Measurement and Analysis of Obscured Luminous Active Galaxies

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ASTR4993 and 4998 - Measurement and Analysis of Obscured Luminous Active Galaxies

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1 Introduction

Throughout the Fall 2018 and Spring 2019 semesters, I improved my skills in DS9 and IRAF programs by completing a number of tasks in the pursuit of further characterizing a series of high-redshift galaxies believed to be hosts to active galactic nuclei (AGN) as a part of my Tutorial course. These tasks include identifying a radio source in optical images by overlaying contours from the radio onto the optical, investigating several physical characteristics of the objects (including physical size and absolute magnitude), and spectral reduction and analysis. This writeup summarizes the work done during these semesters, with explanations of the processes used and some of the astrophysics behind them, and including the results of the image analysis.

The optical images used were obtained using the Large Binocular Telescope (LBT). The sample of objects are a crossmatch between WISE and Northern VLA Sky Survey (NVSS). The objects were specifically chosen because they are red, dusty (optically faint), and radio bright. The original sample included 160 objects, but this project uses a subsample of only 12 of those objects. As for the radio images, both the A and B arrays were taken using the Very Long Baseline Array (VLBA).

The goal of this project is to better understand this point in massive galaxy evolution. Professor Mark Whittle is investigating this project, and Dr. Ricky Patterson is a key contributor as well. During the Spring 2019 semester, Chris Li also helped with the project by attending meetings and helping to gather documentation and code he wrote previously for data/image processing.

1.1 Scientific Details

Studying galaxy evolution is a difficult task. Unlike stars, there are not a lot of galaxies in our vicinity that are vastly different in age to the Milky Way. This means that we have to look further away and back in time in order to observe galaxies when they were young. Measuring properties like galaxy luminosity and color gives us information about star formation in the galaxy, which in turn gives us more details about the age of the galaxy and gives us insight into patterns among galaxy groups and clusters.

To learn more about a galaxy, we need to know its distance. Distance is related to age, so determining distance is important to understanding galaxy evolution. Edwin Hubble and his colleagues determined that the universe is expanding. We were already familiar with the concept of redshift, a shift caused by the Doppler effect in which the wavelengths of light emitted by an object moving away from us are stretched and shifted to longer wavelengths, so the light appears redder. If the object is moving toward us, the wavelengths of light are shifted to shorter wavelengths and appear bluer, and experience blueshift. In 1929, Hubble announced that his research determined the universe is expanding, and that more distant galaxies are moving away from us at higher speeds. He determined the speeds of the galaxies by measuring their redshifts. See Figure 1 for his original velocity-distance diagram illustrating his findings.

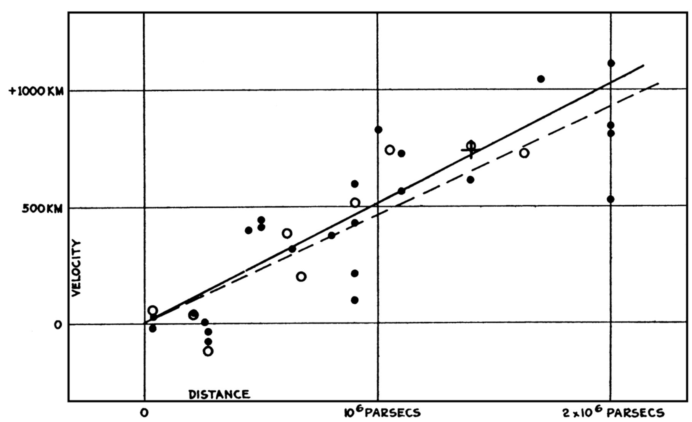

Figure 1: Hubble's velocity-distance diagram.

Consider Hubble's law:

$$\mathrm{v} = \mathrm{H_o} * \mathrm{d} \tag{1}$$

where H_o is the Hubble constant. If we take the inverse of H_o - $1/H_o$ - we can learn about how long the universe has been expanding. Estimates put the age of the universe at about 14 billion years, based on the best available evidence. Because expansion affects distance measurements, astronomers tend to state large distances in terms of lookback times, or how long it has taken for an object's light to reach us. When we think of redshift for very distant objects, we need to shift our thinking from the redshift being caused by the Doppler effect as described earlier to it being a cosmological redshift caused by photons being stretched by the expanding universe. Because of this, a galaxy's redshift can tell us how much space has expanded during the time it took the light to reach us, while the lookback time tells us how much distance the light has traveled. There is a linkage between lookback time and the age of galaxies that allows us to view galaxies at different stages of evolution simply by photographing galaxies of different distances. The larger the distance at which we observe, the younger the galaxy we can see.

The rates of star formation in galaxies can be quite variable, as it depends on how much cold gas is available for star formation at any given time. Some galaxies - "starburst galaxies" - are undergoing a huge burst of star formation, and are a good example of evidence that the star formation rate depends on cool gas supply. Starbursts use massive amounts of gas, so they are likely very short stages in a galaxy's lifetime, otherwise all of the gas in the galaxy would be used up in a much shorter amount of time than the age of galaxies we have observed. If a supernova occurs in a starburst galaxy, a bubble is created by the shock front. More and more supernova occur within the bubble and add to its kinetic energy, eventually causing ejection of gas from the galaxy. The ejection of most of a galaxy's gas shuts down star formation for a long time, but it can eventually start up again.

