BROADBAND INTENSITY TOMOGRAPHY: SPECTRAL TAGGING THE COSMIC UV BACKGROUND

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ABSTRACT

Cosmic photons can be efficiently collected by broadband intensity mapping but information on their emission redshift and frequency is largely lost. We introduce a technique to statistically recover these otherwise collapsed dimensions by exploiting information in spatial fluctuations and apply it to the GALEX All Sky and Medium Imaging Surveys. By spatially cross-correlating photons in the GALEX far-UV (1500 Å) and near-UV (2300 Å) bands with a million spectroscopic objects in SDSS as a function of redshift, we robustly detect the redshift-dependent intensity of the UV background (UVB) modulated by its clustering bias up to $z \sim 2$. These measurements clearly reveal the imprints of UVB spectral features redshifting through the filters. Using a simple parameterization, we simultaneously fit a UVB emissivity and clustering bias factor to these observations and constrain the main spectral features of the UV background spectrum: (i) the Lyman break, (ii) the non-ionizing UV continuum, which agrees with the Haardt & Madau model but does not rely on any assumption regarding the nature of the sources, and (iii) the Lyα emission, whose luminosity density is consistent with estimates of the combined galaxy and AGN contributions at $z \sim 1$. Since the technique probes the total background including low surface brightness emission, we place constraints on the amount of UV light originating from the diffuse intergalactic medium (IGM). Finally, the clustering bias of UV photons is found to be chromatic and evolving. Our frequency- and redshift-dependent UVB measurement delivers a summary statistic of the universe’s net radiation output from stars, black holes and the IGM combined.

1. INTRODUCTION

Photons in the extragalactic background light (EBL) can be more efficiently collected in broadband observations than in spectroscopic observations but information on their emission redshift and frequency gets diluted or lost. Depending on the instrument and survey depth, a significant fraction of the collected photons may belong to a diffuse field as opposed to detected sources. Such photons are often discarded, together with potentially valuable astronomical information. For this reason, intensity mapping is being developed as a technique to measure and analyze the total radiation as a continuous field as opposed to the study of discrete objects. It provides us with a powerful probe of the universe that does not rely on the use of a surface brightness thresholding required for source detection. Using this approach, the study of the three-dimensional universe can be enabled by targeting specific emission lines and selecting redshifts by tuning the frequency of the observations. This is referred to as line intensity mapping and a recent review on the subject is given by Kovetz et al. (2017).

Being able to use the concept of intensity mapping with broadband data in a redshift-dependent manner would open up a number of new scientific explorations. In this work we develop a method geared toward this goal. The idea is to statistically tag the rest-frame frequencies of EBL photons (in a diffuse field and/or detected sources) in broadband observations with a spectral resolution finer than that of the bandwidth. This is achieved by combining the technique of clustering-based redshift inference (Newman et al. 2013) and a data-driven estimation of the long-established concept of the K-correction (Huang et al. 1995) and Hogg et al. 2002. We can measure the cosmic K-correction, i.e., the differential EBL intensity as a function of redshift using the clustering technique. Since this K-correction depends on the spectral energy distribution (SED) of the EBL, one can constrain the main spectral features in the EBL.

We apply this technique to study the cosmic ultraviolet background (UVB) in the All Sky and Medium Imaging Surveys of the GALEX satellite. Astrophysically, the UVB is of critical importance as the photo-ionization and excitation of most of the atomic elements are tied to this radiation field. The overall amplitude and redshift evolution of the UVB traces galaxy formation and the cosmic star-formation history (Madau & Dickinson 2014). The Lyman-Werner background in the UV photo-dissociates molecular hydrogen and regulates galaxies’ star-formation efficiency especially in the early universe (Haiman et al. 1997). The metagalactic UVB is also a starting point in modeling the circumgalactic medium (CGM) in both absorption (Werk et al. 2014) and emission (Corlies & Schiminovich 2016). Finally, the diffuse intergalactic medium (IGM) is expected to radiate in the UV in both the continuum and Lyα (Davidson et al. 1974; Paresce & Jakobsen 1980; Haardt & Madau 2012); and only very recently observational studies have started to deliver the first detections but still limited in fluorescent radiation near bright objects (Cantalupo et al. 2014; Martin et al. 2014).

In this paper we present new constraints on the spectrum of the UVB volume emissivity at $z < 2$ based on GALEX imaging data. This extends the explorations of intensity mapping from radio (Chang et al. 2010), infrared (Pullen et al. 2018), optical (Menard et al. 2011, Croft et al. 2016).
2018) to the ultraviolet. Throughout the paper we assume a Planck Collaboration et al. (2014) cosmology. All of the cosmic volumetric quantities are expressed in comoving units. Magnitudes are given in the AB system.

2. THE FRAMEWORK

We introduce a broadband intensity tomography technique to recover the spectrum of the universe and its evolution over cosmic time. The target quantity is thus a frequency- and time-dependent EBL volume emissivity. The general approach is to: (i) de-project the observed broadband EBL intensity into differential contributions as a function of redshift using the technique of clustering-based redshift estimation, (ii) build a generative forward model describing the observed redshift de-projected intensity given any input EBL emissivity and fit to the data under the Bayesian framework to determine the emissivity posterior distribution. This framework allows us to propagate the information content from spatial fluctuations in the broadband intensity maps to the redshift distribution of EBL photons, and finally to its spectral features and cosmic time evolution. It allows us to address some science questions that are typically thought to be accessible only with spectroscopic intensity mapping data. It is applicable to all wavebands across the electromagnetic spectrum. Below we describe our technique in detail.

2.1. Information content in redshift

The redshift $z$ of a photon, by definition, carries spectral information that quantifies the fractional change in its frequency or wavelength between the emitted- and observed-frames. On cosmological scales, the expansion of the universe relates redshift to the distance or cosmic time at which the photon was emitted. Neglecting the effects of peculiar velocities, the information content carried by any redshift-dependent quantity $X = X(z)$ is:

$$
\left( \frac{d}{dz} \right) X = \left( \frac{dv}{dz} \frac{\partial}{\partial v} + \frac{dt}{dz} \frac{\partial}{\partial t} \right) X, \tag{1}
$$

where $v$ is the frequency of the photon and $t$ is the cosmic time. Equation (1) implies that by constraining the redshift dependence of the quantity of interest, we can also probe its frequency and time dependence. Conversely, this also presents the challenge of breaking the potential degeneracies between these two quantities. Most of the time, Equation (1) is used to infer $\partial / \partial t$ while trying to model out the impact of the $\partial / \partial v$ term, historically called the “K correction” (Humason et al. 1956; Hogg et al. 2002). One of our major goals here is to independently constrain the two terms of Equation (1) by making direct measurements of the redshift dependence of the quantity $X$, can we also obtain meaningful constraints on the spectral dependence of $X$?

2.2. EBL integral constraint

Our physical quantity of interest is the metagalactic co-moving emissivity $\epsilon_v = \epsilon_v(v, z)$ of the EBL (with units ergs $^{-1}$ Hz$^{-1}$ Mpc$^{-3}$), as it provides a summary statistic of the total radiation output in the universe as a function of frequency and cosmic time. Observationally, one measures the specific intensity $j_v$ (ergs $^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$). In the expanding universe, these two can be related by the cosmological radiative transfer equation (e.g., Gnedin & Ostriker 1997):

$$
\left( \frac{\partial}{\partial t} - v H \frac{\partial}{\partial v} \right) j_v + 3H j_v = -c \kappa j_v + \frac{c}{4\pi} \epsilon_v (1+z)^3, \tag{2}
$$

where $c$ is the speed of light, $H$ is the Hubble parameter, $\epsilon_v$ serves as the source term, and the opacity $\kappa$ characterizes the sink term due to IGM absorption. Integrating over the entire line-of-sight path length, or equivalently over redshift, we get

$$
j_v(v_{\text{obs}}) = \frac{c}{4\pi} \int_0^\infty dz \frac{dt}{dz} \epsilon_v(v,z) e^{-r} \tag{3}
$$

for an observer at $z = 0$, where $v_{\text{obs}}$ is the observed-frame frequency, $v = v_{\text{obs}}(1+z)$, $|dt/dz| = H(z)^{-1}(1+z)^{-1}$ and $r = \int \kappa ds$ is the optical depth describing IGM absorption along the line-of-sight, with $ds$ being the path-length element. Photometric observations using a filter $i$ for which the normalized response is denoted by $R_i(v)$ lead, for a photon-counting detector, to the band-averaged specific intensity

$$
J_i^v = \frac{\int_{v_{\text{obs}}}^\infty dv_{\text{obs}} j_v(v_{\text{obs}}) R_i(v_{\text{obs}})}{v_{\text{obs}}}. \tag{4}
$$

The quantity $J^v_i$ is an integral constraint of $\epsilon_v$, collapsed over cosmic time and a range of frequency.

