The Variability of "Normal" Galactic Nuclei

Jacob Nelson

A senior thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Bachelor of Science

J. Ward Moody, Advisor

Department of Physics and Astronomy

Brigham Young University

April 2011

ABSTRACT

The Variability of "Normal" Galactic Nuclei

Jacob Nelson
Department of Physics and Astronomy
Bachelor of Science

It is likely that the nuclei of all galaxies contain black holes. If matter falls in toward the black hole, some of it can be heated an ejected creating an active nucleus. Astronomers monitor the infall and estimate black hole masses by measuring variations in the brightness of the nuclei. If all galaxies contain nuclear black holes, then all of them should vary in brightness, not just those termed active. The variability of these normal galactic nuclei will be less since a higher variability would have placed them in the active class. Using data obtained with a robotic telescope from 2004 to 2007, I investigated the variability in their nuclei.

Keywords: [A comma-separated list of descriptive words for search purposes]

ACKNOWLEDGMENTS

I would like to thank Dr. J Ward Moody for his invaluable direction and consistent support. Also, thanks to Dr. Mike Joner for creating the script which reduced the Tenagra data. Thanks to the Physics and Astronomy Department of Brigham Young University for the data obtained with the Tenagra telescope. The Tenagra data has been the backbone of my senior project.

Contents

Chapter 1

Introduction

The Hubble Space Telescope site estimates there are hundreds of billions of galaxies in the universe [1]. Astronomers believe that about 10% of these are active galactic nuclei (AGNs). AGNs were first studied by Soviet-Armenian physicist Prof. Victor Ambartsumian in the early 1950s [2]. Today, AGNs are widely studied. AGNs are compact and extremely luminous. The AGN model consists of a super-massive black hole containing from a million to ten billion solar masses with an accretion disk of matter orbiting and falling into the black hole. The accretion disk can potentially convert potential and kinetic energy to radiation very efficiently. The matter in the accretion disk becomes extremely hot as it nears the black hole and gives off high-energy emissions. These emissions are the "activity" we measure coming from AGNs.

We expect all AGNs with sufficient matter near its black hole to display similar characteristics. There are several possible exceptions however. First, large amounts of interstellar gas and dust can obscure our view of the radiated energy, making the galaxy seem less active than it truly is. Second, there may not be much accreting matter. This is the case when it comes to viewing the black hole we believe to be at the center of our own Milky Way galaxy. Third, the efficiency of the super-massive black holes (SMBH) to convert matter to energy may not apply in all cases. There are solutions to accretion equations that allow for "radiatively inefficient" accretion [3].While these

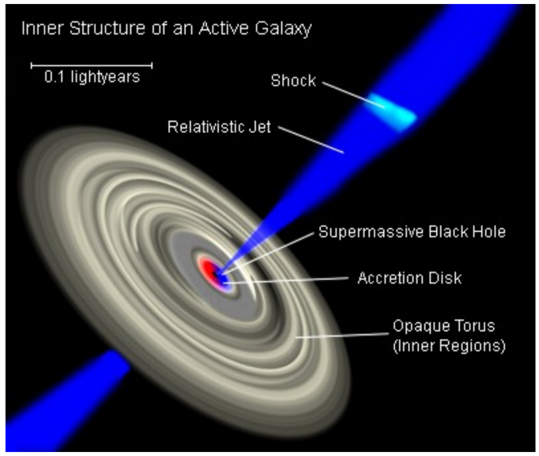

Figure 1.1 An artist's rendition of a close up of an AGN and its constituent parts [5].

two matters complicate the issue of figuring whether a galaxy harbors a SMBH, they do not make it impossible to determine whether there are high levels of activity there. Some accretion disks also produce jets of matter that flow outward from close to the disk in opposite directions. These jets are known as radio jets due to their high percentage of energy radiated in the radio wavelength. However, the jets have been observed to radiate even high energy gamma rays [4].

AGNs are found in many different objects. These include quasars, blazars, radio galaxies and LINERS. A quasar is a very energetic and distant AGN. They are believed to be among the most energetic and luminous objects in the universe. A blazar is a quasar with the radio jets facing toward the earth. In other words, we seem to be looking down the jet when we view it. A radio galaxy is similar to a quasar except for the exceptionally high luminosity in the radio wavelength. Some galaxies contain low ionization nuclear emission regions, known as LINERS. LINERs are characterized by optical spectra that reveal that ionized gas is present but the gas is only weakly ionized (the atoms are missing relatively few electrons). LINER nuclei, which are present in many nearby galactic bulges, may be the manifestation of low-rate accretion around SMBHs [6]. However, it is unclear whether the compact nuclear sources present in many LINERs are clusters of massive stars, rather than being related to the accretion process. We are not 100% sure of the

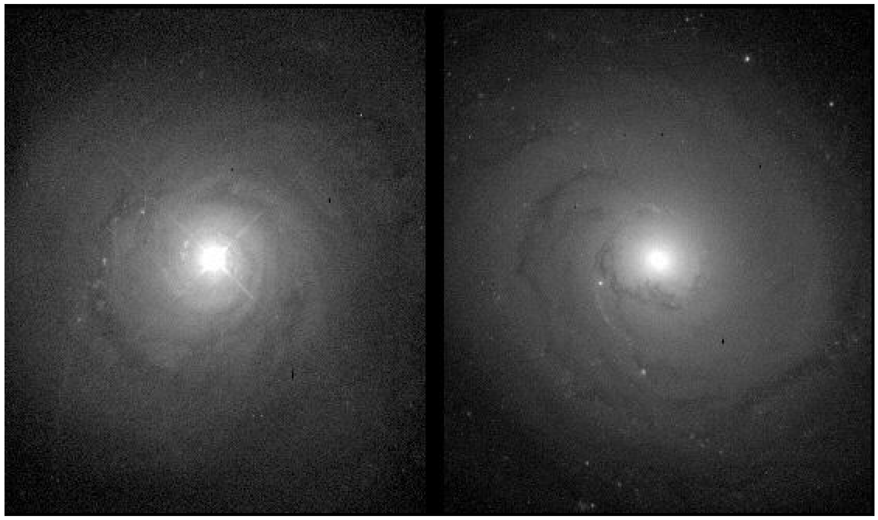

Figure 1.2 Comparison of two similar galaxies under the same brightness contrast. NGC 5548 (left) hosts an AGN while NGC 3277 (right) is classified as a normal galaxy. Notice the marked difference in nucleus luminosity [7].

energy source responsible for exciting the gas. LINERS are classified as AGNs, though they are thought to be AGN with lower accretion rates, and hence, we detect less "activity" in them. Most galaxies are classified as normal since they do not display the distinct characteristics found in AGNs.

