DIRECT COLLAPSE OF MOLECULAR CLOUDS BECAME THE SEED BLACK HOLES FOR QUASARS AT Z > 2 BASED UPON THE \( M_\bullet - \) GALACTIC DIAMETER PROPORTIONALITY AS OBSERVED IN THE DWARF GALAXY HENIZE 2-10

A Master Thesis
Submitted to the Faculty
of
American Public University
by
Frank William Hardy
In Partial Fulfillment of the Requirements for the Degree of Master of Science
December 2014
American Public University
Charles Town, WV
The author hereby grants the American Public University System the right to display these contents for educational purposes.

The author assumes total responsibility for meeting the requirements set by United States copyright law for the inclusion of any materials that are not the author’s creation or in the public domain.

© Copyright 2014 by Frank William Hardy

All rights reserved.
ABSTRACT OF THE THESIS

DIRECT COLLAPSE OF MOLECULAR CLOUDS BECAME THE SEED BLACK HOLES FOR QUASARS AT Z > 2 BASED UPON THE \( M_* - \text{GALACTIC DIAMETER} \) PROPORTIONALITY AS OBSERVED IN THE DWARF GALAXY HENIZE 2-10

by

Frank William Hardy

American Public University System, February 15, 2015

Charles Town, West Virginia

Professor Lisa Kearney, Ph.D., Thesis Professor

The paper’s objective was to explain how supermassive black holes, at the center of distant quasars, became so large so early. The hypothesis was that the direct collapse of molecular clouds provided the seed black holes to explain this conundrum. The research explored the Sloan Digital Sky Survey (SDSS) and Two Micron All Sky Survey (2MASS) databases for acceptable quasars (QSOs) with specific parameters at \( z > 2 \). Six QSOs were selected that had appropriate infrared spectrum, reliable luminosity flux densities, acceptable velocity dispersion rates and accurate optical images. Quasar bulge masses were calculated based upon flux density and luminosity distance, and related to black hole mass using long standing ratios. Galactic size was determined by the simple angle formula and a black hole mass to galactic size ratio calculated. These values were compared to both the subject black hole and associated galaxy size (Henize 2-10) and Sgr A* and the Milky Way’s galactic size. The results were inconclusive because of large redshift sample differentials; however, those QSOs with redshifts > 3 produced convincing outcomes within 49.2% of the target galaxy’s data (< 11% of the Milky Way’s ratio). These two findings strongly suggested the hypothesis had merit.
# TABLE OF CONTENTS

**LIST OF TABLES** .................................................................................................................................................. vi

**LIST OF FIGURES** .................................................................................................................................................. vii

**CHAPTER I: INTRODUCTION** .................................................................................................................................. 1

- Statement of the Problem ........................................................................................................................................ 1
- Background ............................................................................................................................................................ 2
- Significance of the Problem .................................................................................................................................. 5
- The Hypothesis ...................................................................................................................................................... 5
- Research Question .................................................................................................................................................. 6
- Definition of Terms ................................................................................................................................................ 6
  - *Active Galaxies* ................................................................................................................................................ 6
  - *Black hole* ....................................................................................................................................................... 6
  - *Collapsing Molecular Clouds* .......................................................................................................................... 6
  - *Comoving* ......................................................................................................................................................... 6
  - *Light Year* ......................................................................................................................................................... 6
  - *Molecular Clouds* ............................................................................................................................................ 7
  - \( M_\odot \) .......................................................................................................................................................... 7
  - \( M_\star \) .......................................................................................................................................................... 7
  - *Newton’s Gravitational Constant* ................................................................................................................... 7
  - *Quasars, QSO Or Active Galactic Nuclei* ........................................................................................................ 7
  - *Redshift* ............................................................................................................................................................ 7
  - *Supermassive Black Hole (SMBH)* .................................................................................................................. 7
  - *Schwarzschild Radius* ...................................................................................................................................... 7
- Summary ................................................................................................................................................................. 8

**CHAPTER 2: LITERATURE REVIEW** ..................................................................................................................... 12

- How Did the Question Arise? ................................................................................................................................. 12
- Direct Collapse of Molecular Clouds: A Possible Solution? ................................................................................ 12
Recommendations .............................................................................................................. 42
Conclusions ..................................................................................................................... 43

BIBLIOGRAPHY .................................................................................................................. 45
LIST OF TABLES

Table 1 Assigned QSO Number, Correlating SDSS Object ID and Associated “J” Number........8
Table 2 Calculated 0.1 EddLim MassSE..........................................................................................30
Table 3 QSO Diameters ....................................................................................................................31
Table 4 Mass BH to Galactic Diameter.............................................................................................311
LIST OF FIGURES

Figure 1. QSO #1, J141421.53+522940.1 from SDSS Data.................................................................9
Figure 2. QSO #2, J141647.20+521115.2 from SDSS Data.................................................................9
Figure 3. QSO #2, J141647.20+521115.2 from SDSS Data.................................................................10
Figure 4. QSO #4, J141904.09+495033.2 from SDSS Data.................................................................10
Figure 5. QSO #5, J234147.26+001551.9 from SDSS Data.................................................................11
Figure 6. QSO #6, J120441.73-002149.6 from SDSS Data.................................................................11
Figure 7. Quasar vs. Elliptical Galaxy EMR.............................................................................................14
Figure 8. Dotted line gives the linear regression fit for BH mass to Bulge Mass.................................17
Figure 9. Henize 2 10 using 2MASS Database.......................................................................................22
Figure 10. Increasing Luminosity with Increasing Redshift.................................................................23
Figure 11. z = 2.019 from SDSS Database .............................................................................................24
Figure 12. z = 2.151 from SDSS Database .............................................................................................24
Figure 13. z = 2.828 from SDSS Database .............................................................................................25
Figure 14. z = 2.995 from SDSS Database .............................................................................................25
Figure 15. z = 3.958 from SDSS Database .............................................................................................26
Figure 16. z = 5.092 from SDSS Data......................................................................................................26
Figure 17. Redshift Age Converter...........................................................................................................27
Figure 18. Output Values for GSO #4.....................................................................................................28
Figure 19. Single Epoch Mass to Energy Graph.....................................................................................29
Figure 20. SE Bulge to MDO Mass Estimator Graph for z>2 QSOs based on $H_{\beta}$ , Mg II & C IV 29
Figure 21. Result Comparison Graph.....................................................................................................35
Figure 22. J141421.53+522940.1..............................................................................................................36
Figure 23. J141647.20+521115.2 from SDSS Data.................................................................37

Figure 24. J094534.03-004117.8 from SDSS Data...............................................................38

Figure 25. J141904.09+495033.2 from SDSS Data...............................................................39

Figure 26. J234147.26+001551.9 from SDSS Data...............................................................40

Figure 27. J120441.73-002149.6 from SDSS Data...............................................................41
CHAPTER 1: INTRODUCTION

The standard model of galactic formation has been widely accepted for some time; however, ever since the discovery of quasi-stellar objects (QSOs or quasars) in the 1960s, a problem has existed. It was revealed that these powerful radio sources had a large object (a black hole) which was emitting enormous amounts of energy in all known wavelengths. In fact these strong “radio galaxies” emitted the weakest energy in radio frequencies. Nonetheless, the problem was soon evident; the emitting object must be a supermassive black hole (SMBH). These SMBHs were too large to form by the standard (conventional) galactic method and the mystery was widely ignored for decades. The purpose of this paper was to provide evidence in support of an alternative method of galactic formation – direct collapse of molecular clouds into seed black holes (BH). The research attempted to definitively explain the quasar enigma.