2.3. Redshift tomography using clustering

$J_i^v$ is typically measured as a function of angular position on the sky, $J_i^v = J_i^v(\phi)$. The corresponding angular fluctuations carry redshift-dependent information. We can use the technique of clustering-based redshift estimation to transfer the phase and amplitude information of these angular fluctuations into line-of-sight distance, or redshift distribution of the photons in these photometric observations. The technique of clustering-based redshift estimation is laid out in Newman (2008), McQuinn & White (2013), and Ménard et al. (2013), and tested against simulations in Matthews & Newman (2010) and Schmidt et al. (2013). It has been applied to a wide range of survey datasets to estimate the redshift probability distribution of discrete objects (Ménard et al. 2013; Rahman et al. 2015; 2016a; Scott et al. 2016; Morrison et al. 2017; Davis et al. 2018) as well as that of the diffuse radiation field (Schmidt et al. 2013; Chicang & Ménard 2018). We refer the readers to these papers for details. Here we briefly describe the formalism tailored for broadband tomography.

The goal here is to measure $dJ_i/dz(z)$ (same unit with $J$) defined as

$$
J_v = \int_0^\infty \frac{dJ_i}{dz}(z) dz. \tag{5}
$$

This is achieved by using an external set of reference galaxies or quasars whose redshifts are already known spectroscopically. Since the spatial distribution of any extragalactic sources of radiation are influenced by gravity and clustered with the matter density field in their 3D local volumes, we expect $J(\phi)$ to correlate with the reference objects in the 2D angular space if the redshift ranges of the two overlap. We construct an angular cross-correlation estimator between
Given a matter power spectrum $P$ and the 3D matter density field over the entire path length $\theta$, kind and $X_b$ (Limber 1953), where the auto-correlations of the reference objects, our $\bar{b}$ by the CLASS code (Lesgourgues 2011). In Equation 8, $\bar{b}$ estimator measured in bins of redshift thus constrains the intensity field and the reference sample as function of redshift of the latter:

$$w_{Jf}(\theta, z) = \langle J_f(\theta, z) \rangle - \langle J_f \rangle,$$

where $\langle J_f(\theta, z) \rangle$ denotes the mean intensity at angular separation $\theta$ around reference objects at redshift $z$ (usually measured in bins of $z$), and $\langle J_f \rangle$ is the global, or large-scale mean intensity. We note that $w_{Jf}$ here is not the usual normalized, dimensionless cross-correlation function but carries the unit of $J_f$. This estimator is ideal for extragalactic intensity data whose normalization is hard to estimate due to the presence of a considerable foreground. As long as the foreground does not correlate with extragalactic large-scale structures, its contribution is canceled out in the two terms on the right-hand side, thus this $w_{Jf}$ estimator is unbiased. The goal here is to relate $w_{Jf}(\theta, z)$ to the desired quantity $d/dz(z)$. Since the latter does not depend on $\theta$, we can integrate $w_{Jf}$ over $\theta$ to get a one-bin measurement to enhance the signal-to-noise:

$$\bar{w}_{Jf}(z) = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} W(\theta) w_{Jf}(\theta, z) d\theta,$$

where $W(\theta)$ is an arbitrary weight function carrying the unit of $\theta^{-1}$. Following Ménard et al. (2013), we set a normalized $W(\theta) \propto \theta^{-0.8}$, same angular scaling with that of the typical galaxy angular correlation functions, which optimizes the signal-to-noise. We set our integration boundaries $\theta_{\text{min}} - \theta_{\text{max}}$ to those correspond to 0.5–5 physical Mpc at each redshift bins; this is chosen to avoid strongly non-linear clustering at small scales and uncontrolled zero-point in typical photometry datasets at large scales.

We are now ready to relate our estimator $\bar{w}_{Jf}(z)$ in Equation 7 to the redshift decomposition $d/dz(z)$. Under a linear biasing assumption (whose validity over our chosen $\theta_{\text{min}} - \theta_{\text{max}}$ has been tested in Schmidt et al. 2013), the cross-correlation amplitude scales not only with the amount of differential intensity $d/dz(z)$ emitted at a given redshift but also the clustering bias factor of the intensity field $b_f$ and that of the reference sample $b$. We therefore have

$$\bar{w}_{Jf}(z) = \left( \frac{dJ_f}{dz}(z) b_f(z) \right) \left( b_r(z) w_m(z) \right),$$

where $\bar{w}_m(z)$ is the dark matter angular clustering $w_m(\theta, z)$ integrated over $\theta$ the same way as $w_{Jf}(\theta, z)$ in Equation 7. The $w_m(\theta, z)$ is the angular cross-correlation function between an infinitely thin 2D slice of matter at redshift $z$ and the 3D matter density field over the entire path length. Given a matter power spectrum $P(k, z)$,

$$w_m(\theta, z) = \frac{1}{2\pi} \int_0^{\infty} dk k P(k, z) \int_0^{\infty} dz' J_0(k\theta X(z')) \frac{dz'}{dz},$$

(Limber 1953), where $J_0$ is the Bessel function of the first kind and $X(z)$ is the comoving radial distance. For $P(k, z)$ we use the non-linear matter power spectrum calculated by the CLASS code (Lesgourgues 2011). In Equation 8 $\bar{w}_m$ is determined by the cosmology, $b_r$ can be measured using the auto-correlations of the reference objects, our $\bar{w}_{Jf}$ estimator measured in bins of redshift thus constrains the product of $dJ_f/dz(z)$ and $b_f(z)$.

### 2.4. Spectral tagging

The observable $\bar{w}_{Jf}(z)$ carries information on the combination $dJ_f/dz(z) b_f(z)$. Following Equations 3–5, the first term of this product is given by

$$\frac{dJ_f}{dz}(z) = \frac{c}{4\pi H(z)(1+z)} \int \frac{dv_{\text{obs}}}{v_{\text{obs}}} R(v_{\text{obs}}) e_v(v, z) e^{-\tau},$$

where $v = v_{\text{obs}}(1 + z)$. We now illustrate how we can use the observable $\bar{w}_{Jf}(z)$ to constrain the EBL emissivity $e_v(v, z)$. To first gain intuition on the extraction of spectral information based on tomographic redshift measurements, let us first consider a special case of a non-evolving EBL with a single emission line, whose bias $b_f$ is also redshift independent and line-of-sight absorption can be ignored. In this simplistic scenario, the redshift trend $dJ_f/dz$ is given by a sliding integral of the spectral feature $e_v$ with the filter curve. This can be visualized in Figure 1. For convenience of the visualization we multiply the y-axis of the bottom panel by a factor $C(z) \propto H(z)(1+z)$ to cancel out redshift factors that carry no extra information once a cosmology is assumed. In this case the $dJ_f/dz$ measurements uniquely determine the emissivity $e_v$ over the frequency range accessible at a factor $1 + z$ bluewards of the filter bandpass. One can simply deconvolve $dJ_f/dz$ to get $e_v$. In fact, this works for cosmic emissivity of any spectral shape as long as its not evolving over cosmic time. The spectral resolution is not limited by the filter bandwidth but the redshift uncertainty in the $dJ_f/dz$ measurements. For the clustering redshift technique, the redshift uncertainty is limited by the correlation length (Rahman et al. 2015), about 10 comoving Mpc, which can be translated into a spectral resolution $R = \lambda/\Delta\lambda \approx 1/\Delta z = 200$–500. This is a two orders of magnitude gain from that of the typical broadband observations. Another way to appreciate the potential constraining power of our technique is that beyond the correlation length, the $dJ_f/dz$ measurements in different redshift bins are independent. Over an appreciable range of redshift the clustering amplitude can be sampled by hundreds (the number of correlation lengths along the line-of-sight) of quasi-independent measurements.