We are still learning much about the observed activity in AGNs, but there are defining phenomena that separate AGNs from the rest of the galaxy in the universe. First, AGNs are extremely compact and luminous compared to their host galaxies. If the galaxy is near enough, the flux from the AGN can rival that of the entire galaxy in optical images [8]. Second, AGNs typically display a broadband continuum emission. The fraction of power that emerges from AGNs is surprisingly spread out over the entire spectrum (see Fig. 1.3). Normal galaxies emit a much larger percentage of their energy in longer wavelengths. Third, AGNs have prominent emission lines. This stands in contrast to normal galaxies whose emission lines are relatively weak and mostly in absorption. Fourth, AGNs vary in luminosity more than normal galaxies, though the typical amplitude over a few years is 10% [8]. My research focuses only on the variability of galactic nuclei.

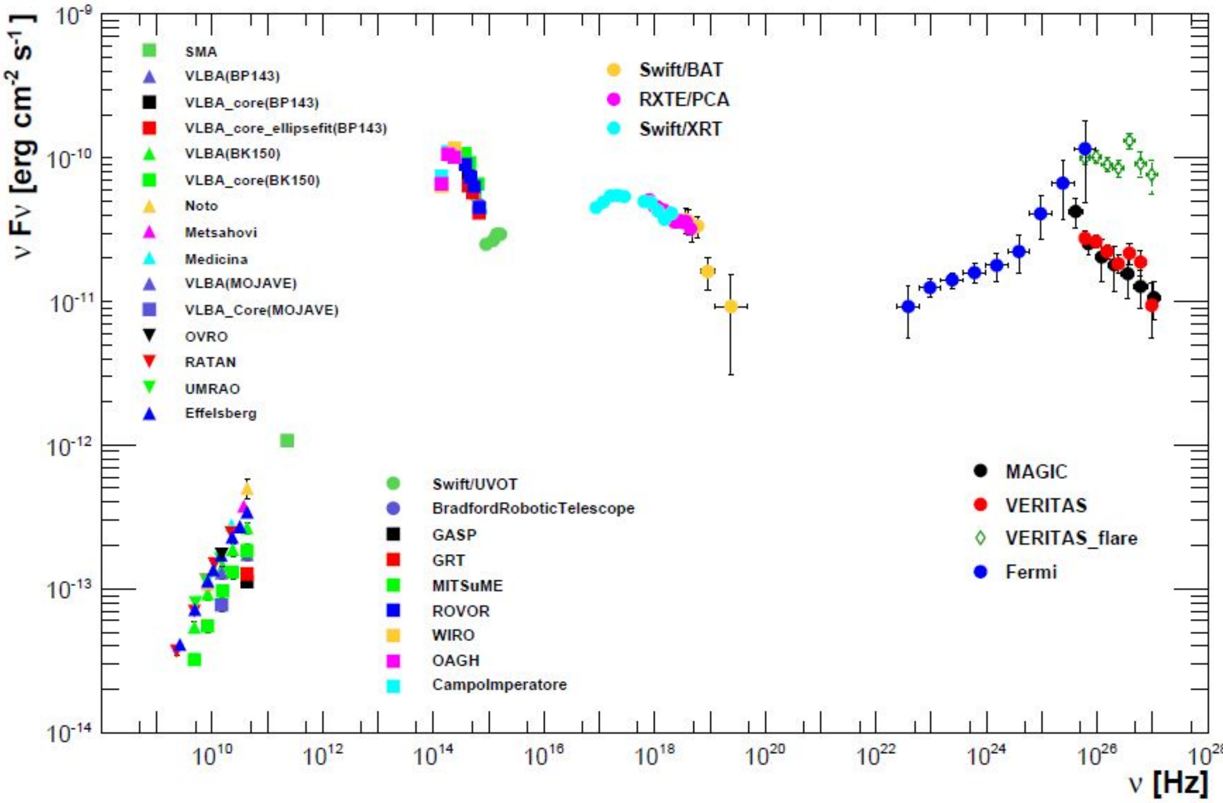

Figure 1.3 Range of frequencies emitted from Mrk501 observed with various telescopes [9].

1.1 Galaxies of Interest

The purpose of this research is to look for long-term (on the scale of a few months) variability in the galactic nuclei, similar to what has been found in Seyferts and quasars. Variability is one signature of an active black hole. I am looking for evidence of black holes in two suspect classes, namely LINERs and normal galaxies. My thesis consists of data from three normal galaxies: M33, M51, and M101 and two LINERS: M81 and M94. The energy signature found in AGNs has been shown not to radiate from stars. However, it is possible that not all galaxies harbor a black hole in the nucleus since only a small percentage of galaxies display significant activity. Galaxies that show little or no activity must be researched further to discover why.

1.2 Background

Figure 1.4 The Triangulum constellation harbors this face on view of M33. Also known as NGC 598, M33 is over 50,000 light years in diameter, third largest in the Local Group of galaxies [10].

