Personal Section

I have always been naturally inclined towards mathematics and science, but a field as foreign as astrophysics seemed like a topic that I would never explore. It wasn't until the spring of 2013 when I was introduced to the Science Internship Program at UC Santa Cruz, a program that primarily offers astrophysics internships, that I took interest in the topic. Instead of being turned away by the unknown world of outer space, I took it as an opportunity to take a chance and learn something new.

I was placed under the mentorship of Dr. Jonathan Trump, and I found out my project would be researching quasars, the extremely bright nuclei of some active galaxies, and their scattered light. I calculated the effect of this scattered light on the overall brightness of the galaxy in order to see if the scattered light was affecting the results of past research on quasars and their host galaxies. I had absolutely no idea what a quasar or an active galaxy was. And although I can ramble about my project for longer than necessary, at that point in time, I had never taken a single physics class, so I felt ill equipped to take on an internship where a primary focus was physics.

That summer brought on its fair of challenges—in addition to my lack of physics knowledge, I also had no programming experience—which I found was an integral skill in astrophysics. But for every syntax error, there was an excited smile that appeared as I navigated my way through my problems and found success. As the summer went on, my project finally began to come together. I recalled math from both my basic algebra classes to my calculus classes; every complicated equation, colorful graph, and line of code culminated into research that mattered; I had created a novel method that combined both observational and simulation data to calculate the amount of scattered light in quasars. In the end, every dreaded syntax error and complex equation had worked together to bring a smile to my face when I ended my research. As I stood on stage presenting my research to professors, researchers, and fellow students, I realized the past summer had truly brought to life the frontier of possibilities that the combination of science and math can have.

My advice to future high school researchers would be to not be afraid of new topic areas. Even with a lack of experience, pursuing a field unknown to you can be incredibly rewarding, just like my astrophysics research. I would like to give special thanks to my mentor Dr. Jonathan Trump for providing support and guidance throughout this entire process; without him and his patience, I would not be where I am today, and I will be eternally grateful for this experience.

Research Section

1. Introduction

Supermassive black holes (SMBHs) are the largest type of black hole, and evidence suggests that they reside in every galaxy (Ho 2004). Most supermassive black holes are currently inactive and extremely weak, but some galaxies contain active supermassive black holes that are rapidly growing and accreting matter.

Past research has suggested that there is a relationship between a galaxy's black hole mass (BH) and its host galaxy's bulge mass. The galaxy bulge mass is the thick round, mature center of a galaxy that contains stars with a total mass approximately a thousand times the mass of the black hole. This relationship is known as the "BH-bulge" relation. Observation shows that the mass of the central black hole in a galaxy correlates with the mass of its host galaxy's bulge (Magorrian et al., 1998). A large bulge mass indicates a large black hole, and a small bulge mass indicates a small black hole. This relationship exists over four orders of magnitude, implying that the two must "know" about each other, posing the question of why and how a galaxy and its black hole grow together (Magorrian et al., 1998).

A center of an active black hole is called an active galactic nucleus (AGN); the most luminous AGNs are quasars (QSOs), which were first discovered in 1963 (Schmidt, 1963). Quasars are the most luminous and rapidly accreting SMBHs and are rare—only around 1% of galaxies contain quasars (Trump et al., 2013). QSOs are formed when supermassive black holes accrete matter, and when gas clouds collide with each other, high amounts of friction cause the black holes to emit high amounts energy, giving quasars their high luminosity and energy.

In a galaxy, when the light from a quasar bounces off of galaxy dust and gas, a "scattered light" problem is created, which interferes with both the study of QSO host galaxies and the investigation of why a galaxy and its black hole grow together. Originally, BH-bulge relations were thought to be formed because rapidly growing quasars caused feedback that quenches, or stops, star formation and keeps the bulge and black hole in a rigid lock-step growth (Silk & Rees, 1998; Di Matteo et al., 2005). If this were true, quasars should lie in quenching red or green galaxies. Instead, observation indicates that quasars lie in star-forming galaxies and that stronger quasars lie in galaxies that more rapidly form stars (Jahnke et al., 2004; Trump et al., 2013). This contradiction between theory and observation has proved to be puzzling, and one suspicion for why QSOs seem to lie in star-forming galaxies is the influence of large-scale scattering of quasar light. As a means of measuring scattered light, a novel approach of combining observations with simulations created the first systematic study of how quasar scattered light might impact the understanding of BH-bulge relations.

