HIGH SCHOOL EDITION
Journal of Student Research
Volume 11 Issue 3 (2022)

What Causes the Active Galactic Nuclei of Quasars during the Quasar Epoch to be so Luminous?

Amaliya Atamalibekova[1] and Sanah Bhimani[#]

[1]Thornton Donovan School, New Rochelle, NY, USA
[#]Advisor

ABSTRACT

The brightest quasars were born 10 billion years ago during the Quasar Epoch. These quasars were bigger and brighter than any of the quasars formed after, and this paper seeks to find out why. Quasars are a type of Active Galactic Nucleus, which is a compact center of a galaxy. The type of galaxy that contains the Active Galactic Nucleus plays an important part in their luminosity, as elliptical galaxies have much brighter Active Galactic Nuclei than spiral galaxies. The reason that Active Galactic Nuclei form in galaxies is because galaxies contain supermassive black holes, since only supermassive black holes may contain an Active Galactic Nucleus. The stars and gas clouds present in galaxies make a bigger accretion disc. This was happening at a large rate during the Quasar Epoch as opposed to now.

Introduction

In the early universe, about 10 billion years ago (10Gyr), stellar formation occurred 10 times more than its current rate (1). As more stars formed and gathered mass, they reached an upper limit which caused them to go supernova. Because this period of stellar formation led to a high rate of stellar astrophysical mechanics, the rate of supernova explosions was also high, occuring once every 600 years in each galactic nebula. (2). This period of stellar formation started a period of time in the Universe known as the Quasar Epoch (3).

Quasi-stellar objects, more commonly known as quasars, are one of the most luminous phenomena in the known universe (3). They are a type of Active Galactic Nucleus (AGN) —an extremely luminous compact center of an active galaxy, and the family name for any supermassive black hole (SMBH) powered by an accretion disc (4). An accretion disc is a cluster of gas particles made from stellar matter that circles in a disklike manner around the SMBH. In fact, quasars can only form from SMBHs with an AGN. (5). The quasars that formed during the Quasar Epoch are the most luminous quasars in existence, and this paper will look into exploring reasons behind that phenomenon. In order to study this, however, it is important to understand more quasars and AGNs.

The size and brightness of a quasar depends on the mass of the black hole in the center of the galaxy, the rate of the gas accretion, the orientation of the accretion disc, the obscuration of the nucleus (how visible that nucleus is), and the presence or absence of jets at the poles (6).

Although all quasars are a type of AGN, not all SMBHs that have an AGN are quasars. In order for a SMBH to form, it must be at least 10 solar masses. Supermassive black holes are more than a million solar masses (7) It is impossible to calculate the age of a SMBH, but it is possible to find the age of the galaxy surrounding it, since the age of the galaxy correlates to the mass of the SMBH (7). The age of the galaxy in respect to the mass can be calculated using the following equation, where Mbh is the mass of the black hole, Msph is the spheroidal component of the host galaxy of the black hole, and Gyr is giga-years (7).

$$\log \frac{M_{BH}}{Msph} = \log \frac{M_{BH}}{Msph} - \log \frac{t}{10Gyr} \quad (1)$$

While spiral galaxies can be active, they are not strong enough to contain a quasar. Seyfert galaxies are an example of an active spiral galaxy, as they also are very luminous and contain AGN, however they are just not luminous enough to be considered quasars (6). Elliptical galaxies are some of the oldest galaxies in the universe, lack the spiraling hands that spiral galaxies, such as our Milky Way, have, and only they can contain quasars (8).

Quasars

During the Quasar Epoch, it was extremely easy for quasars to form because of the abundance of stardust and black holes, and this meant an abundance of AGN with accretion discs (8). The quasars formed during that time are the oldest ones, some of the brightest, and they emit the most energy from their poles in the form of jets. Only 10% of all existing quasars emit jets, a majority of which are quasars formed during the Quasar Epoch (8).