M33 is classified as a late-type Sc spiral, consistent with its almost nonexistent bulge. The nucleus of M33 is very compact, reaching a central mass density of several million solar masses per cubic parsec. While such high nuclear densities might lead to conclusions of a SMBH, Merrit et al.

find no evidence for a central rise in stellar velocities that would indicate the presence of a SMBH in the nucleus [11]. Galaxies that contain bulges appear to contain black holes whose masses correlate with the velocity dispersion of the bulge. Gebhardt et al. show that no corresponding relationship applies in the pure disk galaxy M33. Hubble Space Telescope photometry and Space Telescope Imaging Spectrograph data agree that models work best if the central black hole mass is zero while it allows for an upper limit of 1500 solar masses [12].

M51, also known as NGC 5194, is a Sc spiral galaxy, classified as normal. Its proximity, combined with low-level nuclear activity have made it a popular target for observation [13]. Ford et al. showed that the morphology and high gas velocities are indicative of radio jets. However,

Figure 1.5 M51 is a classic spiral galaxy. Its smaller companion is well behind M51. We believe this "Whirlpool Galaxy" gets its unique look from interaction with its companion galaxy [14].

they also showed that much of this activity originates outside the nucleus, specifically in a cloud to the south and a ring of emission line regions to the north of the nucleus. They do not believe there is a non-stellar source such as a SMBH present because they showed that the emission line gas is probably excited by shocks rather than photoionization [15].

M81, also known as NGC 3031, is the nearest example of a LINER. It also shares charac-

Figure 1.6 Similar in size to the Milky Way, M81 is one of the brightest galaxies in our sky. This deep image reveals detail in the bright, active core [16].

teristics with radio galaxies and quasars, including that of a slightly inverted synchrotron radiation [17]. Based on resolved stellar kinematics the mass estimate of the central object is 6e7 solar masses [18]. It contains a variable point-like X-ray source that has been shown to vary significantly on a short scale and has also been shown to vary on a longer timescale (from days to a few years) [19].

Figure 1.7 The bright, active core of spiral galaxy M94. Astronomers believe the bright core is partially due to the high formation of stars near the center which are then pushed out due to the spiral arms [20].

M94, also known as NGC 4736, is a Sab galaxy and classified as a LINER. It has a very high central surface brightness. Bright X-ray sources have been detected in the central region of M94. The brighter source appears to be at the nucleus, suggesting that it may be the non-stellar source that powers the emissions. Feldkhun and Braun believe evidence is strong for the presence of a non-stellar continuum source at the galaxy nucleus, similar to those found in Seyfert galaxies [21].

M101 is a giant Sc galaxy classified as a normal galaxy. It has active star formation ongoing in the nuclear region [22]. Roming et al. found evidence for periodic outflow from the nucleus suggesting it is active [23]. But Kormendy et al. find no evidence for a black hole more massive than 1e5 solar masses [24]. There is some evidence for activity but only at a low level.

Figure 1.8 M101, also known as the Pinwheel Galaxy lies 22 million light years away. It is still debated whether it hosts an AGN [25].

Chapter 2

Analysis

The data used was obtained with the Tenagra 32" robotic telescope located in Arizona. The Tenagra telescope takes 14.8 square arcminutes images and has 24 micron pixels. The plate scale is 0.87 arcminutes/pixel. This data was taken from April 2004 to April 2007.

Standard IRAF procedures were used to calibrate the frames. Dr. Mike Joner created the script

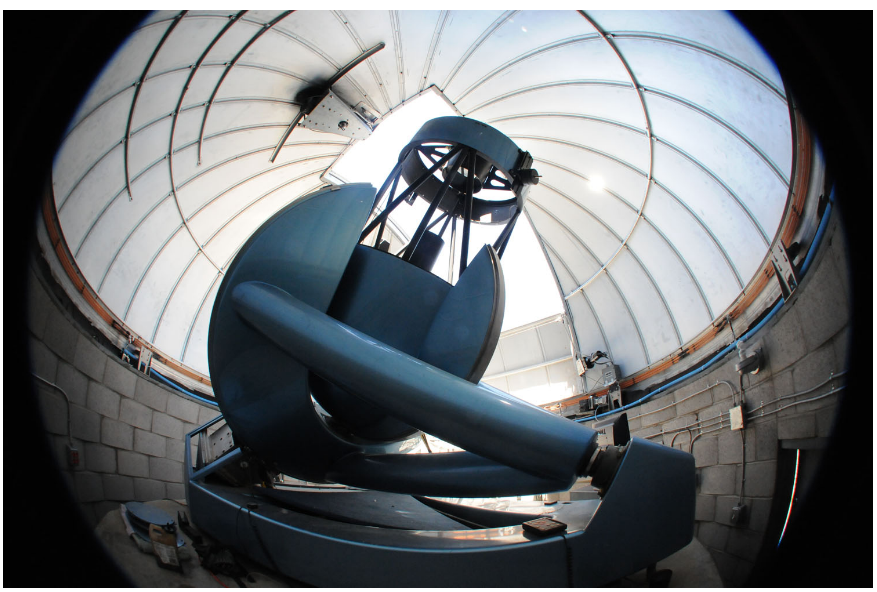

Figure 2.1 The 32" Tenagra robotic telescope [26].

that reduced the Tenagra data. Mira was used in performing the differential photometry because I felt it was more user-friendly than IRAF.

2.1 Error Analysis

I measured variability by charting the relative changes in magnitude in the galactic nucleus overtime. There are two types of photometry I could use to track the variability: differential and absolute. Absolute photometry is the measurement of the apparent brightness of an object on a standard photometric system. These measurements can be compared with other absolute measurements obtained with different instruments. In general, differential photometry can be done with the highest precision, while absolute photometry is less precise. If the standard stars cannot be observed in the same frame as the target, the target must be observed under photometric conditions. For this research, I am only concerned with relative changes. The easiest and most accurate way to test for this variability is to use differential aperture photometry.