Galaxies with extremely bright centers are known as active galaxies, and the bright centers themselves are known as active galactic nuclei (AGN). The most luminous active galactic nuclei are known as quasars, and are found generally billions of light years from the sun. Because of how luminous active galactic nuclei are, the only type of central object known to be possible is a supermassive black hole with an accretion disk around it. Accretion of material onto the supermassive black hole account for the extreme luminosities we observe. In order to confirm that black holes are the sources of the massive amounts of energy at the centers of AGN, we have to observe their effects on their surroundings. We can observe radio lobes, or huge jets on either side of a radio galaxy that are filled with radio-emitting plasma, that interact with the hot gas around galaxies. These jets can push out gas from the galaxy and affect star formation rates. Blowing gas out exposes the bright quasar in center, which is how most quasars are observed. Our objects are hidden – bright in mid IR but not optical. These objects are caught at an early stage of galaxies colliding when stars are being formed and gas is falling on black holes, possibly triggered by the galaxies colliding.

The objects chosen for this project were chosen in part because they are very luminous in the mid-infrared range (3, 4, 12, and 20 microns). They have strong radio sources in them, likely active black holes. The 12 objects we are looking at were chosen from a larger sample of 160 objects, and they were chosen because they have been observed by the VLBA, which has provided very high resolution images in the radio in the centers of the galaxies. Because these objects are so hard to observe, we use very large telescopes, and have gathered images in the g, r, J, and K bands for most objects. Hopefully by studying these objects, we can learn more about this point in massive galaxy evolution.

2 Identifying Radio Sources in Optical Images

The first task I worked on for this project was to use DS9 to display the optical image in each band, g, r, J, and K, for each object, and to then identify the radio source in each object. This is helpful in identifying anomalies and visualizing the size, location, and orientation of the object in the radio vs. in the optical. I used DS9 for this, and my first attempt is described as follows. I have since improved on this process, and will include the revised steps below.

1. Display the optical image in DS9 by clicking "open" and then selecting the desired image from your directory.

2. Adjust the scale parameters if necessary (this is almost always necessary) by opening the "scale parameters" tool and dragging the limits to the appropriate values. Further adjustments can be made by clicking on the image with the right-click mouse button and dragging around the image. Up and down adjust the contrast and left and right adjust the level.

3. Create a new frame and open the radio image. Adjust the scale parameters using the same method as described in step 2.

4. Apply contours to the radio image using the "Contour Parameters" option under "Analysis" in the menu at the top of the window. DS9's default setting for contours is usually too many levels and too smooth. I adjusted these levels and clicked "Generate" until I was happy with the contour it produced, which can be seen on the images in the appendix.

5. When you are happy with the contour on the radio image, center the object in the window and zoom to a suitable magnification. Then, in the menu at the top of the window, click "Frame", hover over "Match", hover over "Frame" in the drop down options, and click "WCS". This step matches the WCS coordinates of the radio image to those of the optical image, ensuring that the images are both centered on the object of interest, with the same coordinates matched for each image. This is an effective way to locate the object in the optical image.

6. While in the radio image and in the "Contour Parameters" window, click "File" and "Copy contours".

7. Move to the optical image without changing the zoom/moving the image around. In the "Contour Parameters" window, click "Paste contours". This should place the same contours from the radio image onto the optical image, showing the location, size, and orientation of the radio source on the optical image.

I used this process for each of the objects available. Some objects had all of the optical bands available, while others didn't, and some objects had both A and B array radio images while others had only B or only A. If an object had both A and B, both contours were applied to the images in different colors - green for A and red for B (for the new images, green for A and yellow for B). The images with contours for each of the objects can be found in the appendix at the end of this paper.

The above process is that which I used during the Fall 2018 semester during my Tutorial course. The images I produced were okay, but not great. I ended up re-processing them this semester (Spring 2019) and made several changes, including now putting all four bands (g, r, J, and K0 in one tiled image, inverting the color map to make the objects easier to see, adding labels identifying the bands and the object, adding a compass and a scale bar, and changing the colors of the contours to make them easier to see against the objects. The new images have more information and are much better quality for seeing the objects and contours. The images included in this document are screenshots of the tiled screen on DS9. I found that taking a screenshot produced a better quality image than saving the images using DS9's image-saving features. I have also saved back-ups of the work I have done to them in DS9. Simply importing the back-up for the object in question into DS9 should restore the session as I left it. This allows for one to make further adjustments or to do further analysis without having to re-do all of the work I have already done. One disclaimer: to import the back-ups, I believe the user must have the version of DS9 installed that I was using at the time, which is Version 7.6. I will now re-write the process I followed for making the new images that are included in the appendix of this document. Part of it will be the same as before, but with adjustments to account for the new steps.

1. Display the optical image in DS9 by clicking "open" and then selecting the desired image from your directory.

2. Adjust the scale parameters if necessary (this is almost always necessary) by opening the "scale parameters" tool and dragging the limits to the appropriate values. Further adjustments can be made by clicking on the image with the right-click mouse button and dragging around the image. Up and down adjust the contrast and left and right adjust the level.

3. Invert the colormap by clicking "Color" in the menu at the top of the menu and selecting "Invert Colormap". You may need to make further adjustments to the contrast and level, but if you were happy with it before inverting, you shouldn't need to do much.

4. Create a new frame and repeat steps 1-3 for each band of the object that is available. Usually this is g, r, J, and K, but for some of the objects we don't have data for all of them. If you aren't sure where the object is located in the image, it may be helpful to complete steps 5-7 and then come back to this step. Doing steps 5-7 would just allow you to center the image on the object first using the radio image.

5. Create a new frame and open the radio image. Adjust the scale parame-

ters using the same method as described in step 2.

6. Apply contours to the radio image using the "Contour Parameters" option under "Analysis" in the menu at the top of the window. DS9's default setting for contours is usually too many levels and too smooth. I adjusted these levels and clicked "Generate" until I was happy with the contour it produced, which can be seen on the images in the appendix.