Statement of the Problem

The problem exists with time. In the early universe there was simply insufficient time for stars to form, live, die and collapse into the large seed black holes needed by these active galactic nuclei (AGN). The replacement hypothesis that this paper supported with observational results, was that there was a direct collapse of molecular clouds, which became the seed black holes for these galaxies. Those types of nuclei formed the gravity well that was to become the support mechanism for future first and second generation stars. Early stars, well within the BH’s sphere of influence ($r_h$), provided the fuel (along with mergers and collisions\(^1\)) for the BH mass ($M_\times$) to grow into the size, relative to its galaxy, observed today.

The difficulty began with stars and how they affected the standard galactic model. The

maximum mass a star may attain, based upon the photon radiation limit\(^2\) was about 150 solar masses \((M_\odot)\).\(^3\) Since discovering that the Wolf–Rayet star (WR) R136a1 had an estimated mass of 265 solar masses; new upper limits (300 solar masses) had been applied to star formation parameters.\(^4\) However, these new thresholds did not help explain the quasar conundrum.

**Background**

A 10 solar mass star-core corresponds to a 30-35 solar mass progenitor star.\(^5\) While star R136a1 probably did (or will) not end its life as a hypernova (due to its low metallicity and angular momentum); it was assumed that other early stars could have had similar masses, but with high metallicity. Extrapolating this worst case core to mass ratio given by Iwamoto et al.,\(^6\) such a 300 solar mass star formed an initial black hole of 100 solar masses. The luminosity of R136a1 was “10 million times greater than the Sun;”\(^7\) therefore, this star had a lifetime of \(3\times10^5\) solar years. That was about 300,000 years\(^8\) and while short, it remained too long a time to properly explain the quasar problem.

Assuming stellar evolution theory held for all stars (even those in the early universe)\(^9\) the time it took for such massive stars like R136a1 to form was determinable. It was calculated that at the time of the quasar ULAS J1120+0641 (discussed below) the temperature of the universe was about 22.07K (well below the thermal pressure limits to allow gravitational collapse of the

---


\(^6\) Iwamoto, 668.

\(^7\) Crowther.


molecular cloud).\textsuperscript{10} Based upon the collapsing part of the nebula under the gravitational acceleration of the mass of that part of the cloud, equation (1) was derived.

\begin{equation}
    dt = \left[ \frac{a}{(G M)^{0.5}} \right] \{ (2 r - \frac{r^2}{a})^{0.5} + 2 a^{0.5} \text{Arc tan} \left[ \frac{2a}{r} - 1 \right]^{0.5} \}
\end{equation}

where $dt$ was the collapse time, $a$ was the initial half radius of the cloud, $r$ was the final cloud/star radius and $M$ was the mass of the collapsing nebula used by the star. Applying values of the Sun with a molecular cloud fragment equal to 0.5 light years; the time to collapse was about $2.81 \times 10^6$ years. On average a 30 solar mass O class star formed approximately 30 times faster than a G5 star like our Sun.\textsuperscript{11} Thus it took a mere 100,000 years for the cloud to collapse into this hyper O star; however, the collapse time could also have been this short for stars similar to R136a1 to form in the early universe.

This raised the question as to the number of stars formed per year in an early galaxy. Walter et al. argued that star formation in a host star burst galaxy around the quasar J114816.64+525150.3 at $z = 6.42$ was about 1,000 solar masses per year per kpc\textsuperscript{2}.\textsuperscript{12} This implied that nearly three stars the mass of R136a1 were formed per year per square kpc. Similarly Gonzalez’s models indicated an average of $8 \times 10^{-3}$ M solar masses per year per Mpc\textsuperscript{3} in the 80 million years following the Big Bang.\textsuperscript{13} This supported the concept that $2.7 \times 10^3$ R136a1 type stars formed per year per million cubic pc; nearly equal to Walter’s value (2.7 verses 3 stars).

\begin{flushright}
\textsuperscript{10} Jeffrey Bennett et al., \textit{The Cosmic Perspective}, 7th ed. (Upper Saddle River: Pearson Education Inc., 2014), 517.
\end{flushright}
Equation (2) showed that during the era of recombination, the Cosmic Microwave Background (CMB) had a redshift of \( z \approx 1098 \) that corresponded to an age of roughly 379,000 years after the Big Bang. This yielded a comoving distance of more than 46 billion light years.\(^\text{14}\)

\[
(1 + z \approx \frac{3000K}{2.73K} \approx 1099)^{15}
\]

The quasar ULAS J1120+0641 was the most distant known quasar (at \( z = 7.085 \)) having a comoving distance of 28.85 billion light-years\(^\text{16}\) or 770 million years after the Big Bang.\(^\text{17}\) As a result of its distance it was difficult to determine the size of the galaxy that contains ULAS J1120+0641; however, it was possible to determine the size of the quasar itself (about the size of our solar system extending from the Sun to the orbit of Neptune).\(^\text{18}\) This quasar consisted of a supermassive black hole that was 2 billion solar masses; therefore, it was possible to extrapolate values based upon ratios of nearer quasars using black hole galactic area/volume proportions.

Quasar 3C 273 had a 900 million solar mass black hole and a galactic diameter of 30 arc" at a distance of 749 Mpc.\(^\text{19}\) If it were circular its area was 41 Mpc\(^2\) or about 1.4% the area of the Milky Way galaxy. Using the McLeod, Rieke, & Storrie-Lombardi method of bulge luminosity to black hole mass relationship;\(^\text{20}\) QSO CXO J084837.9+44535 (CXO 52) at \( z = 3.288 \)\(^\text{21}\) had a

SMBH greater than 1 billion solar masses.\textsuperscript{22} Therefore it was possible to extrapolate the volume of a spherical ULAS J1120+0641 as 90 Mpc\textsuperscript{3} and determine the number of massive stars born per year in this sample early starburst galaxy.

Significance of the Problem

According to Dr. Daniel Mortlock there were about 100 bright quasars with redshift greater than seven.\textsuperscript{23} Assuming the average quasar volumes above and that each star lived the mentioned 300,000 years and took the minimum 10,000 years to form; and sufficient collapse continued at the mentioned pace; the total number of stars born per year for the first 770 million years (excluding the 380,000 pre recombination era time) was less than 240,000, each with the mass of R136a1. With all stars dying and their cores collapsing into 100 solar mass black holes, and each immediately accreting material at the Eddington limit (1.0 Edd\textsubscript{lim}); the total volume of all black holes extended 20,386 billion cubic light years (which = 5% of the volume = 588 billion cubic pc). This was 588,000 times the number of stars formed by the above values (or 1.764 million solar masses produced). This equaled 588 million solar mass black holes, which was 0.59\% (99\% too low) for the estimated 100 billion solar mass quasars in the universe at \( z \geq 7 \). Fundamentally there was insufficient time to form all the early supermassive black holes observed in quasars and their SMBH’s must have formed via another method.\textsuperscript{24}

The Hypothesis

Direct collapse of molecular clouds provided the seed black holes for distant quasars.

\begin{itemize}
\end{itemize}
Research Question

Does observational evidence indicate that the relationship between the mass of a quasar’s SMBH and its galactic size is closely proportional to the ratio of the mass of the SMBH found in Henize 2-10 and its galactic size or to Sgr A* and the Milky Way galaxy’s size?