The basic idea behind differential photometry is to compare a changing galactic nucleus with the unchanging starlight in the same field of view. The first step is to pick a few stars in the field of view of the galaxy, distributed throughout the frame as much as possible. These are considered standard stars, since the assumption is they are unchanging in magnitude. I used four standard stars for each galaxy with the exception of M81, for which I used five. Next, an appropriate aperture size had to be chosen for the stars and galactic nucleus. There are two apertures I needed to consider to create the best data possible: first, the sky annulus, or the area between the two outer apertures, and second, the aperture radius for the star or galactic nucleus. To create the best sky annulus count, which will be subtracted from the star, it was important to choose stars that were not too close to other stars or the galaxy. If another star is in the sky annulus, it will increase the counts to more than they truly are, creating an instrumental magnitude that is less than it should be. The

Galaxy	Aperture Size	Data Points	Nights
M33	6.96"	26	7
M51	4.35"	106	22
M81	6.09"	136	25
M94	4.35"	22	8
M101	5.22"	102	19

Figure 2.2 Table of aperture size, total data points taken in filters B, V, and R and number of nights of data.

same happens if the chosen standard star is on top of too much galaxian light. Each galaxy has a different aperture setting that, once decided, is fixed for all the frames. These sizes were chosen based on a good visual fit of the aperture around the stars along with a clean fit of the radial profile given by Mira. The aperture sizes are given for each galaxy in Fig. (2.2). Using those apertures, the software then calculated an instrumental magnitude (M) by summing the counts in the aperture (S), subtracting the sky counts and plugging it into the following equation.

$$M = -2.5 \log(\mathrm{S}) \tag{2.1}$$

To find a comparison star, I simply needed to find the star that varied the least compared to the remaining stars. Each comparison star I used was the one that had the smallest standard deviation in its instrumental magnitude. The standard deviation equation I used in this case and for calculating error in the next section is the following.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{2.2}$$

After subtracting the instrumental magnitude of my chosen star from the galactic nucleus, I am left with a residual. The residual of each galaxy is what I used to look for variability in each of the five galaxies. They are the values I used to create the graphs found in the results section. This process was done for all galaxies with the exception of M51. The standard stars used for M51 varied on a greater scale, though not always in sync with one another. Using a star that varies too much as a standard skews the galaxy variability, so that the variability may be coming from the star rather than the galaxy. To minimize errors by choosing one star, I averaged all of them together and used that value as the comparison star.

Overall, differential photometry works very well on point objects, such as stars, since where the star ends is easily distinguishable (as long as the seeing is acceptable). However, differential photometry has its problems when trying to implement it on extended objects, such as galaxies. With galaxies, it is more difficult to decide an aperture size since the gradient of light is over an extended area. If the aperture is too small, many photon counts will be omitted. If the aperture is too big, the nuclear count is diluted by bulge light. The other problem with performing differential photometry when there is a galaxy on the frame is background photon counts. Stars must be chosen to avoid too much contamination from galaxian light though this is not always possible. Even with its drawbacks, I decided that differential photometry would be accurate enough for finding differential variability in galaxies.

The error bars located on each data point take into account both the error due to variation of the standard stars and the instrumental error of the CCD since it cannot count or readout photons perfectly. To calculate the error due to an imperfect standard star or stars, I first calculated the mean of each star and subtracted it from each star respectively. These values are my residuals. I calculated the standard deviation from the residual values of all the stars from each night. This standard deviation is the value of the star error. The instrumental error is calculated solely from the galaxy count given by Mira while doing the photometry. This error is calculated with Poisson statistics. The error is simply the square root of the counts.

Once the error is found, we need to add and subtract it to the original count value to get the upper and lower limits of the error. However, the upper and lower limits are still in counts and are not magnitudes. To convert to the magnitude scale, I plugged the limits into Eq. (2.1). Then

I subtracted the two magnitude values to give me the instrumental error. For the most accurate statistics, if two measurements are independent and subject to random uncertainties, they should be added in quadrature [27]. To add in quadrature is to square the two values, add them, and then take the square root. Quadrature addition was performed with the two sources of error for each night of data so that the magnitude of the error bars vary, according to the statistics of each night.

Chapter 3

Results

3.1 M33

Data for M33 are shown in Fig. (3.1). I did not expect M33 to display much variation in magnitude since it is classified as a normal galaxy. It varied only about 0.025 magnitude in all three filters over a few months with essentially no correlation. It is possible that these variations in magnitude are from factors having nothing to do with a SMBH, such as high-mass stellar variability in star formation regions. My data agrees with earlier findings that M33 does not host an AGN and may not have a central SMBH.

3.2 M51

Data for M51 are shown in Fig. (3.2). There is little variability from JD 39105 to JD 39152, at which point, all three filters rise 0.05 magnitude. Afterward, the magnitude continues as it was before. Since the rise is found in all three filters, I am confident it is true and accurate. More detailed research outside of variability measurements must be done on M51 to discover where this variability is coming from and to determine if it is non-stellar. M51 is a good candidate to research further to determine whether it is possible that even normal galaxies harbor SMBHs.

3.3 M81

Data for M81 are shown in Fig. (3.3). One possible outcome of my observations was to determine the level of variability that can be expected from LINERs. M81 data shows that we can expect very little. However, the data also give evidence to support the LINER classification of M81. There is a time lag in the continuum between H_α and H_β. A small decrease in magnitude peaks at JD 39086 in the V filter. This same decrease in magnitude also occurs in the R filter but at JD 39091, about five days later. This is typical of what occurs in LINERS and is expected from a galaxy classified as a LINER. It is a small evidence of activity in the M81 nucleus. The B filter does contain the same decrease in magnitude but it may be from a higher signal-to-noise ratio.

3.4 M94

Data for M94 are shown in Fig. (3.4). M94 has fewer data points than the other galaxies and was only taken in two filters, making it hard to conclude much about the variations. While other types of studies support evidence for a massive non-stellar source, this study in variability does not. The R filter obviously shows a marked decrease in magnitude though it does not show up in the B filter. Two images that were taken on the same night are 0.25 magnitude different which is an incredible jump, causing me to be suspicious of the data validity. The data point before also has error bars that are much bigger than the other data. While it is possible that this is evidence of an extremely active object in the nucleus, it is extremely unlikely. It is more likely that there was a cosmic ray hit or problems with the calibration or CCD during those nights. Overall, M94 shows only 0.03 magnitude variation which is little for being classified as a LINER. This data does not support the notion of an central, active SMBH. As always, it is possible we have observed it during a quiescent period.