2. Data and Methods

2.1 Cosmology Basics

Because this study is concerned with distant galaxies, the following section will introduce a few basic cosmological concepts of the universe.

Redshift (z) is the measurement of how long wavelength has been stretched. As the universe expands and objects move further away from each other, light from other objects begins to look "stretched" because of the Doppler effect, and this is perceived as redder to the human eye. Redshift can be calculated using the following equation, where λ is wavelength.

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

(Equation 1)

An object's redshift is indicative of its age and distance. Because redshift is relative to the Earth, which has a redshift of 0, an object with high redshift is older and further away from Earth, while an object with low redshift is younger and physically closer to the Earth.

Other measures of distance related to redshift include comoving distance (DM), angular diameter distance (DA) and luminosity distance (DL). Comoving distance is the distance from Earth to an object based on its redshift, given by the equation below.

$$DM = \int_0^z \frac{dz'}{\sqrt{0.3(1+z)^3 + 0.7}}$$

(Equation 2)

The angular diameter distance of an object is the relationship between an object's comoving distance and its redshift, as shown in the equation below.

$$DA = \frac{DM}{1+z}$$

(Equation 3)

Angular diameter distance is used in order to account for the expansion of space. It is used to translate apparent angular size of an object to a physical size. For the purpose of this research, physical size is the radius of a galaxy, which is calculated by the following equation, where radius is r and theta (θ) is the apparent size of the radius in the inner aperture:

$$r = \theta(DA)$$

(Equation 4)

In order to calculate the radius of the inner aperture, it is assumed that theta (apparent radius size) is 1.5 arcseconds, which is typical of an average galaxy.

Luminosity distance is another measure of distance that is based on the luminosity of an object and its redshift. It can also be found from angular diameter distance (DA) and redshift (z), which is provided in the equation below.

$$DL = (1+z)^2 DA$$

(Equation 5)

2.2 Observational Data

2.2.1 Observational Data Overview

The observational data used were from the Sloan Digital Sky Survey (SDSS) Data Release Nine, which were collected by a 2.5-meter telescope at the Apache Point Observatory in New Mexico (York et al., 2000). The SDSS database contains spectroscopy that separates active galaxies from normal (inactive) galaxies. For each object, the SDSS provides photometric data in measures of magnitude (*m*), which is the measure of an object's apparent brightness. Magnitude is found as a logarithmic function of an object's flux (*F*), which is the amount of energy given off by an object.

$$m = -2.5\log(F)$$

(Equation 6)

The SDSS provides its photometric data in five filters: ultraviolet (*u*) at $\lambda = 3534 Å$, green (*g*) at $\lambda = 4770 Å$, red (*r*) at $\lambda = 6231 Å$, near infrared (*i*) at $\lambda = 7625 Å$, and infrared (*z*) at $\lambda = 9134 Å$. For each filter, the SDSS provides the total magnitude of a galaxy, as well as the magnitude of the inner and outer apertures of the galaxy. The inner aperture magnitude is the magnitude of the inner 3 arcseconds of the galaxy, while the outer aperture gives the magnitude beyond this 3-arcsecond diameter. Since quasar light dominates the inner aperture, astronomers research the outer aperture to examine QSO host galaxies; however, if there is a large problem of scattered light in the outer aperture, astronomers will come to incorrect conclusions.