In more realistic cases the cosmic radiation field can be wavelength and redshift dependent. Furthermore, the clustering amplitude bias term $b_f(z)$ can also be wavelength and redshift dependent. To further relate these two terms, it is useful to introduce a more fundamental quantity: a rest-frame photon clustering bias $b = b(v, z)$. It is related to the quantity

$$\frac{dJ_f}{dz} b_f(z) = \frac{c}{4\pi H(1+z)} \int \frac{dv_{\text{obs}}}{v_{\text{obs}}} R(v_{\text{obs}}) b(v, z) c_v(v, z) e^{-\tau},$$

where the left-hand side is the actual observable accessible with the clustering redshift technique. The effective intensity bias $b_f(z)$ is a weighted photon bias seen in the observer-frame given by the combination of Equation 10 and 11

$$b_f(z) = \frac{1}{\int dv_{\text{obs}} v_{\text{obs}}^{-1} R(v_{\text{obs}}) c_v(v, z) e^{-\tau}} \int dv_{\text{obs}} v_{\text{obs}}^{-1} R(v_{\text{obs}}) b(v, z) c_v(v, z) e^{-\tau}.$$
Equation 11 is key in our generative EBL modeling: for any given EBL emissivity and photon bias on the right-hand-side, one can calculate the clustering redshift observable on the left-hand-side. As mentioned above, the product \((dJ/dz \times C)\) can potentially be sampled by hundreds of data points. If the number of degrees of freedom of the EBL frequency and redshift dependencies is sufficiently small and if observations in multiple broadbands are available, it is possible to break (some of) the degeneracy between the two terms of the product and constrain separately the emissivity and the clustering bias of the cosmic radiation field.

2.4.1. Application to the UV background

In this paper we aim to probe the radiation background over near- to extreme-UV (EUV) at \(0 < z < 2\) using GALEX All Sky and Medium Imaging Surveys. As a physical spectrum typically shows a high correlation between independent resolution elements, we can reduce the complexity via simple parameterization. We parameterize the volume emissivity with a piecewise power-law function with a Ly\(\alpha\) line and Lyman break as shown in the top panel of Figure 2. This includes spectral slopes \(\alpha\) (where \(\epsilon_\nu \propto \nu^{\alpha}\)) at 900, 1100, and 1500 Å, with the first one fixed as we do not have enough signal-to-noise to constrain the faint ionizing continuum. These two non-ionizing continuum slopes, together with the Ly\(\alpha\) equivalent width \(EW_{\text{Ly}\alpha}\), the strength of the Lyman break or the Lyman continuum escape fraction \(f_{\text{LyC}}\) and the normalization \(\epsilon_{1500}\) at 1500 Å each are allowed to evolve with redshift with one additional parameter, amounted to a total of 10 free parameters. Middle: the emissivity as a function of observer-frame wavelength to show the spectral sampling available for an observer at \(z = 0\). Bottom: normalized filter response for the FUV and NUV bands of GALEX.

The equations fully describing our UVB parameterization are given in the Appendix A.

With the two broadbands on board of GALEX—FUV (1350–1750 Å) and NUV (1750–2800 Å) shown in the bottom panel of Figure 2 we can continuously sample the UVB at different rest-frame frequencies. The accessible spectral sampling starts from the non-ionizing continuum at \(z = 0\) to ionizing continuum at \(z = 1\) in FUV and \(z = 2\) in NUV as illustrated in the middle panel in Figure 2.

We also parameterize the unknown bias factor in Equation 11 and will fit it simultaneously with the emissivity using the redshift tomographic intensity measurements. We consider a simple 2D power-law with three free parameters for the bias factor:

\[
b(v, z) = b_{z=0}^{\nu=0} \left( \frac{v}{v_{1500}} \right)^{\gamma_{bv}} (1 + z)^{\gamma_{bz}},
\]

where \(b_{z=0}^{\nu=0}\) is the normalization at \(z = 0\) at 1500 Å, and \(\gamma_{bv}\) and \(\gamma_{bz}\) are the power indices of its frequency- and redshift-dependence, which are assumed to be separable.
Using solely the \( \frac{dJ}{dz} \times b(z) \) measurements there is a complete degeneracy between the emissivity and bias normalizations \( c_{1500}^z \) and \( f_{1500}^z \) such that only their product can be constrained (see Equation 1). We will break this degeneracy later by using an additional observational constraint from the total intensity in detected sources. For our redshifted tomographic model of the UV background, we effectively have a total of 12 free parameters (10 in the emissivity plus 3 in the bias minus 1 normalization degeneracy).

To gain intuition on the spectral tagging using GALEX data, Figure 3 shows a grid of models in the observable space. The redshift-deprojected FUV (top row) and NUV (bottom row) intensities are shown after varying the non-ionizing UV slope \( \alpha_{1500} \), Ly equivalent width \( \text{EW}_{\text{Ly} \alpha} \), and ionizing photon escape fraction \( f_{\text{LyC}} \) of the background emissivity one at a time in the left, central, and right columns, respectively. We fix other parameters to a set of fiducial values. One can see that these three spectral features trigger different modes of redshift response and at different redshift intervals in these two bands. One can thus unambiguously separate the effects of these main spectral features in the data space. For simplicity, in this example we set \( \alpha_{1500} \), \( \text{EW}_{\text{Ly} \alpha} \), and \( f_{\text{LyC}} \) constant over cosmic time, but one can see that a joint modeling in two bands does allow us to constrain their first order redshift evolution as these features are being sampled twice at different redshift intervals.

3. DATA ANALYSIS

3.1. GALEX intensity maps

The Galaxy Evolution Explorer, GALEX, is a satellite mission designed to perform wide field imaging and grism spectroscopy in the UV (Martin et al. 2005; Morrissey et al. 2007). In this paper we use its All-Sky Imaging Survey (AIS) and Medium Imaging Survey (MIS) in the data release GR6/GR7 with observations taken over 2003 to 2012. The surveys cover a large fraction of the sky above the Galactic plane in two broadbands, FUV (1350–1750 Å) and NUV (1750–2800 Å) down to varying point source depths of AB magnitude 20.5 to 23.5 with a spatial resolution of 5–10 arcsec. Individual pointings have a circular field of view of 1.2 degree in diameter, and the exposure in the two bands are done simultaneously.

In principle, our cross-correlation tomography takes the total intensity as input and does not require source detection. Practically, we do separate the total intensity into two components, one in detected sources and one in diffuse light below the detection limit. This is for different foreground removal schemes in the data processing, as the foreground for sources are stars, while that for the diffuse light are dust scatter light and near-Earth airglow. Another consideration is that since low-redshift EBL is preferentially in detected sources while the high-redshift EBL is mostly in the diffuse component, the former actually acts as a noise-inducing foreground for the latter. To better extract the faint, high-redshift component using angular cross-correlations, we keep the sources and diffuse light separated on the map level.

3.1.1. Diffuse light

For the diffuse light, we start from the product generated by Murthy (2014a) who masked out all sources detected by the GALEX survey team pipeline and rebins the images to pixels of 2 arcmin. An attempt to remove the zodiacal light and geocoronal oxygen airglow has been made utilizing the variation seen towards the same patches of the sky as a function of time and location of the spacecraft (Murthy 2014b). Their final diffuse radiation maps in FUV and NUV are dominated by star light scattered by Milky Way dust, especially at low latitudes. At high latitudes the extragalactic contribution is significant but its amplitude is under debate due to the uncertainties in the near-earth and Galactic foregrounds (Flamend et al. 2013; Henry et al. 2015; Akshaya et al. 2018). Our cross-correlation analysis has the advantage that the result should not be biased by the presence of foregrounds, as they only add noise but do not correlate with extragalactic large-scale structures. To obtain a random sampling of the sky we keep only tiles from the AIS or MIS programs and exclude those observed as part of other guest ob-
Fig. 4.— Galex diffuse background anisotropy in FUV displayed using an equal-area Lambert projection. Color maps show the sigma-clipped, tile-median subtracted intensity at $b > 30^\circ$ (top) and the zoom in near the North Galactic Pole at $b > 85^\circ$ (bottom). Tiles with high foreground with $E(B-V) > 0.05$ mag have been removed. Small, gray-scale maps show the per-tile variance to be used for optimal weighting in our cross-correlation measurements.
server programs targeting pre-selected sources.

