The spectral shape of the ionizing extragalactic background radiation at z ~ 0

Scientific Category: QUASAR ABSORPTION LINES AND IGM

Scientific Keywords: Interstellar And Intergalactic Medium, Lyman-Alpha Forest Clouds, Metal Absorption Systems

Total Budget Amount: Medium

UV Initiative: Yes

Abstract

The intensity and spectral shape of the cosmic ionizing UV background radiation is important for understanding the structure formation/evolution and the physical state of the low-density intergalactic medium (IGM). The UV background radiation is produced by the integrated radiation from QSOs and galaxies reprocessed by the clumpy IGM. Despite its importance, the UV background is still poorly known both observationally and theoretically, especially at low redshifts. We propose to constrain the spectral shape of the ionizing UV background radiation at $z \sim 0$ in the energy range $1 < E < 6$ ryd using 16 optically thin metal absorbers which are in photoionization equilibrium with the extragalactic UV background. The selected absorbers have C III and C IV detections often accompanied with Si II, Si III and Si IV, which are clearly associated with each other and H I at the same redshift. Comparing the predicted metal column densities from the photoionization code CLOUDY with the observed ones, this proposal aims to study the spectral shape, fluctuation, dominant ionizing source of the UV background at $z \sim 0$ for the first time as well as the physical properties of each absorber.

Investigators:

	Investigator	Institution	Country
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Number of investigators: 3

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& Phase I contacts: 2

Dataset Summary:

Instrument	No. of Datasets	Retrieval Method	Retrieval Plan
COS	156	FTP	All the data at the beginning of the analysis
STIS	190	FTP	All the data at the beginning of the analysis

■ Scientific Justification

The intensity and spectral shape of the cosmic ultraviolet background radiation

The cosmic ionizing ultraviolet (UV) background radiation field is one of the key ingredients influencing galaxy formation/evolution and many other astrophysical processes. It suppresses star formation in low mass dark matter halos and affects the neutral hydrogen H I distribution in outskirts of galaxies (Bullock et al. 2000, Siana et al. 2010, Adams et al. 2011). It also controls the temperature and ionization state of the intergalactic medium (IGM) with which galaxies interact through gas infall and outflow (Bolton et al. 2005).

Despite its importance, the cosmic UV background radiation field is still poorly constrained both observationally and theoretically. The current paradigm assumes that the cosmic UV background radiation is produced by the integrated radiation from QSOs and star-forming galaxies reprocessed by the clumpy IGM. However, the relative contributions of these sources as a function of redshift are still highly uncertain (Adams et al. 2011, Haardt & Madau 2012).

In theory, the integrated radiation from QSOs is absorbed and re-emitted by neutral hydrogen, helium and metals in the IGM, high-density Lyman limit absorbers and damped Lyα absorbers (the blue dot-dashed curve in Figure 1, the theoretical HM model (Haardt & Madau 2001)), producing various bumps and dips in an initial integrated power-law-like QSO spectral energy distribution. With more intergalactic absorption, the UV background radiation becomes softer. Additional stellar contributions from galaxies increase the intensity of the UV background at $E < 3$ ryd (the solid black curve in Figure 1). They also make the spectral shape much softer at $E > 4$ ryd than the QSO-only model.

Observational measurements of the cosmic UV background radiation

The intensity of the UV background is measured by three methods. 1) The line-of-sight proximity effect utilizes that the IGM is more ionized near a background QSO than average due to more available ionizing photons from the QSO (Bajtlik et al. 1988, Davé & Tripp 2001, Scott et al. 2000, Dall'Aglio et al. 2008). 2) The IGM mean flux decrement uses that the IGM mean H I flux is determined by the ionization state of the IGM in photoionization equilibrium with the UV background (Bolton et al. 2005, Faucher-Giguère et al. 2008). 3) Hα emission is expected in outskirts of local disk galaxies due to the gas photoionized by the UV background radiation (Adams et al. 2011). The first two IGM methods are suitable at high redshifts and a few existing estimated background intensities differ by a factor of 5–10 between various studies for a given redshift. The Hα method works better at $z \sim 0$, with only upper limits which are below current theoretical models (Adams et al. 2011).

The spectral shape of the UV background can be constrained from metal column densities of optically thin metal absorbers at all redshifts (Songaila 1998, Kim et al. 2002, Simcoe et al. 2006, Agafonova et al. 2007). Several inferred spectral shapes also disagree between different studies at $z > 1.5$, in part due to a small-scale UV background fluctuation.