The following equation calculates the luminosity of a quasar as a function of its flux (F) and its luminosity distance (DL).

$$L = DL^2 4\pi F$$

(Equation 7)

2.2.2 Data Selection Criteria

The first criterion for the galaxies selected is that both the active and inactive galaxies have a redshift between 0.04 and 0.05, meaning that the galaxies are relatively nearby. The galaxies selected have a magnitude brighter than 17.77 in the *r*-band filter because the SDSS does not detect objects fainter than this (York et al., 2000); this is important in distinguishing active and inactive galaxies because a quasar's spectroscopy has broad emission lines, while a normal galaxy does not. Below are images of a normal galaxy and an active galaxy along with their optical spectra—both provided by the SDSS database.

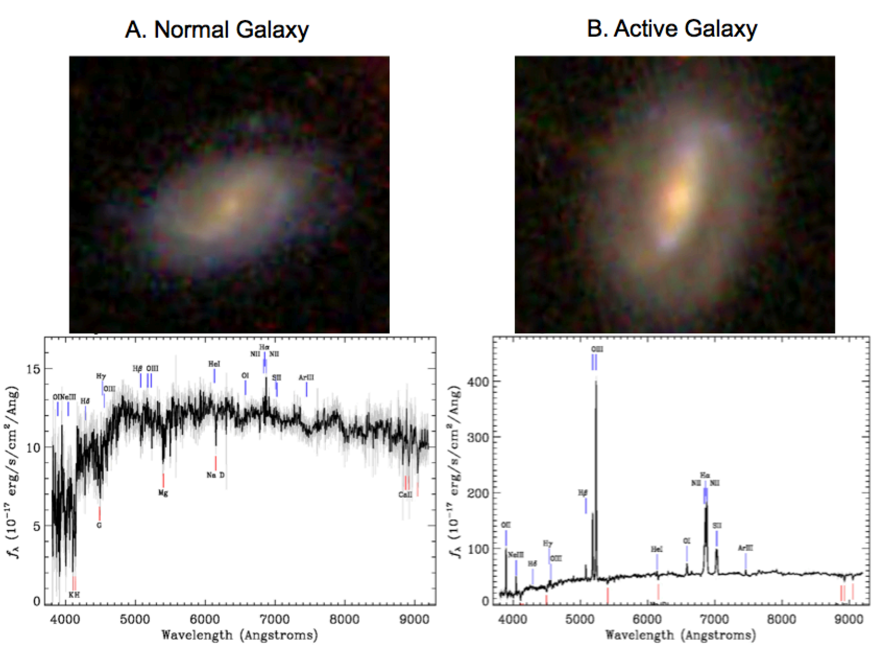

Figure 1.The figure above compares the images and optical spectra of a normal galaxy (A) and an active QSO-containing galaxy (B). While the emission spectrum is relatively constant for normal galaxies, an active galaxy has emission lines that dominate the spectrum. Active galaxies have a higher flux level than normal galaxies and are brighter because of QSO-contributed light.

In total, 31,296 inactive galaxies and 104 active galaxies were included in this research.

2.2.3 The Color-Mass Diagram

Color-mass diagrams are used as a basic schematic of the different types of galaxies in the universe, plotting a galaxy's color versus its mass. The color of a galaxy is the difference between two magnitudes of an object in different filters. The equation below calculates color, with m1 and m2 as the two different magnitudes.

$$m_1 - m_2 = -2.5\log\left(\frac{F_2}{F_1}\right)$$

(Equation 8)

Color can be determined either as a logarithmic function of the ratio of two fluxes or as a difference between two magnitudes. In this research, color was measured as the difference between the magnitudes in the ultraviolet and infrared filters (*u-z*). A lower *u-z* value indicates a blue object, whereas a high *u-z* value indicates a red object. The log of the mass of the galaxies (log(M*)) was also obtained from the SDSS database in order to create a color-mass diagram. The *y*-axis is color (*u-z*) and the *x*-axis is the log of the galaxy mass (log(M*)) in units of solar masses. All graphs were made with the Python programming language.

