Final Performance Report

Grant # HST-GO-13398.001-A
Contract Number NAS5-26555
Title A Breakaway from Incremental Science: Full Characterization of the z<1 CGM and Testing Galaxy Evolution Theory
Investigator Prof. Christopher W. Churchill
Institution New Mexico State University
Institution ID 24732
Start Date 11/01/2013
End Date 10/31/2017
Request Date 07/20/2018
Submitter Prof. Christopher W. Churchill
Reporting Period 11/01/2013 To 10/31/2017

Summary Of Project Activities

1. Brief description of the primary objectives and scope of the project

We origianlly proposed COS NUV+FUV high-resolution quasar spectra to uniformily measure OVI, CIV, and HI (and many other low and high ionization metals, including NeVII and OIV) in the CGM of 39 z=0.08-0.97 spectroscopically measured galaxies with HST images. As originally proposed, we augmented these 39 galaxies with 12 additional galaxies from our previous programs, for a total of 51 galaxies. However, during the course of this project, we performed an extensive archival search and found additional galaxies-absorber pairs observed with HST imaging and COS FUV spectra. In all, we now have a total of roughly 80 useful galaxies-quasar pairs.

We proposed for archival funding during Cycle 23 for this "Extended Sample", but were unsuccessful. In addition to increasing the sample, we have also identified a subset of the galaxies that arise in groups. Thus, we have expanded our original study to examine how CGM in group environments is different and/or similar to the CGM in isolated galaxies.

Our analysis directly addresses and tests the current theoretical paradigm of galaxy evolution. Our program promises a Legacy for HST, providing the essential data for ground-based follow up and for testing galaxy evolution as theory /simulations progress in coming decades. A main goal with this program is to fill in the redshift space from 0.3-1.0, which is not well studied (COS-Halos coverse z<0.3; KBSS covers z=2-3).

2. Brief description of the findings

In short, I very happy to report that we have learned a great amount about the OVI absorbing CGM during the course of this program. Not only were the COS spectra key to what we learned, but also the ESI/Keck spectra of the galaxies we obtained during the course of this HST program. But most of all, what was key to what we learned was the fact that our sample was selected by having HST imaging of the galaxies. This allowed us to examine the spatial location of the gas with respect to the galaxy and to obtain the galaxy rotation curves. I am pround to say that our research team has been the only team able to address the questions that require the HST imaging and, as such, we learned unique properties about the CGM that other teams could not address. In short, I summarize NEW results from this HST program (meaning we did not know this information before we started this program). I might add that we have additional results that I will not report here, as those results are all consistent with the findings of the COS-Halos project.

OBSERVATIONAL

1. The spatial distribution of OVI absorbing gas is bimodal around galaxies. Most OVI bearing CGM gas resides along the projected minor axis and major axis of their host galaxies. This result lead us to propose a simple hypothesis that gas along the minor axis may be polar outflow from star forming regions, and this would have higher metallicity since it had been processed through stars. Then we would expect that the the major axis gas (planer) would be inflow with lower metallicity (having not been processed through the stars within the host galaxy). We would then anticipate that the gas velocity dispersion would be higher and the kinematics more complex in the winds (minor axis gas) and

conversely that the gas velocity dispersion would be smaller and the kinematics more quiescent in the accreting gas (major axis gas). Furthmore, we would anticipate that the accreting (major axis) gas would follow the rotation kinematics of the host galaxy (as is seen for lower-ionization MgII absorbing gas). [see Kacprzak etal 2015, ApJ, 815, 22]

2. The velocity dispersion of OVI absorbing gas is uniform around galaxies. Statistically, speaking, the velocity dispersion for gas residing along the project minor axis of the host galaxy is identical to the velocity dispersion of the gas residing along the projected major axis (planer gas) of the host galaxy. In addition, the velocity dispersion of the OVI absorbing gas around "red" galaxies is statisitcally the same as the velocity dispersion around "blue" galaxies. Thus, OVI bearing gas does not care about the stellar population of the galaxy, nor its location around the galaxy. This is not conistent with our hypothesis of polar winds and planer accretion. [see Nielsen etal 2017, ApJ, 834, 148]

