ASTR375: Literature Review Practicum (WI)
The Goal

Kathy Cooksey
University of Hawaiʻi at Hilo

Version 0: July 23, 2014

The Goal

The final product of ASTR375 will be a ≥ 2500 paper on a science topic, equivalent to an introduction of a science paper (though a bit on the long side).[1] But like so many things, the path to the goal is where the important stuff happens, actually. So ASTR375 is focused on the methodology of producing a synthesis of science content. The process starts with the example detailed in this document, which demonstrates The Goal with a real-world example. In Section 1, the history of ASTR375 is detailed. The real-world example is laid out in Section 2, and the original document is reproduced in Appendix A.

1. Background on ASTR375

Circa 31 Aug 2004, a document titled "OVI Absorber Survey—2$^{\rm nd}$ Year Project" was first drafted as a way for young Cooksey to wrap her head around the field of quintuply ionized oxygen (O VI) absorption-line systems and the so-called "warm-hot intergalactic medium" (WHIM). On 3 September 2004, she showed the document to her advisor, Professor X (seriously), so he could gauge her understanding and resolve misunderstandings/misconceptions,[2] which would further Cooksey's progress towards completing her "second-year project," a requirement at UC Santa Cruz equivalent to getting a master's degree.

Records of the original 3 September 2004 document have been lost to history[3] but a roughly similar 28 April 2005 version exists. By that time it had expanded to include information about the analysis (to be) used in the project that resulted in the publication: "Characterizing the Low-Redshift Intergalactic Medium towards PKS1302–102" (Cooksey et al. 2008, ApJ, 676, 262). In fact, "OVI Absorber Survey" formed the foundation for a significant portion of the introduction to Cooksey et al. (2008). In Section 2, paragraphs from "OVI Absorber Survey" are laid next to the

---

[1] For reference, Appendix A is approximately 3300 words, while the introduction derived from it was ≈1100 words.

[2] Cooksey still has her notes on what Professor X said, were anyone desirous of seeing them.

[3] This could have been averted if Cooksey had started using a version control software way back in the day. Version control refers to tracking the changes of files. Cooksey later adopted `CVS`, which she uses to this day; it would better if she switched to `SVN`, at least, or better yet, `Git`.

paragraphs in the PKS1302–102 paper as they existed in the version ultimately first submitted to *The Astrophysical Journal* on 8 Jun 2007. The (nearly) entire "OVI Absorber Survey" document is reproduced in Appendix A, with the paragraphs highlighted in the side-by-side comparison *italicized* and cross-referenced back to Section 2. All text from "OVI Absorber Survey" is as it stood on 28 April 2005; no recent[4] updates have been made, neither to grammar, syntax (including LaTeX),[5] punctuation, spelling, etc.

Fast-forward to fall 2013, when UH Hilo is requesting each program have an upper-division course that satisfies the writing intensive (WI) core competency. Cooksey tosses out the idea for a writing course focused on students reading science papers and synthesizing their understanding of the field into a paper equivalent to the introduction of a journal article. Professor Binder runs with the idea to create ASTR375: Literature Review Practicum, on the books starting Fall 2014. Cooksey envisions the course as a practice in technical/science writing (an infinitely transferable skill) but also a chance for students doing research and reading papers to "double dip" (university credit for something already being done for enrichment, credit, and/or money). Plus, writing can improve understanding.[6]

---

[4] Actually, two citations were updated from their arXiv pre-print version to the final published version. Those two are Prochaska et al. (2004) and Sembach et al. (2004).

[5] LaTeXis a "document preparation system and document markup language" (Wikipedia). It's how Cooksey makes the vast, vast majority of her documents. It's like a programming language, in that it has its own syntax and compiler. Cooksey has way better LaTeX skills in 2014 than she did in 2005, but she didn't change the "OVI Absorber Survey," even to replace ion notation, e.g., OVI, with the nicer O VI text used in the PKS1302–102 paper, which makes a space between the element abbreviation and the (shrunken) Roman numeral. LaTeX, through `BibTeX`, also makes handling citations and mathematical notation exceedingly easy.

[6] See "The Writing Revolution" by Peg Tyre, *The Atlantic Monthly*, October 2012; `http://www.theatlantic.com/magazine/archive/2012/10/the-writing-revolution/309090/`.