In principle, the UV background shape can be better constrained at $z \sim 0$ theoretically.

The QSOs are the dominant source of the UV background as the ionizing photon escape fraction from galaxies is expected to be negligible, cf. Siana et al. (2010). The much sparse IGM and high-density intervening absorbers make the IGM reprocessing less complicated than at high redshift. However, there have been no observational efforts. Therefore, **we propose to constrain the UV background spectral shape at $z \sim 0$ in the energy range 1–6 ryd using 16 optically thin metal absorbers** in order to test whether QSOs are the main contributor and whether the UV background is uniform, and to obtain the physical properties of metal absorbers.

Reconstructing the UV background shape: a trial-and-error approach

Optically thin (H I column density $\log N(HI) \leq 17.3$) metal absorbers seen in QSO spectra provide a unique probe to constrain the UV background shape, since their *optically thinness* makes them in photoionization equilibrium with the UV background radiation without any complicated radiative transfer effect as is the case for optically thick Lyman limit absorbers (Reimers et al. 2006, Agafonova et al. 2007). Commonly observed ions are C II–C IV and sometimes Si II–Si IV. Their ionization potentials lie between 1 and 6 Ryd (Figure 1), thus constraining the spectral shape in this energy range.

The adopted approach to constrain the UV background shape is a *trial-and-error* method. For simplicity, the absorbing gas is assumed to be in photoionization equilibrium, and to have the constant number density, metallicity and UV background, the solar abundance pattern and the plane parallel slab geometry.

1. For a measured N(HI), a first-guess UV background such as the QSO+galaxies HM model is assumed. The background intensity is characterized by the ionization parameter U, i.e. the number of photons divided by the number of total hydrogen atom.

2. Using the photoionization code CLOUDY (Ferland et al. 2013), construct the predicted column densities of C II–C IV and Si II–Si IV for a range of U and the metallicity Z.

3. Using the observed column densities of two adjacent ions of the same element such as C III and C IV, determine the ionization parameter U and the metallicity Z as illustrated in Figure 2.

4. If no adequate solution is found in the CLOUDY predictions, modify the spectral shape in Step 1) around the ionization potentials of ions available using both detections and upper limits. As the UV background intensity, the total hydrogen number density and the metallicity are unknown and dependent on each other in CLOUDY, changing the UV background intensity without modifying the spectral shape has a negligible effect on the predicted metal column densities.

5. Repeat Step 1) to 4) until a satisfactory solution is found.

The final solution provides the UV background spectral shape incident on the absorber and other physical parameters such as Z and the size of the absorbing gas.

The pre-requisite for this modeling is that all the lines of interest should be co-spatial. The lines also should be properly deblended and have at least one unsaturated ionic transition available to obtain a robust column density measurement. These requirements make the CLOUDY modeling work only on clean, individual *components* of an absorber, not on the total column densities from all the components in the absorber. In other words, a H I component should have other metal components at the same redshift without contamination by other H I and metal lines as illustrated in Figure 3.

The C III-C IV absorbers at $z \sim 0$

We searched for the archival *FUSE* ($S/N \geq 5$ per resolution element), COS G130M/G160M ($S/N \geq 10$) and STIS E140M ($S/N \geq 5$) spectra to find an optically-thin H I absorber having unsaturated C III λ977.020 and C IV $\lambda\lambda$1548.204, 1550.778 detections at the same redshift. Any absorbers with a much broader C III profile than both C IV and H I profiles were discarded assuming that C III is likely to be blended with other lines. At $z \sim 0$, COS and STIS spectra also cover Si II λ1260.422, Si III λ1206.500 and Si IV $\lambda\lambda$1393.760,1402.772. We found 16 such absorbers suitable for the CLOUDY modeling to constrain the UV background shape as listed in Table 1. Since our basic assumptions such as the constant density and the uniform UV background are not likely to be applicable for all absorbers, more samples give a better constraint to the *mean* spectral shape of the UV background.

We also searched for any galaxies near the redshift of our target absorbers (the 6th column in Table 1) in the NASA/IPAC Extragalactic Database, since the additional radiation from nearby galaxies can become important if an absorber is closer than 50 kpc from the galaxy (Fox et al. 2005), i.e. the final recovered spectral shape is not solely for the UV background radiation. All absorbers but one are either at more than 50 kpc away from an associated galaxy or do not have any galaxies brighter than $\sim$1L$_\star$ within 2 Mpc, although there is always a possibility that a metal absorber is closely associated with a much fainter galaxy through an outflow. Either way, our approach provides a general pattern of the UV background spectral shape at $z \sim 0$.