We post-process these data with aggressive cleaning for our analysis. We first trim the per-tile field of view from 1.2 degree diameter to 1 degree to reduce edge effects. For each tile we discard outlier pixels associated with ghosts, bright dust cirrus, or other artifacts by carrying out a 3-sigma clipping in the intensity in FUV and NUV separately. Since the Galactic foreground in the UV correlates strongly with other dust observables, we further remove tiles whose median Galactic reddening (as measured in $E(B - V)$ in Schlegel et al. 1998) is above 0.05 mag. This restricts our analysis to area with Galactic latitude $|b| \gtrsim 30^\circ$. We remove a small number of tiles with highly asymmetric intensity distribution whose mean-to-median ratio or standard deviation to 68-percentile range ratio differ substantially from unity. Finally, since the Galactic foreground fluctuates on all, especially large-scales but the extragalactic information we wish to extract is primarily at sub-tile scales, we subtract the median intensity in each tile to get a flat cross-tile zero point. As our cross-correlation estimator (Equation 5) uses the absolute but not fractional intensity fluctuations, at this point we do not need to know the amplitude of the monopole extragalactic background being subtracted together with other foregrounds.

We combine all our selected and processed tiles using the HEALPix scheme (Górski et al. 2005). A $N_{\text{side}}$ of 4096 with 50 arcsec pixels is used to resample the 2 arcmin pixels in the Murthy (2014a) images. We show the processed FUV diffuse background map in the Northern sky in Figure 4. After masking the area outside the footprint of our cross-correlation reference objects (see the next subsection), the final diffuse intensity maps used in our UVB measurement cover about 5500 deg$^2$ (4500/1000 deg$^2$ in the Northern/Southern hemisphere) for both FUV and NUV. In addition to the intensity maps in two bands, we also construct a set of corresponding error maps to be used as the optimal inverse-variance weighting for our cross-correlation estimator. Assuming large-scale homogeneity for the UV background, the spread of the intensity distribution within each tile thus reflects the level of noise, which is spatially variant due to both varying exposure time and foregrounds. We calculate the per-tile variance based on its 68-percentile range, and combine them using the same HEALPix scheme. Effectively these error/variance/weight maps have a resolution of 1 degree. The FUV variance map over the Northern sky is shown together with the intensity in Figure 4 one can visually see the correlation between the two.

3.1.2. Light in detected sources

The GALEX pipeline provides a catalog of sources combining those detected in FUV and NUV bands (the "mcat"). These sources correspond to the pixels masked in the Murthy (2014a) diffuse maps used above. We construct a set of intensity maps in FUV and NUV summing up photons in detected sources. Objects brighter than 20 mag but unresolved in GALEX are excluded as they are more likely to be stars, which do not correlate with the extragalactic sky but will add noise to our correlation measurements. For spatial sampling we treat all objects as point sources and attribute the total flux density of a source to its centroid. The combined flux density field is then placed onto a HEALPix grid of $N_{\text{side}} = 4096$ and converted into the same intensity unit used in the diffuse maps. We keep the AIS and MIS coverage separated in two maps for each band. Compared to the diffuse light maps, these source maps are spatially sparse especially for the shallower AIS maps where the surface density of sources is low; the source maps are also much less subject to foreground contamination especially at high latitudes. Our source maps differ from typical galaxy density field used in other large-scale structure studies since ours are light-weighted; we expect this to skew the redshift distribution to a more bottom-heavy one by a factor roughly scaled with the luminosity distance. We use the same inverse variance maps built using diffuse light.

3.2. SDSS large-scale structure reference

Our intensity cross-correlation tomography requires a reference sample of matter tracers in the cosmic web with known redshifts. For this purpose we combine four spectroscopic samples of galaxies and quasars from the Sloan Digital Sky Survey (SDSS). At $z \lesssim 0.2$ we take the "MAIN" galaxy sample from the NYU value-added catalog made for large-scale structure studies (Blanton et al. 2005). Over 0.1 $\lesssim z \lesssim 0.4$ and 0.4 $\lesssim z \lesssim 0.7$, respectively, we rely on the BOSS "LOWZ" and "CMASS" luminous red galaxy samples. These are from the large-scale structure catalogs built in Reid et al. (2016). At higher redshift all our reference objects are from the SDSS DR14 quasar catalog, which is an incremental release containing all SDSS I–III quasars as well as the new objects being obtained by the SDSS IV eBOSS survey. To ensure reliable redshifts for the quasars, we further select those without the z-warning flag set. The combined reference sample has a total of about 1.5 million objects within the footprint of the GALEX maps that we build. The reference catalog we use here is very similar to that used in Chiang & Ménard (2018) but includes both the Northern and Southern SDSS fields. We refer the readers to Chiang & Ménard (2018) for the redshift distribution of each sub-sample and their redshift-dependent bias factors with respect to matter clustering.

4. RESULTS

4.1. Redshift tomography of GALEX maps

Here we present our clustering-based redshift de-projection of the background intensity in GALEX FUV and NUV bands. For each band and for both the diffuse and detected source maps, we measure $w_J(\theta, z)$, the angular cross-correlation functions between the intensity field and the reference sample as function of redshift of the latter, as defined in Equations 6–9. To increase the signal-to-noise of our correlation estimator we use an inverse variance weighted mean for the ensemble average in Eq. 6, where the variance is given by the GALEX error maps introduced in Section 3.1. We estimate the scale-integrated amplitude $\langle w_J(z) \rangle$ by summing up the measured clustering amplitudes over the range 0.5–5 physical Mpc using a power-law angular weighting as described in Eq. 7. Lastly, we correct for the known, redshift-dependent matter clustering amplitudes and the bias factors of the reference sample to get $\tilde{w}_J / (\tilde{w}_m) = (\langle dJ_{\ell}/dz \rangle b) / (\langle dJ_{\ell}/dz \rangle) b$ (Equation 8), which is the bias weighted intensity in the observer bandpass emitted per unit redshift interval as function of redshift.

We perform a simple Galactic extinction correction on the normalization of these correlation amplitude measurements but not on the map level. This is to avoid the spatially correlated bias due to extragalactic imprints in the Galactic
Figure 5.— Redshift de-projected, clustering bias weighted GALEX FUV (top) and NUV (bottom) intensities obtained via the clustering redshift technique. Blue and yellow-hatched bands show the 1σ range of the contribution from diffuse light and light in detected sources (down to 20.5–23.5 mag). Data points show the total, which is dominated by diffuse light at high redshifts. The best-fit model in the data space is shown in red curves and a random subset of 100 MCMC samples is shown in gray curves.

Dust maps currently available (Chiang & Ménard 2018). Using the Cardelli et al. [1989] extinction law, Bianchi (2011) calculated the band-averaged Aλ/E(B−V) ≈ 8 nearly the same in FUV and NUV due to the presence of the “2175 Å bump” in NUV. Over the sky area that we use under our inverse variance weighting scheme, the effective E(B−V) is about 20 mmag using Schlegel et al. [1998] measurements re-scaled according to Schlafly & Finkbeiner (2011). The Galactic extinction is thus of an amplitude about 0.15 mag, independent of the band and redshift. To correct for dust extinction globally, we therefore scale up our measured (dJν/dz)bj by 15%. We also note that our cross-correlation measurements would not be affected by potential reference galaxy–Galactic foreground correlation induced by dust extinction. This is demonstrated in Chiang & Ménard (2018) by the stringent limit and null detection in the cross-correlation between SDSS galaxies/quasars and an HI-based reddening map.

