UNDERSTANDING THE CIRCUMGALACTIC MEDIUM THROUGH ARCHIVAL SPECTROSCOPIC STUDIES

BY

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"Understanding the Circumgalactic Medium Through Archival Spectroscopic Studies," a dissertation prepared by Nigel L. Mathes in partial fulfillment of the requirements for the degree, Doctor of Philosophy, has been approved and accepted by the following:

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DEDICATION

I dedicate this work to my cat, Stellar, for enduring my relentless inane nicknames and providing love and affection in the form of headbutts.

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My greatest thanks to Stellar, for also making sure I wake up each morning by biting my nose.

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To all those who have supported quasar absorption line studies.

VITA

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Mathes, N.L., Churchill C.W., and Murphy, M.T., 2017, The Astrophysical Journal, NUMBERS. *The Vulture Survey I: Analyzing the Evolution of MgII Absorbers*

Muzahid, S., Kacprzak, G.G., Churchill, C.W., Charlton, J.C., Nielsen, N.M., Mathes, N.L., and Trujillo-Gomez, S., 2015, The Astrophysical Journal, 811, 132. *An Extreme Metallicity, Large-scale Outflow from a Star-forming Galaxy at z 0.4*

Mathes, N.L., Churchill C.W., Kacprzak, G.G., Nielsen, N.M., Trujilo-Gomez, S., Charlton, J., Muzahid, S., The Astrophysical Journal, 792, 128. *Halo Mass Dependence of H I and O VI Absorption: Evidence for Differential Kinematics*

FIELD OF STUDY

Major Field: Galaxy Evolution
Minor Field: Quasar Absorption Line Spectroscopy

ABSTRACT

The Vulture Survey: Feasting on the Bones of Archival Spectra Left to Die

BY

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Las Cruces, New Mexico, 2012

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We present detailed measurements of the redshift path density, equivalent width distribution, column density distribution, and redshift evolution of Mg II and C IV absorbers as measured in archival spectra from the UVES spectrograph at the Very Large Telescope (VLT/UVES) and the HIRES spectrograph at the Keck Telescope (Keck/HIRES) to equivalent width detection limits below 0.01 Å. This survey examines 432 VLT/UVES spectra from the UVES SQUAD collaboration and 170 Keck/HIRES spectra from the KODIAQ group, representing 580 unique sightlines, allowing for detections of intervening Mg II absorbers spanning redshifts $0.1 < z < 2.6$ and intervening C IV absorbers spanning redshifts $1 < z < 5$. We employ an accurate, automated approach to line detection which consistently detects redshifted absorption doublets. We find that an increased number of high column density Mg II and C IV absorbers at $z = 2$ drives an overall increase in the

quantity of metals around galaxies as compared to the present epoch. We conclude that galaxies eject more metal enriched gas into their halos around $z = 2$ than at any other redshift through star formation driven outflows. We determine that weak Mg II and C IV absorbers, those with equivalent widths less than 0.3 Å, are physically distinct and evolve separately from very strong absorbers, which have equivalent widths greater than 1.0 Å. Over this same time period, evolving ionizing conditions in the halos of galaxies gives rise to an increasing population of low equivalent width, passive Mg II and C IV absorbers. From $z = 2$ to the present, feedback processes decline and we observe fewer very strong systems. From $z = 2$ to $z = 5$, SOMETHING ELSE HAPPENS. EXPLAIN THIS SOMETHING ELSE.

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LIST OF ABBREVIATIONS

AGN	Active Galactic Nucleus
FITS	Flexible Image Transport System
FWHM	Full-Width Half Max
HIRES	The high-resolution optical spectrograph of the Keck I Telescope
ISM	Interstellar Medium
MW	Milky Way
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
STScI	Space Telescope Science Institute
UV	Ultraviolet
UVES	The high-resolution optical spectrograph of the VLT
VLT	Very Large Telescope

1. INTRODUCTION

Testing **??**

1.1. Quasar Absorption Line Spectroscopy

One of the most important questions in modern studies of galactic evolution asks, how do baryons cycle into and out of galaxies, and how does this cycle determine the growth and evolution of galaxies themselves? More specifically, how does the process of gas accretion, star formation, and subsequent supernovae-driven feedback shape both the galaxies themselves and their circumgalactic medium (CGM)?