3.5 M101

Data for M101 are shown in Fig. (3.5). M101 shows only 0.025 magnitude or less variations in all three filters with variability that is completely uncorrelated. This is the least variability out of all five galaxies studied. If there is evidence for a SMBH as some claim, it is possible that it is dying, has used up all of its energy sources, or has been observed during a quiescent period. This data is evidence that M101 does not harbor a SMBH, or at least one that is active.

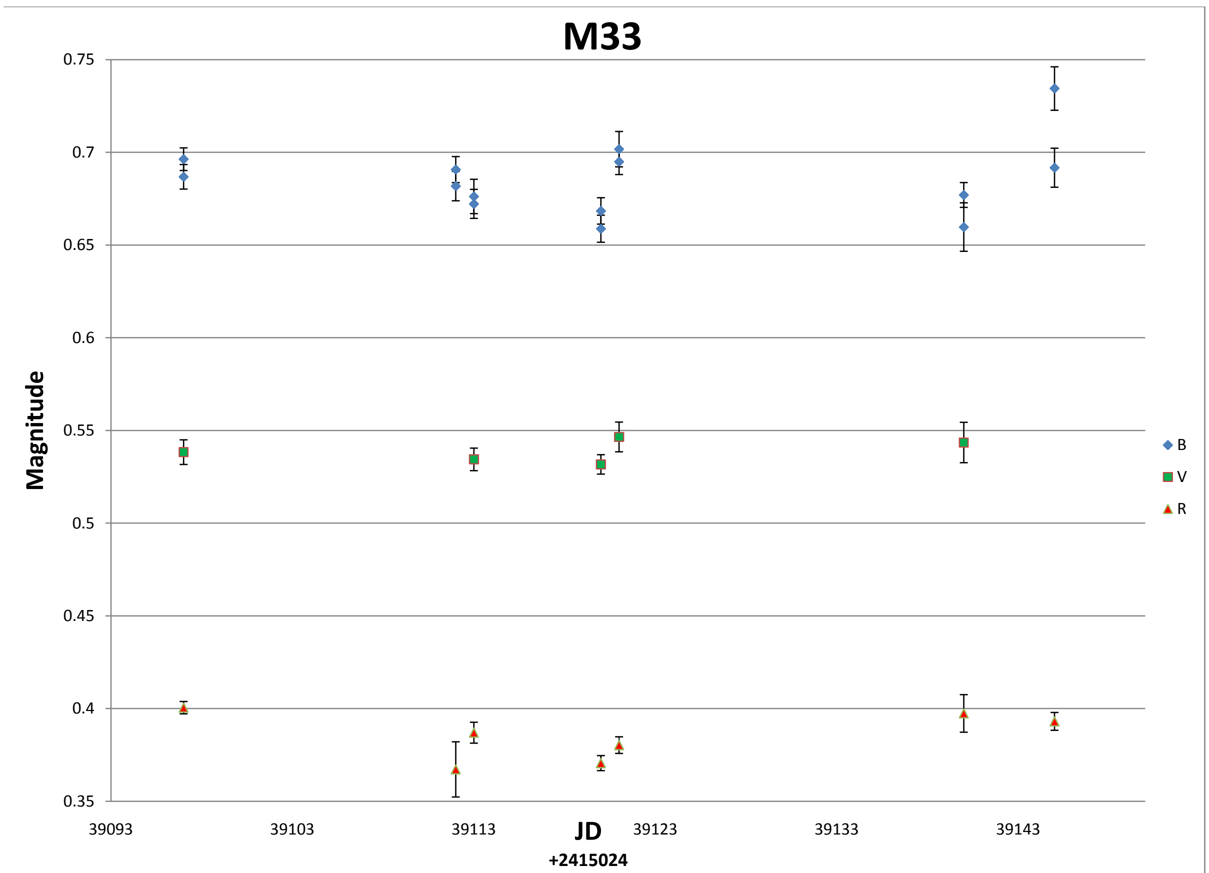

Figure 3.1 Instrumental differential magnitude of M33 nucleus.