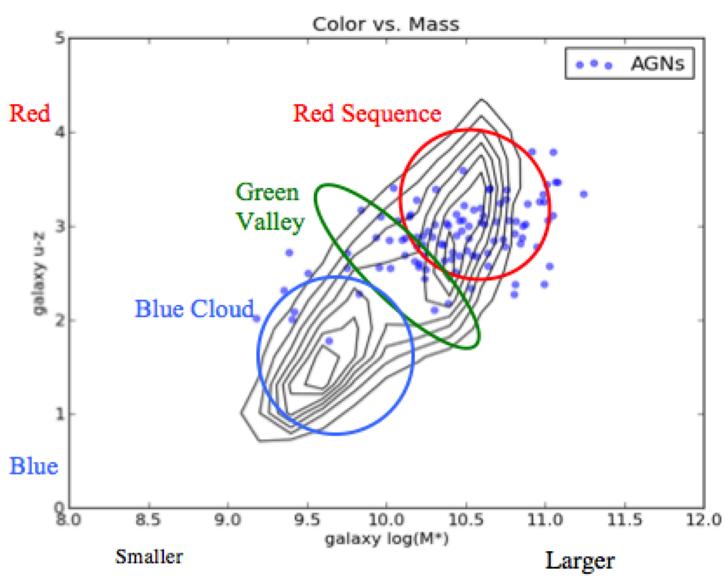

Figure 2. The inactive galaxies are plotted as contours while the active galaxies are plotted as the blue points. As the *u-z* value on the *y*-axis grows larger, this indicates a redder galaxy, and a lower *u-z* indicates a bluer galaxy; moving towards the right on the *x*-axis, the mass increases.

The color-mass diagram distinguishes galaxies in the blue cloud, green valley, and red sequence. The “blue cloud” consists of low mass, star-forming galaxies. The “red sequence” galaxies are older, bigger galaxies with a less rapid star formation rate than blue galaxies. The “green valley” is the stage between a galaxy’s evolution from the blue cloud to the red sequence.

2.3 Simulation Data

The goal of computer simulations is to attempt to understand the physics of the universe, which is done by recreating the entire universe starting from the Big Bang theory. By simulating the dark matter and energy that make up approximately 95% of the universe (Sánchez et al. 2012), simulations continue to add to the universe by including gravitational interactions and collisions of dark matter that surround normal galaxies. Stars and gas are then included, while aspects of physics—gravity, fluid dynamics, and friction—are included. The simulations used here are unique because they include the effects of radiative transfer—the emission and scattering of light—which allows for the measure of large-scale scattering from a quasar (Snyder et al., 2013). The SUNRISE program was used to create the images of the simulated galaxies, and the gravity and fluid dynamics were simulated using the GADGET code.

Two pairs of snapshots of a larger simulation were used. One pair had a very high-luminosity QSO, which is rare, while the other pair had a moderate-luminosity QSO, which is more common in galaxies. Each of the pairs contains one galaxy with scattered light, and one without. The snapshots shown below are of the high-luminosity QSO. The simulations used were provided by Snyder et al. (2013).

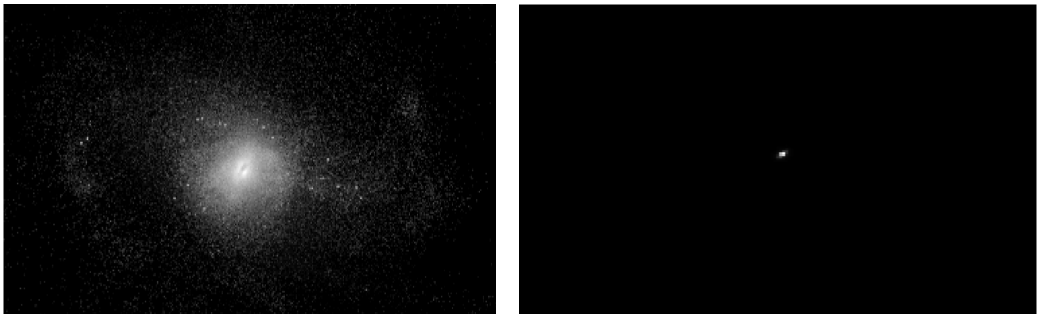

Figure 3.The simulation on the left is an AGN with scattering, while on the right is an AGN that has no scattering. The galaxy on the left looks more like a typical observed galaxy, while the galaxy on the right is a point source of light from the QSO, because there is no scattering.