Figure 3 shows our estimate of the angular cross-correlation between GALEX specific intensity and the density of reference spectroscopic objects as a function of redshift. As described in Section 2.3, this quantity corresponds to the product (dJν/dz) bj. The top/bottom panels show measurements for FUV/NUV in diffuse light (blue bands; 1σ range) and detected source (yellow hatched regions) components. The black data points show the sum of these two components. The error bars are estimated by bootstrapping our reference sample and calculating the dispersion in the estimated cross-correlation amplitudes. A 3% cosmic variance error (calculated based on Trenti & Stiavelli 2008) and 3% zero-point error are added in quadrature to the bootstrapping errors. At z > 1/1.5 in FUV/NUV we only include the diffuse component in the total since the source contribution is consistent with zero at those redshifts and only adds noise. We can observe that the redshift dependence of (dJν/dz) bj mainly reflects the emission redwards of the Lyman break being present in a given filter. Our clustering-based redshift measurements are revealing spectroscopic features of the background light (i.e., the cosmic K-correction). Below we present quantitative constraints on the redshift dependent UVB spectrum.

4.2. Spectral tagging the UVB
4.2.1. Bayesian inference and MCMC

Given our redshift tomographic measurements, a generative model describing the response in the observable for any given UVB emissivity and bias (Eq. 11) and our specific parameterization, we now constrain the time- and frequency-dependent UVB under a Bayesian framework. A Markov chain Monte Carlo (MCMC) method will be used to obtain the posterior probability distributions of model parameters. Here we describe the ingredients of our inference:

• Data D: The primary dataset we use to constrain the model is the redshift de-projected, bias weighted FUV and
NUV intensities \(dJ_N/dz\) by \(j\) shown in Figure 5. Ideally one would also include the total, redshift-projected extragalactic monopole intensities as additional integral constraints. However, in the UV, the amplitudes of the monopoles are still under debate. We therefore use only the ratio of the monopoles in NUV versus FUV, which is better known. We use the value \(J_N^{\text{NUV}}/J_V^{\text{FUV}} = 3 \pm 0.3\) based on analyses in the integrated galaxy light down to faint magnitudes [Xu et al. 2005; Driver et al., 2016]. This effectively appends one data point to our data vector,

\[
D = \begin{pmatrix}
\frac{dJ_N^{\text{FUV}}}{dz}(z), & \frac{dJ_N^{\text{NUV}}}{dz}(z), & J_N^{\text{NUV}}/J_V^{\text{FUV}}
\end{pmatrix},
\]

where \(z\) is the redshift bin vector.

- **Model \(M, \theta\):** As laid out in Section 2 our model \(M\) involves the functional form of \(c_i(v, z)\) (see Appendix A) and \(b(v, z)\) (Equation 13) and how they relate to the observables in the data space based on radiative transfer (Equation 3, 4, and 11). This includes the filter response functions taken from Morrissey et al. (2005) and the amount of IGM absorption with the optical depth taken from the analytic approximation in [Inoue et al., 2014] based on observations of intervening neutral clouds seen as absorption line systems in quasar spectra. There are 12 free parameters in our model:

\[
\theta = \left(\log(c_0^{\text{5000}}), b_0^{\text{5000}}, \gamma_{\text{5000}}, a_0^{\text{1500}}, \gamma_{\text{1500}}, \gamma_{\text{1100}}, a_0^{\text{1100}}, \gamma_{\text{1100}}, \gamma_{\text{b}}, \gamma_{\text{Ly}\alpha}, C\right).
\]

- **Likelihood \(P(D|\theta, M)\):** Given a set of parameters \(\theta\) that determine the UV background emissivity and clustering bias factor, we calculate the expected data. For \((dJ_N/dz)\) by \(j\) we use Equation 11. For the monopole ratio, we take \(J_N\) in the two bands using Equations 3 and 4. As our redshift binning is wider than the typical correlation length in redshift space, we treat all the data as independent measurements. Assuming Gaussian errors, the likelihood function is thus

\[
L = P(D|\theta, M) = \prod_i \frac{1}{\sqrt{2\pi \sigma_i^2}} \exp\left(-\frac{(D_i - D_i^0)^2}{2\sigma_i^2}\right),
\]

where \(D_i^0\) and \(D_i\) are the expected and measured data vectors, respectively and \(\sigma_i\) are the errors in the measurements.

- **Prior \(P(\theta)\):** We employ flat priors for most of the parameters with a few exceptions. For \(C_{\text{5000}}\) and \(C_{\text{1100}}\) parameterizing the redshift evolution of the corresponding spectral slopes (see Appendix A), we do not have strong constraints from our data. We therefore set a wide Gaussian prior of 0 ± 1.5 for each. The redshift evolution power index \(\gamma_{\text{5000}}\) for the 1500Å emissivity normalization is highly degenerate with spectral slopes \(\gamma_{\text{1100}}\) and \(\gamma_{\text{5000}}\), and also \(b(v, z)\), which can be appreciable in the left panel of Figure 3 as all these parameters affect the long-range tilt of \((dJ_N/dz)\) by \(j\). We expect a strongly rising 1500Å emissivity from \(z = 0\) to \(z = 2\) following the cosmic star-formation, or similarly the black hole accretion history [Madau & Dickinson, 2014]. Based on direct rest-FUV measurements in detected sources down to faint magnitudes uncorrected for interstellar medium (ISM) dust attenuation [Schiminovich et al., 2005; Alavi et al., 2016] we set a Gaussian prior of 2 ± 0.3 in \(\gamma_{\text{5000}}\). We note that this prior is not model dependent and originates directly from observations. Our priors and the ranges allowed are summarized in Table 1.

| parameter | range | prior | posterior |
|-----------|-------|-------|-----------|
| \(\log(c_0^{\text{5000}}, b_0^{\text{5000}})\) | [20, 30] | flat | \(25.13^{+0.01}_{-0.01}\)|
| \(\gamma_{\text{5000}}\) | [-7, 7] | Gaussian 2 \(\pm 0.3\) | \(2.06^{+0.31}_{-0.30}\)|
| \(\alpha_0^{\text{1500}}\) | [-7, 7] | flat | \(-0.08^{+1.34}_{-0.84}\)|
| \(C_{\text{5000}}\) | [-7, 7] | Gaussian 0 \(\pm 1.5\) | \(1.85^{+1.22}_{-1.28}\)|
| \(\alpha_0^{\text{1100}}\) | [-7, 7] | flat | \(-3.71^{+1.34}_{-0.98}\)|
| \(C_{\text{1100}}\) | [-7, 7] | Gaussian 0 \(\pm 1.5\) | \(0.50^{+1.34}_{-1.44}\)|
| \(\gamma_{\text{b}}\) | [-500, 500] | flat | \(-6.17^{+12.63}_{-11.43}\)|
| \(\gamma_{\text{Ly}\alpha}\) | [-500, 500] | flat | \(88.02^{+51.44}_{-48.87}\)|
| \(\log f_{\text{Ly}\alpha}^{\text{L}1}\) | [-20, 0] | flat | \(<-0.53 (3\sigma)\)|
| \(\log f_{\text{Ly}\alpha}^{\text{L}1}\) | [-20, 0] | flat | \(<-0.84 (3\sigma)\)|
| \(\gamma_{\text{Ly}\alpha}\) | [-7, 7] | flat | \(<-0.86^{+0.83}_{-1.29}\)|
| \(\gamma_{\text{b}}\) | [-7, 7] | flat | \(0.79^{+0.32}_{-0.33}\)|

Having specified all the ingredients in the Bayes’ rule,

\[
P(\theta|D) \propto P(D|\theta)P(\theta),
\]

we use an MCMC package of Foreman-Mackey et al. (2013) to sample the posterior distributions \(P(\theta|D)\) of our model parameters given the data. The fitted posterior median and 16/84 percentiles for each parameter are summarized in Table 1. Certain level of covariances between the parameters are present, which we visualize in Appendix B.