A major problem in studying galaxy evolution at high redshifts is that faint, low mass galaxies cannot be observed with current facilities. These smaller, more numerous galaxies pose major problems when attempting to characterize the ionization conditions of the early universe and detailing the growth history of galaxies. They are all but invisible due to their low luminosities, which makes it nearly impossible to completely inventory galaxy populations and find modern day galaxy analogs at high redshift. Studying properties of galaxy evolution, then, must involve a luminosity-independent tracer of the processes which grow and affect galaxies across cosmic time. One such technique involves observing absorbing gas in quasar spectra, effectively measuring properties of the shadows of gaseous structures around galaxies.

Quasars are exceptionally bright objects, often found at large distances, or high redshift. Their luminosities can exceed SOMETHING BIG, and they can be observed at distances corresponding to light travel times near to that of the beginning of the universe. They serve as extreme cosmic lighthouses, illuminating material located between observers and the quasars themselves.

By taking a spectrum of a quasar, we can learn about material at large distances which may not emit light of its own. By absorbing the light of the quasar at specific wavelengths, this mater, or gas, imprints onto the spectrum a characteristic absorption feature. These absorption features can be measured in order to determine their redshift, and also their underlying physical properties.

In §**??** we talk in extensive detail about the biology and presumed intelligence of the discovered whales.

We conclude that we should worship these exowhales as our benevolent overlords, (see Chapter **??**).

1.2. Galaxy Formation and Evolution

The Milky Way serves as the closest and best example of a galaxy. However, galaxies come in all kinds of different shapes and sizes. To truly understand how we came to be, as humans on the planet Earth, we must work to understand how our galaxy came to be, and what processes played part in creating the local environment we live in today.

It is theorized by Haardt & Madau (2012) that something crazy happens. THIS IS A TEST CItation for now[1].

[1] Testing out footnotes here as well

1.3. The Circumgalactic Medium

The cgm is pretty big. Like, bigger than most things you know about.

1.4. The Baryon Cycle

Baryons go in, more baryons come out. YOU can't explain that.

2. DATA

2.1. Spectral Properties

Properties of UVES and HIRES and things.

Table of spectroscopic observations of quasars.

2.2. Reduction and Pre-Analysis

Describe reduction process for each instrument and describe the processes of higher order continuum fitting and things like that.

2.3. Redshift Path Length

Describe g of w z and show the pretty heat map plot and explain it.

3. AUTOMATED LINE DETECTION

3.1. Motivating Automated Line Detection

Large spectral data sets are becomming the norm in both galactic and extragalactic astronomy. In the Milky Way, the spectra of hundreds of thousands of stars may be analyzed by routines which fit templates to find the best agreement. Unfortunately, when dealing with redshifted systems composed of a multitude of components (stars, gas, AGN), the number of free parameters increases significantly and templates/matching techniques become unfeasable. Therefore, we require a more general, but no less robust line finding algorithm to handle large spectral libraries.

4. Automated Line Detection

We employ a cross-correlation method similar to that of Zhu & Menard, 2013.

4.1. Defining the Search Window

In any large survey, a well-defined search window is important. In the case of analyzing quasar spectra, we are constrained by several factors: the wavelength coverage of the spectrum, the redshift of the observed quasar, and the confidence with which we can identify individual doublets in regions of low signal-to-noise and regions with atmospheric absorption features (telluric lines).

We limit our wavelength search window for CIV and MgII absorbers to regions redward of the Lyman-alpha emission feature, or the blue limit of the spectrum if the Lyα is not observed, and 3000 km/s blueward of either the corresponding

CIV/MgII emission feature, or the red limit of the spectrum if these features are also not observed.

We also do not search in regions of strong telluric absorption, cutting out the following wavelength chunks: [6277 - 6318Å], [6868 - 6932Å], [7594 - 7700Å], and [9300 - 9630Å].

4.1.1. The Step-By-Step Recipe for Finding Redshifted Lines

1. Define Search Window
2. Convert wavelength search window to a redshift range for each ion to search
3. Define redshift resolution based upon the spectrograph resolution
4. Define filter sized based upon FWHM of an unresolved line at the given spectrograph resolution
5. Do the cross-correlation
    - At each redshift, place the filter for each transition (MgII 2796,2803 and CIV 1548,1551)
    - Compute the area between the filter and the observed spectrum - This is the POWER at that redshift. Higher power = stronger absorption.
    - Step forward, doing the same thing. Build up a power spectrum which has the observed power for each transition at a given redshift.
6. Normalize the power spectrum
    - The raw power spectrum's amplitude is tied directly to the wavelength range (or redshift range depending on how you want to think about it at

this point), as we are taking the area beneath a variable-length object (in this case, the spectrum or filter). We wish to analyze a power spectrum which ranges between 0 and 1 for any spectrum analyzed. This means we want to subtract the baseline value (the result of the correlation if there is zero absorption detected) from the raw power spectrum, and then divide by the difference between the minimum value (no absorption) and the maximum value (a fully saturated absorption line whose width is equal to or greater than the width of the filter used).