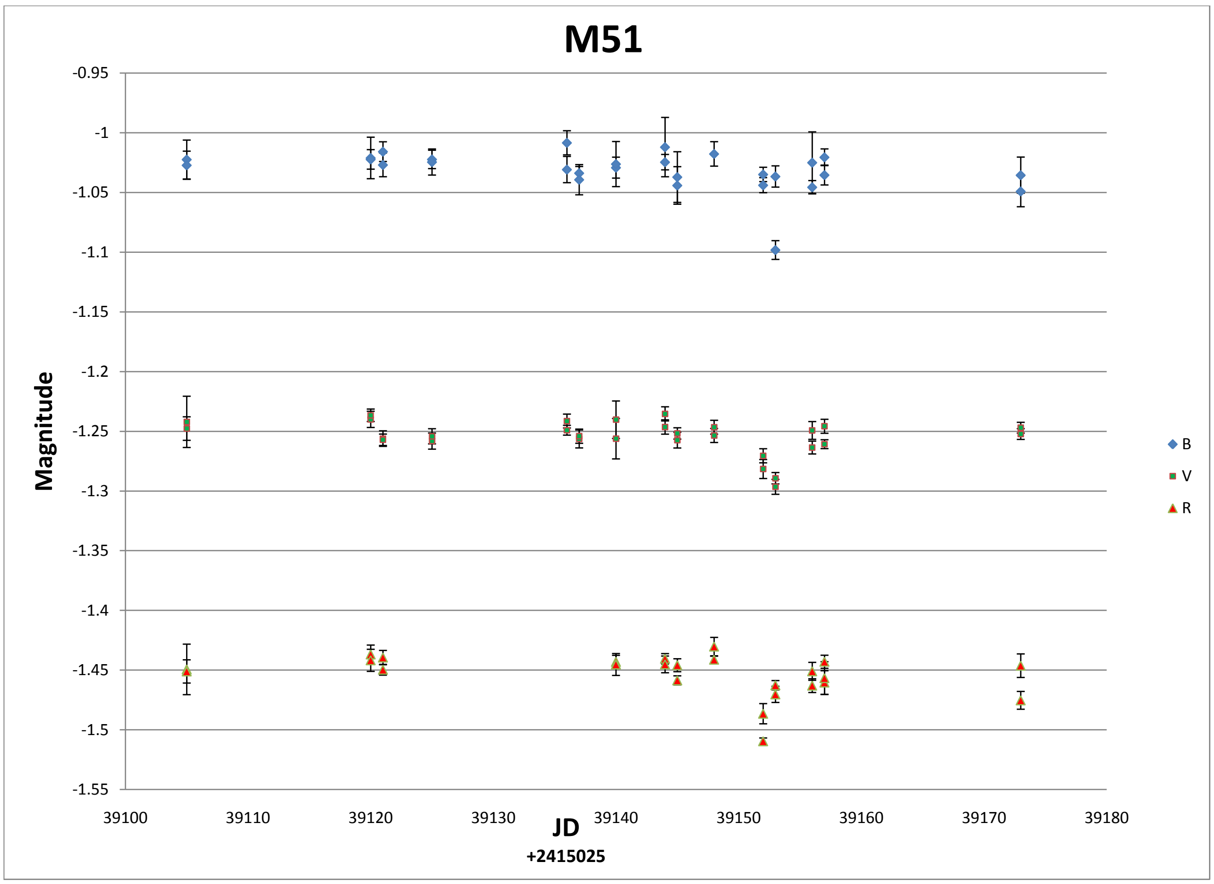

Figure 3.2 Instrumental differential magnitude of M51 nucleus.

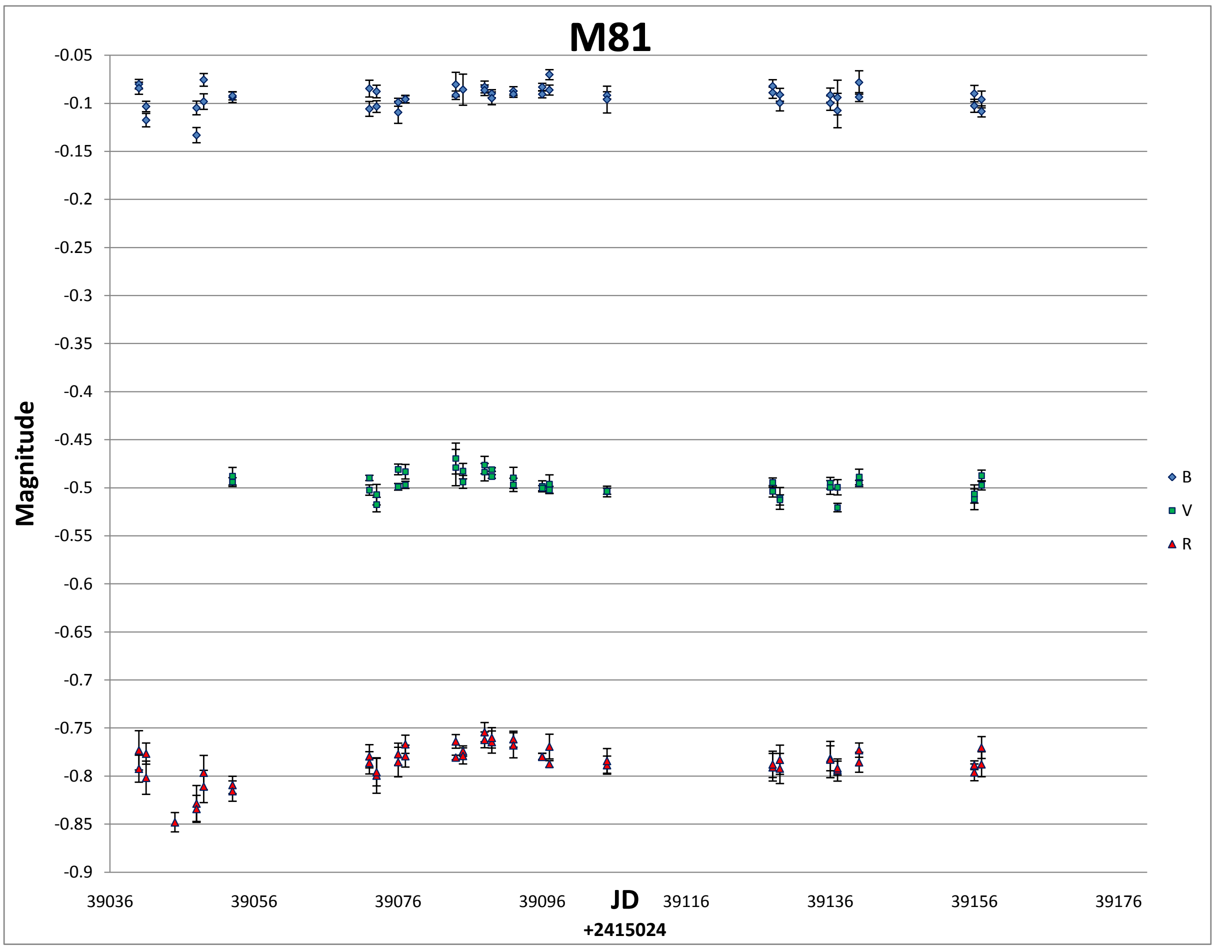

Figure 3.3 Instrumental differential magnitude of M81 nucleus.

