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 physical state of the low-density intergalactic medium (IGM). The UV background radiation is produced by the integrated radiation from QSOs and galaxies, which is then 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 by Si II, Si III and Si IV, which are clearly associated with each other and with H I at the same redshift. Comparing observations to metal column density predictions based on the photoionization code CLOUDY, we propose the first study of the spectral shape, fluctuation and dominant ionizing source of the UV background radiation at $z \sim 0$.

Investigators:

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Number of investigators: 3

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& Phase I contacts: 1

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 for galaxy formation and 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 the 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 it is produced by the integrated radiation from QSOs and star-forming galaxies, after it is reprocessed by the clumpy IGM. However, the relative contributions of these sources as a function of redshift remain 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, showing the theoretical model (Haardt & Madau 2001)), producing various bumps and dips in an initial 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 takes advantage of the fact that the IGM is more ionized near a background QSO 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 the property 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 the outskirts of local disk galaxies due to the gas being photoionized by the UV background radiation (Adams et al. 2011). The first two IGM methods are suitable at high redshifts, but the 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 $z \sim 0$, but observationally there are only upper limits (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 small-scale UV background fluctuations.

In principle, the UV background shape at $z \sim 0$ can be well constrained as the QSOs are the dominant source and the fraction of ionizing photon escaping from galaxies is expected to be negligible (Siana et al. 2010). The much sparser IGM and high-density intervening absorbers also make IGM reprocessing less complicated than at high redshift. However, there have been no observational efforts. Therefore, **we propose to constrain the spectral shape of the UV background radiation 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, 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 *optical-thinness* puts them in photoionization equilibrium with the UV background radiation without any complicated radiative transfer effects 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.

Our 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 constant number density, metallicity and UV background, a solar abundance pattern and plane parallel slab geometry. The approach consists of:

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

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

3. Using the observed column densities of two adjacent ions of the same element, such as C III and C IV, determine U and Z (Fig. 2).

4. If no adequate solution is found in the CLOUDY modeling, modify the spectral shape in Step 1 around the ionization potentials of ions available using both detections and upper limits. The spectral shape can be approximated by a power law for a small E rang. Modifying the spectral shape means changing the power-law slope for each energy range. As the UV background intensity, the total hydrogen number density and the metallicity are unknown and dependent on each other in CLOUDY, just changing the UV background intensity without modifying the spectral shape would have a negligible effect on the predicted metal column densities.

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

The final solution will provide observationally-based improvements over HM for the spectral shape of the UV background incident on the absorber. It will also yield physical parameters such as Z and the size of the absorbing gas.

A pre-requisite for this modeling is that all the lines of interest are 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 corresponding metal line 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 through 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 optically-thin H I absorbers 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 then 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 constant density and 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 galaxies near the redshift of the 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 within 50 kpc of the galaxy (Fox et al. 2005), i.e. the final recovered spectral shape is not solely for the UV background radiation. All but one absorbers are either 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, our approach provides the 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 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 predicted metal column densities from the photoionization model CLOUDY with observed ones, we can for the first time constrain the spectral shape/fluctuation/dominant ionizing source of the UV background as well as the physical properties of intergalactic gas at $z \sim 0$.