3. The metallicty of OVI absorbing gas is uniform around galaxies. Statistically speaking, the metallicity of the polar gas (minor axis) is the same as that of the planer gas (major axies). This too is inconsistent with our hypothesis of polar winds and planer accretion. [in preparation, Pointon etal 2018]

4. The OVI absorbing CGM in galaxies residing in groups is different than that for isolated galaxies. We find the average equivalent width to be smaller for group galaxies than for isolated galaxies. However, the covering fractions are consistent with both samples. Examination of the velocity dispersion of the OVI absorbing gas suggests that the gas arises in single galaxy halos and not in the intra-group medium. [see Pointon etal 2017, ApJ, 844, 23]

SIMULATIONS

Here, I report unpublished work from the simulations. So, far we have examined only the spatial distribution of the OVI absorbing gas in the simulations. Our findings are that the simulatins produce a unform OVI absorbing CGM, inconsistent with the observed data. Beyond the life of this grant, we are continuing to examine the kinematic behavior and the metallicity. We anticipate three to four simulation-based publications in the coming 18 months fromthis writing.

3. Name and date (or anticipated date) of the publication of results

Manuscript In Preperation (in order of anticipated completion)

Kacprzak, G.G., Churchill, C.W., Nielsen, N.M., Pointon, S., Muzahid, S., & Charlton, J.C., "The Kinematic Connection between OVI Absorption and Host Galaxy Rotation"; this is a very exciting paper showing that OVI absorption resides at the systemtic velocity of the host galaxy and is thus not coupled to the rotation of the host galaxy. ESI/Keck spectra of the galaxies accumulated for this program were central for comparing with the COS/HST OVI spectra. This work has been presented at several conferences including in Paadena CA, USA, Kruger Park, South Africa, and Garching, Germany. Anticipated submission date to ApJ is August 2018.

Lewis, J., Churchill, C.W., Kacprzak, G.G., Nielsen, N.M., Pointon, S., Muzahid, S., & Charlton, J.C., "Multivariate Analysis of the OVI Absorbing CGM"; after much research in the area of multivariate analysis, we have obtained a method of using the observed data to drive our subsample selections for comparing the various CGM propoerties of various galaxies. We expect/hope this will become an adopted method for the analysis of galaxy/quasar pairs and CGM research in general. Anticipated submission date is late fall 2018.

Pointon,S., Kacprzak, G.G., Nielsen, N.M., Churchill, C.W., Muzahid, S., & Charlton, J.C., "The Relationship between the Spatial Location the OVI Absorbing CGM and Gas Metallicity"; this is very new results showing that the gas in the planar region of the CGM and the polar region of the CGM are the same. Anticipated submission date to ApJ is late fall 2018.

Churchill, C.W., Kacprzak, G.G., Nielsen, N.M., Pointon, S., Muzahid, S., & Charlton, J.C., "Summarizing the Spatial /Kinematic/Metallicity Relationship of the CGM in OVI and MgII Absorption at Intermediate Redshifts", Anticipated submission date to Science is early spring 2019.

Refereed Journals Submitted (before 10/31/17)

Muzahid, S., Fonseca, G., Roberts, A., Rosenwasser, B., Richter, P., Narayanan, A., Churchill, C.W., & Charlton, J.C. 2018, MNRAS, 476, 4965; COS-Weak: Probing the CGM using Analogues of Weak MgII absorbers at $z<0.3$"

Rosenwasser, B., Muzahid, S., Chalrton, J.C., Kacprzak, G.G., Wakker, B.P., & Churchill, C.W 2018, MNRAS, 476, 2258; Understanding the Strong Intervening OVI Absorption at z=0.93 towards Q1206+459"

Churchill, C.W., Klimek, E.S., Medina, A., Vander Vliet, J.R. ApJ, submitted ((arXiv:1409.0916); "Ionization Modeling Astrophysical Gaseous Structures. I. The Optically Thin Regime"

Refereed Journals Published (as of 10/31/17)