7. When you are happy with the contour on the radio image, center the object in the window and zoom to a suitable magnification. Then, in the menu at the top of the window, click "Frame", hover over "Match", hover over "Frame" in the drop down options, and click "WCS". This step matches the WCS coordinates of the radio image to those of the optical images, ensuring that the images are all centered on the object of interest, with the same coordinates matched for each image. This is an effective way to locate the object in the optical image.
8. While in the radio image and in the "Contour Parameters" window, click "File" and "Copy contours".

9. Move to the first optical image without changing the zoom/moving the image around. In the "Contour Parameters" window, click "Paste contours". This should place the same contours from the radio image onto the optical image, showing the location, size, and orientation of the radio source on the optical image. Repeat this step for each of the optical images. Remember, don't move the images around or change the zoom before you have pasted the contours, or you risk putting the contours on the wrong place. If you have both A and B radio images, you will need to repeat steps 5-9 for the second contour. I also recommend changing the color of the contour to differentiate between A and B. To do this, simply change the color when prompted after clicking "Paste Contours". I also recommend increasing the size of the contour line so it can be seen better. This is done in the same place as changing the color.

10. Once the images are all matched, have contours, and have appropriate contrast and level, click "Frame" in the DS9 menu and then "Tile" to show all of the images at once. If necessary, the radio frames can be deleted to leave only the four (or however band bands are available for that object) g, r, J, and K bands open.

11. For these next 3 steps, make sure you have selected the top right image (usually the g band) before you start for everything except when you want to make the label for each individual band. To add the label for the object and the band, click on "Region" in the top menu bar, hover over "Shape", and select "Text". Enter desired text. This can be moved around and the size can be adjusted. The color can be changed by double-clicking on the text and selecting "Color" in the menu bar at the top of the screen.

12. The process for adding the compass is similar to that of adding text. Rather than selecting “Text”, select “Compass”. Everything else should be the same as for text.

13. The scale bar is also the same as the text and compass but choose “Ruler” instead. To change the units, double click on the ruler and select the desired units in the drop down box next to “Length”. In our case, I used arcsec and adjusted the scale bar for each object to be as close to 10 arcseconds as possible. I also tried to keep the scale bars for each of the images to approximately the same length, but it is likely not possible to get them all to be exactly the same.

3 Investigating Physical Characteristics

Using DS9 and IRAF, we can investigate several physical characteristics of the objects, starting with a rough estimate of the physical size - the major and minor axes - of each object in kiloparsecs (kpc) and the PSF of the objects and a star in the field of each object. Recall the equation for finding the size of an object in kpc:

$$\text{size}(kpc) = \text{angular scale}(kpc/'') * \text{pixel scale}(''/pixels) * \text{axis}(pixels) \tag{2}$$

This equation was used to find the physical size of the major and minor axes of each object. The angular scale was determined using Ned Wright’s Cosmology Calculator and is calculated based on the values input by the user, including redshift, z. The redshift is not known for all of the objects, so for any object without a known redshift, a value of 1 was used. To convert an angle to a size, one needs the distance to the object. For an expanding universe, the appropriate distance is the distance to the object when the light set out, D_A. This is the same as the distance to the object today, r_o, divided by $1 + z$. The distance to the object today is evaluated using an integral which involves the measured values of the matter and dark energy densities, which is where Ned Wright’s calculator comes in. Useful equations for these calculations include the following:

$$\text{s} = \frac{\theta''}{206265} * D_A \tag{3}$$

$$D_A = \frac{r_o}{1+z} \tag{4}$$

It is valuable to note that if the universe had curved geometry, a further correction would be necessary, but because we assume Euclidean geometry, this further correction is not necessary. The pixel scale is found in the header of each image, which is accessed using DS9. The size of the axes in pixels is found using the ruler tool on DS9. For many of the objects, it is difficult to determine what the edge is, so the values for the axis size in pixels are a little rough.

In addition, we can find the absolute magnitude, M, of each object using apparent magnitudes, m, calculated by Patrick Edwards and the luminosity distance, D_L, calculated using Ned Wright's Cosmology Calculator. D_L can be expressed using the flux-luminosity relation:

$$F = \frac{L}{4\pi(D_L)^2} \tag{5}$$

While this equation is true for a static Euclidean space, we can still use it for an expanding universe as long as we substitute the appropriate distance for D_L. This distance is the comoving distance - the true distance when the light arrives - multiplied by $1 + z$, which becomes squared in equation 4. This factor corrects for the loss of energy and the slowed rate of arrival the photons due to the redshift. Similar to what is stated above regarding the angular scale, if the universe had curved geometry, a further correction would be necessary due to the shape of a sphere. However, measurements over the past years have shown that the universe is in fact Euclidean.

Recall the equation for finding absolute magnitude:

$$m - M = 5\log d - 5 \tag{6}$$

By plugging in the values for apparent magnitude, m, and distance, d, we can get a value for absolute magnitude M. In this case, the value for d is that which is obtained from Ned Wright's calculator, D_L. For the majority of the objects, the calculations for M and the size of the axes were done using the r band image, with the exception of W0739 and W1521. These objects were not visible on the r images, therefore the K images were used, with the appropriate values for pixel scale, m, etc.

Object	**Filter**	**z**	**Major axis (kpc)**	**Minor axis (kpc)**	**m**	**M**
W0204	r	1	14.37	13.82	23.64	-20.49
W0342	r	0.47	44.63	16.29	20.85	-21.27
W0404	r	1	5.07	4.78	26.98	-17.16
W0739	K	1	8.58	7.72	20.68	-23.45
W0943	r	1	23.46	8.91	23.86	-20.27
W1046	r	1	15.84	15.84	21.98	-22.15
W1210	r	1	4.59	3.63	25.12	-19.01
W1238	r	2.25	9.87	7.60	21.94	-24.37
W1521	K	0.7	14.61	9.45	20.86	-22.32
W1703	r	1.08	13.74	8.83	22.39	-21.95
W1958	r	1.8	5.56	3.81	24.36	-21.36
W2331	r	1	14.55	12.55	27.93	-16.20
W2345	r	1	10.61	9.65	23.84	-20.30

Table 1: Several of the physical characteristics of the objects.