Definition of Terms

*Active Galaxies*

Are another term used to imply quasars and does not (for the purpose of this paper) refer to galaxies with high star formation activities.

*Black hole*

This is the scientific object resulting in a singularity that is formed from the total collapse of a star core following a supernova event. Its size is defined by its Schwarzschild radius (thus its mass).

*Collapsing Molecular Clouds*

Are molecular clouds as defined below, with rotational velocity and its material is gravitationally attracted.

*Comoving*

Is a measure of time (as opposed to distance) and utilizes the concept that the universe is expanding at a speed greater than light. It measures the amount of time that has passed since an object (seen at a fixed distance) is observed. In this paper it is not used with reference to the light horizon and comoving values (in some cases in this analysis) do exceed that horizon.

*Light Year*

Is a measure of distance (as opposed to time). It is the distance light travels in one year.
Molecular Clouds

Are free-floating conglomerations of dust and gas.

\[ M_\odot \]

Is the mathematical symbol for one solar mass equal to the Sun’s mass.

\[ M_\bullet \]

Is the mathematical symbol for black hole mass.

Newton’s Gravitational Constant

Is described first in terms of solar masses and parsecs and written as

\[ G = 4.302 \times 10^{-3} \text{ pc} M_\odot^{-1}(\text{km/s})^2 \text{ or } G \approx 6.673 \times 10^{-11} \text{ N(m/kg)}^2 \]

Quasars, QSO or Active Galactic Nuclei

These are one in the same for this paper. They are the result of black holes emitting energy at any rate (no matter the rotation velocity) and may or may not produce visible jets.

Redshift

Is the term that refers to the Doppler movement, of an object, away from an observer. In this paper it can be equated to a comoving time or a light year (parsec) distance. It is interchangeable with the lower case letter “z”.

Supermassive Black Hole (SMBH)

Is defined, in this paper, as any black hole whose mass is greater than one million solar masses.

Schwarzschild Radius

It is also referred to as the event horizon. It’s that region beyond which electromagnetic radiation (EMR) cannot escape the gravitational attraction of a BH and the conventional laws of physics fail to describe events.
Summary

The solution was to explore how supermassive black holes at the center of distant quasar galaxies, $z > 2$, became so large at an early time in the universe. If the direct collapse of molecular clouds hypothesis explained the process, then there should have been a similarity between the mass of the observed object and its galactic size, and that of the mass of Henize 2-10 and its galactic size. If the hypothesis were invalid, then that ratio of the observed object would be similar to the ratio of the mass of Sgr A* and the size of the Milky Way galaxy (within 50% in either case). The objects chosen needed large SMBHs and therefore, quasars were examined.

Discussed in CHAPTER 3: METHODOLOGY were the procedures used in the selection process; however, the quasars required several parameters. Each quasar needed reliable spectrum with distinguishable $C_{IV}$, flux density (luminosity) and wavelength (angstrom, Å) values. The velocity dispersion rates had to be available and the quasar’s bulge needed to obscure the light from non-bulge objects (stars). Finally the object necessitated a measurable area of luminosity dominated by this bulge. The six chosen QSOs were presented in Figures 1 thru 6 and listed in Table 1 below in the various identifiable states used in the study, along with the sky position for recognition and location.

<table>
<thead>
<tr>
<th>QSO Number</th>
<th>Redshift (z)</th>
<th>SDSS Object Number</th>
<th>SDSS “J” Number</th>
<th>RA</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.019</td>
<td>1237659120932880546</td>
<td>141421.53+522940.1</td>
<td>213.58974</td>
<td>52.49447</td>
</tr>
<tr>
<td>2</td>
<td>2.151</td>
<td>1237659120933077046</td>
<td>141647.20+521115.2</td>
<td>214.19669</td>
<td>52.18757</td>
</tr>
<tr>
<td>3</td>
<td>2.828</td>
<td>1237650795146379695</td>
<td>094534.03-004117.8</td>
<td>146.93861</td>
<td>-0.68701</td>
</tr>
<tr>
<td>4</td>
<td>2.995</td>
<td>1237662303508430971</td>
<td>141904.09+495033.2</td>
<td>214.76705</td>
<td>49.84254</td>
</tr>
<tr>
<td>5</td>
<td>3.958</td>
<td>1237666408440398560</td>
<td>234147.26+001551.9</td>
<td>355.44695</td>
<td>0.26444</td>
</tr>
<tr>
<td>6</td>
<td>5.092</td>
<td>1237674649929187737</td>
<td>120441.73-002149.6</td>
<td>181.17389</td>
<td>-0.36379</td>
</tr>
</tbody>
</table>
Figure 1. QSO #1, J141421.53+522940.1 from SDSS Data

Figure 2. QSO #2, J141647.20+521115.2 from SDSS Data

26 Ibid.
Figure 3. QSO #3, J094534.03-004117.8 from SDSS Data

Figure 4. QSO #4, J141904.09+495033.2 from SDSS Data

---


28 Ibid.
Figure 5. QSO #5, J234147.26+001551.9 from SDSS Data

Figure 6. QSO #6, J120441.73-002149.6 from SDSS Data


30 Ibid.
CHAPTER 2: LITERATURE REVIEW

Recent research questioned the long held theory of galactic formation. Literature had presented the problems mentioned in CHAPTER 1: INTRODUCTION that there was insufficient time in the early universe to allow for the observed formation of supermassive black holes at some galactic centers. A review of the literature followed a systematic, sequential process, initiated by questions raised and problems associated with the scholarly articles evaluated. The central conundrum remained: The theory did not follow observations.

How Did the Question Arise?

A 2011 paper by Reines et al. indicated that new observations may explain the enigma of supermassive black hole sizes that existed in quasars.\(^{31}\) The authors observed the dwarf starburst galaxy Henize 2 10, and noted that (1) the SMBH was not rotating, (2) it did not have an associated bulge and (3) that the size of the SMBH was disproportionately large compared to the size of its associated galaxy.\(^{32}\) Their conclusion was that a “seed” black hole could have predated the Henize 2 10 galaxy.\(^{33}\) If correct, then young active galaxies should have SMBHs in proportions comparable to the ratios observed in Henize 2-10 and not the Milky Way galaxy.

Direct Collapse of Molecular Clouds: A Possible Solution?

The hypothesis of direct collapse (DC) of molecular clouds had gained noteworthy support the last decade through observation and modeling. Regan, Johansson and Wise advocated that galaxies started with a significantly large seed mass, devoid of metals, dust and H\(_2\) (which would inhibit direct collapse and create stars instead of black holes).\(^{34}\) They

---


\(^{32}\) Reines et al., 66-67.