Churchill, C.W., Vander Vliet, J.R., Trujillo-Gomez, S., Kacprzak, G.G., & Klyptin, A. 2014, ApJ, 802, 10; "Direct Insights into Observational Absorption Line Analysis Methods of the Circumgalactic Medium Using Cosmological Simulations"

Ho, S.H., Martin, C.L., Kacprzak, G.G., & Churchill, C.W. 2017, ApJ, 835, 267; Quasars Probing Galaxies. I. Signatures of Gas Accretion at Redshift Approximately 0.2"

Kacprzak, G.G., Martin, C.L., Bouché, N., Churchill, C.W., Cooke, J., LeReun, A., Schroetter, I., Ho, S.H., & Klimek, E.S. 9/2014, ApJ, 792, 12; "New Perspective on Galaxy Outflows from the First Detection of Both Intrinsic and Traverse Metal-line Absorption"

Kacprzak, G.G., Muzahid, S., Churchill, C.W., Charlton, J.C., & Nielsen 2015, ApJ, 815, 22; "The Azimuthal Dependence of Outflows and Accretion Detected Using OVI Absorption"

Muzahid, S., Kacprzak, G.G., Charlton, J.C., & Churchill, C.W. 2016, ApJ, 823, 66; "Molecular Hydrogen Absorption from the Halo of a z~0.4 Galaxy"

Muzahid, S., Kacprzak, G.G., Churchill, C.W., Charlton, J.C., Nielsen, N.M., Mathes, N.L., & Trujillo-Gomez, S. 2015, ApJ, 811, 132, "An Extreme Metallicity, Large-Scale Outflow from a Stat Forming Galaxy at z~0"

Nielsen, N.M., Churchill, C.W., Kacprzak, G.G., Murphy, M.T., & Evans, J.L. 2016, ApJ, 818, 171;"MAGIICAT IV. Kinematics of the Circumgalactic Medium and Evidence for Quiescent Evolution Around Red Galaxies"

Nielsen, N.M., Kacprzak, G.G., Muzahid, S., Churchill, C.W., Murphy, M.T., & Charlton, J.C. 2017, ApJ, 834, 148; "The Highly Ionized Circumgalactic Medium is Kinematically Uniform around Galaxies"

Pointon, S., Nielsen, N.M., Kacprzak, G.G., Muzahid, S., Churchill, C.W., & Charlton, J.C. 2017, ApJ, 844, 23; The Impact of the Group Environment on the OVI Cicumgalactic Medium"

Conference Presentations (limited to those with published Abstracts and/or Proceedings)

Churchill, C.W., 1/2014, American Astronomical Society Meeting Abstracts, 223, 237.06; "Bridging the Observational Gaps: Milestones toward Understanding the Circumgalactic Medium"

Churchill, C.W., Nielsen, N.M., Kacprzak, G.G., Charlton, J.C., & Muzahid, S. 1/2017, American Astronomical Society Meeting Abstracts, 229, 321.03; "The Spatial Distribution and Kinematics of the Circumgalactic Medium"

Kacprzak, G.G., Muzahid, S., Churchill, C.W., Nielsen, N.M., & Charlton, J.C. 3/2017, in Formation and Evolution of Galaxy Outskirts, Proceedings of the International Astronomical Union, IAU Symposium, Volume 321, pp. 342-344; "HST Observations Reveal the Curious Geometry of Circumgalactic Gas"

Kacprzak, G.G., Muzahid, S., Churchill, C.W., Nielsen, N.M., & Charlton, J.C. 4/2016, at "The Interplay Between Local and Global Processes in Galaxies" (Cozumel, Mexico); "HST Observations Reveal the Curious Geometry of Circumgalactic Gas"

Kacprzak, G.G., Muzahid, S., Churchill, C.W., Nielsen, N.M., & Charlton, J.C. 6/2016, in The Interplay between Local and Global Processes in Galaxies, Cozumel, Mexico, 2016-4, Eds. S. F. Sanchez, C. Morisset and G. Delgado-Inglada; HST Observations Reveal the Curious Geometry of Circumgalactic Gas