2. Side-by-Side Comparisons

"OVI Absorber Survey–2$^{\mathrm{nd}}$ Year Project" → "Characterizing the Low-Redshift Intergalactic Medium towards PKS1302–102"

Author: Kathy Cooksey, Ph.D. student → Ph.D. candidate,
UC Santa Cruz

Dates: 28 April 2005 → 8 June 2007

2.1. Example Paragraph 1 (see p. 8)

28 April 2005: The OVI doublet is a useful absorption feature not only because it has a characteristic separation and equivalent width (W_{r}) ratio (2:1 for $\lambda\lambda$1031.93, 1037.62) but because it is the most abundant metal and is an effective tracer of the warm-hot intergalactic medium (WHIM), which has a characteristic temperature of 10^{5-7} K (Simcoe et al. 2002). Assuming collisional ionization equilibrium, other ion species (e.g. OVIII, MgX, NeVII; see Figure 3, Prochaska et al. (2004)) have greater abundances in the WHIM temperature range than OVI, which peaks at $\sim 3x10^5$ K; however, these other ions are hard, if not impossible, to detect at low redshifts with current technology. For example, MgX has a rest-frame wavelength of 609.8 Å(Heckman et al. 2002), which would be possibly visible in the ultraviolet at $z \sim 1.5$. Richter et al. (2004) argue that broad Lyα features can be used to trace the WHIM if there are no OVI lines, and the simulations of Fang & Bryan (2001) indeed find broad Lyα features at the redshift of OVI absorption. This conclusion is based on the assumption of a single-phase absorber.

8 June 2007: The O VI doublet is a valuable absorption feature observationally because it has a characteristic separation and rest equivalent width (W_r) ratio for unsaturated features ($2:1$ for the $\lambda1031.93 : \lambda1037.62$ pair). Furthermore, Oxygen is the most abundant metal and the O^{+5} ion is an effective tracer of the low temperature WHIM (Tripp et al. 2006). Assuming collisional ionization equilibrium, other ion species (e.g. O VIII, Mg X, Ne VIII) have greater abundances in the higher WHIM temperature range, where it is predicted there are more baryons; however, these other ions are extremely difficult to detect at low redshifts. Current X-ray telescopes are not up to the task but for a few systems (Wang et al. 2005; Williams et al. 2006; Nicastro et al. 2005).

2.2. Example Paragraph 2 (see p. 8)

28 April 2005: Cosmological simulations make many predictions about the evolution and nature of the WHIM and their baryonic content. It is believed that the WHIM contains $\sim 40\%$ of the baryons in the low-redshift Universe (Fukugita et al. 1998). Through their suite of simulations with varying computational implementations and simulation physics, Davé et al. (2001) claim the WHIM has characteristic overdensity $\delta = \rho/\bar{\rho} - 1 = 10 - 30$ and is not virialized but is shock heated to 10^{5-7} K as it collapses into/onto large-scale structures (e.g. filaments). Indeed, Davé et al. (2001) believes the majority of the WHIM is in filaments. There must be some heating process that maintains the WHIM's high temperatures and low overdensities; Davé et al. (2001) proposes something like cosmic rays to heat the WHIM, while also adding pressure support and lowering its density. Davé et al. (2001) uphold the soft X-ray radiation background (SXRB) as a constraint on the WHIM, which emits thermally in SXR. More specifically, the WHIM cannot be in virialized (dense) objects because the SXRB constraints will be exceeded if Ω_b(OVI) is to meet the necessary amount; collapsing filaments cool and emit less SXR in the simulations, which fit observations. Davé et al. (2001) did not include supernova feedback or radiative cooling, so questions abound: How important are these processes? Might they be more important for WHIM located closer to condensed objects? Oxygen is at the peak of the (radiatively?) cooling curve; is it wise to neglect it?

8 June 2007: Cosmological simulations make four important predictions about the content, temperature, ionization mechanism, and density of the WHIM. The WHIM contains $\sim 40\%$ of the baryons in the low-redshift Universe (Davé et al. 2001; Cen et al. 2001). It has characteristic overdensity $10 \lesssim \delta \lesssim 30$ and is shock heated to $T \approx 10^5$–10^7 K as it collapses onto large-scale structure (*e.g.*, filaments; Davé et al. 2001; Fang & Bryan 2001). The WHIM thermally emits soft X-rays; Davé et al. (2001) argue that the WHIM must be in a filamentary structure to agree with the soft X-ray background. Collisional ionization dominates in high-temperature, high-density regions (*e.g.*, WHIM), and photoionization dominates in low-temperature, low-density regions (*e.g.*, local Lyα forest; Fang & Bryan 2001). Cen & Ostriker (2006) and Cen & Fang (2006) include new and improved prescriptions for galactic super-winds and collisional non-equilibrium. Their recent results substantitate previous simulations which argue for a large contribution of WHIM gas to the baryonic census as well as demonstrate the importance of galactic super-winds in dispersing metals to large distances from the galaxies, with impact parameters $\rho \approx 1$ Mpc.