3.1 Issues with Some Objects

Some of the objects had issues in various ways. For example, the directory for W0612 is empty - there are no optical images and no radio images. This is likely due to issues with the original images, but this occurred before my involvement with the project.

Another object that posed an issue is W1332. Its directory did not contain a radio image, so it was impossible to apply contours and identify the location of the radio source for this object.

Because of these issues, those objects were not included in the physical characteristic analysis.

4 Spectroscopy

We touched on the spectroscopy aspect of this project very briefly at the end of the semester. The hope with using spectra of the objects is to find redshifts of the objects - a major goal of the project. So far, the only object with spectroscopy data is W2345. This object was used as a test of sorts to see if it is possible to extract the redshift from this object, and therefore if it is useful to take spectra of the other objects as well. This data was previously untouched, so the work done with it this semester is the beginning of the spectral analysis, and is therefore a little rough. The images were taken using the Large Binocular Telescope, specifically the LBT Utility Camera in the Infrared (LUCI1 and LUCI2) instruments. The instruments provide "imaging, longslit spectroscopy, and MOS spectroscopy over a 4 arc-minute square field of view." More detail about these instruments can be found on the LBT website, included in the references portion of this paper. [1]

The first step of the spectral analysis was to download the raw images from the LUCI archives. It took a bit of time to figure out which images to download, but emails from Dave Thompson at LBT were useful. The images are grouped in pairs, in an "A" position and "B" position. In order to get a roughly optimized image for both the LUCI1 and LUCI2 data sets, some spectral reduction needs to be done. This was accomplished using the imarith package in IRAF. The steps of this quick-and-dirty analysis are to sum the "A" positions, sum the "B" positions, subtract $A - B$, subtract $B - A$, shift the $B - A$ image by the dithering offset between them, and add $(A - B) + \text{shifted}(B - A)$. This process was done twice, for each dataset. The following are the exact steps entered into IRAF for the LUCI1 images.

```
imarith luci1.20180917.0046.fits + luci1.20180917.0047.fits sumA.fits
imarith sumA.fits + luci1.20180917.0050.fits sumA1.fits
imarith sumA1.fits + luci1.20180917.0051.fits sumA2.fits
imarith luci1.20180917.0048.fits + luci1.20180917.0049 sumB.fits
imarith sumB.fits + luci1.20180917.0052.fits sumB1.fits
imarith sumB1.fits + luci1.20180917.0053.fits sumB2.fits
imarith sumA2.fits - sumB2.fits AminusB.fits
```

```
imarith sumB2.fits - sumA2.fits BminusA.fits
imshift BminusA.fits BminusAs.fits 0 -80
imarith AminusB.fits + BminusAs.fits final.fits
```

The final image is saved as "final.fits", which can then be opened in DS9 for further manipulation until the spectra can be distinguished. I have included both the LUCI1 and LUCI2 final images, as well as images zoomed in to show the objects. The emission lines aren't very obvious, but a more detailed reduction might produce better images. This may be a project for next semester, or further in the future.

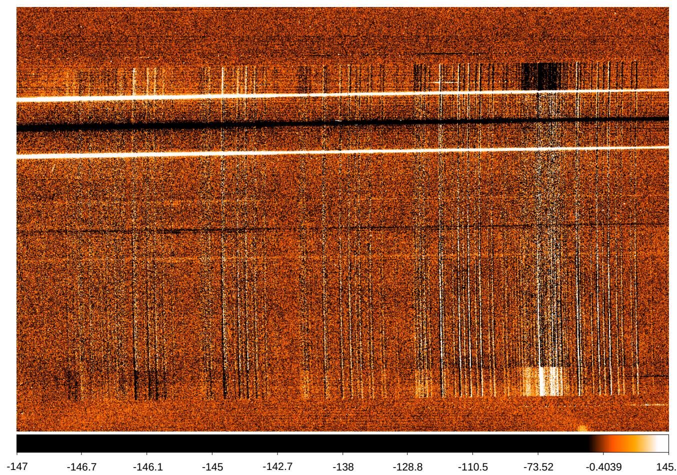

Figure 2: Whole LUCI1 final image.

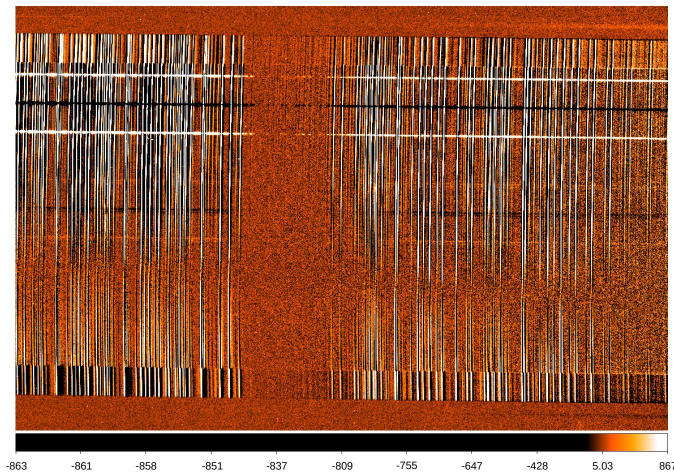

Figure 3: Whole LUCI2 final image.