Lewis, J., Churchill, C.W., Nielsen, N.M., & Kacprzak, G.G. 1/2017, American Astronomical Society Meeting Abstracts, 229, 150.06; "Deeper Insights into the Circumgalactic Medium using Multivariate Analysis Methods"

Lewis, J., Churchill, C.W., Nielsen, N.M., Kacprzak, G.G., Muzahid, S., & Charlton, J.C. 1/2018, American Astronomical Society Meeting Abstracts, 231, 302.04; "Insights to Galaxy Evolution Utilizing a Multivariate Comparison of Circumgalactic OVI and MgII"

Mathes, N., Churchill, C.W., Kacprzak, G.G., Nielsen, N.M., Charlton, J.C., & Muzahid, S. 1/2014, American Astronomical Society Meeting Abstracts, "A Detailed Spatial Study of HI and OVI Absorbing Gas Around Galaxies"

Mathes, N., Churchill, C.W., Kacprzak, G.G., Nielsen, N.M., Trujillo-Gomez, S., Charlton, J.C., & Muzahid, S. 1 /2015, American Astronomical Society Meeting Abstracts, 225, 314.03; "Halo Mass Dependence of HI Absorption: Evidence for Differential Kinematics"

Nielsen, N.M., Kacprzak, G.G., Churchill, C.W., Murphy, M.T., Muzahid, S., Charlton, J.C., & Evans, J.L. 3/2017, in Formation and Evolution of Galaxy Outskirts, Proceedings of the International Astronomical Union, IAU Symposium, Volume 321, pp. 345-347; "Gas Kinematics in the Multiphase Circumgalactic Medium"

Rosenwasser, B., Muzahid, S., Norris, J., Charlton, J.C., Rodriguez-Hidalgo, P., Wakker, B.P., Narayanan, A., Misawa, T., Churchill, C.W., Mathes, N., Nielsen, N.M., & Ganguly, R. 1/2014, American Astronomical Society Meeting Abstracts, 223, 458.02; "Constraining the Properties of OVI in the 0.4<z<1.0 Circumgalactic Medium"

Vander Vliet, J.R., Churchill, C.W., Trujillo-Gomez, S., Klimek, E.S., & Klypin, A.A. 1/2014, American Astronomical Society Meeting Abstracts, 223, 458.12; "A Comparison of the Circumgalactic Medium of Present-Day Dwarf and Milky Way Galaxies using Absorption Line Analysis through Hydrodynamic Cosmological Simulations"

4. Suggestions and additional comments

I will repeat my **Comments from the 3rd Interim Report** (because I think they are important).

We mention that one of our senior personnel, Sowgat Muzhid, who has been a postdoc hired on this project working under co-PI Jane Charlton at Penn State, accepted a job in Leiden starting in August 2016. Thus, we had significantly reduced human power starting in the late summer of 2016.

Churchill was not able to hire a postdoc due to the originally proposed budget being cut in this area (or by the amount of the postdoc support). It was unfortunate in the long run. Given how valuable Sowgat Muzahid has been to the project, we estimate that the productivity of our team was reduced by roughly 40% over the last two years. We expect that the final push to get results out in the coming year will now be substanitally impacted as well. It is our hope that other Large Progams are not suffering the same fate of being understaffed with highly qualified personnel; graduate students are important to support, but they are not as productive. Furthermore, graduate students greatly benefit from the invaluable presence of a postdoc on their team for multiple reaons. Thank you for considering our opinion on this.

Final Comments:

Roughly half of the telescope time that we were awarded was utilized for NUV/COS gratings observations in order to obtain CIV absorption in addition to the targeted OVI absorption. In practice, we would discourage awarding large amounts of time on the NUV/COS gratings as they were so highly inefficent (meaing that the COS-ETC appears to not be accurate based upon our estimates). As such, we were not able to engage in a study that included CIV and OVI absorption.

I deeply believe that had I not had the budget cut to eliminate a post-doc that we would have completed the simulations component of the proposed research and that the program, as original conceived and proposed, would have come to a much higher percentage of completion.

Please note that a copy of the report should be forwarded to the Authorizing Official of your Institution.