OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

Confirming the Discovery of Massive 10^6 K Gas Reservoirs in Spiral-Rich Galaxy Groups

P.I.: Brian Keeney (Univ. of Colorado; *brian.keeney@colorado.edu*; 720-935-3220)

CoI(s): John Stocke (Univ. of Colorado), Buell Jannuzi (Univ. of Arizona), Chris Impey (Univ. of Arizona)

Abstract of Scientific Justification

A large portion (∼30%) of the baryons in the local Universe are still unaccounted for by observations. These "missing baryons" are almost certainly in the diffuse, hot gas that surrounds spiral galaxies where they constitute the gaseous medium from which galaxies like the Milky Way continue to form and evolve. Recently due to high S/N far-UV spectra now being delivered by the Cosmic Origins Spectrograph on *HST*, we have discovered several examples of very broad, shallow $\mathrm{Ly}\alpha$ and O VI absorption lines which appears to be 10^6 K gas in the vicinity of small groups of spiral galaxies. Because COS observations provide only pencil-beam probes through this gas, its full extent is not known by direct observation. But if this gas is > 600 kpc in extent it contains $> 10^{11}\ M_{\odot}$ of gas and is a major reservoir of baryons and metals surrounding spiral galaxies. If this inference is correct, the presence of the hot gas in spiral-rich groups like the Local Group has significant implications for the cosmic baryon census (~ 20% of the total) and galactic chemical evolution (accretion reservoir for low metallicity gas). Here we propose to use MMT/Hectospec multi-object spectroscopy to confirm this interpretation by verifying the presence of small spiral-rich groups around each absorber and determining if the velocity dispersion of the group matches the expectations based on gas temperatures inferred from $\mathrm{Ly}\alpha$ and O VI line widths. We propose our six best sight lines, containing ten broad, shallow O VI absorbers at $z = 0.06$-0.19.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT		Hectospec			3.0	dark	Aprr–May	Mar–Jun	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	PG 0953+414	09:56:52.4	+41:15:22	Galaxy group near $z = 0.142$.
2	PG 1116+215	11:19:08.7	+21:19:18	Galaxy group near $z = 0.138$.
3	3C 263	11:39:57.0	+65:47:49	Galaxy group near $z = 0.063$, 0.114, 0.140.
4	3C 273	12:29:06.7	+02:03:09	Galaxy groups near $z = 0.090$, 0.120.
5	Ton 236	15:28:40.6	+28:25:30	Galaxy group near $z = 0.195$.
6	H 1821+643	18:21:57.3	+64:20:36	Galaxy groups near $z = 0.121$, 0.170.

Approval for Instrument Use from PI: N/A

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

One of the exciting, early discoveries of the Cosmic Origins Spectrograph (COS) aboard the *Hubble Space Telescope* (*HST*) was a broad, symmetrical O VI absorber in the PKS 0405–123 sight line at $z \approx 0.167$ (see Figure 1; Savage et al. 2010). The O VI line width suggests $T > 10^6$ K gas, which is confirmed by the absence of H I Lyα absorption. At slightly cooler temperatures, absorbers in other sight lines show both broad, shallow Lyα (BLA) and broad O VI (see Figure 2; Savage et al. 2014; Stocke et al. 2014), despite being partially masked by the stronger, shock-heated O VI thought to be associated with spiral galaxy halos (Tumlinson et al. 2011). The O VI and BLA line widths (see Figure 2) of each of these two dozen "warm absorbers" suggests $T \sim 10^{5-6}$ K gas (Savage et al. 2014) and our shallow and broad WIYN/HYDRA galaxy redshift survey finds small groups of spiral galaxies present in all cases at $z \leq 0.1$ (Stocke et al. 2014), where the WIYN survey depth ($r \leq 19.5$) allows measurement of sufficient group galaxies. This spiral group gas was predicted to be present by Mulchaey et al. (1996), who presciently suggested that it was most easily detected using O VI absorption in background QSO spectra. These broad, shallow absorbers are detected **only** in high-S/N (> 20) COS spectra and are distinct from the strong, individual galaxy halo absorbers studied by other programs (e.g., Tumlinson et al. 2011; Werk et al. 2014; Stocke et al. 2013).