Summary

The intensity and spectral shape of the ionizing UV background radiation is one of the key ingredients for understanding the structure formation/evolution and the physical state of the low-density IGM. Despite its importance, the cosmic UV background is still poorly constrained. At $z \sim 0$, only a few upper limits on the UV background intensity measurement exist and no efforts have been made to constrain its spectral shape. We propose to constrain the spectral shape of the ionizing UV extragalactic background radiation at $z \sim 0$ in the energy range $1 < E < 6$ ryd using 16 optically thin metal absorbers through C III and C IV, and sometimes C II, Si II–Si IV. Comparing the predicted metal column densities from the photoionization model CLOUDY with the observed ones, the spectral shape/fluctuation/dominant ionizing source of the UV background can be constrained as well as the physical properties of each absorbing gas at $z \sim 0$ for the first time.

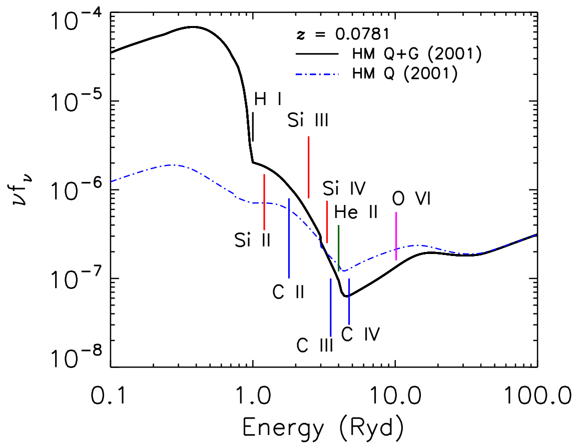

Figure 1: The theoretical models of the UV background radiation by Haardt & Madau (HM, 2001). The solid curve and the blue dot-dashed curve represent the QSOs and galaxies (Q+G) model and the QSO-only (Q) model, respectively. The x-axis is in the unit of energy in ryd, while the y-axis is μJ_μ in erg cm^{-2} s^{-1} sr^{-1}. Reprocesses by the clumpy IGM gives the various bumps and dips in the HM Q model. Including the stellar contributions increases the intensity at $E < 3$ ryd and makes the shape softer than the Q model at $E > 3$ ryd. The ionization potentials of our interest are labeled, with the convention that C IV indicates the ionization potential required from C III to C IV.

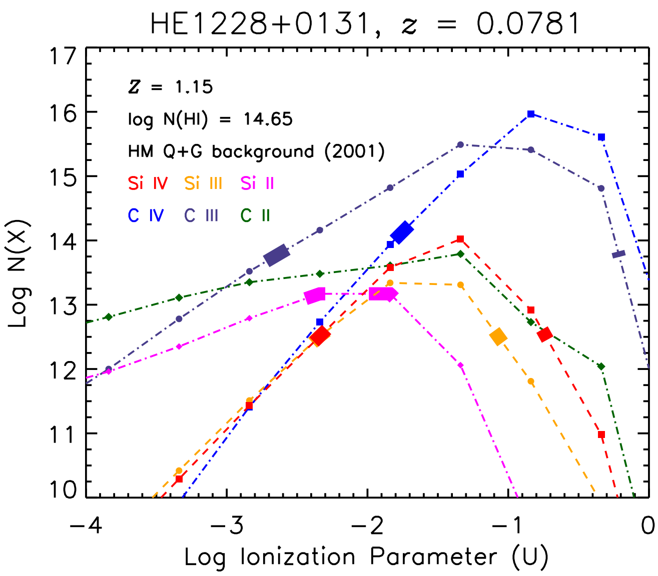

Figure 2: Predicted column densities calculated with version 10.03 of CLOUDY (Ferland et al. 2013) for the metallicity of $Z = 1.15$, $\log N(HI) = 14.65$ and the Haardt-Madau (HM) Q+G background for the $z = 0.0781$ absorber toward HE1228+0131. The curves in different colors represent a different ion labeled. The thick area in each curve indicates the observed column density ranges. No adequate solution of the metallicity Z and the ionization parameter U is found to match both N(C III) and N(C IV) at the same time. Only a high metallicity of $Z \sim 1.15$ matches all the observed column densities of Si II–Si IV. These indicate that the assumed UV background shape around $E \sim 4$ ryd is not adequate for this absorber and requires to be modified.