2.3. Example Paragraph 3 (see p. 10)

28 April 2005: The observations seems to converge on the idea that the WHIM is a multiphase medium, with hot collisionally ionized components ($T \sim 10^{5-7}$ K) and warm photoionized components ($T \sim 10^4$ K) (e.g. Tripp et al. 2000; Simcoe et al. 2002; Shull et al. 2003; Sembach et al. 2004). Otherwise, the OVI absorbers are in CIE (Richter et al. 2004), not in equilibrium (Tripp & Savage 2000), or photoionized and therefore not part of the WHIM (Prochaska et al. 2004). In case of multi-phase absorbers, CLOUDY appears unable to model the complete picture but merely to give limits to the observations.

8 June 2007: Several observational papers propose that O VI absorption occurs in a multiphase medium, with hot collisionally ionized components ($10^5 \lesssim T \lesssim 10^7\,$K) and warm photoionized components ($T \approx 10^4\,$K) (e.g. Tripp et al. 2000; Simcoe et al. 2002; Shull et al. 2003; Sembach et al. 2004; Danforth et al. 2006). Other papers suggest that the O VI absorbers are in collisional ionization equilibrium (CIE; Richter et al. 2004), not in equilibrium (Tripp & Savage 2000), or photoionized and therefore not part of the WHIM (Prochaska et al. 2004). Richter et al. (2004) argue that broad Lyα features can be used to trace the WHIM if there are no O VI lines, and the simulations of Richter et al. (2006) indeed find broad Lyα features at the redshift of O VI absorption.

2.4. Example Paragraph 4 (see p. 11)

28 April 2005: Finally, for a single line of sight, I can investigate whether the (OVI) absorbers correlate with galaxies, filaments or voids. Sembach et al. (2004) performed a simple Monte Carlo statistical test to determine if the OVI absorbers were correlated with galaxies. For many realizations, they randomly distributed a number of absorbers (equal to the number they observed) along the line of sight to the quasar and measured the likelihood that these absorbers correlated with the galaxies along the line of sight as well as the real absorbers. They found that the correlation of the detected OVI absorbers is statistically significant (i.e. it is not by chance that the absorbers are found close to galaxies). Richter et al. (2004) searched NED (http://nedwww.ipac.caltech.edu/) for galaxies and clusters with redshifts and coordinates close to their detected metal-line systems. They found many galaxies and a few clusters that appeared to correlate with some of the absorbers.

[. . .]

The latter concluded that the majority of the absorbers that make-up the Lyα forest reside in the large-scale structures of galaxies. However, simulations place the majority of the WHIM in filaments, where collapsing structure shock heat the gas to 10^{5-7} K (Davé et al. 2001). It seems to me that the majority of OVI absorption detections will be correlated with galaxies because the gas density in mostly virialized objects is greater than in the structures still collapsing and thus the signal will be strongest. In other words, there seem to be an observational bias that skews the distribution of OVI absorbers towards being associated with galaxies.

8 June 2007: Recent observations have argued that O VI absorbers are often correlated with galaxies or galaxy groups (*e.g.*, Richter et al. 2004; Prochaska et al. 2004; Sembach et al. 2004). Typically, O VI absorbers are identified because Lyα absorbers were first identified at the corresponding redshifts. If O VI absorption were truly tracing the WHIM, the hydrogen should be predominantly ionized at $T \approx 10^5\,\mathrm{K}$ and therefore very broad and shallow due to thermal broadening, precluding easy detection (Richter et al. 2004). This may explain the tendency to detect O VI absorbers near galaxies and to model the absorbers as a multi-phase medium.

