model of a normal black hole (as shown in Fig. 3).

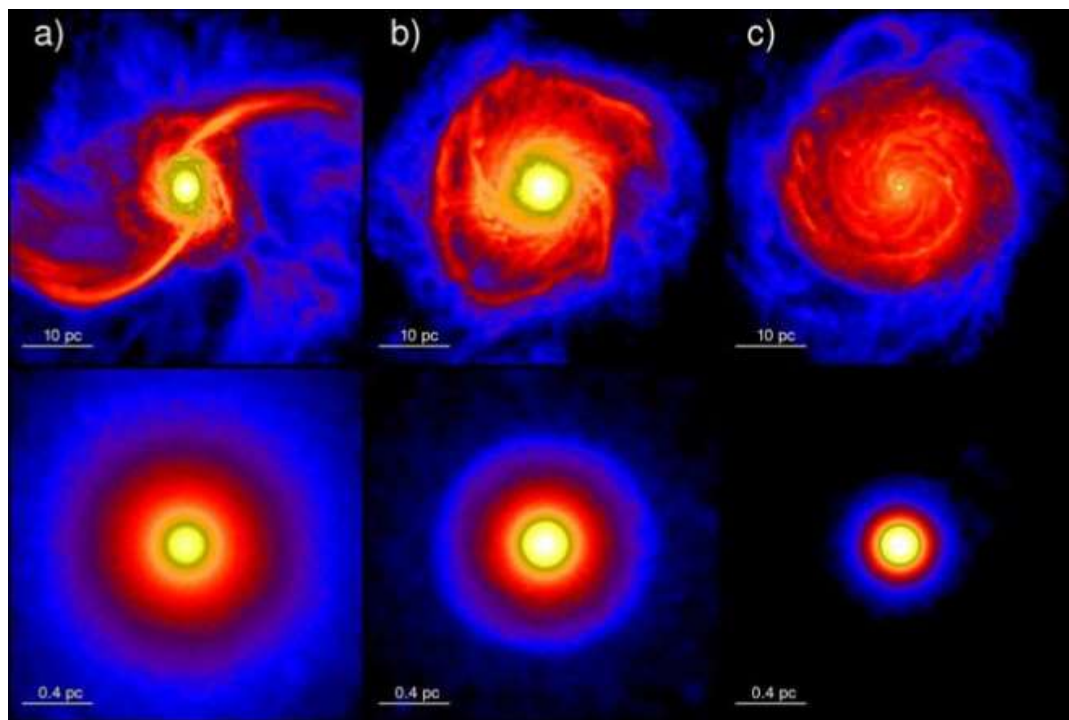


Figure 3. Formation model of a normal black hole [9]

The formation model above shows the increasing size of one black hole due to a black hole merge. We can suggest and go back to a knowledge that is already known to us: black holes can only increase in size by devouring particles or merging with another black hole. Nevertheless, this rule does not apply when we get to Super-massive black holes and Ultra-massive black holes. As mentioned, the existence time of the universe is simply not enough for that many stellar black holes to merge into super black holes. Therefore, a proposed theory involves quasi stars, quasi black holes, and how they would supercharge a black hole development, as displayed in Fig. 4.

The idea is that throughout the early years of our universe, matters were so dense that some of these stars could grow to thousands of times the mass of our sun. These stars are so dense to a point where their weight might have crushed the core of these Quasi-stars and collapsed into a black hole while the star was still forming. If this happens today, 99 percent of stars with their mass known to us would instantly collapse into a bright supernova explosion. Whereas a deadly balance was formed within these quasi stars, gravity press the supermassive star together, feeding the black hole and heating the material falling into it to a point where the radiation pressure emitted by the star kept the star stable. The black holes inside these quasi stars can consume the quasi star for millions of years and grow far bigger and denser than any known modern stellar black hole. These black holes are called Quasi black holes, and with studies so far, are the most likely candidate to be the seeds of Super-massive black holes, which are the seeds for Ultra-massive black holes.