3. Methods

3.1 Observational Data Analysis

3.1.1 Total Scattered Luminosity

Previous research uses the inner and outer apertures of a galaxy to distinguish galaxy light and QSO light (Trump et al., 2013). However this method can only be successful if scattered light is not a problem. The created analytical model calculates the potential scattered light contribution in the outer aperture, which in turn is used to study galaxy properties.

The following analytical model calculates the total amount of scattered luminosity and is based on the schematic shown below, which is based on a galaxy's radius (r) and its length (d).

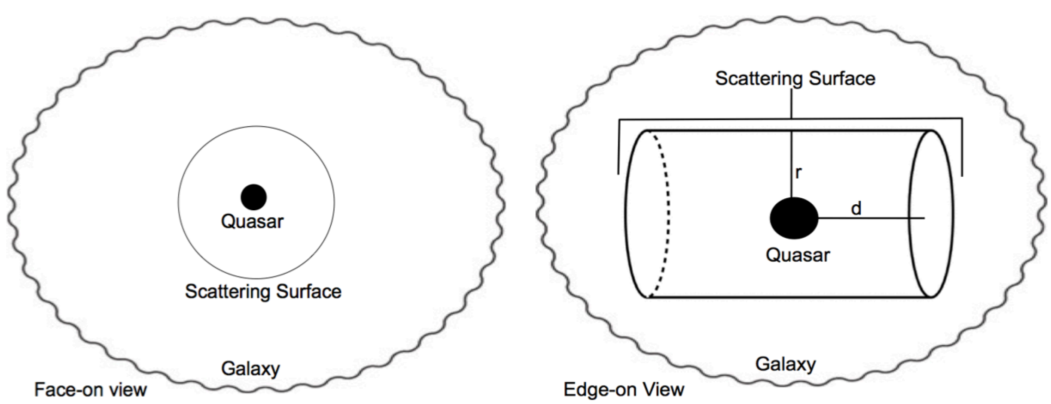

Figure 4.The figure on the left is the face-on view of a galaxy, and the figure on the right is the edge-on view of a galaxy. This model assumes that the scattering surface is a cylindrical shape that is based on the radius and the total length of the galaxy, representing a maximal scattering surface. When calculating the

scattered luminosity, it was assumed that the maximum d value was 10 kiloparsecs (kpc), a typical galaxy size, and the radius for each galaxy was found using Equation 4.

Based on Figure 4, the total amount of scattered luminosity is calculated by taking into account the size of the galaxy using the radius (r) and the length of the scattering surface in a galaxy (d), using the following integral.

$$L_{scatter} = \int_0^{d\max} \frac{L_{QSO}(r)}{r^2 + d^2} dd$$

(Equation 9)

Using Figure 4 as a basic schematic for the integral in Equation 9, scattered light was calculated by assuming that the scattering surface is a cylinder from which the quasar luminosity bounces off of; the analytical model shown is used to calculate the potential scattered light contribution in the outer aperture, which is used to find galaxy properties. This is considered a conservative estimate of scattered light because it was assumed that 10% of scattered light would reach Earth, when typically only 3% of scattered light is re-emitted in a single direction.