REFERENCES

Cen, R., & Fang, T. 2006, ApJ, 650, 573

Cen, R., & Ostriker, J. P. 2006, ApJ, 650, 560

Cen, R., Tripp, T. M., Ostriker, J. P., & Jenkins, E. B. 2001, ApJ, 559, L5

Coles, P., & Lucchin, F. 1995, Cosmology. The origin and evolution of cosmic structure (Chichester: Wiley, —c1995)

Danforth, C. W., Shull, J. M., Rosenberg, J. L., & Stocke, J. T. 2006, ApJ, 640, 716

Davé, R., et al. 2001, ApJ, 552, 473

Fang, T., & Bryan, G. L. 2001, ApJ, 561, L31

Fitzpatrick, E. L., & Spitzer, L. J. 1997, ApJ, 475, 623

Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518

Heckman, T. M., Norman, C. A., Strickland, D. K., & Sembach, K. R. 2002, ApJ, 577, 691

Marinoni, C., Davis, M., Newman, J. A., & Coil, A. L. 2002, ApJ, 580, 122

McLin, K. M. 2003, Ph.D. Thesis

Nicastro, F., et al. 2005, ApJ, 629, 700

Outram, P. J., Carswell, R. F., & Theuns, T. 2000, ApJ, 529, L73

Paredes, S., Jones, B. J. T., & Martinez, V. J. 1995, MNRAS, 276, 1116

Penton, S. V., Stocke, J. T., & Shull, J. M. 2002, ApJ, 565, 720

Prochaska, J. X., Chen, H.-W., Howk, J. C., Weiner, B. J., & Mulchaey, J. 2004, ApJ, 617, 718

Richter, P., Fang, T., & Bryan, G. L. 2006, A&A, 451, 767

Richter, P., Savage, B. D., Tripp, T. M., & Sembach, K. R. 2004, ApJS, 153, 165

Savage, B. D., & Sembach, K. R. 1991, ApJ, 379, 245

Sembach, K. R., & Savage, B. D. 1992, ApJS, 83, 147

Sembach, K. R., Tripp, T. M., Savage, B. D., & Richter, P. 2004, ApJS, 155, 351

Shull, J. M., Tumlinson, J., & Giroux, M. L. 2003, ApJ, 594, L107

Simcoe, R. A., Sargent, W. L. W., & Rauch, M. 2002, ApJ, 578, 737

Tripp, T. M. 2001, ArXiv Astrophysics e-prints

Tripp, T. M., Bowen, D. V., Sembach, K. R., Jenkins, E. B., Savage, B. D., & Richter, P. 2006, in Astronomical Society of the Pacific Conference Series, ed. G. Sonneborn, H. W. Moos, & B.-G. Andersson, 341–+

Tripp, T. M., & Savage, B. D. 2000, ApJ, 542, 42

Tripp, T. M., Savage, B. D., & Jenkins, E. B. 2000, ApJ, 534, L1

Wang, Q. D., et al. 2005, ApJ, 635, 386

Williams, R. J., Mathur, S., & Nicastro, F. 2006, ApJ, 645, 179

A. Original "OVI Absorber Survey—2$^{\rm nd}$ Year Project" (28 April 2005)

The OVI doublet is a useful absorption feature not only because it has a characteristic separation and equivalent width ($W_{\rm r}$) *ratio (2:1 for* $\lambda\lambda$*1031.93, 1037.62) but because it is the most abundant metal and is an effective tracer of the warm-hot intergalactic medium (WHIM), which has a characteristic temperature of* 10^{5-7} *K (Simcoe et al. 2002). Assuming collisional ionization equilibrium, other ion species (e.g. OVIII, MgX, NeVII; see Figure 3, Prochaska et al. (2004)) have greater abundances in the WHIM temperature range than OVI, which peaks at* $\sim 3x10^5$ *K; however, these other ions are hard, if not impossible, to detect at low redshifts with current technology. For example, MgX has a rest-frame wavelength of 609.8 Å(Heckman et al. 2002), which would be possibly visible in the ultraviolet at* $z \sim 1.5$. *Richter et al. (2004) argue that broad Ly*α *features can be used to trace the WHIM if there are no OVI lines, and the simulations of Fang & Bryan (2001) indeed find broad Ly*α *features at the redshift of OVI absorption. This conclusion is based on the assumption of a single-phase absorber. (See §2.1)*