There are different types of quasars, those being radio loud and radio quiet quasars, the latter being more common. About 10 percent of the quasars that we know are radio loud (8). Radio loud quasars have extremely bright and powerful beams of light from their poles (8).

The jets from the radio loud quasars are radio, optical, and X-ray synchrotron-emitting plasma jets. This is only possible for AGN with elliptical galaxy hosts (8). These jets, along with the mass of the black hole, the rate of gas accretion (how much gas is circling the black hole and how fast it accumulates), the orientation of the accretion disc itself, and the obscuration of the nucleus (how hard it is to see) are all ways that quasars get classified (6).

Quasars themselves were officially discovered in 1963, but we have been aware of their presence since the 1950s. Since then, we have discovered more than a million quasars (3). In fact, we are constantly finding more and more of them, which is why the most distant quasar from us keeps changing. As of March 2021, the title of the most distant known radio-loud quasar belongs to PSO J172.3556+18.7734. It has a red-shift of 6.82! (3).

Red-shift is the wavelength of radiation that we are able to capture (9). These wavelengths have been moving since the beginning of the universe, the longer they have been traveling, the redder the line appears on the spectrum. This means that the frequency of the wave is bigger, and it travels slower (9). The redshift of today is 0, and any redshift greater than 0 is further back in history.

Upon calculating redshift, the variable z is used to show the number of years it has taken for light to travel to us. It is calculated using $\lambda_{observed}$ to show the observed wavelength, and using λ_{rest} to show the wavelength if the source was not in motion. The equation to calculate z is

$$z = \frac{(\lambda_{observed} - \lambda_{rest})}{\lambda_{rest}} \tag{2}$$

(9).

Black Holes

Accretion discs

Because there were so many AGN during the Quasar Epoch, and because they were able to get so big, sometimes some parts of an accretion disc got sucked into a black hole. Most of it, however, never reached the event horizon (6). The event horizon of a black hole is the point beyond which light can no longer escape, i.e. In simpler terms, this is the point of no return. The event horizon can be calculated using with the help of the Schwarzschild Radius equationformula, which was named after Karl Schwarzschild (10). The equation is

$$r = \frac{2GM}{c^2} \qquad (3)$$

where r is the event horizon of the black hole/radius of the black hole, G is the gravitational constant, M is the object mass, and c is the speed of light (10).

The size of a black hole directly relates to its former size as a star. Its radius is 2 times its mass, and the radius is simply the radius of the event horizon, for which the calculation was shown earlier in this paper (10).

There are several requirements for a quasar to form. When a black hole becomes more than 0.1 million solar masses, it becomes classified as a SMBH, and begins to consume more of the stars around it. The stars are not immediately swallowed, but they are slowly torn apart by the SMBH. The stellar matter which escapes the event horizon circles around the SMBH and creates an accretion disc. It is so fast, and produces so much energy, that it is 1,000 times lighter than the entire Milky Way! (8).

Supermassive Black Holes

AGN is the family name for any supermassive black hole with an accretion disc (4). Stellar mass black holes are black holes that weigh several tens of the masses of the sun, however they are nowhere near big enough to have an accretion disc. (4) These black holes are relatively young, however. SMBH are much older than other types of black holes in the universe.

Most stars are in binaries, which means there are two stars orbiting one another. (4) After the first star goes supernova, the second star may also be at the end of its life. If that second star becomes a black hole, the stellar system becomes a binary black hole system. (4) The remains from the supernova of the first star will then turn into an accretion disc, and the black hole will become an AGN, and if it is powerful enough, it will become a quasar (4).

Supermassive black holes are still largely a mystery to astrophysicists. For a long time, people only theorized their existence, until it was proved by Maarten Schmidt in 1963 (11). In modern times, there is direct evidence for the existence of SMBH by observing objects orbiting the SMBH. Their extremely high orbital velocities are explained by the fact that they are orbiting an extremely massive object – that object being the SMBH (12).