Figure 5 overlays the measurements with the best-fit (posterior median) model in the data space with red curves. A random subset of 100 MCMC samples are also shown in gray curves. One can see that overall the model can sufficiently describe the data. At high redshift the drop-offs in both bands are due to the presence of the Lyman break. At low redshift before the break comes in, the overall flat or increasing \((dJ_N/dz)\) by \(j\) suggests an increasing emissivity and/or clustering bias towards high redshift otherwise the steep cosmic dimming factor (i.e. \(1/\sqrt{H(z)}(1+z)\)) in Equation 11 would quickly suppress the correlation amplitudes. There is a hint of cosmic Ly\(\alpha\) emission present at \(z = 1\), resulting in a small bump when the line is redshifting through the NUV filter. This will be discussed in detail later. Interestingly, one can see that the model tries to match the the wiggles in the data at \(z = 0.3\) in FUV. This is possible because we include a sharp feature, i.e., Ly\(\alpha\) that is convolved with the filter response at these redshifts (see the middle column in Figure 3). The exact shapes of the filter curves are only known to \(5-10\%\) precision. If improved, we will gain constraining power on line detection. It is equally interesting that the data in NUV over the same redshift range do not show significant wiggles, and indeed the model do not allow short-mode fluctuations as the corresponding spectrum is a featureless continuum at 1400–2800Å; this provides evidence that the wiggles in FUV may be real and not due to underestimation of the errors.

**4.2. Breaking the intensity-bias degeneracy**

We now have gathered enough information to break the intensity-bias degeneracy in the normalization parameter.
\[ \epsilon_{\nu}^{z=0} b_{\nu}^{z=0} \] This utilizes the finding that at \( z = 0 \), almost all of the clustered UV background photons are from detected extragalactic sources (Figure 5), whose projected monopole intensity \( J_{\nu} \) is much better known. Additionally, the contamination from foreground sources (i.e. stars) is low especially at high latitudes. Combining the measured \( J_{\nu} \) and \( (dJ_{\nu}/dz) b_{\nu} \) in detected sources, the relationship between \( b_{\nu} \) and \( b(\nu, z) \) given in Equation 12 (which depends on the fitted \( \epsilon(\nu, z) \)), and the integral constraint in Equation 5, one can solve for the bias normalization \( b_{\nu}^{z=0} \). In our case we can greatly simplify Equation 12 since no frequency weighting for the filter and emissivity is needed as the fitted spectral slope \( \alpha_{\nu}^{z=0} \) is about 0 and the IGM absorption at low redshifts for non-ionizing photons is negligible. The effective intensity bias becomes the emitted photon bias evaluated at the observed bands:

\[ b_{\nu}(z) \approx b(\tilde{\nu}, z) , \quad (18) \]

where \( \tilde{\nu} = \tilde{\nu}_{\text{obs}} (1 + z) \) for \( \nu_{\text{obs}} \) as the effective frequency of FUV or NUV. Given our parameterization for \( b(\nu, z) \), we therefore have

\[ b_{\nu}^{z=0} = \frac{1}{J_{\nu}} \int dz \frac{(dJ_{\nu}/dz) b_{\nu}}{(\tilde{\nu}_{\text{obs}}/\nu_{1500})^{\gamma_{\nu}} (1 + z)^{\gamma_{\nu} + \gamma_{bz}}} \]  

(19)

where \( J_{\nu}, dJ_{\nu}/dz, \gamma_{bz} \) are in this case the values for detected sources instead of that for the total UVB. A flux-limited sample of sources corresponds to an increasingly rarer and highly biased part of the total background emissivity at higher redshift. Based on the redshift-dependent luminosity threshold in GALEX and the luminosity-dependent galaxy bias measurements in SDSS from [Zehavi et al. 2011], the bias for a flux-limited source sample scales roughly like \((1 + z)^2\), i.e. a factor \((1 + z)\) steeper than that given by our best-fit slope \( \gamma_{bz} \) for the total EBL. To properly propagate the covariance with other parameters, we assume that the detected source component follows \( \gamma_{bz}^{\text{sources}} = \gamma_{bz} + 1 \); for each MCMC sample of the total UVB posteriors for \( \gamma_{bz} \) and \( \gamma_{b1500} \) we can therefore sample the posterior of the bias normalization \( b_{\nu}^{z=0} \) using detected source component.
The result is \( b_{1500}^{z=0} = 0.32 \pm 0.05 \). Given the rapid decline of the detected source contribution at higher redshift, we note that the precise value of the slope describing the redshift dependence \( y_{1500}^{\text{sources}} \) has a weak effect on the estimation of the bias parameter \( b_{1500}^{z=0} \). Increasing/decreasing the slope \( y_{1500}^{\text{sources}} \) of the redshift dependence by 0.3 decreases/increases the best fit \( b_{1500}^{z=0} \) by about 5% only.

4.2.3. Cosmic UV background emissivity

We now present our results on the UV background volume emissivity \( \epsilon_{1500}(v, z) \) as a function of redshift and rest-frame frequency. Figure 6 shows our posterior \( \epsilon_{1500}(v, z) \) at 5 different redshifts or cosmic time, with the corresponding redshift-dependent spectral parameters shown in Figure 7. In these two figures the black lines show the posterior median and gray bands show the 1σ errors obtained from the 16/84 percentiles of the MCMC posterior sampling projected onto these one-dimensional spaces. We have obtained the intensity normalization \( \epsilon_{1500}^{z=0} \) by dividing the fitted, joint normalization \( \epsilon_{1500}^{z=0} h_{1500}^{z=0} b_{1500}^{z=0} \) presented in the previous subsection and propagated the error. The hatched area shows regions with no direct data constraint using GALEX bands; the results there are thus considered extrapolations. Out of the 12 parameters (plus the \( \epsilon_{1500}^{z=0} h_{1500}^{z=0} b_{1500}^{z=0} \) degeneracy now broken), we obtain meaningful constraints on all but the relative redshift evolution of the 1500Å emissivity normalization and continuum slopes \( (\gamma_{1500}, C_{1500}, C_{\alpha1100}) \) for which external priors are used. Our UVB inference is done without any assumption on the nature of the sources involved.

Our analysis constrains some of the key properties of the non-ionizing UVB continuum. These include the amplitude of the overall 1500Å emissivity, which quantifies the total radiation output of the universe in this spectral window. The spectral slopes that we obtain at both 1100 and 1500Å probe a combination of the emission and absorption mechanisms in galaxies or quasars before the light enters the metagalactic space into the IGM. For a galaxy dominated scenario, these spectral slopes are related to the age and metallicity-dependent stellar populations as well as the absorption in the dusty ISM averaged over all galaxies. We note that although we set a prior of non-evolving \( a_{1500} \), the data seem to favor a \( a_{1500} \) steepening towards high redshift with marginal significance. The physical implications will be discussed in more detail in Section 5.2 together with a widely used synthetic UVB model.

We find clear evidence of the presence of the Lyman break in the UVB, while the leakage of cosmic ionizing photons at \( \lambda < 912\AA \) is not detected. Our 3σ upper limits for the cosmic Lyman continuum escape fraction are placed at 30% and 14% at \( z = 1 \) and 2 probed by FUV and NUV bands, respectively. The constraint is not particularly tight compared to those obtained using Ly\( \alpha \) forest absorption [Meiksin & White2003; Khare et al.2018] but we note that our method is distinct in that it more directly traces the ionizing emission.

It is also interesting to mention the constraints we obtain for the Ly\( \alpha \) line. At low redshift, \( z \lesssim 0.4 \), our estimate of EW\( \lambda_{\alpha} \) is consistent with zero. At \( z \approx 1 \), we find a 2σ indication of Ly\( \alpha \) emission with \( \text{EW}_{\lambda_{\alpha}} = 88.02^{+51.44}_{-40.87} \) Å. This is represented in Figure 6 using an arbitrary line width of Ly\( \alpha \) set to FWHM = 5Å for visualization purposes. Our intensity mapping approach is sensitive to all the Ly\( \alpha \) photons from recombination powered by star-formation or black hole accretion, and potential low surface brightness IGM emission. One caveat of our estimate is that if the luminosity weighted clustering bias factor for Ly\( \alpha \) differs from that of the continuum around 1216Å, the equivalent widths or luminosity densities need to be scaled with the continuum-to-line bias ratio. We will discuss our the cosmic Ly\( \alpha \) constraints together with that in the literature in Section 5.2.