Cosmological simulations make many predictions about the evolution and nature of the WHIM and their baryonic content. It is believed that the WHIM contains $\sim 40\%$ *of the baryons in the low-redshift Universe (Fukugita et al. 1998). Through their suite of simulations with varying computational implementations and simulation physics, Davé et al. (2001) claim the WHIM has characteristic overdensity* $\delta = \rho/\bar{\rho} - 1 = 10 - 30$ *and is not virialized but is shock heated to* 10^{5-7} *K as it collapses into/onto large-scale structures (e.g. filaments). Indeed, Davé et al. (2001) believes the majority of the WHIM is in filaments. There must be some heating process that maintains the WHIM's high temperatures and low overdensities; Davé et al. (2001) proposes something like cosmic rays to heat the WHIM, while also adding pressure support and lowering its density. Davé et al. (2001) uphold the soft X-ray radiation background (SXRB) as a constraint on the WHIM, which emits thermally in SXR. More specifically, the WHIM cannot be in virialized (dense) objects because the SXRB constraints will be exceeded if* $\Omega_b({\rm OVI})$ *is to meet the necessary amount; collapsing filaments cool and emit less SXR in the simulations, which fit observations. Davé et al. (2001) did not include supernova feedback or radiative cooling, so questions abound: How important are these processes? Might they be more important for WHIM located closer to condensed objects? Oxygen is at the peak of the (radiatively?) cooling curve; is it wise to neglect it? (See §2.2)*

Fang & Bryan (2001) model the nature of the WHIM with simulated spectra from numerical simulations; their simulations also do not include the effect of radiative cooling or supernova feedback. They had two models for the spectra, one with collisional ionization and the other a mix of collisional ionization and photoionization. For

---

This preprint was prepared with the AAS LaTeX macros v5.2.

high densities and warm temperatures, the two models agree in baryon number density, peculiar velocity, temperature, OVI number density and transmission spectrum. At the extremes, collisional ionization dominates in high-temperature, high-density regions (e.g. WHIM), and photoionization dominates in low-temperature, low-density regions. Fang & Bryan (2001) also find that OVI absorption lines from collisionally ionized gas outnumber lines from photoionization at $W_r > 40$ mÅ, and below this limit the opposite is true. At $W_r > 80$ mÅ, virtually all the OVI absorption lines are from collisionally ionized gas; both models agree in this limit. Fang & Bryan (2001) also made an interesting plot of a Doppler parameter b_{ln}, which is the normalization parameter in a log-normal distribution of Doppler parameters, versus equivalent width. The found that for their collisional ionization model, $b_{ln} \sim 20$ km s^{-1} while for their mixed ionization model, b_{ln} rises for $W_r < 70$ mÅand is ~ 20 km s^{-1} above that limit.

I have this strange note to myself, from reading Davé et al. (2001), that it seems most logical for at least half of the WHIM to be in filamentary structure. Since the measured amount of baryons in condensed objects is less than that seen at high redshift and presuming the mass of the WHIM associated with/surrounding condensed material is not more than the condensed objects, to make up the rest of Ω_b with Ω_b(WHIM), at least half of the WHIM must be in the filaments.

I intend to analyze HST/STIS and FUSE spectra of an as-yet unnamed quasar for absorption features, specifically: Lyα, OVI, NV $\lambda\lambda$1238.8,1242.8, SiIV $\lambda\lambda$1393.8,1402.8 and CIV $\lambda\lambda$1548.2,1550.8. The initial steps towards this end have been mostly completed. Multiple HST/STIS observations, reduced with the latest CalSTIS pipeline, of the same object have been coadded with home-brewed programs. Once the latest version of CalFUSE (v3.0.7) becomes available, the FUSE spectra from one observation run will be combined with *idf_combine*; then the spectra from different years will be coadded. Richter et al. (2004) and Sembach et al. (2004), working on similar projects as this, adjusted the FUSE wavelengths to the more accurate STIS scale by correlating common Galactic absorption features. This is probably a good idea for this project.

The general prescription for analyzing a line of sight found in the, relatively, little literature (e.g. Prochaska et al. 2004) is described here. First, I should fit the continuum to areas where there are no or few features; this can be done with the home-brewed program *x_continuum.pro*. Then I should locate the interstellar absorption features (Richter et al. 2004), which I guess are the Galactic lines, etc., that block or blend more interesting absorption lines.

Next, I need to pinpoint all the Lyα lines at $\lambda >$ 1216 Å (Sembach et al. 2004). Once a Lyα line is found and its redshift measured, it should be straightforward to look for other lines of the HI Lyman series and metal lines (e.g. OVI doublet), in general. OVI should be detected with close velocity alignment to Lyα; the difference in velocity should be small for photoionized gas; and if no Lyα features is detected where expected based on an OVI line the gas must be very hot (i.e. collisionally ionized; Simcoe et al. 2002). Richter et al. (2004) made the interesting assumption that all unidentified lines (i.e. not Galactic lines and not metal lines associated with a, presumably, stronger Lyα feature) were in fact tentative Lyα features and were analyzed as such. This is a better assumption than thinking Lyα lines are OVI lines because this artificially raises the baryonic content in OVI absorbers Ω(OVI), as obliquely mentioned in Tripp (2001). I will need to determine the completeness of my OVI absorber survey as well as estimate the number of false-positive detections; a few ideas can be found in Simcoe et al. (2002).