\(^{33}\) Ibid., 68.

confronted the time issue for quasars (QSOs) at $z > 7$ and refined simulations to account for the diffusion of H$_2$. Their results repeatedly indicated that at distances of $< 1$ parsec for the central region, primary cooling was due to H1; thus allowing continued collapse. While the H$_2$ region contained $\sim 100 \, M_\odot$ the surrounding envelope was a much larger $10^5 \, M_\odot$ allowing for direct cloud collapse.\footnote{John Regan, Peter Johansson and John Wise, “The Direct Collapse of a Massive Black Hole Seed under the Influence of an Anisotropic Lyman-Werner Source,” \textit{The Astrophysical Journal} 1407 (Draft Version July 2014): 15.}

This confirmed the earlier 2009 Sloan Digital Sky Survey (SDSS) observational results at $z \sim 6$ by Shang, Bryan and Haiman. Their inspections indicated that collapsing cloud regions ($10^5 \, M_\odot$) exceed those of $10^2 \, M_\odot$ required for early star formation.\footnote{Cien Shang, Greg Bryan and Z. Haiman, “Supermassive Black Hole Formation by Direct Collapse: Keeping Protogalactic Gas H2–Free in Dark Matter Halos with Virial Temperatures $T_{\text{vir}} > 10^4$ K,” \textit{Royal Astronomical Society} 000 (June 2009): 2.}

Begelman, Volonteri and Rees further argued that the conventional self-generating, gravitational collapse of a rotating cloud of gas (assuming sufficient cooling) did not need to form a supermassive star (with high entropy throughout); but the ‘bars within bars’ mechanism they support produced a ‘quasistar’ with very low specific entropy near the center. This allowed for lesser seed black holes than the conventional direct collapse model identified above needed.\footnote{Mitchell Begelman, Marta Volonteri and Martin Rees, “Formation of Supermassive Black Holes by Direct Collapse in Pre-Galactic Haloes,” \textit{Royal Astronomical Society} 370 (April 2006): 290.}

What is Essential?

Accepting the hypothesis of direct molecular collapse into a black hole, other information was mandated. To support the postulation (young active galaxies should have supermassive black holes in proportions comparable to the ratios observed in Henize 2-10 and not the Milky Way galaxy), it must be determined if there is a relationship between a QSO SMBH and the quasar galaxy’s size, and a $z = 0$ SMBH and modern galaxy size such as Sgr A* and the Milky Way.
Way galaxy. The mass of the SMBH and galactic size of Henize 2 10 was known from the Reines’ et al. observations and the SMBH near Sgr A* and the size of the Milky Way galaxy was also well known; therefore, the question became; (1) how to get the mass of an observed QSO SMBH and (2) how to get the size of its associated galaxy?

Michael Disney’s paper presented the graph shown in Figure 7 that indicated there was a relation between luminosity (across all wavelengths of the spectrum) and a quasar that differed from the small frequency range of giant elliptical galaxies. The examination of a QSO’s luminosity and spectra could be a possible means to determine its mass and galaxy size.

![Figure 7. Quasar vs. Elliptical Galaxy EMR](image)

The Luminosity Problem

Luminosity presented a problem because in the most luminous active galaxies the light from the central black hole region overwhelmed any evidence of stars and galactic size. These high luminosity Type II quasars (what Stern et al. call Seyfert 2 galaxies) were devoid of FEII

---

40 Disney, 54.
emissions and difficult to measure; however, Stern et al. indicated that others had identified certain Type II quasars (what they call narrow-line region Seyfert 1, NLS1) which had broad Balmer emission lines.\(^{42}\) This could be a possible solution if proper correlation were achievable.

**The Spectrum Problem**

Stern et al. indicated that specific Type II QSOs may be spectrally separated based upon iron 2 emissions (or the lack thereof). Examination of papers by Hainline et al. stated that there was an upper limit (10–20 kpc) to the size of narrow line region QSO.\(^{43}\) This information was used later in assumptions made following the experimental observations; however, it did not solve the problem of mass and size determination of QSOs. Furthermore, these observations were of radio quiet NLS1 objects at \(z < 0.5\).\(^{44}\)

This led to the inspection of two vitally important papers; (1) Hopkins et al.\(^{45}\) and (2) Ikeda et al.\(^{46}\) that investigated the quasar luminosity function (QLF, the distribution of quasar density per comoving volume as a function of intrinsic luminosity and redshift) at redshifts > 4. Hopkins et al stated there was a relationship between the black hole and the quasar host galaxy that was proportional to the evolution of the black hole.\(^{47}\) However, Hopkins indicated that at all power values, the peak QSO activity was at \(z \sim 2\) that was confirmed by many other papers on the QLF.\(^{48}\) Therefore, BHs at these redshifts had the best influence over their host galaxy.\(^{49}\)


\(^{44}\) Ibid., 3.


\(^{48}\) Ibid., 742.

\(^{49}\) Ibid., 742.
Ikeda et al. solved the problem of small seed black holes existing in QSOs prior to their observational period of $z \sim 4$. For a non-comoving distance of $z = 4.5$ the distance was 12.8 Gly (comoving time $\sim 38$ Gyr) and at $z = 7$ about 13.4 Gly (comoving time $\sim 45$ Gyr); therefore for the problem in this paper, the formation of this type of seed black hole was not an issue.

*Our results do not show any evidence of such a breakdown of the downsizing scenario at $z \sim 4$, suggesting that numerous seeds of high-mass SMBHs should exist at even higher redshift ($z > 5$)....the type-II (i.e., obscured AGN) fraction is reported to be higher in lower-luminosity samples at higher redshifts.*

Black Hole Calculations

The findings of Hopkins et al. and Stern et al. presented the data on Bolometric QLF and Yue Shen had successfully demonstrated the relationship between this luminosity and Type I quasar black hole size. His single-epoch (SE) virial black hole mass estimators measured quasar luminosity and the width of the broad emission line to calculate black hole mass accurately. This was valid only if there were sufficient data and the apt broad line regions (BLR) width estimates used. Furthermore, Shen presented data (from others) that suggested luminosity contamination from the host galaxy was “usually negligible, although may be significant for rare objects with excessive ongoing star formation.” For this research, while presenting a problem for direct observations and rotational determination, it did aid setting the SMBH to bulge mass relation.

SMBH to Bulge Mass

Accurate bulge masses for a quasar host galaxy at $z > 0.5$ was difficult because an active

---

52 Ibid., 75.
nucleus interfered with measurements as previously mentioned with the SMBH.\textsuperscript{53} However, Magorrian, et al. confirmed two important relationships in a 1998 study; (1) the mass to light ratio that was modified by Shen and others above can be determined and (2) the massive dark object (MDO) to bulge mass ratio was also determinable for standard (non AGN) galaxies.\textsuperscript{54} The MDO to bulge mass ratio they calculated (0.005) fit well with the known value of the Sgr A* to the Milky Way bulge ratio of 0.0061. Figure 8 confirmed this ratio may be used for QSOs at $z = 1.3$ by Inskip et al. The dotted regression line presented the BH$_M$ and the Stellar$_M$ for $z = 0$.\textsuperscript{55}

![Figure 8. Dotted line gives the linear regression fit for BH mass to Bulge Mass\textsuperscript{56}](image)

The significance of the data was that Inskip et al. had determined a central BH growth rate of $\sim 45\%$ over its active time (for this quasar that was $5 \times 10^7$ years, at an accretion rate of