While it is widely known that stellar black holes form from collapsed stars, it is still largely a mystery how supermassive black holes form, however there are several theories. These include that perhaps they formed from collapsed huge clouds of gas, which were abundant in the early universe (12). Another theory is that the older the SMBH, the more stellar material it was able to collect, and the bigger it became. Others say that when clusters of black holes merge, they create a SMBH. What is known for sure, however, is that the older the SMBH, the bigger it is (12).

Galaxies Which Contain Quasars

During the early universe, the temperature was much hotter than it is now. As the universe expands, its temperature drops (13). The temperature of the universe can be calculated by measuring the cosmic microwave radiation waves. The cosmic microwave background (CMB) is the electromagnetic radiation which remains from when the universe was created (13). The equation for calculating this is

$$T_{CMB}(z) = T_o(1 + z) \qquad (4)$$

T_{CMB} is the temperature of the CMB, T_o is the average temperature of the CMB, which is equivalent to (2.726 ± 0.001)K. As mentioned before, z is the redshift (14).

The temperature of the universe is related to galaxy formation because galaxy formation requires a two-body radiative process where photons are released because of two-body interactions (15). A two-body radiative process is the release of energy in the form of electromagnetic radiation (16). The cooling of the universe is what causes the changes in the atoms which begins the release of photons (15). The different processes create different types of galaxies.

The type of the galaxy has an effect on the formation of the quasars. In an inactive galaxy, most of the luminosity of it would come from stars. In an active galaxy, however, most of the light comes from the AGN (17). Also, the light is distributed evenly in an inactive galaxy, however, in an active galaxy, the AGN outshines all of the stars in it by a factor of 100 (8). This is the measure of the brightness of objects, also known as magnitude. The magnitude uses the factor of the fifth root of 100 to calculate the brightness of an object. Our sun has a magnitude of -27, and Sirius, the brightest star which we can see, has a magnitude of -1.46 (18).

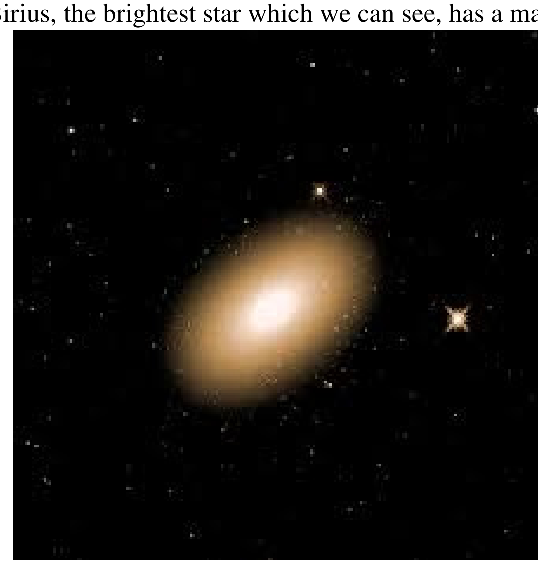

Figure 1. An example of an elliptical galaxy: Markarian 1216 (Credit: NASA).

Figure 2. An example of a spiral galaxy: NGC 1232 (Credit: NASA).

In some active galaxies, the AGN may fire up from time to time, but it would not be as powerful as a quasar. Those types of galaxies are known as Seyfert Galaxies, and they are much more common than galaxies with quasars in them.

Seyfert galaxies are anywhere from 0.1 to 10 times more luminous than the Milky Way (17). They make up 2 percent of all spiral galaxies. Their accretion discs are less than a light month wide, and that means that they have a lot of energy coming out from a very small space. Other than this, they look no different from other spiral galaxies (17).