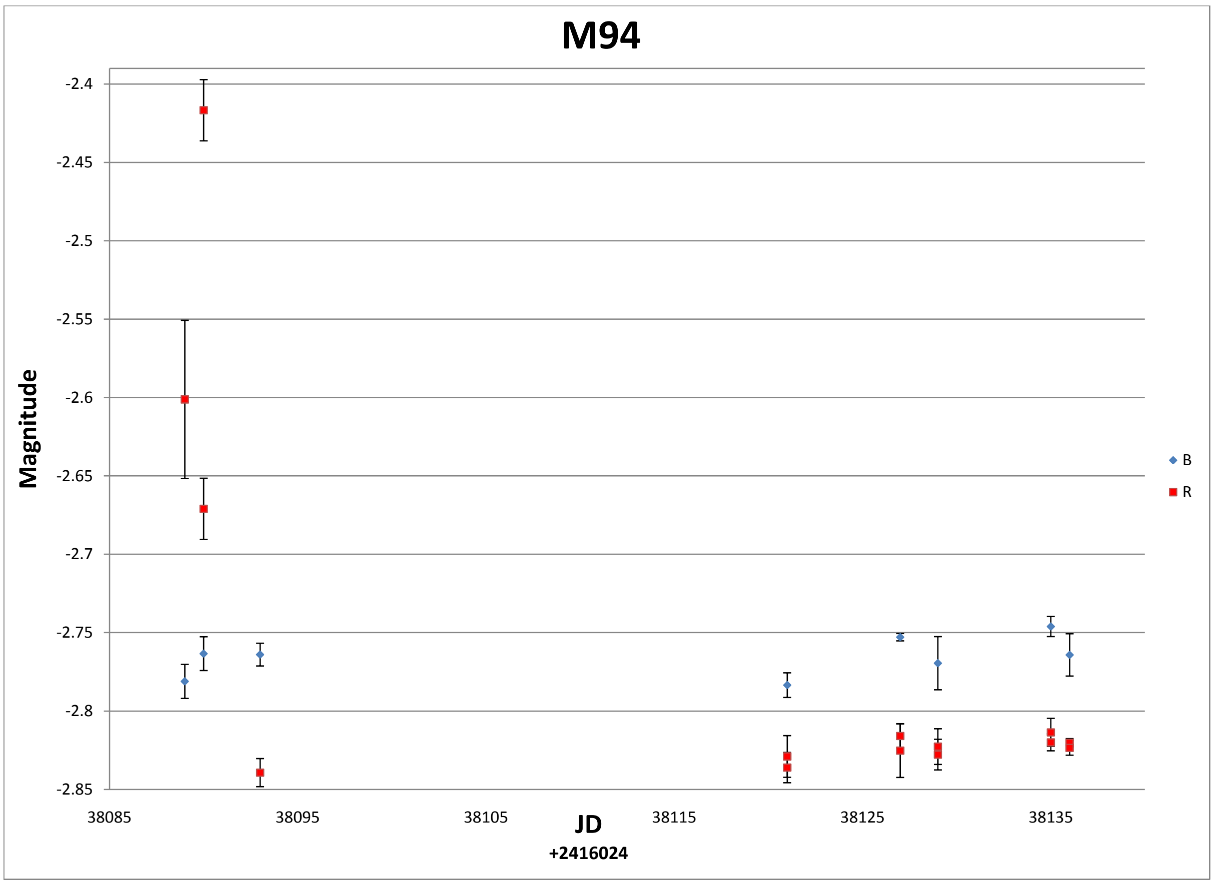

Figure 3.4 Instrumental differential magnitude of M94 nucleus.