5. DISCUSSION

5.1. Comparison with the Haardt & Madau model

We compare our direct UVB emissivity measurement to the widely used synthetic model of Haardt & Madau2012 (hereafter HM12; see also Haardt & Madau 1996, 2001). We focus the comparison on the non-ionizing UV continuum, which, in HM12, is dominated by emission from galaxies. HM12 bases its normalization of FUV emissivity on observed luminosity functions. The shape of the UVB spectrum is obtained from a series of modeling including ISM extinction correction (Calzetti et al.2000), stellar-population synthesis (Bruzual & Charlot2003), cosmic star-formation and metal production history estimations, and transforming back from star-formation to a dust-extincted, frequency dependent emission. Figure 8 shows the UVB emissivity from HM12 in dashed lines compared to our measurements in solid lines at \( z = 0, 1 \), and 2. The overall agreement between these two is remarkable. The match in the emissivity amplitudes supports the fidelity of our overall correlation measurements and the clustering bias normalization using the UVB monopole in detected sources. The consistency in the spectral slopes support both approaches: for our spectral tagging result it is an empirical measurement with minimum assumptions but has not been applied and tested before; for HM12 the need to invoke stellar population synthesis and dust extinction correction makes their result highly model-dependent. As our approach measures the total background agnostic about the type of sources, the overall agreement with HM12 sup-

![Fig. 8.— Comparison between our UV background emissivity measurements with the model of Haardt & Madau2012 at \( z = 0, 1, 2 \). The 1σ error for our measurements (averaged over these three redshifts) is shown in the bottom panel. An overall agreement between the two can be found, while our measurements have a higher \( z = 0 \) normalization, less steep redshift evolution of the normalization, and a hint of hardening in the 1500Å continuum slope towards high redshift.](image-url)
ports the scenario that the non-ionizing UVB is dominated by galaxies as postulated in HM12.

There are however minor differences between the two. Over $0 < z < 2$ our emissivity evolves with $(1 + z)^2$, which is shallower than that in HM12 with $(1 + z)^{2.6}$. This is driven by different measurements of the FUV luminosity density evolution adopted in HM12 and in the assumed prior of our fitting. Based on the recent compilation of data in Alavi et al. (2016) integrated down to much fainter magnitude limit than previously used, a shallower UV emissivity evolution versus redshift seems to be preferred.

The HM12 emissivity has almost redshift invariant spectral slopes, while our measurement shows a mild hardening of the 1500 Å continuum towards high redshift. This redshift evolution is subtle and is only detected at $z = 0$ both ours and HM12 emissivities have a slope of $\alpha = 0$ in $\nu^{\alpha} \propto \nu^{4}$ or $\beta = -2$ in $\lambda^\beta$ at 1300–2800 Å typical for local starburst galaxies (Meurer et al. 1999). At $z = 1$ before this spectral range exits our bands, we find a best fit $\alpha = 0.5$ ($\beta = -2.5$). This bluer UV slope is consistent with the dominant galaxy population being younger, less dusty, and/or less metal-enriched (Bruzual & Charlot 2003; Reddy et al. 2018) at high redshift. Alternatively, a perhaps counter-intuitive scenario is that an increasing contribution from Far-IR luminous “dusty” galaxies at high redshift could also explain the increasing hardness in the UV; this is because while a substantial amount of light is absorbed, the emerging spectrum is blue and OB star dominated if they are not entirely dust-enshrouded (Casey et al. 2014). We note that an increasing fractional quasar or AGN contribution would not result in a bluer non-ionizing UV continuum at 1300–2800 Å (Vanden Berk et al. 2001).

### 5.2. Cosmic Lyα

Galaxies and AGN are known to produce Lyα emission from the recombination of ionized nebula powered by star-formation or supermassive black holes. Although likely sub-dominant, fluorescent Lyα powered by ionizing UVB in the diffuse IGM (Kollmeier et al. 2010), or gravitational cooling in the denser part of collapsing IGM/CGM (Faucher-Giguère et al. 2010) might also contribute to the cosmic Lyα budget. In Figure 9, we compare our Lyα luminosity density measurements at $z = 0.3$ and $z = 1$ (red limit/data point) and other results in the literature. Gray and blue hatched bands show the contribution from star-forming galaxies, and galaxies plus AGN estimated in Wold et al. (2017). This is obtained via a scaling of the Hα luminosity density measured in the HiZELS survey (Sobral et al. 2013) due to the lack of reliable Lyα luminosity function measurements between $z = 0.4$ and 2. Particularly the current Lyα emitter census at $z \approx 1$ using GALEX grism data in NUV is limited to only the brightest sources (Wold et al. 2014). Interestingly, our spectral tagging measurement is consistent with the allowed region for galaxies plus AGN contribution. Since our technique uses no surface brightness thresholding, it is sensitive to potential IGM emission. Our results therefore indicate that the amount of IGM emission cannot be much greater than the total contribution from galaxies and AGN.

Figure 9 also shows the spectroscopic line intensity mapping results at $z = 2.55$ from Croft et al. (2018), who update their earlier measurement in Croft et al. (2016). By cross-correlating quasars and Lyα in the spectra of SDSS galaxy with the best fit galaxy contribution removed, Croft et al. (2018) detected a metagalactic Lyα emission order of magnitude brighter than that expected from galaxies and AGN (black data point). In addition, they also use the Lyα forest as the large-scale structure tracer to perform the tracer-spectra correlations, resulting in a null detection of Lyα emission (black upper limit). These authors suggest that the Lyα intensity probed by the quasar–Lyα correlation is not representative for the cosmic mean, but instead it is dominated by re-processed emission enhanced in the quasar vicinity even at the 1.4–20 Mpc scale. Our technique shares some of the characteristics with that used in Croft et al. (2016, 2018), but at $z = 1$ where our reference objects are also quasars, we do not find an order of magnitude higher Lyα emission from expected galaxy contribution. We speculate that our approach might be less subject to this quasar proximity bias for two reasons. First, although we do not probe a larger distance span from the quasars in the transverse dimension on the sky, the line-of-sight distance that we probe is much longer, potentially diluting the effect. Second, the quasar proximity bias might be partly absorbed in the clustering bias factor $b(\nu, z)$ that we fit, again reducing its impact in the emissivity estimations. Of course it is still possible that either or both studies have yet unidentified systematics.

The Lyα emission of galaxies originates from recombination in HII regions and is usually strongly suppressed by a dusty neutral ISM before escaping to intergalactic space. We define an effective Lyα escape fraction such that

$$\rho_{Ly\alpha} = f_{esc} C \rho_\star,$$

where $\rho_\star$ is the cosmic star-formation rate density and $C = 1.1 \times 10^{42}$ ergs s$^{-1}$ M$_\odot^{-1}$ yr$^{-1}$ is the scaling factor using the empirical Hα star-formation calibration of Kennicutt (1998) assuming a Case B recombination Lyα-to-Hα ratio $\alpha_{Ly\alpha}$
Given the $\rho_*$ measurements compiled in Madau & Dickinson (2014) we can place constraints on the Lyα escape fraction of $f_{\text{esc}} < 7\%$ (3σ) at $z = 0.3$ and $f_{\text{esc}} = 10^{-6}$ % at $z = 1$ assuming that all the Lyα photons originate from galaxies. If AGN contribute to half of the $\rho_{\text{Lyα}}$ we detect, the Lyα escape fractions for galaxies would have to be reduced by a factor of 2. This cosmic effective escape fraction is well within the range of individual Lyα or continuum selected galaxies (Wold et al. 2017; Oyarzún et al. 2018).

Our estimated UVB Lyα equivalent width of $80 \pm 50$ Å at $z \approx 1$ is very close to that expected for galaxies with a constant star-formation history based on stellar population synthesis modeling (Charlot & Fall 1993), but is perhaps on the high side of the distribution for observed galaxies (Hayes 2015). As reviewed in Hayes (2015), a limited number of observational results have suggested that the equivalent width of Lyα emitting galaxies might indeed reach its peak at $z = 1$ and flatten out towards high redshifts.

5.3. Total UV background

The origin and demography of the UV photons contributing to the diffuse light seen in GALEX or earlier UV missions has been a matter of debate (Bowyer 1991; Henry 1991; Hamden et al. 2013; Henry et al. 2015; Akshaya et al. 2018). The difficulty arises from the estimation of near-earth foreground from airglow and zodiacal light (Murthy 2014b), as deep and wide UV surveys have all been done with spacecrafts in low-earth orbits. Henry et al. (2015) and Akshaya et al. (2018) argue that after taking into account all the known sources of radiation there appears to be an homogeneous excess of the sky monopole in the UVB foreground of unknown origin.