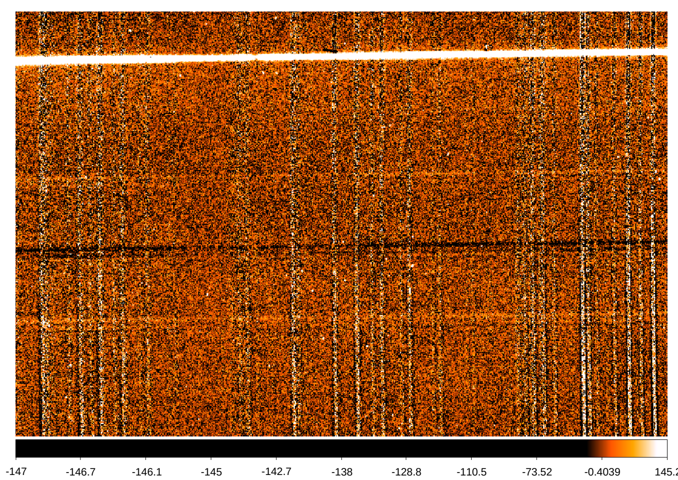

Figure 4: Zoomed LUCI1 final image.

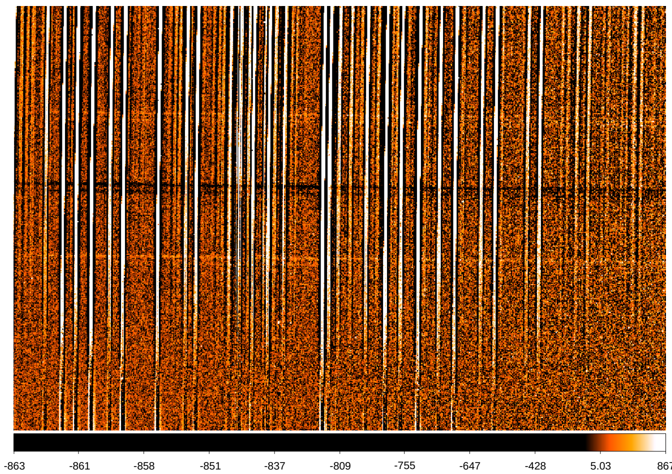

Figure 5: Zoomed LUCI2 final image.

5 Where is the data?

Most of the data, including raw images and some calculated values like apparent magnitude, can be found on Patrick Edwards' directory on the Astronomy Department's computers. Patrick also included a lot of information in his thesis and in his Github repository, to be supplied below. A lot of the work I did can be found either in this document (mostly in the appendix) or in my IRAF directory on the Astronomy Department's computers. This includes the .png images of the objects with contours applied and the raw and processed spectral data. I will also include a link to my Github repository for this project, where the image .pngs and other resources are stored. Some values, like redshift or coordinates of the objects, were given by Professor Whittle. Anything useful that I have is now either on the Collab site for this project or on the CraterShared directory on the astronomy department computers.

Patrick Edwards' Github repository: https://github.com/pme5vc/Senior-Thesis-May2018

My Github repository: https://github.com/smh4bk/tutorialthesis

References

[1] LUCI Overview. (n.d.). Retrieved from https://sites.google.com/a/lbto.org/luci/home, LBT page for LUCI instruments

[2] Edwards, P. (2018). SED FITTING OF WISE-SELECTED LUMINOUS, OBSCURED QUASARS AT REDSHIFT˜2. Patrick Edwards' Thesis

[3] Bennet et al. (2017). The Cosmic Perspective, Eighth Edition

Appendix

A Optical Images with Radio Contours

Previously, this appendix included the images I processed at the beginning of the Fall 2018 semester. The sky is too dark in these images, and in several of them the object is too faint to see. I re-processed these images this semester (Spring 2019) as part of my thesis course and have included the new, better images. The older images are commented out and can still be viewed if desired.

A.1 W0204

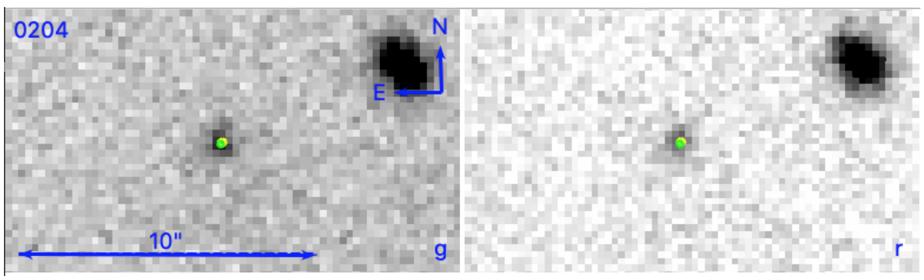

Figure 6: W0204 with A and B contours, scale bar, and North and East orientation. Left is g and right is r.

A.2 W0342

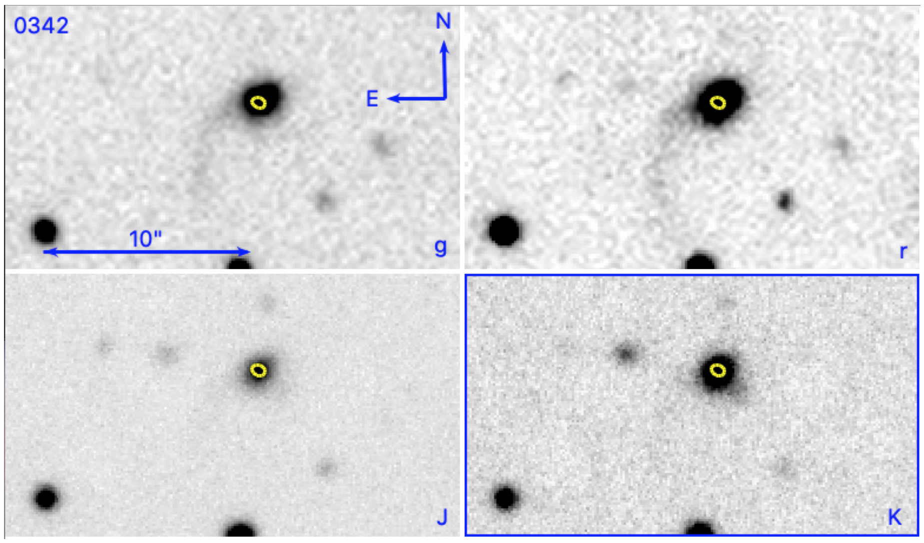

Figure 7: W0342 with B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left J and bottom right K.