Here we propose MMT/Hectospec spectroscopy of our 10 best warm absorbers (6 sight lines) associated with probable spiral galaxy groups, but with insufficient WIYN/HYDRA depth to constrain group characteristics. *HST*/COS provides only a single pencil-beam probe through these absorbers, so that their physical extent and mass are not directly measurable by the observations. Indirect support for a large extent of these warm absorbers ($\sim R_{\rm vir}$) comes from their dN/dz (~ 5 times the line density of Mg II/Lyman limits systems) and from *HST*/COS observations of cooler, photo-ionized gas also found in these and similar spiral groups, which have relatively constant internal pressures at $\rho \leq 300$ kpc from the closest galaxy. If these clouds are in rough pressure equilibrium with an external gas at $T \approx 10^6$ K, this gas would have a density of $n_{\rm H} \sim 5 \times 10^{-6}\ {\rm cm}^{-3}$ and a total mass $> 10^{11}\ M_\odot$ (see Stocke et al. 2014 for a detailed discussion of these points).

This massive gas reservoir would account for the "missing baryons" in spiral galaxies (Klypin et al. 2001; McGaugh et al. 2000) and would provide a source for large amounts of low-metallicity gas for future accretion and star formation. No chemical history of spirals can be complete without understanding this hot, intra-group gas. Also, if this gas is ubiquitous in spiral-rich groups, the large space density of such systems means that this gas contains a significant amount of baryons, $\sim 20\%$ of the cosmic inventory at $z \sim 0$ (Savage et al. 2014; Stocke et al. 2013, 2014). Our proposed observations will:

1. **Confirm that a spiral-rich group is present** as suggested by our shallow WIYN/HYDRA survey. The group will be characterized in numbers and current star-formation properties, and an approximate projected physical center and extent of the group will be determined. Currently several of our best candidates have < 5 members detected owing to the shallow WIYN/HYDRA survey depth.

2. **Cement the physical relationship between the kinetic energy of the group and the kinetic energy in the hot gas** by comparing the group velocity dispersions (σ) with the O VI thermal line widths using galaxy velocities accurate to $\pm 30\ {\rm km\,s^{-1}}$. Our preliminary result finds that where $> 10^5$ K gas is detected by *HST*/COS, $\langle\sigma\rangle \approx 200\ {\rm km\,s^{-1}}$, while $\langle\sigma\rangle \approx 100\ {\rm km\,s^{-1}}$ where it is not. But in many cases the number of group members measured are too few to provide an accurate σ (Zabludoff & Mulchaey 1998), so this result must be considered preliminary.

3. **Determine the likely galaxy properties which gives rise to the stronger, narrower O VI and its associated lower-ionization metal-line absorption** (see Tumlinson et al. 2011; Prochaska et al. 2011; Stocke et al. 2013). At present several absorbers have closest galaxies which are too distant ($\rho > R_{\rm vir}$) to be the likely source of the photoionized warm clouds and their shock-heated interfaces. Deeper spectroscopy to $L < 0.1\,L^*$ is required to identify with confidence the nearest galaxy in these cases.

We will target $\gtrsim 100$ galaxies with $L \gtrsim 0.05\,L^*$ per fiber configuration; of the galaxies targeted, only 10–20 need to be bona fide group members to meet the requirements of this study (i.e., a "complete" redshift survey is not required, only a "sampling of group members"). Our 10 target groups range in redshift from $z = 0.05$–0.19, requiring spectra of galaxies as faint as $r = 21$ to meet our goals. MMT/Hectospec is a far superior instrument for this project than e.g., Gemini/GMOS, because we access a much larger field-of-view and do not need to go exceptionally faint. We estimate that single fiber setups with 2.5hr exposure times centered on our 6 sight lines will be sufficient to obtain $\mathrm{S/N} \geq 5$ per resolution element at $r \sim 21$ to meet our project goals. With time for setup and calibration we request 3 nights centered at $\mathrm{LST} \sim 12$ hours.