3.1.2 Change in Magnitude

Once the total scattered luminosity is found, the effect of this scattered luminosity can be quantified by calculating the change in magnitude (Δm), or change in brightness in a galaxy. As light scatters in the galaxy, it is expected that this extra light contamination would add to the galaxy light and change the overall brightness. This equation estimates the effect that scattered luminosity has on its host galaxy's overall magnitude.

$$\Delta m = -2.5 \log\left(\frac{F_{gal}}{F_{gal} - F_{scattered}}\right)$$

(Equation 10)

The equation above uses the flux of the galaxy (Fgal) and the flux of the scattered light(Fscattered) from the QSO to calculate the difference in magnitude between the flux of the galaxy with the scattered light and the flux of the galaxy with scattered light subtracted from it. Flux can be calculated using Equation 6. If the scattered flux was greater than the flux of the galaxy, the change in magnitude was set to -3, meaning that the QSO scattered light completely overpowered the galaxy light. A more negative change in magnitude indicates that the QSO's scattered light has a large impact on the galaxy's overall magnitude.

3.2 Simulation Analysis

After analyzing the SDSS data, the results were compared to an analysis of simulations. The flux of the galaxy was found by summing the flux of every pixel in the image. For the purpose of analysis, the flux of the galaxy was found in increments, using an "annulus" method. The flux was measured for the entire image at first, and for each interval the inner radius was slowly increased, which decreased the area for which the flux was being calculated in order to find the change in magnitude for every part of the galaxy. This method was applied to all simulations. The equation below uses the calculated flux to directly estimate the change in magnitude (Δm) caused by scattered light.

$$\Delta m = -2.5 \log\left(\frac{F_{scat}}{F_{noscat}}\right) \quad \text{(Equation 11)}$$

The equation above finds change in magnitude by using the flux from the simulation with scattering (Fscat) and the flux from the simulation without scattering (Fnoscat). The change in magnitude was calculated for every interval of the annulus that was calculated as described previously. Where the change in magnitude is greater than 0, the simulation without scattering is brighter, and where change in magnitude is less than 0, the simulation with scattering is brighter.

4. Results

4.1 Observational Data Results

One of the main objectives of the study is to see if in the observational data there was a correlation between the color of a galaxy and the total scattered luminosity from its quasar. An analytical model was developed to estimate the amount of scattered light from a quasar in its host galaxy. Below is the graph of a galaxy's color (*u-z*) on the *y*-axis versus the log of stellar mass (log(M*)) on the *x*-axis. The contours are the inactive galaxies, with the active galaxies plotted as points. On the left, the quasars are color-coded based on the log of their scattered luminosity, and on the right, the quasars are color-coded based on change in magnitude.