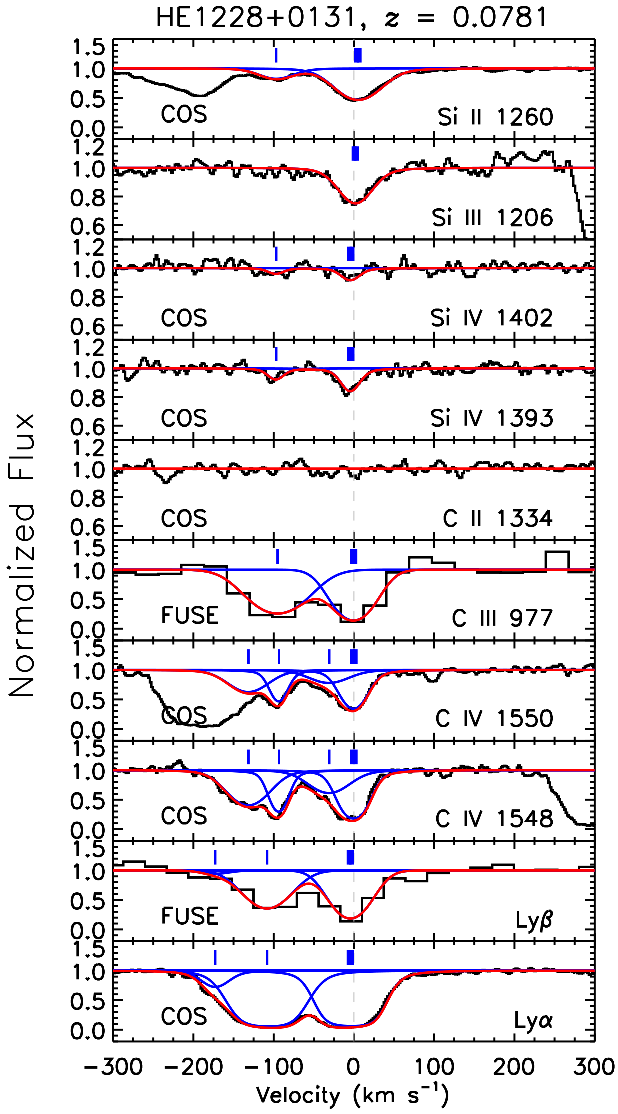

Figure 3: The normalized flux vs relative velocity plot of the $z = 0.0781$ metal absorber toward HE1228+0131. The zero velocity is fixed at $z = 0.0781$, where the C IV absorption is strongest. The instrument and the ionic transition are labeled. The black histogram is the observed spectrum. The overlaid blue solid curves represent the individual fitted components, while the thick red curves show the total profiles. The short, thick ticks mark the positions of the fitted components. The first two C IV components at -130 and -90 km/sec are not unambiguously associated with an individual H I component or other metal components at the same relative velocity. On the other hand, the 4th C IV component at 0 km/sec is clearly associated with H I and other metal components at a similar velocity. The third C IV component at -30 km/sec is weaker than the 4th C IV component, thus can be included in the column density uncertainty of the 4th component. Among 4 C IV components, **only one component at ~ 0 km/sec indicated with the thick ticks can be used for the CLOUDY modeling**. Although H I Lyα component at ~ 0 km/sec is saturated, its Lyβ is not, providing a robust column density measurement and guaranteeing it optically thin.