A.3 W0404

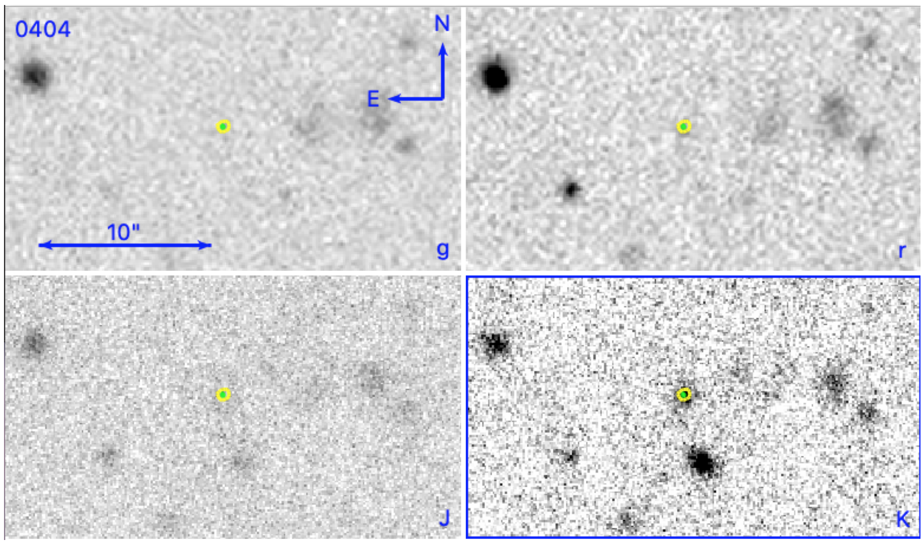

Figure 8: W0404 with A and B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left J and bottom right K.

A.4 W0739

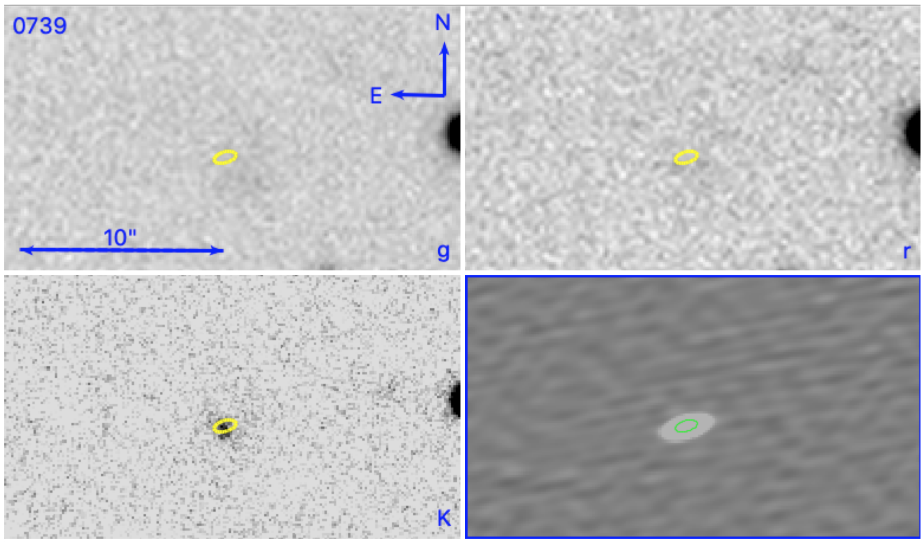

Figure 9: W0739 with B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left K and bottom right is the radio image.

A.5 W0943

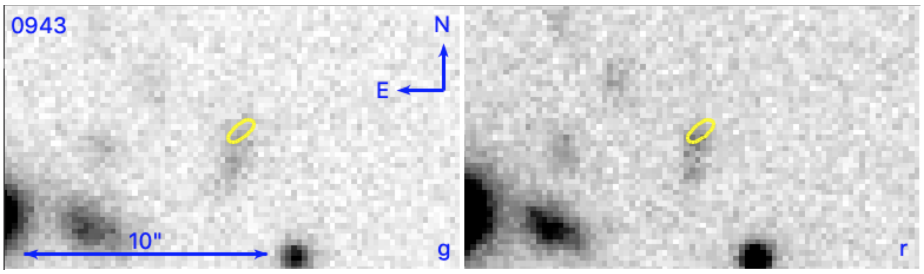

Figure 10: W0943 with B contours, scale bar, and North and East orientation. Left is g and right is r.

A.6 W1046

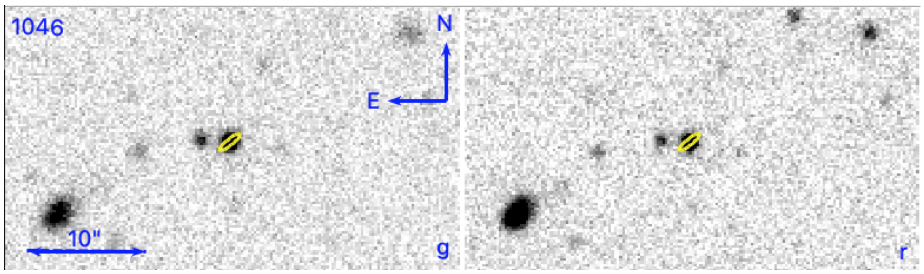

Figure 11: W1046 with B contours, scale bar, and North and East orientation. Left is g and right is r.