Whether a galaxy is active or not depends on several factors. While both spiral and elliptical galaxies are capable of being active, the active spiral galaxies emit much less energy than elliptical galaxies (17). This is because spiral galaxies tend to spread out like discs, while stars in elliptical galaxies wrap around the galaxy's center. This allows the SMBH in the middle of an elliptical galaxy to obtain a bigger accretion disc that spins faster (17).

The Active Galactic Nuclei

History of AGN

In the beginning of the 20th century, there were many optical discoveries that led to radio work being done in the 1950s. The astrophysicists of that time's goal was to test how spiral galaxies show a spectrum that is consistent with the stars, and different from the characteristics of gaseous nebulae. This led them to the discovery of NGC 1068, also known as the Messier galaxy (19).

In 1913, a scientist named Vesto Slipher was able to confirm the spectra of galaxies by showing the spectrum of the Messier galaxy (19). Carl Seyfert wrote a paper that confirmed this, and because of that galaxies with high nuclear emission lines became known as "Seyfert galaxies." Although his paper was accepted in the field, AGN were still not studied fully (19).

In the 1950s, it became much easier to measure the emissions of galaxies because of radio surveys. A survey taken by M. Ryle, F.G. Smith, and B. Elsmore showed some points in the sky that had unnaturally high emissions, even though they seemed like tiny spots (19).

Thanks to this, Hermann Minkowski was able to identify the galaxy 3C 295 with a redshift of 0.46. This was so because the galaxy was an active one. Soon after, on February 5, 1963, quasar 3C 273 became known as the very first quasar. Soon after, many papers were written about the redshift of active galaxies containing AGN, and they were finally being studied (19).

Luminosity of AGN

Thanks to radio astronomy, we were able to investigate and better understand what AGN are and how they work. The concept of AGN was introduced by Viktor Ambartsumian in 1950, almost a decade before quasars were officially discovered (6).

AGN are powered by the accretion of mass in the black hole. The faster the accretion disc spins, the more energy it produces, and the brighter it burns. This idea was introduced by Edwin Salpeter and Yakov Zeldovich in 1964. This was the time when quasars became a major focus for astrophysicists (6).

As mentioned at the beginning of the paper, the most luminous AGN have been found during the Quasar Epoch. This is, in part, due to the fact that the bigger the SMBH is, the brighter the quasar (20). The Quasar Epoch was relatively close to the beginning of the universe, and therefore the black holes during that time were much larger than any black holes formed in the modern universe (20).

The oldest known quasar to us, P172+18 (21), is around 12 billion years old. It existed during the Quasar Epoch, and it has a magnitude of 20.9. The luminosity of a quasar created after the Quasar Epoch, however, such as Markarian 231, is only 11.02 (22). While this is still extremely bright, it is very clear that P172+18 is much brighter.

Conclusion

The most luminous quasars formed during the Quasar Epoch. This paper's purpose was to find the reason why. It went over types of active galaxies, types of black holes, Active quasars, and Active Galactic nuclei. The luminosity of an AGN depended on all of those things, most specifically the type of galaxy that it was in, the size of the black hole at the center of the galaxy, and if it was a quasar or not.

Having all that information taken into account, we can infer that the older quasars are more luminous than the younger ones. We may also infer that the older SMBH are bigger than the more recent SMBH, and we know the connection between the size of the SMBH, it’s accretion disc, and quasar. Since the accretion discs, and SMBH were bigger during the time of the Quasar Epoch, the quasars were brighter. Now that the SMBH are not as big, and since there is not as much gas, the quasars are smaller and less bright than their ancestors.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

References

(1) French DK. Evolution Through the Post-Starburst Phase: Using Post-Starburst Galaxies as Laboratories for Understanding the Processes that Drive Galaxy Evolution. ArXiv, 2106.05982, 2021.

(2) Melinder J, Dahlen T, Trinchant LM, ¨Ostlin G, Mattila S, Sollerman J, Fransson C, Hayes M, Kankare E, Nasoudi-Shoar S. The rate of supernovae at redshift 0.1-1.0 – the Stockholm VIMOS Supernova Survey IV. ArXiv, 1206.6897, 2012.