References

Beers, Flynn, & Gebhardt 1990, AJ , 100, 32
Klypin, Kravtsov, Bullock, & Primack 2001, ApJ , 554, 903
McGaugh, Schombert, Bothun, & de Blok 2000, ApJ , 533, L99
Mulchaey, Davis, Mushotsky, & Burstein 1996, ApJ , 456, 80
Prochaska, Weiner, Chen, Mulchaey, & Cooksey 2011, ApJ , 740, 91
Savage, Narayanan, Wakker, et al. 2010, ApJ , 719, 1526
Savage, Narayanan, Lehner, & Wakker 2011a, ApJ , 731, 14
Savage, Lehner, & Narayanan 2011b, ApJ , 743, 180
Savage, Kim, & Wakker 2014, ApJS , 212, 8
Stocke, Keeney, Danforth, et al. 2013, ApJ , 763, 148
Stocke, Keeney, Danforth, et al. 2014, ApJ , 791, 128
Tumlinson, Thom, Werk, et al. 2011, Science, 334, 948
Werk, Prochaska, Tumlinson, et al. 2014, ApJ , 792, 8
Zabludoff & Mulchaey 1998, ApJ , 496, 39

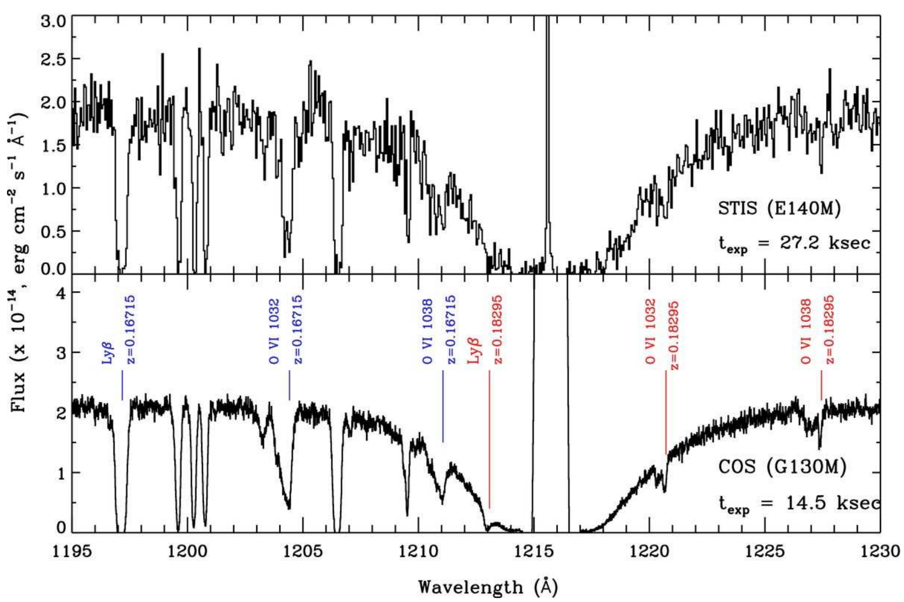

Figure 1: COS (*lower panel*) and STIS (*upper panel*) spectra of the QSO PKS 0405–123 from 1195–1230 Å, reproduced from Savage et al. 2010. Two O VI systems detected in H I Lyβ and O VI $\lambda\lambda$1032, 1038 Å at $z = 0.16716$ and 0.18295 are identified in the lower panel. The weak O VI λ1032 Å absorber with $T > 10^6$ K and no associated H I absorption is located at $\lambda \approx 1203$ Å and only visible in the higher-S/N COS spectrum.