Table 1: List of the 16 optically thin absorbers with C III and C IV

AGN	z_{em}	z_{abs}	Other ions[a]	Nearest galaxy[b]
1H0419−577[c]	0.104	0.0037	C III (F), C IV(C), Si II-IV (C)	75 kpc
3C249.1	0.312	0.0706	C III (F), C IV (S), Si II-IV (S)	none
3C263	0.646	0.1140	C III (F), C IV (C)	965 kpc
HE0226−4110	0.495	0.0175	C III (F), C IV (C, S)	585 kpc
HE1228+0131	0.117	0.0781	C III (F), C IV (C, S), Si II-IV (C, S)	509 kpc
		0.0952	C III (F), C IV (C)	93 kpc
PG0953+414	0.234	0.0681	C III (F), C IV (C, S)	597 kpc
PG1116+215	0.177	0.1385	C III (F), C IV (C, S), Si II-IV (C, S)	132 kpc
PG1211+143	0.080	0.0512	C II (S), C III (F), C IV (S), Si III-IV (S)	133 kpc
PG1216+069	0.331	0.1236	C II (C, S), C III (F), C IV (C, S), Si III (C, S)	90 kpc
PG1259+593	0.478	0.0462	C III (F), C IV (C, S)	134 kpc
PG1302−102	0.278	0.0423	C III (F), C IV (C, S), Si III (C, S)	220 kpc
PHL1811	0.192	0.0778	C II (C, S), C III (F), Si II-III (C, S)	302 kpc
		0.0810	C II (C, S), C III (F), C IV (C, S), Si II-IV (C, S)	34 kpc
PKS0405−12	0.573	0.0918	C III (F), C IV (C, S)	130 kpc
RBS1795	0.344	0.0622	C III (F), C IV (C, S), Si III-IV (C, S)	252 kpc

[a] ‘F’, ‘C’ and ‘S’ indicates *FUSE*, COS and STIS, respectively. [b] From NASA/IPAC Extragalactic Database. When several galaxies are found at the similar redshift, a galaxy with the smallest impact parameter is listed. [c] A rough estimate of H I is $\log N(HI) \sim 17$, at the border line of becoming optically thick.

References:
Adams J. J. et al. 2011, ApJ, 728, 107; **Agafonova** I. I. et al. 2007, A&A, 461, 893; **Bajtlik** S. et al. 1988, ApJ, 327, 570; **Bolton** J. S. et al. 2005, MNRAS, 357, 1178; **Bullok** J. S. et al. 2000, ApJ, 538, 517; **Dall’Aglio** A. et al. 2008, A&A, 491, 465; **Davé** R. & **Tripp** T. 2001, ApJ, 553, 528; **Faucher-Giguère** C.-A. et al. 2008, 682, L9; **Ferland** G. J. et al. 2013, Revista Mexicana de Astronomia y Astrofisica, 49, 1; **Fox** A. et al. 2005, ApJ, 630, 332; **Haardt** F. & Madau P. 2001, Proc. XXXVIth Rencontres de Moriond; **Haardt** F. & Madau P. 2012, ApJ, 746, 125; **Kim** T.-S. et al. 2002, A&A, 383, 747; **Reimers** D. et al. 2006, A&A, 449, 9; **Scott** J. et al. 2000, ApJS, 130, 67; **Siana** B. et al. 2010, ApJ, 723, 241; **Simcoe** R. A. 2006, ApJ, 637, 648; **Songaila** A. 1998, ApJ, 115, 2184

Analysis Plan

1. Profile fitting: After producing a combined spectrum for each AGN from COS G130M/G160M and STIS E140M data, a standard routine of absorption spectrum analysis will be performed. First, the spectrum will be normalized. Second, the identified H I and metal lines for a given absorber will be fitted to derive their column densities and line widths, using the fitting program VPFIT (Carswell: http://www.ast.cam.ac.uk/∼rfc/vpfit.html).

2. The CLOUDY modeling: For each suitable H I–metal-component pair, an extensive set of the CLOUDY modeling will be performed in a broad range of the ionization parameter U and the metallicity Z using the first-guess HM Q+G UV background from their latest calculation (HM 2012 version). We will adjust the spectral shape of the first-guess UV background at $1 < E < 6$ ryd until the predicted column densities of C II–C IV and Si II–

Si IV agree with the observed ones and the upper limits of undetected ions. In this procedure, we will treat carbon ions and silicon ions if detected independently to test whether the assumed solar abundance pattern is valid. If carbon ions and silicon ions are produced in the same gas under the same physical condition, the ionization parameter derived from carbon and silicon independently should agree. Finding adequate input parameters for CLOUDY provides the UV background shape as well as the physical parameters of the absorbing gas such as the hydrogen number density and the line-of-sight thickness.

Management Plan

This proposal is a pure observational study and our team consists of three observers specializing in analysis of absorption spectra.