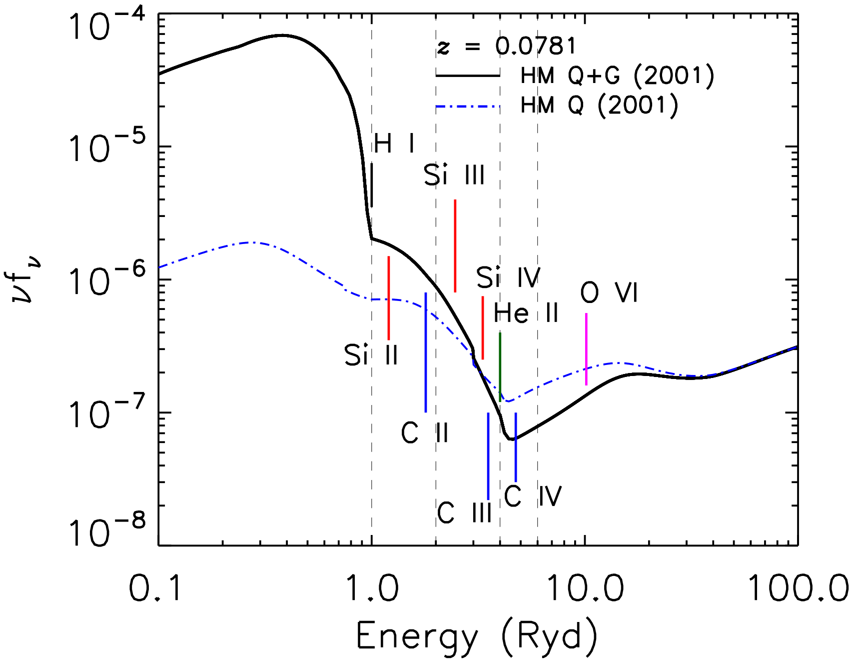

Figure 1: Theoretical UV background radiation at z=0.0781 from Haardt & Madau (HM, 2001). The solid curve and the blue dot-dashed curve represent the contributions of QSOs and galaxies (Q+G) model and the QSO-only (Q) model, respectively. The x-axis gives energy in units of ryd (i.e. the ratio to 13.6 eV), while the y-axis is νJ_ν in erg cm^{-2} s^{-1} sr^{-1}. Reprocessing by the clumpy IGM gives rise to the various bumps and dips in the HM Q model. Including the stellar contribution 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 ions of interest are labeled, with the convention that C IV indicates the ionization potential required to go from C III to C IV. The vertical dotted lines indicate the energies at 1, 2, 4 and 6 ryd, over which range the UV background shape can be approximated by a power law.

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

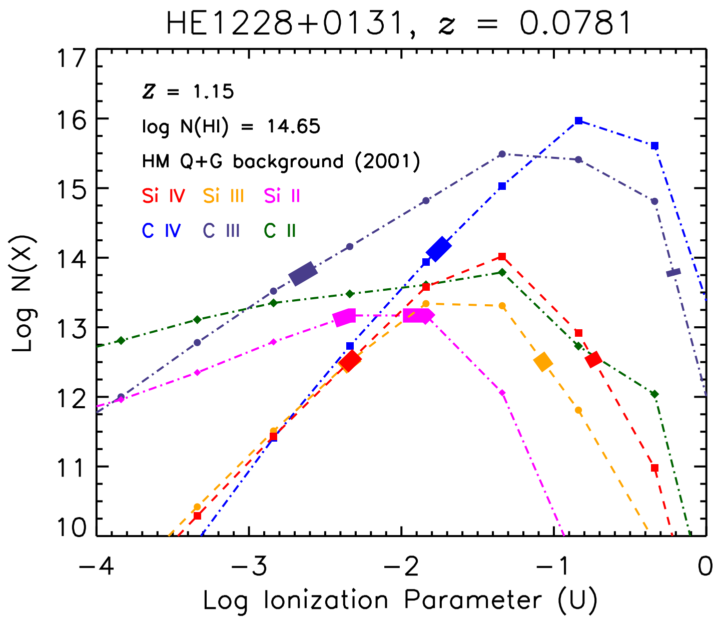

Figure 2: Predicted column densities calculated with version 10.03 of CLOUDY (Ferland et al. 2013) using a metallicity of $Z = 1.15$, $\log N(HI) = 14.65$ and the Haardt-Madau (HM) Q+G background for the $z = 0.0781$ absorber toward HE1228+0131. The curves in different colors represent different ions. The thick area in each curve indicates the observed column density ranges. No combination of the metallicity Z and the ionization parameter U is found to adequately 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 correct for this absorber and requires modification.

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

AGN	$z_{\rm em}$	$z_{\rm abs}$	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 NED. When several galaxies are found at similar redshift, the one with the smallest impact parameter is listed. c: A rough estimate of H I is $\log N(HI) \sim 17$, close to becoming optically thick.

