

## B. Project Description

### *1) Background and Rationale*

One of the biggest questions in astronomy and astrophysics is “How do galaxies evolve?” Because of the large time scales involved in the formation of galaxies, the only way to learn about the formation of galaxies is through studying galaxies outside the Milky Way by observation and simulation. In the late 20th century astronomers began observing and investigating galaxies that contain supermassive black holes in their center that produce more light than all of the stars within the galaxy. These galaxies are hosts active galactic nuclei (AGN), which is a particular stage of galactic evolution. An active galactic nucleus is divided into several regions, based mainly on the distance from the central black hole. One of the outermost regions of an AGN is the narrow line region, which typically have a diameter on the order of 100,000,000 times the distance from the Earth to the Sun. I will be running simulations of the narrow line region of a specific type of AGN galaxy. With the data from these simulations, I will make graphs that show how bright the region is at different wavelengths of light. For example, a graph may show that the narrow line region may have brighter blue light than red light. The results from my research should provide a greater insight into the structure of the narrow line region, which can be used in conjunction with other research to help answer the question of galactic evolution.

A noteworthy characteristic of the NLR in Seyfert galaxies is the similarity between their emission spectra. In many older models, this meant that the ratio of ionizing photons to particles (known as the ionization parameter) was nearly constant. Groves et al. 2004 established a new paradigm for modeling the narrow line region in Seyfert galaxies. In the past, photoionization models did not account for the effects of dust and radiation pressure on the emission spectra. Interstellar dust also absorbs photons, meaning that it can prevent all the atoms in gas clouds in the NLR from ionizing and producing a complete emission spectrum. Groves et al. introduced dusty, radiation pressure-dominated photoionization models, which were shown to accurately fit observed data without the introduction of arbitrary assumptions and parameters. After using dusty models became prevalent, researchers looked into what the shape of the dust cloud takes.

Modern day models often plot the spectral energy distribution (SED) using three different power law indices (the value that a number is raised to in a power law function), which provide the slopes connecting the different ranges of light (Tananbaum et al. 1979). The three power law indices used today are  $\alpha_x$ , which describes the slope of the x-ray spectrum of light,  $\alpha_{uv}$ , which connects light from the optical spectrum to light from the ultraviolet (UV) spectrum, and  $\alpha_{ox}$  which connects the optical spectrum to the x-ray spectrum (Grupe et al. 2010).

In 1998, Grupe et al. noted that the spectral slopes  $\alpha_x$  and  $\alpha_{ox}$  are correlated. Since then, multiple papers have commented on the correlations between the x-ray spectral slope  $\alpha_x$  and the ultraviolet spectral slope  $\alpha_{UV}$  and between the x-ray spectral slope and optical-to-x-ray spectral slope in the narrow line region of Seyfert galaxies. AGN with steeper  $\alpha_x$  tend to have weaker x-ray emission lines than AGN with flatter  $\alpha_x$  (Grupe et al. 2010). However, research into this correlation is lacking. Most research extending from Grupe et al. 2010 has been on the correlation between  $\alpha_{ox}$  and the Eddington luminosity ratio, the ratio of the observed luminosity

of the object and the maximum luminosity the object can reach with the force of radiation pushing out and the force of gravity pushing in staying at equilibrium. One reason for this lack of research is due to the lack of simultaneous observations in the UV and X-ray band. Researchers observed the same AGN years apart, and AGN have been found to be variable in UV and X-ray bands. One of the biggest accomplishments of Grupe et al. 2010 was the compilation of observational data of 92 different AGN over the course of 5 years. This allows for better observational data that models can fit. This data allows for the establishment of average values for all three power law indices, which were given in the paper as both the mean and the median of the results. They noted that the median provided a more accurate representation than the mean.

Another potential type of AGN that is the subject of much research are Low-Ionization Nuclear Emitting Region (LINER) galaxies. The emission spectra of LINER galaxies produce lines that are typical of both AGN and their counterparts, star-forming regions, which are regions with extremely high rates of star formation, which is the primary source of emission lines for those regions. Scientists are uncertain if these galaxies are strictly AGN galaxies, star-forming galaxies, or some combination of the two. These regions contain emission line widths that are comparable to the lines produced by the NLR in Seyfert. While Seyfert galaxies are modeled using photoionization models, many researchers simulate LINERS using shock models (Heckman 1980). The reason for this difference is lack of understanding of the primary excitation mechanism for LINER galaxies, as they display properties of both star-forming regions and AGN galaxies.