\textsuperscript{56} Ibid., 100.
∼5.4 \( M_\odot \) yr\(^{-1}\)).\(^{57}\) When combined with the derived J090543.56+043347.3 data, the SMBH to bulge mass was reverse calculated to \( 2 < z < 3 \). Intuitively the universe was much smaller; however, these data provided a fairly accurate ratio of a QSO SMBH to its galactic size at any redshift value. When using the Inskip range of 45% – 200% for \( 0 < z < 1.3 \)^{58} the higher values increased proportionally as \( z \) increased since, “this particular diagnostic route [was] widely applicable to other quasars in the redshift range \( 1 < z < 3 \) at the peak epoch of quasar activity.”\(^{59}\)

Alternate Literature

Additional literature was reviewed that refuted some of the associated data used above. Fulvio Melia acknowledged that SMBH in early quasars were not explained with the standard model; however, he contended that they must be the result of extremely early BH collisions and then growth at the Eddington value. “In this cosmology, \( 5 - 20 \ M_\odot \) seeds produced after the onset of re-ionization (at \( z < 15 \)) could have easily grown to \( M_\bullet > 10^{9} \ M_\odot \) by \( z > 6 \), merely by accreting at their standard Eddington rate.”\(^{60}\) This conjecture was disregarded in that it did not support the observations of Reins et al. that Henize 2-10 was accreting below its rate.\(^{61}\)

McLeod, et al., accept \( M_{\text{MDO}}/M_{\text{Galaxy}} \sim 0.006 \) presented by Magorrian; but, they argued at high \( z \), where very large galaxies had not arisen, SMBH mass was due to halo dark matter.\(^{62}\) Dark matter, while a fundamental part of the mass of the quasar galaxy, was not a variable in this study.

\(^{58}\) Ibid., 101.
\(^{59}\) Ibid., 101-2.
Another alternate piece of literature was reviewed by Ferrarese and Merritt. Their hypothesis was examined; and while compelling, was irrelevant for the research undertaken in this study. Fundamentally, they proposed the black hole’s mass was proportional to the velocity dispersion and the luminosity function was inaccurate. Their arguments were powerful, however for this research, luminosity–distance was the only available variable (even though $\sigma$ was obtainable).

---

CHAPTER 3: METHODOLOGY

This paper used the mixed methodology approach that followed a systematic, sequential process, designed to produce deductive research. It began with primary and secondary sources which defined the experimental observations necessary. Those surveillance results were based upon the resources’ information, but new examinations and outcomes were uniquely quantitative.

Restatement of the Problem

How did supermassive black holes at the center of distant quasar galaxies, $z > 2$, become so large at the observed time in the universe?

Hypothesis

The direct collapse of molecular clouds provided the seed black holes for quasars at $z > 2$.

Description of Research Design

The research method used was a quasi-experimental method, since not all relevant variables were easily discerned, calibrated or controlled. Furthermore, the “control” over many independent variables was controversial because those variables used were debatable. Since the variations in the dependent variables relied on the variations in the potentially contentious independent variables, the method was labeled quasi-experimental.

The desired subjects consisted of high luminosity quasars at $z > 2$ obtained from the Sloan Digital Sky Surveys (SDSS) database.$^{64}$ The quasars needed to have very low velocity dispersion values similar to Henize 2-10 ($\sim 10 \text{ kms}^{-1}$).$^{65}$ This request was input via a revised input stream suitable to examine QSOs at $z > 2$. The following string was entered into the special

---


purpose programming language Structured Query Language (SQL) search offered by the SDSS team and CSV selected:\textsuperscript{66}

```
select top 1000
  objid, modelmag_u, modelmag_g, modelmag_r, modelmag_i, modelmag_z,
z
from
 SpecPhoto
where z between 2 and 6.0 and
 specclass=3 and zconf > 0.95
select objID,
  field, ra, dec
from
 PhotoObj
```

The rotational requirement became a problem because in order to be a QSO the BH needed rotation, and the faster it rotated, the greater its mass and energy. Therefore, the string was further reduced to provide a series of six acceptable quasars ranging from $z = 2.019$ to $z = 5.092$. These quasars were relabeled as QSO #1 thru QSO #6 as presented above in Table 1.

**Procedure**

Registration on the SDSS site was not required as access was encouraged for students and researchers. Following a detailed, multiday review of the tutorial section, specific regions of the website were examined. Proficiency was gained in modifying the SQL search program; and the ability to locate objects, identify regions, and collect EMR spectrum data from the desired object became routine. The Navigate window\textsuperscript{67} was used to visually identify the selected bodies. The chosen reference galaxy, Henize 2 10, was unavailable in the SDSS catalog, subsequently found in the associated Two Micron All-Sky Survey (2MASS) database and depicted below in Figure 9 as an optical image.

Discussion of Data Processing

Once familiarization was accomplished and the quasar data collected, processing was undertaken. The dataset was augmented and reduced with an Excel program written by Nikolay Hardy\textsuperscript{69} that separated the high z quasars (initially \( z > 4 \) then reduced to \( z > 2 \)) from unacceptable objects. The number of items in the search string was also reduced from 1000 to 100. The selected data were entered into the object id list and the SDSS spectrum retrieval tool utilized. This presented the first problem. The vast majority of QSOs (all but Figures 15 and 16 below) did not have acceptable spectrum in the SDSS database. The investigation required further reduction in z and the six chosen QSOs provided all necessary statistics.

The first requirement was to insure that the new SDSS generated quasars followed the


pattern described in Chapter 2. The graph shown in Figure 10, confirmed that the correct QSOs were chosen since the relationships were as desired.\textsuperscript{70}

![U-G vs. Redshift](image)

*Figure 10. Increasing Luminosity with Increasing Redshift*

Most of the SDSS spectrum and mass data was cataloged for nearer QSOs by the surveyors; so an additional search was performed looking for $z < 3$, yet with similar magnitudes. Several were found and similarly processed; however four, with the closest luminosity values, were chosen (Figures 11, 12, 13 and 14). This situation severely limited the sample size; however, it was sufficient and assumed adequate.

Figure 11. $z = 2.019$ from SDSS Database

Figure 12. $z = 2.151$ from SDSS Database
Figure 13. $z = 2.828$ from SDSS Database

Figure 14. $z = 2.995$ from SDSS Database
Mathematical Analysis

Once the data were collected and the adjustments made, the assumptions generated in the literature review sections were applied. Since all the quasars were \( z > 2 \), \( C_\text{IV} \) spectral values were used. Each QSO was identified by a number, which corresponded to its redshift value. These redshifts were correlated with their SDSS Object ID as presented in Table 1 above.
The first mathematical requirement was to determine the cosmic age of each QSO (in Mpc) and convert that into a luminosity distance \( D_L \), also in Mpc. The process began by translating the \( z \) value of the spectrum into cosmic age (mega years) as shown in Figure 17 (in Gyr); however, the actual calculations were performed by computer software\(^{71}\) with \( \Omega_m = 0.286 \), and \( h_0 = 0.696 \) and compared to online software with the same input parameters.\(^{72}\) The comparison values were listed in Table 2 as \(*R\) and \(*W\) for the respective authors.

\[ \text{Figure 17. Redshift Age Converter}^{73} \]

Once converted the units were listed in column three thru six on Table 2. Since \( z > 2 \), \( C_{IV} \) flux density \( (F_{\lambda}) \) was used per Shen. The individual \( F_{\lambda} \) for the six QSOs were read directly from the spectrum slider as represented by the \( C_{IV} \) spectral values (Figures 11 thru 16). These were

---


taken from the DR10 Science Archive Server’s (SAS) interactive graph\textsuperscript{74} and listed in column eight on Table 2 (wavelength in column seven from the same data).