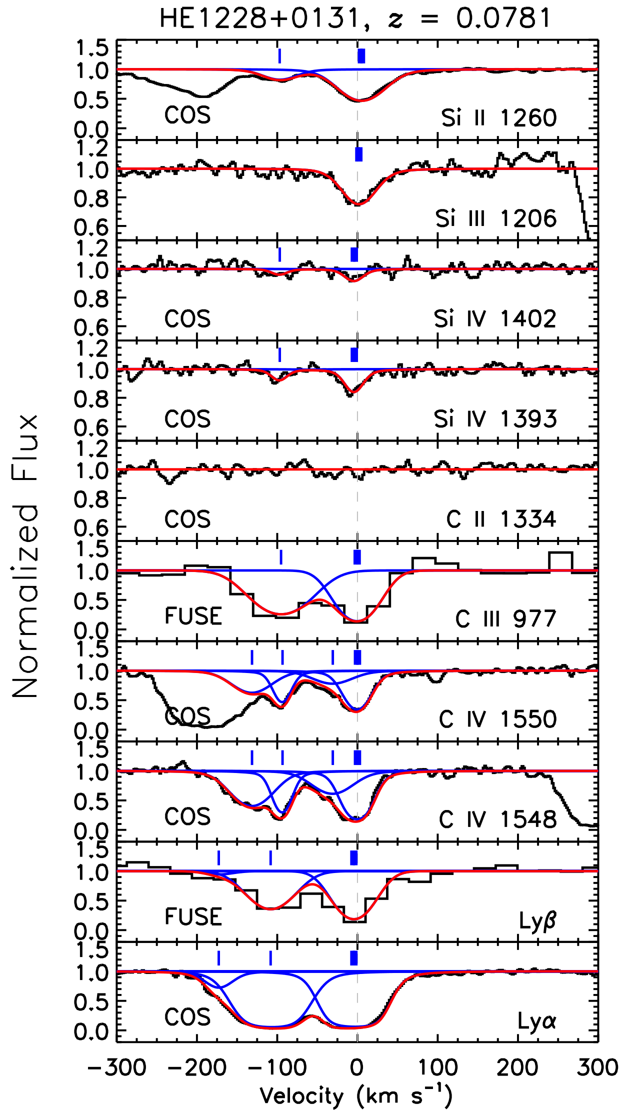

Figure 3: Normalized flux against relative velocity for the $z = 0.0781$ metal absorber toward HE 1228+0131. Zero velocity is fixed at $z = 0.0781$, where the C IV absorption is strongest. The instrument and the ionic transitions are labeled. The black histogram is the observed spectrum. The overlaid 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 s^{-1} 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 s^{-1} is clearly associated with H I and other metal components at a similar velocity. The third C IV component at -30 km s^{-1} 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 s^{-1} indicated by the thick ticks can be used for CLOUDY modeling**. Although the H I Lyα component at ~ 0 km s^{-1} is saturated, its Lyβ is not, providing a robust column density measurement and guaranteeing it is optically thin.

Analysis Plan

1. Profile fitting: After producing a combined spectrum for each AGN from COS G130M/G160M and STIS E140M data, a standard 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. CLOUDY modeling: For each suitable H I–metal-component pair, an extensive set of CLOUDY modeling will be performed, using a broad range of values for ionization parameter U and metallicity Z, taking the first-guess HM Q+G UV background from the latest calculation (HM 2012 version). Next, 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 independently with the observed ones and the upper limits of undetected ions.

The spectral shape of the UV background will be fit by a power law over a small E range, for E= [1–2] (covering H I, Si II, C II), [2–4] (covering Si III, Si IV and C III), [4–6] (covering C IV) ryd (Figure 1). To modify the spectral shape we will adjust the power-law slope in these three energy ranges.

In this procedure, we will treat carbon ions and silicon ions 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 conditions, the ionization parameter derived from carbon and silicon 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 described below.

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

COS spectra produced by CalCOS and retrieved from MAST suffer from a large wavelength calibration uncertainties, often greater than 20 $\mathrm{km\,s^{-1}}$. Our method to constrain the UV background spectral shape requires that H I and associated metal components are co-spatial. If the velocity difference between H I and metal components is ≥ 10 $\mathrm{km\,s^{-1}}$ (cf. Savage et al. 2014, arXiv1403.7542), such a 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. Thus, to make sure our velocity scales are correct, we have developed a customized post-processing program to re-calibrate the CalCOS wavelengths to be better than 10 $\mathrm{km\,s^{-1}}$ 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 $\mathrm{km\,s^{-1}}$ and a factor of 3 higher resolution than COS, for sightlines where both are available the STIS spectra will be used to improve the COS wavelength calibration accuracy and thus better determine the metal line component structure. In those sightlines, the COS data have higher S/N ratio and provide more accurate measurements.