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5. ANALYSIS OF ABSORPTION PROPERTIES

This is how we look at squiggles and tell you they mean something.

5.1. Equivalent Width Regions

We put windows on things.

5.2. Calculating Redshifts and Velocities

Something something optical depth weighted medians.

5.3. Equivalent Widths and Kinematic Spreads

Integrate the things and do something with tau.

5.4. Column Densities

AOD stuff here.

6. PROPERTIES AND EVOLUTION OF MG II ABSORBERS

Now we can finally get down to the science!

6.1. Number of Absorbers Per Path Length

Dat path doe.

6.2. Parameterizing dN/dX to Derive Physical Properties

Describe how we interpret evolution in terms of n, σ, and ϵ.

6.3. Equivalent Width Distribution

Schechter that shit.

6.4. Column Density Distribution

Schechter it HARDER.

6.5. $\Omega_{\mathrm{Mg\,II}}$

Such cosmology.

6.6. Strong vs. Weak Absorbers

Here's where the cool stuff really lies.

7. PROPERTIES AND EVOLUTION OF C IV ABSORBERS

Now we can finally get down to the science!

7.1. Number of Absorbers Per Path Length

Dat path doe.

7.2. Parameterizing dN/dX to Derive Physical Properties

Describe how we interpret evolution in terms of n, σ, and ϵ.

7.3. Equivalent Width Distribution

Schechter that shit.

7.4. Column Density Distribution

Schechter it HARDER.

7.5. $\Omega_{\mathrm{C\,IV}}$

Such cosmology.

7.6. Strong vs. Weak Absorbers

Here's where the cool stuff really lies.

8. KINEMATICS PROPERTIES USING TPCF ANALYSIS

Here we do the whole Nikki thing and interpret the results.

8.1. Mg II Kinematics

Here we slice it, we dice it, and we look at a lot of TPCFs.

8.1.1. Mg II *Redshift Evolution*

Slice with respect to z.

8.2. Mg II Optical Depth Behavior

Slice with respect to tau.

8.3. C IV Kinematics

Here we slice it, we dice it, and we look at a lot of TPCFs.

8.3.1. C IV *Redshift Evolution*

Slice with respect to z.

8.4. C IV Optical Depth Behavior

Slice with respect to tau.

9. CONCLUSIONS

WHAT DOES IT ALL MEAN?!

9.1. Mg II

Long song and dance about how MgII is so great and all.

9.1.1. Strong Absorbers

Talk about all the properties of strong absorbers.

9.1.2. Weak Absorbers

Talk about all the properties of weak absorbers.

9.1.3. Kinematics

Talk about kinematic properties of MgII absorbers.

9.2. C IV

Even longer song and dance about how CIV is arguably even more interesting and important.

9.2.1. Strong Absorbers

Talk about all the properties of strong absorbers.

9.2.2. Weak Absorbers

Talk about all the properties of weak absorbers.

9.2.3. Kinematics

Talk about kinematics properties of CIV absorbers.

9.3. Evolution in the Context of Galaxy Evolution

Evolution.

9.4. Consequences, and Verification

Consequences.

9.5. Future Work

This is where my postdoc stuff would go...IF I HAD ONE.

APPENDIX

APPENDIX A. THERE BE MATH IN THEM THERE HILLS

In this appendix we further explain the line detection technique introduced in Section 4. Equations show we can match the filters.

$$P(F,T) = \frac{F}{F_o} - \int_{T_D}^{0} \frac{T}{T_D} dT \tag{A.1}$$

where P is the probability of me giving a Fuck at a given point in time, F is the number of Fucks I currently have, F_o is the total number of Fucks available, T is the current time remaining until a deadline, for a given total given to complete the task, T_D.

A.1. Appendix subsection

Did you know that this won't show up as listed in the table of contents, in accordance with NMSU thesis policy? Exciting.

REFERENCES

Haardt, F., & Madau, P. 2012, ApJ, 746, 125