A.7 W1210

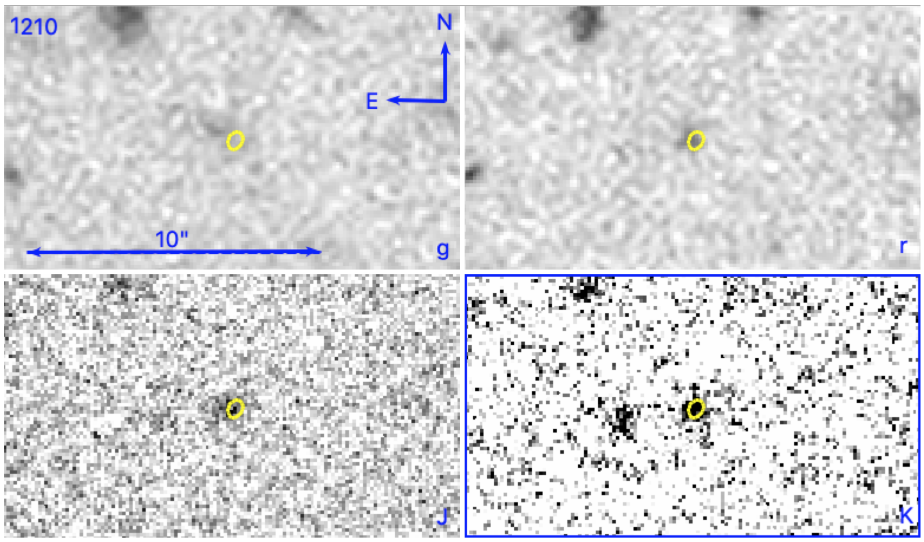

Figure 12: W1210 with B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left J and bottom right K.

A.8 W1238

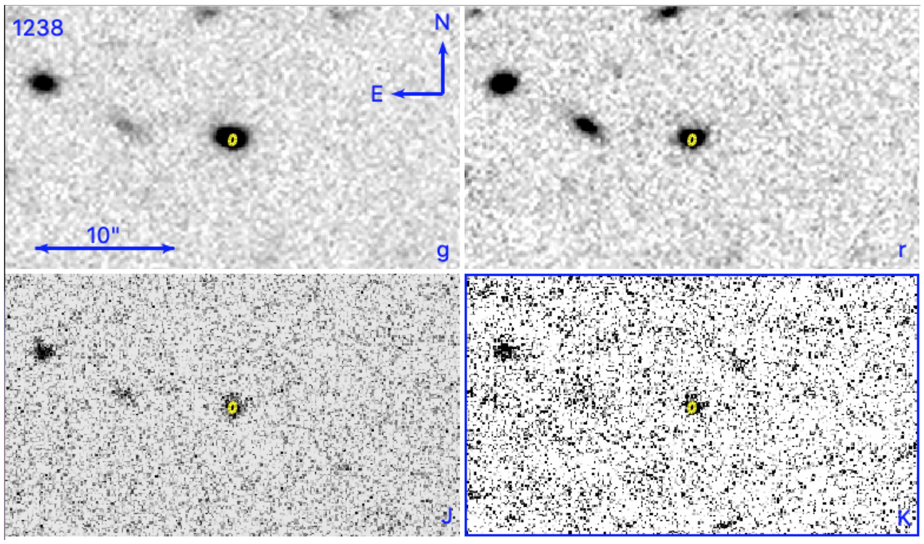

Figure 13: W1238 with B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left J and bottom right K.

A.9 W1521

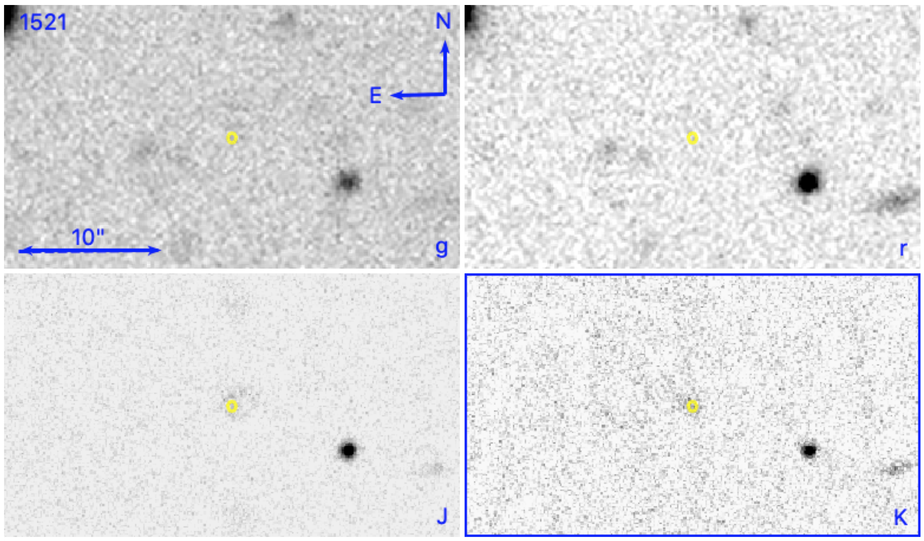

Figure 14: W1521 with B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left J and bottom right K.