Our COS post-processing program involves some steps handled manually. Our experience with COS data suggests that it takes about a day to produce a final properly combined spectrum for each QSO. With 12 COS QSOs and 11 STIS QSOs, it would take about 1 month to produce the final combined COS and STIS spectra. Reassessing the archive to find more C III absorbers, especially in recent COS data will add another month.

2. Profile fitting (4 months led by Kim and French):

Although the initial line identification was 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 4 months.

3. CLOUDY modeling (6 months led by Wakker and Kim): Since our approach to the CLOUDY modeling is a *trial-and-error* method, it requires many iterations of the same modeling process under a slightly different assumption for each run. Playing with the $z = 0.0781$ absorber toward HE1228+0131 as seen in Figure 2 took several days. We plan to make this process more automatic for this project. We estimate it may take up to 6 months to develop an automatic, iterative CLOUDY-using modeling program that is suitable for our purpose.

4. Interpretation and publications (6 months by all the team members): When we complete the CLOUDY modeling, interpretating the observational results will be straightforward. For instance, we will check whether or not the inferred spectral shapes of the UV background for the different absorbers agree 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 PI, Dr. Wakker, for 5 months, salary for CoI French for 4 months, a travel fund of $5,000 to conferences, publication costs of $3,000 for one expected paper.

Past HST Usage

Over the lifetime of HST, Wakker has been CoI on 10 HST programs, and PI of 10, including: the following in the past 4 cycles:
Cycle 18 – ”Measuring gas flow rates in the Milky Way” (GO-12275),
Cycle 18 – ”Mapping a nearby galaxy filament” (GO-12276).
Cycle 21 – ”Constraining the size of intergalactic clouds with QSO pairs” (GO-13444).

Wakker's pre Cycle 18 programs have led to several publications, including the first determination of the metallicity of the Magellanic Stream (Lu et al. 1998, AJ, 115, 162), the determination that the LMC has a hot gaseous halo (Wakker et al. 1998, ApJ, 499, L87), the first measurement of the metallicity of HVC complex C, establishing it as an infalling low-metallicity cloud (Wakker et al. 1999, Nature, 400, 388), a complete overview of the available data relating Lyα absorbers to nearby galaxies (Wakker & Savage, 2009, ApJS, 182, 378) and an analysis of all available data on O VI, N V and C IV absorption in the Milky Way corona (Wakker et al. 2012, ApJ, 749, 157)

Wakker is PI on two Cycle 18 programs. Program 12275 (49 orbits; 20 targets) aimed at measuring metallicities in high-velocity clouds (HVCs), while program 12276 (37 orbits, 20 targets) consisted of observing 20 AGNs that sample a nearby galaxy filament. The analysis of program 12275 targets yields new metallicities for 13 HVCs, ranging from about solar to 1/20th times solar. For many clouds the resulting value is similar to our original expectations, for some it is not. From the data for program 12276 we observationally showed that Lyα forest lines that originate away from galaxy halos sample the large-scale galaxy filaments: sightlines outside of the filament did not show absorption, while sightlines through the filament showed absorption, even when the nearest galaxy was more than a Mpc away. The column density of the absorption is correlated with the distance to the filament axis.

Only one of the seven dataset has been obtained for program 13444 so far. The data for programs 12275 and 12276 have not yet been published. The reason for that is that we found it necessary to correct the wavelengths and errors produced by CALCOS. The issues we discovered have been reported to ST. Thus, instead of doing the science, we worked on producing proper spectra, discovering new problems several times. Fortunately, all these problems seem to have been solved and in the next half year we should be able to finish the analysis for programs 12275 and 12276.

Wakker is also a CoI on program 12263 to study the Magellanic Bridge as seen in three sightlines (PI Misawa). Wakker is the administrative PI for the Cycle 19 program 12604 (see under CoI Fox below). Wakker further has an advisory role on program 12446 (PI Charlton), a study of O VI absorption associated with galaxies at z=0.4 to 1.0 in whose haloes C IV and Mg II were previously detected. Finally, Wakker is administrative PI for the Cycle 21 program 13448 "The closest galactic wind: UV properties of the Milky Way nuclear outflow", with PI Fox.

Co-PI Kim is the 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 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 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".