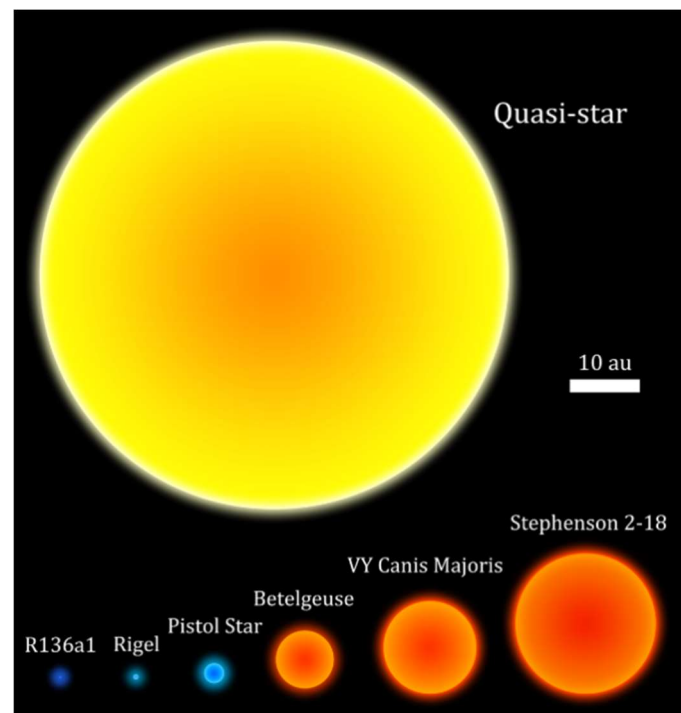


Figure 4. comparison between Quasi Star with the largest existing star today [10]

5. Conclusion

In summary, it is impossible for large ultra-massive black holes to even exist as looking at the amount of time the universe existed, i.e., it is not possible for black holes of this mass to even form. Based on the analysis, we demonstrate the detection method for black holes and black holes' mass and the formation model of ultra-massive black holes, which involves concepts like Quasi Stars and Quasi Black holes. One can detect black holes by looking at stars' motion around the black hole due to its gravity and by detecting the X-ray emitted by the black hole. The final hypothesis for forming ultra-massive black holes is that the stars were so dense that the cores of quasi-stars might have been crushed by their weight while the star was still forming and collapsed into a black hole throughout the early days of our universe. These results offer a guideline for discovering Ultra-massive black holes and Super-massive black holes that humans have not yet found of the cause of their formation with modern technology.

References

- [1] Hurt, R. "Sizes of Black Holes in Galaxy OJ 287 Relative to the Solar System." Sizes of Black Holes in Galaxy Oj 287 Relative to the Solar System, NASA/JPL/Caltech/Ipec, www.spitzer.caltech.edu/image/ssc2020-11b-sizes-of-black-holes-in-galaxy-oj-287-relative-to-the-solar-system.
- [2] Bromm, Volker, and Abraham Loeb. "FORMATION OF THE FIRST SUPERMASSIVE BLACK HOLES." The Astrophysical Journal, vol. 13, no. The American Astronomical society, ser. 596:34-46, 10 Oct. 2003, pp. 34-46. 596:34-46.
- [3] Carr, B. f., and S. W. Hawking. "BLACK HOLES IN THE EARLY UNIVERSE." Mon. Not. R. Astr. Soc., vol. 17, no. (1974), ser. 169, 25 Feb. 25AD, pp. 399-415. 169.
- [4] Volonteri, M. "FORMATION OF THE FIRST NUCLEAR CLUSTERS AND MASSIVE BLACK HOLES AT HIGH REDSHIFT." The Astrophysical Journal, vol. 12, no. The American Astronomical Society, ser. 694:302-313, 20 Mar. 2009, pp. 302-313. 694:302-313.
- [5] Sillanpaa, A., et al. "OJ 287: BINARY Pair of Supermassive Black Holes." NASA/ADS, Astrophysical Journal V.325, P.628, Feb. 1988, ui.adsabs.harvard.edu/abs/1988ApJ...325.628S/abstract.

- [6] Mitra, Abhas, and K. K. Singh. "THE MASS OF THE OPPENHEIMER–SNYDER-BLACK HOLE: ONLY FINITE MASS QUASI-BLACK HOLES." *International Journal of Modern Physics D*, vol. 22, no. 9, ser. 1350054, 11 June 2013, pp. 1350054–1-1350054–18. 1350054, doi:10.1142/S0218271813500545.
- [7] Ciprini, S. OJ 287, www.astro.utu.fi/OJ287MMVI/OJ287findchart.htm.
- [8] Event Horizon Telescope collaboration et al. Black Hole Image Makes History; NASA Telescopes Coordinated Observations, National Aeronautics and Space Administration, 10 Apr. 2019, www.nasa.gov/mission_pages/chandra/news/black-hole-image-makes-history.
- [9] McNally, Jess. Supermassive Black Holes Formed by Colliding Primordial Galaxies, 25 Aug. 2010, www.wired.com/2010/08/massive-black-hole-origin/.
- [10] Náhl'adu, Veľkost' tohto. "Quasi-Star Size Comparison." *Archivo: Quasi-Star Size Comparison.png*, Sauropodomorph, 2016, es.m.wikipedia.org/wiki/Archivo:Quasi-star_size_comparison.png.