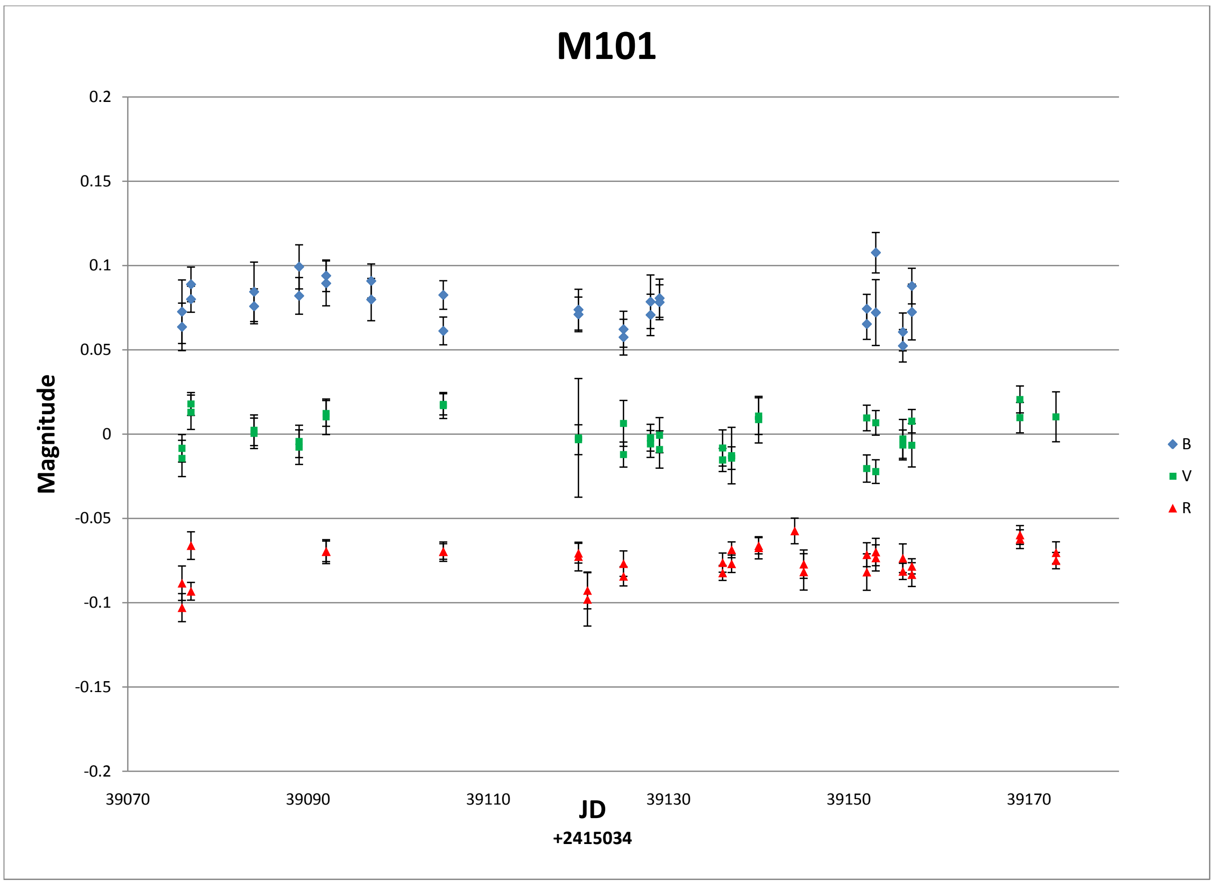

Figure 3.5 Instrumental differential magnitude of M101 nucleus.

Chapter 4

Conclusion

I have observed five galaxies, two LINERs (M81 and M94) along with three normals(M33, M51, and M101). I conclude that one LINER, M81, and one normal, M51, are active and are good candidates for harboring a SMBH. I disagree with previous studies such as those done by Ford et al. [15] that M51 does not host a SMBH. I believe it is necessary to carry out a study of the same galaxies over a few years with a larger data sample to find out the typical variability of each type of galaxy. I cannot discredit the hypothesis that every galaxy contains a SMBH in its center. My studies do seem to imply that if the timing of the observation is correct, we may be able to find high energy, non-stellar emissions coming from every galaxy, whether a normal, LINER, or AGN. If this implication is true, then variability studies must make way for a more certain method for discovering SMBHs.

Bibliography

[1] NASA, http://hubblesite.org/ (Accessed April 5, 2011).

[2] The Hot Star Newsletter (1996).

[3] R. Narayan and I. Yi, "Advection-Dominated Accretion: A Self-Similar Solution," Astrophys. J. p. 428 (1994).

[4] S. Writers, "INTEGRAL Discovers Gamma Rays Originating from Black Hole Jets," http://www.spacedaily.com/reports/INTEGRAL_Discovers_Gamma_Rays_Originating_From_Black_Hole_Jets_999.html (Accessed April 12, 2011).

[5] "The Inner Structure of an AGN," http://en.wikipedia.org/wiki/Relativistic_jet (Accessed April 13, 2011).

[6] D. Maoz, N. M. Nagar, H. Falcke, and A. S. Wilson, "The Murmur of the Sleeping Black Hole: Detection of Nuclear Ultraviolet Variability in LINER Galaxies," Astrophys. J **625,** 699–715 (2005).

[7] H. Archive, http://www.astr.ua.edu/gifimages/ngc5548.html (Accessed April 5, 2011).

[8] J. K. Krolik, *Active Galactic Nuclei* (Princeton University Press, New Jersey, 1999).

[9] A. Abdo *et al.*, "Insights Into the High-energy Gamma-ray Emission of Markarian 501 from Extensive Multifrequency Observations in the Fermi Era," Astrophys. J. **727,** 129–155 (2011).

[10] NASA, P. Mortfield, and S. Cancelli, "M33: Triangulum Galaxy," http://apod.nasa.gov/apod/ap080913.html (Accessed April 10, 2011).

[11] D. Merritt, L. Ferrarese, and C. L. Joseph, "No Supermassive Black Hole in M33?," Science **293,** 1116–1119 (2001).

[12] K. Gebhardt *et al.*, "M33: A Galaxy with No Supermassive Black Hole," Astr. J. 122 (2001).

[13] C. J. Grillmair *et al.*, "The Nuclear Region of M51 Imaged with the HST Planetary Camera," Astr. J. 113 (1997).

[14] NASA and S. Beckwith, "M51 Hubble Remix," http://apod.nasa.gov/apod/ap080614.html (Accessed April 10, 2011).

[15] H. C. Ford *et al.*, "Bubbles and Jets in the Center of M51," Astrophys. J. 293 (1985).

[16] T. Hallas, "M81 in Ursa Major," http://apod.nasa.gov/apod/ap070427.html (Accessed April 10, 2011).

[17] M. F. Bietenholz and N. Bartel, "The Location of the Core in M81," Astrophys. J. **615,** 173–180 (2004).

[18] K. T. Lewis and M. Eracleous, "Black Hole Masses of Active Galaxies with Double-Peaked Balmer Emission Lines," Astrophys. J. **642,** 711–719 (2006).

[19] L. Parola, G. Fabbiano, M. Elvis, F. Nicastro, D. W. Kim, , and G. Peres, "Long-Term X Ray Spectral Variability of the Nucleus of M81," Astrophys. J. **601,** 831–844 (2004).

[20] H. Mathis and N. Sharp, "Starburst Galaxy M94," http://apod.nasa.gov/apod/ap080614.html (Accessed April 10, 2011).

[21] C. Feldkhun and R. Braun, "Detection of Compact Nuclear X-ray Emission in NGC 4736," Astrophys. J. **477,** 693–699 (1997).

[22] K. Davidson, R. M. Humphries, and C. Blaha, Astro. J. 90 (1985).

[23] P. W. A. Roming, J. W. Moody, and E. G. Hintz, Astro. J. **117,** 1733 (1999).

[24] J. Kormendy, N. Drory, M. E. Cornell, and R. Bender, "Detection of Compact Nuclear X-ray Emission in NGC 4736," BAAS (2007).

[25] J.-C. Cuillandre, "M101: The Pinwheel Galaxy," http://apod.nasa.gov/apod/ap030310.html (Accessed April 10, 2011).

[26] http://www.tenagraobservatories.com/ (Accessed April 9, 2011).

[27] J. R. Taylor, *An Introduction to Error Analysis*, 2nd ed. (University Science Books, 1997).