In order to measure the redshift density, dN/dz, of a specific absorber, the total unblocked redshift $z_{\rm B}$ must be measured. This is defined as the redshift of the emitting quasar less the redshifts where Galactic lines or IGM absorption prevent detection of the species. Then unblocked distance interval of the spectrum is as follows:

$$X = 0.5\bigg([1+z_max-\Delta\, z_B)^2-1]-[(1+z_min)^2-1]\bigg) \quad \text{(A1)}$$

where $z_{\rm min}$ and $z_{\rm max}$ are the redshift limits at which the absorption line can be observed (equation 1, Sembach et al. 2004). A slightly better technique would be to considered a redshift range blocked only if one line of the OVI doublet is detected where the other falls in a region of a Galactic line (Tripp 2001). Then, dN/dz is equal to the number of absorbers divided by X. Cen et al. (2001), in their simulations and in two observations, find an evolution of dN/dz with detection W_r limit (increasing dN/dz with decreasing W_r), which they attribute to the majority of OVI absorbers being located in the filaments. Fang & Bryan (2001) find a similar trend in their simulations.

In order to gain insight into the nature of the absorber(s) causing the spectral features, I need to measure the column density and Doppler parameter. To this end, I will fit the lines so I can measure W_{r}:

$$W_{obs} = W_r(1+z) \tag{A2}$$

where W_{obs} is the equivalent width I actually measure from the spectra. Richter et al. (2004) fit the features with Voigt profiles convolved with the Gaussian instrumental profiles. This can be done with the program VPFIT (Carswell et al., http://www.ast.cam.ac.uk/~rfc/vpfit.html). However, Voigt profiles are not appropriate for the non-Gaussian absorption lines in our spectra. (I mostly know this because Jason told me: a lot of astronomers seem to use VPFIT. Outram et al. (2000), one of whom is Carswell, has statistically studied the departures from the Voigt profile in the Lyα forest.) Perhaps, a better method of fitting is to use Legendre polynomials, as done in Sembach & Savage (1992) to measure W_{r}. Other possibilities include pixel integration over normalized velocity profile (Richter et al. 2004) or taking the variance weighted mean for transitions with multiple measurements (Prochaska et al. 2004). With respect to the FUSE data, there appears to be differing opinions on whether to keep the channels separate to increase statistical significance of the measurements ((Sembach et al. 2004)) or to combine them to increase the signal-to-noise ratio in regions of overlap (Prochaska et al. 2004).

The column density of a species (e.g. $N(\mathrm{OVI})$) is another important quantity to measure for every feature. I have found three possible methods for determining the column density: curve of growth (COG) method, apparent optical depth method (AODM), and Voigt profile fitting of high S/N IGM lines (Richter et al. 2004). I suspect this last method is probably not useful for the aforementioned reasons, though Richter et al. (2004) prefers it to AODM for lines where COG analysis was not possible. Prochaska et al. uses COG analysis for HI gas and AODM for metal-line systems. The COG method is used when there are multiple lines of the same species and has the benefit of measuring the Doppler parameter b as well as the column density, with only W_{r} as the input parameter. Even if there are not multiple lines, COG analysis can fit the column density based on W_{r} and b determined from other lines. AODM requires that there be two or more lines from a species. The apparent optical depth is proportional to the ratio of the estimated continuum intensity to the observed intensity. The apparent optical depth(s) of a species can be used to measure the apparent column density. This method is described in detail in (Savage & Sembach 1991). For high redshift, Simcoe et al. (2002) mentions that b is enhanced for photoionized gas by Hubble expansion and peculiar velocities. Does this apply to low-redshift observations?