In order to check the accuracy of their models, researchers compare ratios of certain emission lines in diagnostic diagrams. These diagrams can be used to classify the type of AGN based on their primary excitation mechanism, as well as act as a check for multiple parameters that we have to consider for our simulations. Taking into account this background, my research asks the question:

*Does constraining the power law indices according to slopes derived from past research create an accurate model of Narrow Line Seyferts that can be used to simulate their properties across the AGN Sequence and can these models be extended to modeling emission lines from Low Ionization Nuclear Emitting Region (LINER) galaxies?*

## 2) *Methods*

Using the data from Grupe et al. 2010, I will determine the average power law indices that will be used in the baseline spectral energy distribution that will be run through our simulations. To vary these indices in our models, I will use the data given from the same paper to determine if the correlations between the different power law indices are significant enough that linear regression slopes between the indices can be used to constrain the values. Because the data from the paper includes Broad Line Seyfert Galaxies, I will have to reduce the data by removing any sources that have a Full Width at Half Maximum (FWHM), which is the spectral width of the light wave at half of the maximum amplitude, greater than 2000 units. From there I will then look at the values for the power law indices and remove any of the sources that do not give  $\alpha_x$  and  $\alpha_{uv}$  values that have been corrected for galactic reddening. Then I will plot linear regression curves to and use the slopes to vary  $\alpha_x$ ,  $\alpha_{ox}$ , and  $\alpha_{uv}$ .

Once these slopes have been determined I will begin running simulations through the CLOUDY program. In the simulation, I will use the parameters established by Groves et al. 2004b to make the cloud that the light will be run through. These parameters include the metallicity, chemical abundances, hydrogen density, dust grain size distribution, dust grain composition, and ionization parameter. Once the simulations have been run, I will look at the predicted line emission ratios for a large variety of atomic transitions. Many of these ratios are between one ionized state of an element and the first two ionizations of hydrogen ( $H\alpha$  and  $H\beta$ ). The most important of these ratios are those established by Baldwin, Philips, and Terlevich 1981. I will gather data on how these specific ratios change according to the model.

The next stage of the research is to fit our model to existing observations. We will need a very large data set that is publicly available, as Elon does not have an observatory. As such, I will be using data collected from the most recent release of the Sloan Digital Sky Survey (SDSS). The SDSS provides the spectra of at least 1.5 million galaxies collected since it began in 2000. Furthermore, the data is publicly available, provided you understand the coding required to select your data. Using parameters determined by past research, I will take the data from galaxies to produce diagnostic plots that can be used in conjunction with our simulations to act as a check of the validity of our model.

After determining that our models are good fits for the NLR of Seyfert galaxies, we will adjust our models to simulate LINER galaxies, and then examine the data produced by the simulations to determine if we can accurately simulate them as well.

### 3) References

- Baldwin, Phillips & Terlevich. 1981, *PASP Publications of the Astronomical Society of the Pacific*, 93, 5–5
- Fischer, Crenshaw, Kraemer, Schmitt & Trippe. 2010, *The Astronomical Journal*, 140, 577–583
- Groves, Dopita & Sutherland. 2004, *The Astrophysical Journal Supplement Series ASTROPHYS J SUPPL S*, 153, 75–91
- Groves B, Heckman T, Kauffmann G. 2006. *MNRAS* 371:1559
- Grupe, D., Beuermann, K., Thomas, H.-C., Mannheim, K., & Fink, H. H. 1998a, *A&A*, 330, 25
- Grupe, D., Komassa, S., Leighly, K., Page, K., 2010, *ApJS*, 187, 64
- Heckman, T. M. 1980, *Astr. Ap.*, 87, 142
- Jiang, Ho, Dong, Yang & Wang. 2013, *ApJ The Astrophysical Journal*, 770, 3–3
- Khachikian & Weedman. 1974, *The Astrophysical Journal*, 192, 581–581
- Nenkova, M., Ivezić, Ž., & Elitzur, M. 2002, *ApJ*, 570, L9
- Netzer. Cambridge University Press, 2013,
- Ryden & Peterson. Pearson , 2010,
- Hönig S. F., Kishimoto M., 2010, *A&A*, 523, A27
- Tananbaum, H., et al. 1979, *ApJ*, 234, L9