The timeline for the project is

1. Data retrieval and combining spectra (3 months led by French):

CalCOS-produced COS spectra from the HST MAST suffer from a large wavelength calibration uncertainties, often greater than 20 km s^{-1}. Our method to constrain the UV background spectral shape requires that H I and associated metal components should be co-spatial. If a velocity difference between H I and metal components is $\geq$ 10 km s^{-1} (cf. Savage et al. 2014, arXiv1403.7542), this H I–metal pair cannot be used for the CLOUDY photoionization modeling, as they are clearly produced in a different place under different physical conditions. Therefore, we have developed a customized post-processing program to re-calibrate the CalCOS wavelengths to be better than 10 km/sec and to combine the re-calibrated COS spectra. The current version of this customized program gives a better recalibration than the version used in Savage et al. (2014, arXiv1403.7542).

Since STIS spectra have a velocity accuracy better than 1 km s^{-1} and a factor of 3 high resolution than COS, it is complimentary to analyze STIS spectra together with COS spectra when STIS spectra are available. This ensures the COS wavelength calibration accuracy and probes the metal line component structure better.

Our COS post-processing program involves some steps handled manually. Our experience with COS data suggests that it takes about a couple of days to produce a combined spectrum for each QSO. With 12 COS QSOs and 11 STIS QSOs, it would take about 3 months to produce the final combined COS and STIS spectra.

2. Profile fitting (3 months led by Kim and French):

Although the initial line identification has been done on the fly, we need to have a more complete line identification in each QSO spectrum in order to minimize any previously unidentified blending by weak metal lines or high-order H I lines. With the continuum placement adjustment, the time-consuming profile fitting for both COS and STIS spectra will take about 3 months.

3. CLOUDY modeling (6 months led by Wakker and Kim):

Since our approach on the CLOUDY modeling is a *try-and-error* method, it requires many iterations of the same modeling process under a slightly different assumption each time. Playing with the $z = 0.0781$ absorber toward HE1228+0131 as seen in Figure 2 takes several days. We plan to make this process more automatic for this project. At the current stage, it is difficult to state how long it would take to develop an automatic, iterative CLOUDY modeling program for our purpose. However, this should not take more than 6 months, as we will do the CLOUDY modeling manually as well to test the automatic program.

4. Interpretation and publications (6 months by all the team memebers):

When we complete the CLOUDY modeling, interpretation on the observational results will be straightforward, such as whether our CLOUDY modeling approach works for each absorber, and whether the inferred spectral shape of the UV background for each absorber agrees with each other. We plan to write one observational paper and publish all the CLOUDY modeling results and the velocity plots like Figure 3 electronically.

5. Budget request: Medium (∼\$100,000):

We expect to complete this project in 1.5 years. The requested funds will cover salary for the co-PI, Dr. Wakker, for 6 months, a travel fund of \$5,000 to conferences, publication costs of \$3,000 for one expected paper.

Past HST Usage

PI Kim is a PI of HST-AR-12842 for Cycle 20. The archival data is being analyzed and the first paper is about to be submitted to MNRAS. Kim has extensive experience in analyzing very high-resolution, high S/N quasar spectra from Keck and the VLT involving the IGM at $z > 1.5$ (Kim et al. 2013) and has been involved in the analysis of high S/N COS quasar spectra in a program being lead by co-I Savage to study the properties of the highly ionized metal line absorption systems tracing warm/hot gas in circumgalactic environments. As part of that program she has developed the COS data handling techniques necessary for improving the extraction of high S/N observations including the fixed pattern noise removal and improved co-addition techniques. Some of the recent papers based on the COS spectra are Savage et al. 2014, ApJS in press (arXiv1403.7542), "The Properties of Low Redshift Intergalactic O VI Absorbers Determined from High S/N Observations of 14 QSOs with the Cosmic Origins Spectrograph"; Savage et al. 2012, ApJ, 753, 80, "The Properties of Two Low-redshift O VI Absorbers and Their Associated Galaxies toward 3C 263".

Co-Is Wakker has extensive experience in ultraviolet ISM and IGM absorption line spectroscopy from a number of HST programs involving STIS and COS. Several of their recent IGM papers include Wakker & Savage 2009, ApJS, 182, 378 "The Relationship Between Intergalactic H I/O VI and Nearby ($z < 0.017$) galaxies"; Savage, Narayanan, Lehner, & Wakker 2011, ApJ, 731, 14, "A Multiphase Absorber Directly Tracing 10^6 K Plasma at Low Redshift Toward HE 0153−4520"; Narayanan, Wakker, Savage, et al. 2010, ApJ, 721 960, "COS and FUSE Observations of 10^5 K Gas in a Nearby Galaxy Filament".