COG analysis for me is based on *fuse_cog.pro* and *x_calccog.pro.* I should also substantially cite the notes from Physics of Astrophysics B. The pertinent equations are as follows:

$$\tau = \frac{\sqrt{\pi}e^2}{m_e c} f \lambda \frac{N(X)}{b} \tag{A3}$$

$$W_\lambda = \frac{2b}{c}\int_0^{infty} (1 - exp(-\tau exp(-x^2)))dx \tag{A4}$$

$$x = \frac{v}{b} \tag{A5}$$

$$P_x(\chi^2, \nu) = \frac{(\chi^2)^{1/2(\nu-2)} exp(-\chi^2/2)}{2^{\nu/2}\Gamma(\nu/2)} \tag{A6}$$

Once the Doppler parameter is known, an upper limit on the temperature of the absorbing system can be measured as:

$$T \leq A\left(\frac{b}{0.129}\right)^2 K \tag{A7}$$

where A is the atomic weight of the species (Richter et al. 2004). Obviously, this equation becomes untrustworthy when A is large. However, better temperature estimates can be found by modeling the absorber with CLOUDY (latest version, 96, http://www.nublado.org/). I gather from the literature (though, I need to study how CLOUDY works and how to work with it) that by assuming some ionization mechanism (e.g. collisional ionization equilibrium (CIE), photoionization), CLOUDY can calculate abundances for a range of temperatures. Unless assuming equilibrium, this requires knowing the mean metallicity of the IGM, Z, which is usually assumed to be $\sim 0.1\mathrm{Z}_\odot$. Heckman et al. (2002) proposes that most all OVI absorption systems obey a relation between $N(\mathrm{OVI})$ and b that is independent of metallicity; they theorize that OVI absorbers are best modeled by radiatively cooling flow of hot gases.

The observations seems to converge on the idea that the WHIM is a multi-phase medium, with hot collisionally ionized components ($T \sim 10^{5-7}$ K) and warm photoionized components ($T \sim 10^4$ K) (e.g. Tripp et al. 2000; Simcoe et al. 2002; Shull et al. 2003; Sembach et al. 2004). Otherwise, the OVI absorbers are in CIE (Richter et al. 2004), not in equilibrium (Tripp & Savage 2000), or photoionized and therefore not part of the WHIM (Prochaska et al. 2004). In case of multi-phase absorbers, CLOUDY appears unable to model the complete picture but merely to give limits to the observations. (See §2.3)

Sembach et al. (2004) argues that $N(\mathrm{HI})/N(\mathrm{OVI})$

indicates that the WHIM is multi-phase, because what could cause so much low energy ionization (i.e. HI) as well as high-energy ionization (i.e. OVI); they measure $N(\mathrm{HI})/N(\mathrm{OVI}) \sim 100$ for the line of sight to PG1116+215. Jason points out, however, that such a high ratio could be due to there being a lot of hydrogen and very little oxygen. CIV can be used to gauge the metallicity of the medium. Sembach et al. (2004) also mentions that $N(/mathrmOVI)/N(\mathrm{CIV})$ is another good discriminator of ionization mechanism. Perhaps both ratios in tandem lead to a more complete picture of the absorbing system. CIV is prevalent when there is photoionization by a hard radiation field but less if the temperature is high (i.e. collisional ionization dominates) (Sembach et al. 2004; Fang & Bryan 2001). Prochaska et al. (2004) make the case for a multi-phase WHIM by considering the velocity offset of absorption lines from where they are expected based on the measured redshift. These are all questions that can be sorted out with modeling.

Simcoe et al. (2002), using the ionization simulations of CLOUDY, determined the characteristic absorption path length for the OVI absorbers at $z \sim 2.5$:

$$L = \frac{N(\mathrm{OVI})}{n_{\mathrm{H}} f_{\mathrm{OVI}}} \left(\frac{\mathrm{O}}{\mathrm{H}}\right)^{-1} \tag{A8}$$

where n_{H} is the number density of hydrogen atoms, f_{OVI} is the ionization fraction ($n_{\mathrm{OVI}}/n_{\mathrm{O}}$), and the last term is the oxygen abundance. Conservatively, they constrain $L \leq 200$ kpc but believe it to be more like $L \leq 60$ kpc. It is useful to characterize the nature of the OVI absorbers in this way. L can be used to approximate the overdensity of the absorbers, $\rho/\bar{\rho}$. Both these quantities seem useful in discerning whether they are more likely associated with galaxies or with filaments and/or whether the OVI absorbers are photoionized or collisionally ionized.