(3) Schmidt M, Schneider D, Gunn J. Spectroscopic CCD Surveys for Quasars at Large Redshift. IV. Evolution of the Luminosity Function from Quasars Detected by Their Lyman-Alpha Emission. The Astronomical Journal, doi:10.1086/117497, 1995.

(4) Latif MA, Khochfar S, Whalen D. The Birth of Binary Direct-Collapse Black Holes. ArXiv, 2002.00983, 2020.

(5) Cattaneo A. Quasars and galaxy formation. ArXiv, 9907335, 1999.

(6) Chiaberge M, Capetti A, Celotti A. Understanding the nature of FR II optical nuclei: a new diagnostic plane for radio galaxies. ArXiv, 0207654, 2002.

(7) Merrifield MR, Forbes DA, Terlevich AI. The black hole mass-galaxy age relation. Monthly Notices of the Royal Astronomical Society, doi:10.1046, 2000.

(8) Antonucci R. Active Galactic Nuclei and Quasars: Why Still a Puzzle after 50 years? ArXiv, 1501.02001, 2015.

(9) Bengochea GR. What do we talk about when we speak of cosmological redshift? ArXiv, 1802.02444, 2018.

(10) Gaztanaga E. The Cosmological Constant as Event Horizon. ArXiv, 2202.00641, 2022.

(11) Kellermann KI. The Road to Quasars. ArXiv, 1412.7867, 2014.

(12) Haemmerl é L, Mayer L, Klessen RS, Hosokawa T, Madau P, Bromm V. Formation of the first stars and black holes. ArXiv, 2003.10533, 2020.

(13) Wands D, Piattella OF, Casarini L. Physics of the Cosmic Microwave Background Radiation. ArXiv, 1504.06335, 2015.

(14) Chluba J. Tests of the CMB temperature–redshift relation, CMB spectral distortions and why adiabatic photon production is hard. Monthly Notices of the Astronomical Society, doi:10.1093, 2014.

(15) Nagai D. THE IMPACT OF GALAXY FORMATION ON THE SUNYAEV-ZELDOVICH EFFECT OF GALAXY CLUSTERS. ArXiv, 0512208, 2006.

(16) Rouan D. Radiative Processes. In: Gargaud M. et al. (eds) Encyclopedia of Astrobiology, doi:10.1007, 2011.

(17) Colbert EJM, Mushotzky RF. COMPACT X-RAY SOURCES IN NEARBY GALAXY NUCLEI. ArXiv, 9809150, 1998.

(18) Bond HE, Schaefer GH, Gilliland RL, Holberg JB, Mason BD, Lindenblad IW, Seitz-McLeese M, Arnett WD, Demarque P, Spada F, Young PA, Barstow MA, Burleigh MR, Gudehus D. The Sirius System and its Astrophysical Puzzles: Hubble Space Telescope and Ground-Based Astrometry. ArXiv, 1703.10625, 2017.
(19) Shields GA. A Brief History of AGN. ArXiv, 9903401, 1999.

(20) The Correlation between Black Hole Mass and Stellar Mass for Classical Bulges and the Cores of Ellipticals. ArXiv, 2011.07216, 2020.

(21) Ba ñados E, Mazzucchelli C, Momjian E, Eilers A, Wang F, Schindler J, Connor T, Andika IT, Barth AJ, Carilli C, Davies FB, Decarli R, Fan X, Farina EP, Hennawi JF, Pensabene A, Stern D, Venemans BP, Wenzl L, Yang J. The discovery of a highly accreting, radio-loud quasar at z = 6.82. ArXiv, 2103.03295, 2021.

(22) Low FJ, Schneider G. High Spatial Resolution HST/NICMOS Observations of Markarian 231. ArXiv, 0407406, 2004.