A.10 W1703

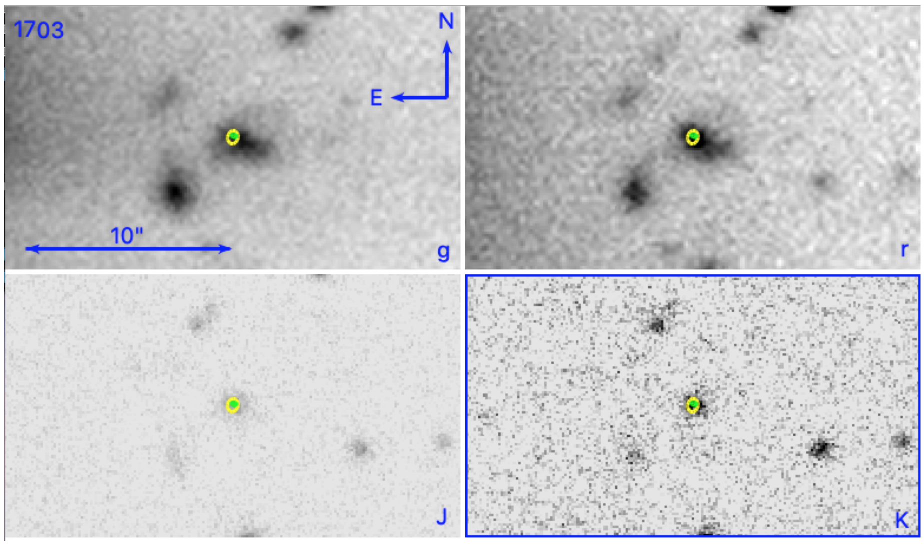

Figure 15: W1703 with A and B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left J and bottom right K.

A.11 W1958

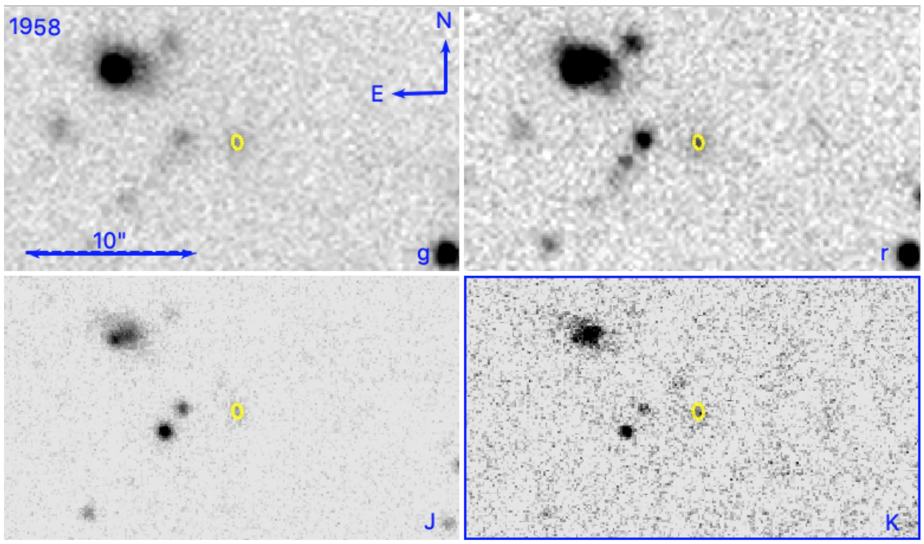

Figure 16: W1958 with B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left J and bottom right K.

A.12 W2331

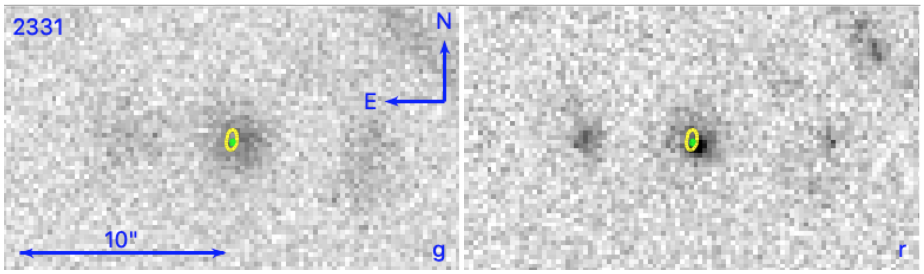

Figure 17: W2331 with A and B contours, scale bar, and North and East orientation. Left is g and right is r.

A.13 W2345

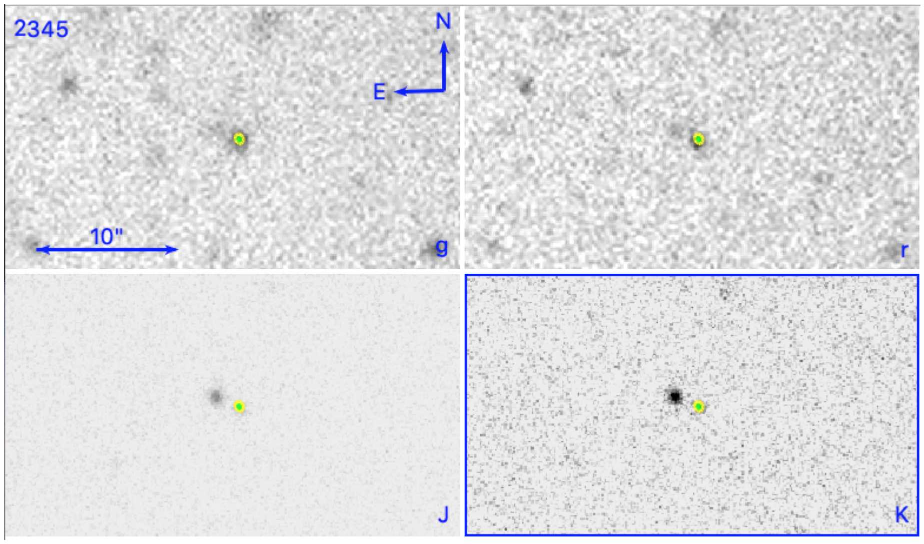

Figure 18: W2345 with A and B contours, scale bar, and North and East orientation. Top left is g, top right r, bottom left J and bottom right K.