Finally, for a single line of sight, I can investigate whether the (OVI) absorbers correlate with galaxies, filaments or voids. Sembach et al. (2004) performed a simple Monte Carlo statistical test to determine if the OVI absorbers were correlated with galaxies. For many realizations, they randomly distributed a number of absorbers (equal to the number they observed) along the line of sight to the quasar and measured the likelihood that these absorbers correlated with the galaxies along the line of sight as well as the real absorbers. They found that the correlation of the detected OVI absorbers is statistically significant (i.e. it is not by chance that the absorbers are found close to galaxies). Richter et al. (2004) searched NED (http://nedwww.ipac.caltech.edu/) for galaxies and clusters with redshifts and coordinates close to their detected metal-line systems. They found many galaxies and a few clusters that appeared to correlate with some of the absorbers. (See §2.4)

For this project, optical spectra were taken for the area around the quasars in our survey; the observations were made at Las Campanas Observatory and Keck Observatory. By knowing the redshift and coordinates of the absorbers and galaxies, I can perform clustering analysis to see what types of absorbers (e.g. OVI and thus, probably, the WHIM) correlate with what cosmic structure (e.g. filaments). There are several promising methods for doing this. I could simply find the characteristic correlation length by measuring the three-dimensional correlation function (Coles & Lucchin 1995). More sophisticated but similar methods determine clusters with the Friends of Friends method (Paredes et al. 1995) or with a more substantive geometric process as outlined in Marinoni et al. (2002). The method most appealing to me is described in Penton et al. (2002) where they statistically determine whether Lyα absorbers in the forest correlate with galaxies, voids, or superclusters.

The latter concluded that the majority of the absorbers that make-up the Lyα forest reside in the large-scale structures of galaxies. However, simulations place the majority of the WHIM in filaments, where collapsing structure shock heat the gas to 10^{5-7} K (Davé et al. 2001). It seems to me that the majority of OVI absorption detections will be correlated with galaxies because the gas density in mostly virialized objects is greater than in the structures still collapsing and thus the signal will be strongest. In other words, there seem to be an observational bias that skews the distribution of OVI absorbers towards being associated with galaxies. (See §2.4)

Of course, the real purpose of this study is to figure out the baryonic content of OVI absorbers, which presumably reside in the WHIM. The following equation is how to determine this fraction:

$$\Omega_b(\mathrm{OVI}) = \frac{\mu_H m_{\mathrm{H}} H_0}{\rho_c c} \sum \frac{\mathrm{N}_i(\mathrm{OVI})}{f_{i\mathrm{OVI}} \Delta X_i (\mathrm{O/H})_i} \tag{A9}$$

(equation 7, (Sembach et al. 2004)). The fraction depends on many quantities that will be derived (e.g. $\mathrm{N}_i(\mathrm{OVI})$ and X_i for each absorber i) but also on quantities that have to be assumed, such as ionization fraction $f_{i\mathrm{OVI}}$ and metallicity (proportional to $(\mathrm{O/H})_i$).

Tripp (2001) forewarns against double counting of the baryons in the low-redshift Universe between census of the WHIM and the local Lyα forest. The WHIM, characterized by OVI absorption, is primarily collisionally ionized (10^{5-7} K), while the local Lyα forest is nominally photoionized ($\sim 10^4$ K). However, there are lines (of OVI or Lyα) due to the alternative ionization mechanism (photoionization or collisional ionization, respectively).

Not only can I analyze on sight line to glean oodles of information about the WHIM and absorption line systems in general, but with the large data set available (with archived HST/STIS and FUSE spectra and the galaxy survey) I could do a large systematic survey and produce some good statistics about the nature of the WHIM, etc. (GHRS spectra may be used, too, and a description of GHRS reduction and analysis can perhaps be found in Fitzpatrick & Spitzer (1997) or McLin (2003).) For example, Simcoe et al. (2002), in their figure 20, show how the upper limit of the temperatures (see equation A7) of the detected OVI absorbers cluster about $10^{5.5}$ K.

On the theoretical side, there are some predictions about the WHIM that I could test with such a large survey or just tackle from the theory side. For example, N-body simulations seem to have trouble modeling metal enrichment, which is important to understanding the WHIM but also in many other areas. This sounds like a possible thesis topic.

A.1. PKS1302-102

PKS1302-102, $z_{\rm em} \sim 0.286$. It has 22 ks of HST/STIS observations from 2001 (E140M) and 149 ks of FUSE observations from 2000 (32 observations, 32 ks) and 2001 (34 observations, 83 ks). The corresponding galaxy survey goes to limiting magnitude $R_{\rm lim} \sim 19.5$. It is 89% complete in 5' and 65% within 10'.