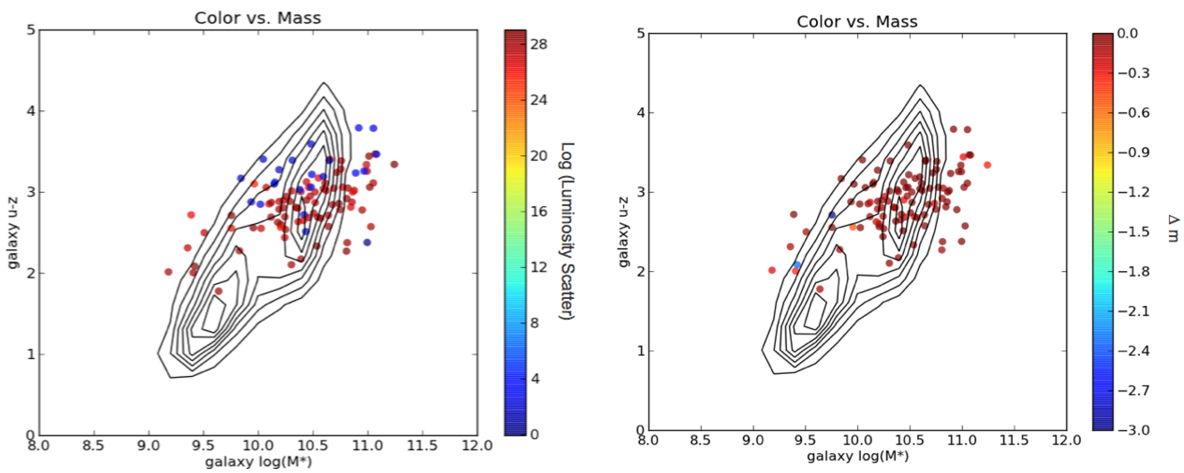

Figure 5. The graph on the left shows quasars color-coded based on their scattered luminosity. Red corresponds to a quasar with more scattered luminosity while blue corresponds to a quasar with less scattered luminosity. The graph on the right shows QSOs that are color-coded based on change in magnitude (Δm). The blue dots correspond to quasars that cause a large change in magnitude while the red dots are quasars that cause a small change in magnitude.

The left graph of Figure 5 implies that quasars with less scattered luminosity tend to lie redder in the color-mass diagram, while the quasars with a high scattered luminosity tend to have a bluer color, suggesting that the powerful quasars reside in bluer galaxies.

Despite the observation that many galaxies hosted very luminous quasars and that a conservative estimate for the amount of scattered light was used, the scattered luminosity overpowered galaxy light in very few cases; for most galaxies, scattered light does not seem to affect the overall magnitude of the quasar's host galaxy.

4.2 Simulation Data Results

In order to compare the observational and simulation data, the following figures visualize the change in magnitude for the simulations. Figure 6 is a plot of change in magnitude (Δm) on the *y*-axis and the minimum radius on the *x*-axis, using the moderate-luminosity QSO.

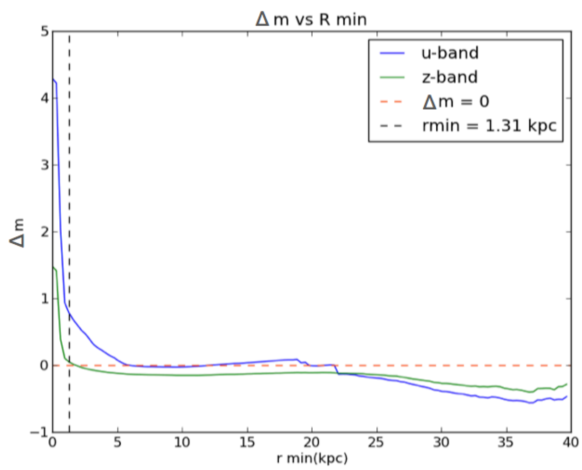

Figure 6. The graph above shows the change in magnitude with a changing minimum radius and a constant maximum radius. The higher the “r min”, the smaller, more outer area of the galaxy is being included in the calculation. The simulation of this moderate-luminosity QSO was given in the *u*-band and the *z*-band filter. The black dotted vertical line separates the inner aperture, on the left, and outer aperture, on the right, of a typical galaxy of redshift between 0.04 and 0.05.

On the left of Figure 6, there is a large change in magnitude because at small radii, the QSO light dominates the galaxy. However, in the outer aperture, which is marked by the vertical dashed line, there is not much effect from quasar scattered light. Even though this is a quasar with full-modeled scattering, the scattered light is not significant enough to affect the measured galaxy properties greatly.

5. Discussion

Because research regarding coevolution of supermassive black holes and galaxies could have been interfered with by scattered light, this research was conducted to ensure that large-scale scattering was not affecting previous research concerning QSO host galaxies. Both the analysis of observed galaxies and simulated galaxies with QSOs demonstrate the idea that scattered light from a quasar does not affect the host galaxy significantly. This contradicts past research that found that scattered light has a large effect on broadband emission from galaxies containing QSOs (Zakamska et al., 2006).

The analytic estimate method used on the galaxies from the SDSS database suggests that while the most luminous quasars lie in bluer host galaxies, there is no apparent correlation between the color of a host galaxy and the change in magnitude from the quasar that resides in it. Figure 5 indicates that quasars that cause a minimal change in magnitude lie in both blue and red galaxies, supporting the idea that scattered light from both strong and weak quasars does not have a very large effect on their host galaxies.