Finally these data were input into the Flux Density $\Rightarrow$ Luminosity Density and Luminosity converter software\textsuperscript{75} and recorded in column nine, Table 2. Figure 18 was the calculated input and output values for QSO #4 ($z = 2.995$).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{flux_lum_converter.png}
\caption{Output Values for QSO #4 ($z = 2.995$) in erg/sec\textsuperscript{76}}
\end{figure}

The single-epoch mass to luminosity estimator, shown in Figure 20 below, for each identified quasar was used to correlate single epoch (SE) luminosity to bulge mass. These output values were generated using 0.1 Eddington Limit graph in Figure 19. This quantity was chosen since there were no visible jets with these QSOs and according to Soria et al., “for rates $\sim 0.03$ to $0.5$ times the Eddington rate, the BH power output is…without a jet.”\textsuperscript{77}


\textsuperscript{76} Ibid.

This paper recognizes that the luminosity to mass relationship was not the best method to calculate bulge mass; yet, it was required at this stage. Figure 20 showed the link between the BH mass and bulge mass. It was Shen’s luminosity correlation that was used in the experiment; however, the limitations section below discussed the alternative Mass ($M_*$) – Velocity Dispersion ($\sigma$) proportion method as well.  

---


Table 2 Calculated 0.1 $Edd_{\text{Lim}}$ Mass$_{\text{SE}}$

<table>
<thead>
<tr>
<th>QSO #</th>
<th>Redshift</th>
<th>Cosmic Age @ Redshift (Mpc)</th>
<th>Comoving Distance (D$_{\text{M}}$) Mpc</th>
<th>Angular Distance (D$_{\text{a}}$) Mpc</th>
<th>Luminosity Distance (D$_{\text{L}}$) Mpc</th>
<th>Wavelength (A)</th>
<th>$F_{\lambda}$ C$_{\text{IV}}$ x10$^{-17}$ erg cm$^{-2}$ s$^{-1}$ A$^{-1}$</th>
<th>Luminosity $\Delta L_v$ ergs$^{-1}$ x10$^{45}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.019</td>
<td>3290</td>
<td>3286</td>
<td>1756</td>
<td>1756</td>
<td>16003</td>
<td>4680</td>
<td>0.42</td>
</tr>
<tr>
<td>2</td>
<td>2.151</td>
<td>3091</td>
<td>3087</td>
<td>1742</td>
<td>1742</td>
<td>17297</td>
<td>4869</td>
<td>24.8</td>
</tr>
<tr>
<td>3</td>
<td>2.828</td>
<td>2321</td>
<td>2318</td>
<td>1648</td>
<td>1647</td>
<td>24139</td>
<td>5918</td>
<td>7.89</td>
</tr>
<tr>
<td>4</td>
<td>2.995</td>
<td>2179</td>
<td>2176</td>
<td>1621</td>
<td>1621</td>
<td>25872</td>
<td>6163</td>
<td>15.5</td>
</tr>
<tr>
<td>5</td>
<td>3.958</td>
<td>1581</td>
<td>1578</td>
<td>1471</td>
<td>1470</td>
<td>36138</td>
<td>7672</td>
<td>3.16</td>
</tr>
<tr>
<td>6</td>
<td>5.092</td>
<td>1163</td>
<td>1160</td>
<td>1312</td>
<td>1312</td>
<td>48679</td>
<td>9445</td>
<td>1.98</td>
</tr>
</tbody>
</table>

*R implies Reims’ calculator and *W implies Wright’s calculator.

The bulge mass was calculated using Figure 19 (the log-log flux limited equation to different magnitude values of Shen).\(^81\) Figure 20 above was used to verify the ratio stated by Magorrian et al of 0.005,\(^82\) with values listed in Table 3. These values coincided with the linear regression fit for BH mass to Bulge Mass as shown above in Figure 8.

Once the mass of the BH had been determined, the calculations of the diameters of the associated galaxies were undertaken. Angular measurements were acquired from the SDSS Explorer Chart Imaging\(^83\) website for the associated QSOs and presented in Figures 22 to 27. Since the luminosity distances (D$_{\text{L}}$) were measured in thousands of mega parsecs, the small angle approximation was used with angles for $\theta$ measured in arcsec (radians listed in parenthesis) in Table 3. The associated diameters were also listed in Table 3 in light years for calculation purposes and the resultant ratios were presented in Table 4.

---

Table 3 QSO Diameters

<table>
<thead>
<tr>
<th>QSO Number</th>
<th>$M_{SE} \times 10^9 M_\odot$</th>
<th>$M_* \times 10^7 M_\odot$</th>
<th>$\sigma$ km/s</th>
<th>$\theta_{\text{arcsec}}$ (radians x$10^{-5}$)</th>
<th>$r_h \times 10^4$ pc</th>
<th>Diameter (ly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.041</td>
<td>0.021</td>
<td>2830.5</td>
<td>4.4 (2.133)</td>
<td>0.1128</td>
<td>1.22 x10^5</td>
</tr>
<tr>
<td>2</td>
<td>2.89</td>
<td>1.45</td>
<td>2683.6</td>
<td>4.5 (2.182)</td>
<td>8.662</td>
<td>1.25 x10^5</td>
</tr>
<tr>
<td>3</td>
<td>2.16</td>
<td>1.08</td>
<td>1922.7</td>
<td>3.9 (1.891)</td>
<td>12.568</td>
<td>1.02 x10^5</td>
</tr>
<tr>
<td>4</td>
<td>6.12</td>
<td>3.06</td>
<td>2339.1</td>
<td>3.4 (1.648)</td>
<td>24.060</td>
<td>87,200</td>
</tr>
<tr>
<td>5</td>
<td>2.47</td>
<td>1.24</td>
<td>1833.7</td>
<td>2.2 (1.067)</td>
<td>15.865</td>
<td>51,200</td>
</tr>
<tr>
<td>6</td>
<td>4.40</td>
<td>2.20</td>
<td>2405.8</td>
<td>2.7 (1.309)</td>
<td>16.352</td>
<td>56,100</td>
</tr>
</tbody>
</table>