## C. Responsibilities of the Student

Chris' proposal builds upon work that he started last year. During that time, Chris has attended research group meetings to learn the basics of the astrophysical code known as Cloudy, which is addressed in the research proposal of this document. Next semester, he will continue to build a solid foundation of the theoretical concepts in nebular astrophysics and test these concepts by performing plasma simulations. Chris already possesses many skills, such as navigating the command line of Unix systems and developing scripts, which are necessary to succeed in a field with an ever-growing dependence on numerical work.

Armed with the background knowledge necessary to conduct astronomy research, this grant would allow Chris to complete the logical next step by undertaking a high quality research project. His responsibilities reflect the proposed plan presented in the research proposal and fit into three broad categories:

**1. Develop working knowledge of running simulations on high performance clusters.** Cloudy has the ability to make use of multi-core processors, which drastically decreases the time required to complete a series of simulations. The research group already has access to a high throughput computing cluster located off campus. Chris will need to learn how to access this cluster, install Cloudy on his own workspace, and configure Cloudy so that it can run on the system. This will also require Chris to develop a basic understanding Bash scripting, which allows each user of the computing cluster to submit simulations to the queue.

**2. Maintain an online code repository.** Chris's project will require him to write code in the programming language Python. He will need to learn how to use the version control system known as Git, and create an online repository on Github, to manage all of the scripts he will write. This will allow others in the research group to make use of his scripts, allow his mentor to easily validate his work, and promote strong programming practices.

**3. Further investigation of Cloudy's capabilities.** While Chris will have a firm understanding of the theoretical underpinnings of Cloudy, the documentation of its capabilities is vast (~600 pages). Chris will need to develop the ability to quickly assess the problem at hand and then determine the appropriate tool in Cloudy best suited to solve it. Additionally, an online message board solely dedicated to Cloudy will assist Chris in investigating questions that other users have encountered and the path they took to solve them.

After successfully completing this work, Chris will formally document the results of the project and present them at the American Astronomy Society Meeting in Jan. 2017.

#### **D. Educational Benefits**

Completing this project holds many educational benefits. First and foremost, I gain experience writing research proposals and grant applications, which is a skill that is required for graduate school and doing research professionally. I also gain experience with coding in Python and Linux based systems. Like most research projects, I learn how to approach a problem analytically, or in some cases determine what the problem/question is that we are trying to solve. I learn how to organize research and data files so that they are easy to access and simple to navigate. Because the field of astrophysics primarily relies on computer based simulations for research, knowing how to run computer programs and to code is a necessary skill. I am in the process of applying for graduate schools, so this project also helps me with the application process by honing my scientific writing skills and providing an example of my work for the schools to look at. In the past year of working on this research project, I have gained a deeper understanding of the field of astrophysics, which has aided my learning in the classroom. By learning how the research process is completed, I gain a respect and appreciation for the efforts of the great scientists and physicists of the past and the rigor that they had to conduct their research with.

## **E. Description of Planned Mentoring Relationship**

Chris' proposed work directly aligns with the research of his mentor. As such, the mentor will be available and ready to offer advise during all stages of the proposed research:

The mentor will provide resources and examples to learn about high performance computing and script writing.

The mentor will work with the student to develop and write code.

The mentor will advise the student in the best practices in documenting research.

The mentor will be frequently available and meet with the student at least one hour per week.

The student will document their research using an electronic notebook that will be backed up online.

The student will regularly inform the mentor about their progress.

The student will spend at least 4 hours per week, per credit hour of PHY 499, performing work related to the project.

The student and mentor will read scholarly publications separately and then discuss the implications of the articles.

The student and mentor will meet at least once a week to reflect upon progress made since the previous meeting and converse about the way forward.