The direct estimate method used on the simulation yielded results that support the conclusion from the analytic method—scattered light from quasars does not affect a galaxy's overall magnitude by a significant amount. It is shown in Figure 8 that where the outer aperture of a typical galaxy with redshift between 0.04 and 0.05 would be, there is minimal change in magnitude caused by scattered light. This observation is true for both the simulation with a moderately luminous quasar and the simulation with a highly luminous quasar.

These results disagree with previous work, which found that scattered light drastically affects its host galaxy (Zakamska et al., 2006). The results differ because this research uses a thorough method of using a combination of observations and simulations to study the effect of QSO scattering; this method concluded that for the majority of QSO-containing galaxies, scattered light does not have much of an effect.

6. Conclusion

In an effort to better understand the role of quasars in their host galaxies and the properties of host galaxies, a combination of analytic and direct estimates on observations and simulations was used. An analytical method was developed to estimate how much the scattered light was affecting the outer aperture of a galaxy; by calculating the amount of scattered light in a galaxy and then estimating how much of an effect this had on the host galaxy's change in magnitude, it was concluded that for most galaxies, the scattered light does not change the overall magnitude significantly. Even though many galaxies contained luminous quasars, galaxies with both strong and weak quasars did not have a large overall change in magnitude caused by scattered light.

Furthermore, the amount of scattered light was directly calculated using simulations of galaxies with both high and moderate luminosity quasars in the center. When comparing the simulations of galaxies with and without scattering, the results also support the idea that scattered light does not have much of an effect in the outer aperture of a galaxy.

When using this novel method of combining observation and simulation to study the effect of scattered light from a quasar, this study furthered the study of the properties of QSO host galaxies because it establishes that scattered light does not have an effect on most galaxies. This research also furthered the study of the BH-bulge relationship by ruling out quasar light scattering as the reason that quasars lie in star-forming galaxies, meaning that physics is the reason behind the coeval growth of supermassive black holes and their host galaxies.

References

Di Matteo, Tiziana, Volker Springel, and Lars Hernquist. "Energy Input from Quasars Regulates the Growth and Activity of Black Holes and Their Host Galaxies." *Nature* 433.7026 (2005): 604-607.

Ho, L. C. *Coevolution of Black Holes and Galaxies*. Cambridge, U.K.: Cambridge University Press, 2004.

Jahnke, K., B. Kuhlbrodt, and L. Wisotzki. "Quasar Host Galaxy Star Formation Activity from Multicolour Data." *Monthly Notices of the Royal Astronomical Society* 352.2 (2004): 399-415.

Magorrian, John. "The Demography of Massive Dark Objects in Galaxy Centers."*The Astronomical Journal* 115.6 (1998): 2285-2305.

Sánchez, Ariel G. et al. "The Clustering of Galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Cosmological Implications of the Large-scale Two-point Correlation Function." *Monthly Notices of the Royal Astronomical Society* 425.1 (2012): 415-437.

Schmidt, M. "3C 273 : A Star-Like Object with Large Red-Shift." *Nature* 197.4872 (1963): 1040.

Silk, Joseph, and Rees J. Martin. "Quasars and Galaxy Formation." *Astronomy and Astrophysics* 331 (1998): L1-L4.

Snyder, Gregory F. et al. "Modeling Mid-infrared Diagnostics of Obscured Quasars and Starbursts." *The Astrophysical Journal* 768.2 (2013): 19.

Trump, Jonathan R. et al. "A Census of Broad-Line Active Galactic Nuclei in Nearby Galaxies: Coeval Star Formation and Rapid Black Hole Growth." *The Astrophysical Journal* 763.2 (2013): 16.

York, Donald G. et al. "The Sloan Digital Sky Survey: Technical Summary." *The Astronomical Journal* 120.3 (2000): 1579-1587.

Zakamska, Nadia L. et al. "Type II Quasars from the Sloan Digital Sky Survey. V. Imaging Host Galaxies with the." *The Astronomical Journal* 132.4 (2006): 1496-1516.