With the use of the observed arcsec ($\theta$) from Figures 22 thru 27, along with the computed luminosity distance ($D_L$) in Table 2, the gravitational influence radius ($r_h$) was determined using velocity dispersion ($\sigma$). Sigma was taken directly from the data list in Figures 11 thru 16 and the results placed into Table 3, where

$$r_h = \frac{GM_{BH}}{\sigma^2} \text{ MBH and } G \text{ is in } M_\odot$$

Table 4 Mass BH to Galactic Diameter

<table>
<thead>
<tr>
<th>Object</th>
<th>$M_*$/Diameter ($M_\odot$/ly)</th>
<th>$r_h$/Diameter (pc/ly) x$10^9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Henize 2 10</td>
<td>667</td>
<td>126.5</td>
</tr>
<tr>
<td>Milky Way</td>
<td>37.3</td>
<td>9.090</td>
</tr>
<tr>
<td>QSO #1</td>
<td>1.67</td>
<td>0.993</td>
</tr>
<tr>
<td>QSO #2</td>
<td>116</td>
<td>6.930</td>
</tr>
<tr>
<td>QSO #3</td>
<td>101</td>
<td>12.32</td>
</tr>
<tr>
<td>QSO #4</td>
<td>351</td>
<td>27.59</td>
</tr>
<tr>
<td>QSO #5</td>
<td>242</td>
<td>30.99</td>
</tr>
<tr>
<td>QSO #6</td>
<td>392</td>
<td>29.15</td>
</tr>
</tbody>
</table>

Methodological Assumptions and Limitations

There were numerous limitations to this study. Initially the problem consisted of finding quasars at the appropriate redshift that also had good spectrum and a $\sigma$ value comparable to Henize 2 10. This was not located and the quasars studied were smaller than desired and had velocity dispersions far greater than Henize 2 10. Fundamentally, Henize 2-10 was not a quasar.
and the two objects were different with diverse properties that limited the sample size; however, the results remained unchanged and further investigation of this distinction was discussed.

The next limitation consisted of the elementary undertakings of the research. It required the use of multiple hypotheses that were controversial or had competing ideologies. It was determined to use the most dominate (or median) thesis in all instances. For example, in the case of Magorrian et al. his hypothesis had been refined multiple times; however, in all situations the values were slightly larger or smaller than the original data; therefore, Mogorrian et al was the median, deemed sufficient and used.

Utilization of flux to mass values was less reliant than mass velocity dispersion relationships; nevertheless, this research necessitated luminosity as an input variable to determine the mass and could only use the \( M \propto \sigma^4 \) relationship (where \( \alpha = 4.8 \)) as verification.

Another limitation was the angular measurements and the utilization of the small angle formula. While the actual SDSS images were overlain on graphs (with proper scaling) the difficulty in measuring the actual bulge was noticeable. It was challenging to differentiate the background intergalactic light from that produced by non-bulge stars; thus possible observational errors may have been induced.

A significant potential problem arose with the utilization of the 10% Eddington Limit value (0.1 \( \text{Edd}_{\text{lim}} \)). Some argued that this rate was closer to 30\%, while other contented it was

---

nearer the 1.0 value.\textsuperscript{91,92} However, the observations of Reines et al. indicated that Henize 2-10 was accreting “significantly below its Eddington limit,”\textsuperscript{93} and when combined with the non-visible jet limitation factor observed, the 0.1 value was chosen.

This problem was followed with one of the research’s fundamental limitations. The rotational rates of the observed quasars did not match that of the subject Henize 2-10. The results indicated this was not a significant problem; but was addressed in detail in CHAPTER 5.

The final limitation was the variability in the QSO’s luminosity. It was well known that AGN luminosities vary with time\textsuperscript{94} and this study did not account for that condition. SDSS images and data were gained from a specific period, which did not account for the potential luminosity, variability discrepancies in the conclusions. Therefore, the data accumulated was dependent upon this fixed period, which may be higher or lower than actual. Nonetheless it was important to note that variability was also an indicator of activity.\textsuperscript{95} Jets too were a gauge of stability;\textsuperscript{96} but QSOs (by definition) had jets (of some magnitude) and this study did not provide for that variable in the examination either.

Ethical Assurances

An important issue was the ethical concept of cherry picking theories in support of research which required discussion. This study used the theories that were obligatory in

\begin{footnotesize}
\begin{itemize}
\item \textsuperscript{91} Ian McGreer et al., “The z = 5 Quasar Luminosity Function from SDSS Stripe 82 Observations Reported here were obtained at the MMT Observatory, A Joint Facility of the Smithsonian Institution and the University of Arizona. This Paper also includes Data Gathered with the 6.5-M Magellan Telescopes Located at Las Campanas Observatory, Chile,” The Astrophysical Society (Draft Version April 23, 2013): 1.
\item \textsuperscript{93} Yue Shen, “The Mass of Quasars,” Astronomical Society of India 41, no. 1 (February 2013):102.
\end{itemize}
\end{footnotesize}
providing the data necessary and it examined other hypothesis and assumptions if they would provide the information essential (even if contradictory). All of the authors of diverging suppositions provided sufficient observational support or theoretical evidence in defense of their conclusions. In some situations the differences were minor changes to the general theory and inconsequential for this study. In other cases they presented observations outside the scope or limitations of this research, or provided a theory that did not allow its use (offering insufficient information essential in this work). When multiple methods would afford useful results they were all presented and used. If different values were available, (like $0.1 \text{ Edd}_{\text{Lim}}$ verses $1.0 \text{ Edd}_{\text{Lim}}$ for the mass calculations) those used were the ones observed in similar cases. Then the reasoning was mentioned in the report and applied only when found fundamental for the subject in question as defined by other researchers.

---

CHAPTER 4: FINDINGS

Results

The results of the research were inconclusive; however, the data were highly supportive of the direct collapse hypothesis. Five of the six quasars studied had ratios within 36% of that expected and observed in Henize 2-10. Three of the six high redshift QSOs were within 49% of the expected ratio as shown in Figure 21. When compared to the Milky Way’s velocity dispersion\(^98\) and known mass diameter ratio,\(^99\) the mean value was only 15.6% of that expected. Thus the total outcomes clearly favored the direct collapse model nearly 2.5 to 1.

---


The first three quasars were those identified as in the best QLF\textsuperscript{100} and peak formation region\textsuperscript{101} (QSOs which occurred between $2 < z < 3$).\textsuperscript{102} The second three quasars were the study’s high redshift QSOs at $z > 3$ that presented the best results (closest to the expected value).

**QSO #1**

QSO #1 (J141421.53+522940.1) at $z = 2.019$ must be considered an outlier for this study. It had a mass that was only 1.14% of the mean of the other five QSOs, while maintaining the highest velocity dispersion of all those measured. Its galactic size was comparable to that of the Milky Way with nearly the largest galactic diameter ($1.22 \times 10^5$ ly) of all QSOs studied. As shown in Figure 22 it was located in the peak $z$ region and had the greatest angular dimensions.

![Figure 22. J141421.53+522940.1 from SDSS Data\textsuperscript{103}](image)


\textsuperscript{102} Ibid, 1.

**QSO #2**

Quasar J141647.20+521115.2 (Figure 23) was another maximum redshift zone QSO \((z = 2.151)\), which had a very high \(\sigma\) at 2,683.6 kms\(^{-1}\). This provided an extremely large galactic diameter \((1.25 \times 10^5 \text{ ly})\); however, its BH mass \((1.45 \times 10^6 M_\odot)\) was closer to the rates expected of high redshift QSOs. Its values were comparable to those anticipated and was not categorized as a research outlier. Unfortunately it provided poor results and was outside the desirable zone.

![Figure 23. J141647.20+521115.2 from SDSS Data](http://skyserver.sdss3.org/dr10/en/tools/chart/image.aspx) (accessed October 12-14, 2014).