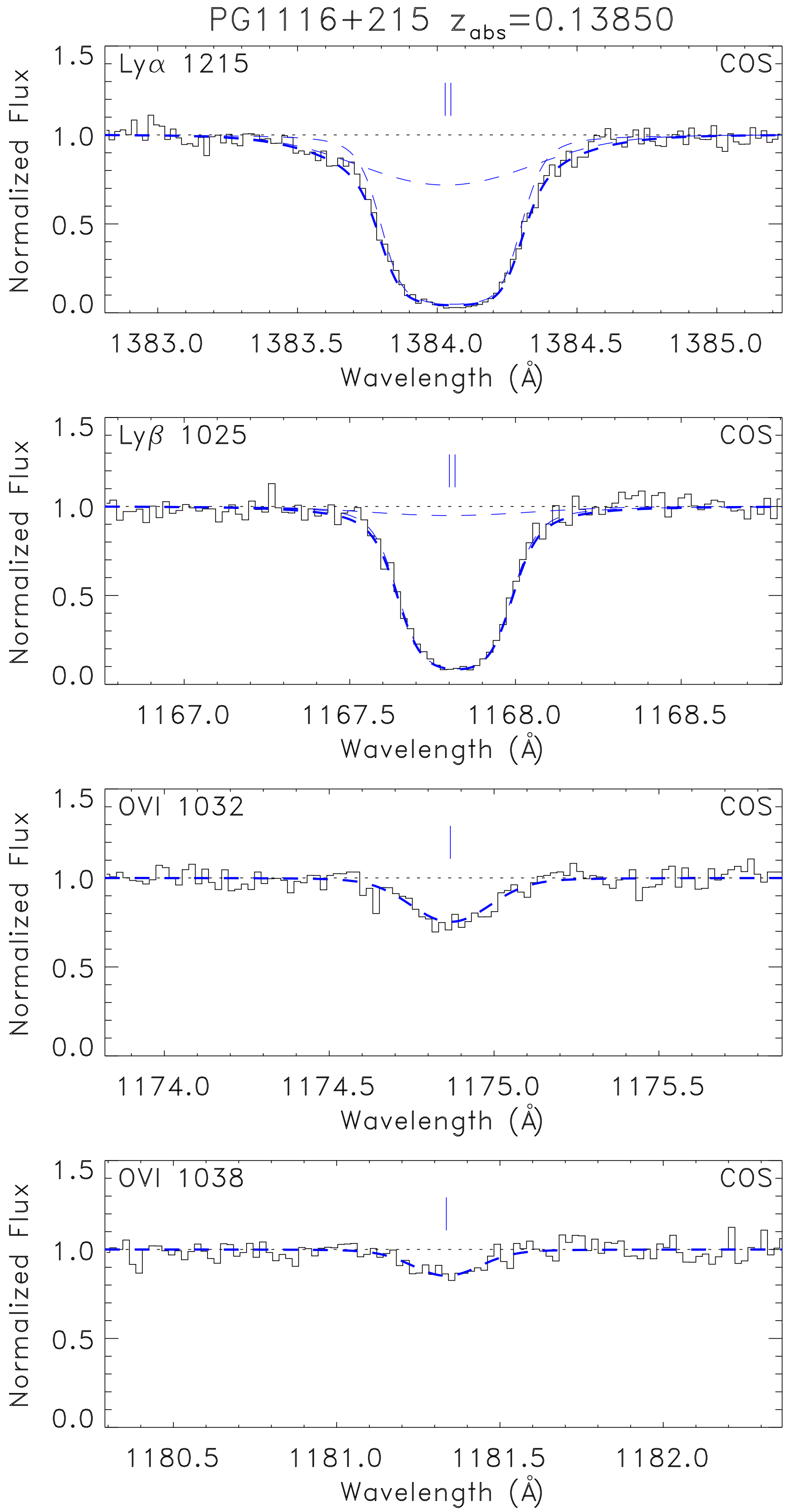

Figure 2: COS and *FUSE* spectra of the QSO PG 1116+215 at $z = 0.1385$, showing a broad ($b \approx 86$ km s^{-1}), shallow Lyα on the blue wing of strong Lyα and broad ($b \approx 35$ km s^{-1}) O VI absorption which combine to predict log T (K) $\approx$ 5.6. Preliminary spectroscopy using WIYN/HYDRA finds evidence for a small, sprial-rich group of galaxies with $\sigma \sim 240$ km s^{-1}. See Stocke et al. (2014) for details.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Our targets were chosen from the O VI absorbers analyzed by Savage et al. (2013). In Stocke et al. (2014), we examine the galaxy environments of these absorbers and find a tentative result that galaxy groups associated with O VI absorbers having $T \sim 10^{5-6}$ K possess larger velocity dispersions than galaxy groups associated with cooler O VI absorbers. The galaxy groups that we target in this proposal currently have insufficient numbers to calculate accurate velocity dispersions to confirm this tentative result.