---

QSO #3

Quasar J094534.03-004117.8 (Figure 24) approached the zone of interest \((z = 2.828)\), and its data were more closely aligned with those in the high redshift zone. With a BH mass of \(1.08 \times 10^6 M_\odot\) it also had a lower \(\sigma\) (1922.7 km s\(^{-1}\)). This produced a galactic size of \(1.02 \times 10^5\) ly which while smaller, did not significantly aid the study.

Figure 24. J094534.03-004117.8 from SDSS Data

---

**QSO #4**

At $z = 2.995$ QSO J141904.09+495033.2 (Figure 25) was the first high $z$ value quasar and provided one of the best fits to the Henize 2-10 data as presented in Table 4. With a black hole mass over $3.06 \times 10^6 M_\odot$ it still had high velocity dispersion ($2339.1 \text{ kms}^{-1}$); however, as expected, the galactic size was reduced to $87,200$ light years. These promising data were within $53\%$ of the Henize 2-10 values, while far from the Milky Way’s rates at only $11\%$.

---

**Figure 25.** J141904.09+495033.2 from SDSS Data

---

**QSO #5**

Quasar J234147.26+001551.9 (Figure 26) was within the target area at \( z = 3.958 \). It had the lowest dispersion of all the sample QSOs (1,833.7 kms\(^{-1}\)) and the smallest galactic size (51,200 ly). Nonetheless it had a relatively small black hole at \( 1.24 \times 10^6 M_\odot \); therefore, its ratio remained low, but well within the expected range and far from that of the Milky Way.

*Figure 26. J234147.26+001551.9 from SDSS Data*\(^{107}\)

---

**QSO #6**

At $z = 5.092$, quasar J120441.73-002149.6 (Figure 27) provided the best supporting evidence for the hypothesis of direct collapse as seeds for QSO black holes. It had a SMBH mass of $2.20 \times 10^6 M_\odot$ with a relatively small galactic size of 56,100 ly. Once again $\sigma$ was large (2,405.8 kms$^{-1}$), but the ratio between Henize 2-10 and QSO #6 was 58.8% and far from the Milky Way ratio of 9.4%.

---

**Figure 27.** J120441.73-002149.6 from SDSS Data

---

CHAPTER 5: SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

Summary

The explanation of how supermassive black holes, at the center of distant quasars, became so large so early was better understood. The hypothesis that the direct collapse of molecular clouds provided the seed black holes was found to have value. Quasar bulge masses, based upon flux density and luminosity distance, related well to black hole mass. Galactic size was determined and a black hole mass to galactic size ratio fit very well for some quasars. When the entire sample of subject black holes and associated galaxy sizes were compared to the Henize 2-10 and Sgr A* ratios the results were less conclusive. This was primarily due to the large redshift sample differentials; however, when those QSOs with redshifts > 3 were examined independently, they produced convincing outcomes. Those values were within 49.2% of the target data, while well outside the limits of the Milky Way ratio (< 11%). These two outcomes strongly suggested the hypothesis had merit.

Recommendations

One of the central principles of the direct collapse hypothesis (as presented in the Henize 2-10 observations) was that black hole rotation remained minimal. All of the observed quasars had velocity dispersion rates far in excess of the Milky Way and the target Henize 2-10 galaxy. Therefore it is recommended that further research be undertaken so as to evaluate the mass - $\sigma$ relationship of specific QSOs and how low $\sigma < 100kms^{-1}$ effects SMBH growth in non QSO galaxies.

Furthermore, another essential factor was the discovery of quasars with good spectrum at the target distances ($z > 4 – 5$): The greater the redshift the better. If such quasars could be examined, with the required data, the conclusions of this study might be irrefutable.
Investigation of the $\sigma$ factor should be undertaken. This variable is an important part of galactic size and the SMBH’s sphere of influence data. Since it is so important for QSO SMBHs and not as important for Henize 2-10, it needs to be investigated so as to determine its ultimate significance with regard to the implications of direct collapse.

Conclusions

The data from the first three quasars were unconvincing, but expected. QSOs at these redshift values have had sufficient time to accrete matter so as to grow via the standard model of galactic formation and limited the conclusions of the study. These galaxies were comparably large (when associated to current $z = 0$ galaxies) and have had adequate time to expand (at their high velocity dispersion rates) such that their data did not support nor refute the hypothesis. However, the last three QSOs were far more compelling. At $3 < z < 5$, the data suggested that the sizes of the black holes, compared to the sizes of the associated galaxies, were as large as expected. Notwithstanding the limitations mentioned in this report and the alternative hypothesis of super Eddington limit accretion rates for seed black holes generated by the standard model of galactic formation; these quasars presented results that strongly supported the direct collapse hypothesis.

One of the findings of this study was the role velocity dispersion plays in this postulation. The dwarf galaxy Henize 2-10 had a SMBH which had little velocity dispersion as did the relation SMBH located at the center of the Milky Way (Sgr A*). These galaxies were not quasars and low $\sigma$ was expected; however the research galaxies were quasars and the results indicated that SMBHs existed in relatively small galaxies even with high $\sigma$. It was expected that at high redshifts the universe was smaller and objects more compact; however, the dispersion values

---

could allow for larger galaxies (at $z < 5$) as calculated by the data generated by McGreer et al.\textsuperscript{110} This study has shown that with high velocity dispersion, galaxies can remain small while black holes grow to SMBH status ($> 1 \times 10^{6} M_{\odot}$). The result presented in this paper implied that the consequence of small $\sigma$ (as proposed by Reines et al.)\textsuperscript{111} may not have had the significance as those authors suggested.

\textsuperscript{110} Ian McGreer et al., “The $z = 5$ Quasar Luminosity Function from SDSS Stripe 82 Observations Reported here were obtained at the MMT Observatory, A Joint Facility of the Smithsonian Institution and the University of Arizona. This Paper also includes Data Gathered with the 6.5-M Magellan Telescopes Located at Las Campanas Observatory, Chile,” The Astrophysical Society (Draft Version April 23, 2013): 4.

BIBLIOGRAPHY


Gonzalez, Valentino, Ivo Labbe, Rychard Bouwens, Garth Illingworth, Marijn Franx, Mariska Kriek and Gabriel Brammer. “The Stellar Mass Density and Specific Star Formation Rate


McGreer, Ian, Linhua Jiang, Xiaohui Fan, Gordon Richards, Michael Strauss, Nicholas Ross, Martin White, Yue Shen, Donald Schneider, Adam Myers, Niel Brandt, Colin DeGraf, Eilat Glikman, Jian Ge and Alina Streblyanska. “The z = 5 Quasar Luminosity Function from SDSS Stripe 82 Observations Reported here were obtained at the MMT Observatory, A Joint Facility of the Smithsonian Institution and the University of Arizona. This Paper also includes Data Gathered with the 6.5-M Magellan Telescopes Located at Las Campanas Observatory, Chile.” The Astrophysical Society (Draft Version April 2013): 1-14.


Walter, Fabian, Dominik Riethers, Pierre Cox, Roberto Neri, Chris Carilli, Frank Bertoldi, Axel Weiss and Roberto Maiolino. “A Kiloparsec-scale Hyper-starburst in a Quasar Host Less