We need to obtain spectra of ≥ 10 group members in order to have the minimal number in-hand with which to determine an accurate group velocity dispersion. For each of our six sight lines, we will use a single fiber configuration centered on the QSO sight line to target $\gtrsim$100 faint galaxies with SDSS photometric redshifts $z_{\rm photo} < 0.25$. One configuration per sight line is sufficient because we are looking for a representative sampling (rather than spectroscopic completeness) for galaxies with $L > 0.05\,L^*$ ($r < 21$) at the group redshift.

We will determine group members using the iterative procedure detailed in Stocke et al. (2014; see Section 3.1). We start with a catalog of all galaxies (i.e., we will combine data from SDSS, our previous WIYN/HYDRA observations, and the MMT/Hectospec observations proposed herein) within ± 1000 km s^{-1} of the absorber redshift with impact parameters ≤ 2 Mpc from the QSO sight line. We then use a friends-of-friends algorithm to search for galaxies associated with the closest galaxy to the sight line and use the combined luminosity of all of the group galaxies identified by this algorithm to estimate the group's halo mass, and thus a characteristic "virialized" scale size in both impact parameter, $R_{\rm grp}$, and velocity, $\sigma_{\rm vir}$. We then compare these "virialized" quantities with the size of the initial search catalog and rerun the friends-of-friends algorithm over a larger area if appropriate to ensure that we have searched within $2.5R_{\rm grp}$ of the group center and $\pm 5\sigma_{\rm vir}$ from the group redshift. We then use the group members identified by the friends-of-friends algorithm as the first step in an iterative procedure to finalize group membership; at each step we determine the group's center on the sky and in redshift space and identify all galaxies within $\pm 3\sigma_{\rm vir}$ of the group redshift and $1.5R_{\rm grp}$ of the group center as being group members for the subsequent iteration, and repeat the process until the group membership converges. Once the group membership is finalized, we determine its velocity dispersion using the robust "gapper" estimator of Beers, Flynn, & Gebhardt (1990).

SDSS imaging and photometric redshifts are available within $30'$ of all of our sight lines, so pre-imaging will not be required before we can select spectroscopic targets. We will use the $600\ {\rm lines\,mm^{-1}}$ grating to achieve sufficient redshift accuracy to calculate group velocity dispersions. Based on our experience with WIYN/HYDRA and AAT/AAOmega for brighter galaxies at similar spectral resolution, we estimate that we can obtain spectra of sufficient depth to determine the redshift of $r \sim 21$ galaxies in 2.5 hours of exposure time per sight line. These exposure times are somewhat longer than is typical for targets as faint as r$\sim$ 21 because we need to measure accurate velocities for low redshift galaxies with and without emission lines. With emission lines we will tilt the grating to ensure good coverage at Hα. Without emission lines we will have only Mg b and Na D, not Ca II H&K to determine accurate velocities. Thus, after factoring in overheads for slews, fiber configurations, and calibrations we request 3 nights of observing time to complete this project.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

We have not had MMTO observation time for this project as yet. If successful, we do not anticipate requesting more time to observe galaxy groups at these redshifts. PI Keeney and co-I Stocke have successfully obtained redshifts of $r < 19.5$ galaxies near sight lines observed by the COS GTO team over the past several years with WIYN/HYDRA, CTIO/HYDRA, and AAT/AAOmega. Four papers using results from this survey have been published to date: Savage et al. (2012, ApJ, 753, 80; 2014, ApJS, 212, 8) and Stocke et al.(2013, ApJ, 763, 148; 2014, ApJ 791, 128). Two other papers are in preparation providing detailed FUV QSO spectra (Danforth et al.) and optical galaxy photometric and spectral observational data (Keeney et al.).

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

PI Keeney and co-I Stocke have not used UAO facilities in the past decade, and co-Is Impey and Jannuzi have not used them in the past two years.