Our UVB measurement is based on spatial correlations with extragalactic matter tracers. The analysis is insensitive to the presence of foregrounds of non-extragalactic origin, providing a robust constrain on the EBL monopole intensity. In Figure 10 we show our measured $dJ/ dz$ similar to that in Figure 5 but with the simultaneously fitted bias factor taken out. We integrate the intensity over redshift

and find a monopole EBL intensity of $90^{+28}_{-16} \ Jy \ sr^{-1}$ in FUV and $259^{+62}_{-33} \ Jy \ sr^{-1}$ in NUV. These correspond to $89^{+28}_{-16}$ and $172^{+40}_{-21}$ photon units (photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ A$^{-1}$) in FUV and NUV, respectively. We also find that about 30% of the total EBL in both bands is in discrete sources already detected in GALEX AIS and MIS down to 20.5–23.5 mag (see Figure 5). By combining much deeper data from the Hubble Space Telescope with GALEX data, Driver et al. (2016) derive and extrapolate UV luminosity functions to calculate the total integrated galaxy light (IGL; including AGN contribution), resulting in IGL monopoles of $73 \pm 8$ and $158 \pm 23$ photon units in FUV and NUV. The differences between our total EBL and the IGL are $16^{+40}_{-18}$ and $14^{+31}_{-31}$ photon units in FUV and NUV, which provide a direct constraint on the cosmic photon production budget allowed for the diffuse IGM.

Table 2 summarizes our results on the monopole UVB demographics. Comparing our measured EBL with the GALEX diffuse light component analysis in Akshaya et al. (2018), we confirm that there is indeed a large unidentified foreground of 200–450 photon units in GALEX whose extragalactic origin can now be firmly ruled out by our clustering analysis.

5.4. Photon bias and cosmic mass-to-light relation

The UVB clustering bias $b(v,z)$ contains valuable information about the relation between the sources of radiation and the matter density field. In Figure 11 we plot our best-fit background photon bias

$$ b = 0.32 \left( \frac{\lambda}{1500 \text{Å}} \right)^{0.86} (1 + z)^{0.79}, $$

(21)

at 1500 and 3000 Å (rest-frame), and extrapolated to 6000 Å in the optical. The uncertainty in $b$ is about 20%. We note that based on our definition of $b(v,z)$, this quantity should be interpreted as the mean bias per-photon of rest-frame frequency $v$ emitted at redshift $z$. It is interesting to note that using this relation at optical wavelengths produces a bias value comparable to that measured for optically-selected $L_s$ galaxies (black data points: Zehavi et al. 2011; Marulli et al. 2013; Skibba et al. 2014), which contribute to most of the cosmic optical background luminosity density. Our tomographic analysis suggests that the EBL bias is likely chromatic, with redder photons more strongly clustered than bluer ones. This is qualitatively consistent with the low clustering bias found for star-forming galaxies compared to that of red, passive ones (Milliard et al. 2007; Heinis et al. 2009; Coil et al. 2008, 2017). Our result suggests that...
the bias for photons at a given frequency evolves with redshift, with a trend similar to that reported for UV-selected galaxies (Heinis et al. 2007). One way to interpret the clustering of the cosmic radiation field is to populate the corresponding sources in dark matter halos using halo models (Cooray & Sheth 2002). In Figure 11, we plot the halo bias from $N$-body simulations compiled in Tinker et al. (2010) in gray dashed lines from $10^8$ to $10^{13}$ $M_\odot$. The UV photon bias is perhaps low compared to that of dark matter halos; if both estimations are robust, this would suggest that it may be hard to attribute all of the sources of radiation to galaxies in collapsed halos. We might therefore already see the contribution from a radiation field of more extended and diffuse origin. One extreme example of an uncollapsed matter tracer is the Ly$\alpha$ forest from neutral clouds in the IGM, whose clustering bias is constrained to be very low (0.2 ± 0.04; Slosar et al. 2011) as indicated by the blue data point in Figure 11.

6. SUMMARY

We present a clustering-based framework to statistically recover frequency and redshift information for the EBL in broadband intensity mapping datasets, and apply it to the GALEX All Sky and Medium Imaging Surveys in the UV. By spatially cross-correlating photons in the FUV and NUV bands with spectroscopic objects in SDSS as a function of redshift, we detect the differential intensity of the UV background (UVB) as a function of redshift up to $z \sim 2$. These tomographic measurements clearly reveal imprints of the main spectral features of the UVB redshifting in and out of the bands, allowing us to set empirical constraints on several aspects of the evolving UVB spectrum:

• The overall amplitude and spectral shape of the non-ionizing UVB continuum at $912 \, \AA < \lambda < 2700 \, \AA$ is in good agreement with the Haardt & Madau (2012) model. Our results, however, do not rely on any assumption regarding the nature of the sources.

• Cosmic Ly$\alpha$ emission is tentatively detected with >95% confidence at $z = 1$ with a luminosity density consistent with being powered by cosmic star-formation with an effective escape fraction of 10%.

• The Lyman break in the UVB is clearly present, while the leakage of the cosmic ionizing photons is not detected at $z \sim 1$–3.

We integrate clustered light over redshift to obtain the total UVB monopoles in FUV and NUV, robust against the presence of foregrounds. These monopoles are in slight excess, but still consistent with the integrated galaxy plus AGN light estimated in Driver et al. (2016), allowing us to set limits on cosmic emission from the IGM. Our analysis also provides direct constraints on the photon clustering bias factor as function of frequency and redshift, which characterizes the cosmic mass-to-light relation. Our GALEX tomography delivers a statistic summary of the net radiation output from cosmological galaxy formation, including the contributions from stars, black holes, and radiative processes in the ISM, CGM, and IGM combined.

This work demonstrates that via combining the concept of intensity mapping, the efficiency of broadband surveys, and the clustering redshift tomography, we can probe the rich astrophysical information in the EBL. The technique can be applied to any wavebands.

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APPENDIX

A. PARAMETERIZATION OF THE UVB EMISSIVITY

In Section 2.4.1 we apply the spectral tagging technique to constrain the spectrum of the UV background using a simple parameterization visualized in Figure 2. This corresponds to a rest-frame comoving volume emissivity

\[ \epsilon_V(v, z) = \begin{cases} 
\epsilon_{1500} \left( \frac{v}{v_{1500}} \right)^{a_{1500}} & \text{if } \frac{c}{v} > 1216 \AA; \\
\left( \frac{v_{1216}}{v_{1500}} \right)^{a_{1216}} + \frac{\epsilon_{1216}}{\epsilon_{1216}} & \text{if } 1216 \AA > \frac{c}{v} > 912 \AA; \\
0 & \text{if } \frac{c}{v} < 912 \AA,
\end{cases} \]

where \( v_{1216} = c \times 1216 \) Å is a wavelength label in the unit of Å, \( \epsilon_{1500} \) is the continuum emissivity normalization at 1500 Å, \( \epsilon_{1216} \) is the continuum emissivity normalization at 1216 Å, \( v_{1216} \) is the Ly\( \alpha \) line equivalent width, \( \delta_D \) is the Dirac delta function for the line shape, and \( f_{\text{LyC}} \) is the ionizing Lyman continuum escape fraction. We fix the slope of the Lyman continuum \( a_{900} = -1.5 \) independent of redshift following Madau (1992). This has no effect in our emissivity inference as the Lyman continuum is not detected. For all the other power indices, emissivity normalization, and line- and break-strength parameters, we allow them to evolve with redshift each with one additional parameter using simple functional forms as shown in Figure 7.

For linear quantities, they follow a power-law of (1 + z); for already logarithmic quantities they are allowed to scale with \( \log(1 + z) \). For \( \epsilon_{1500} \), \( \alpha_{1500} \), and \( \alpha_{1216} \) we normalize...
them at $z = 0$:

$$
\epsilon_{1500} = \epsilon_{1500}^{z=0} (1 + z)^{\gamma_{1500}};
$$

$$
\alpha_{1500} = \alpha_{1500}^{z=0} + C_{\alpha_{1500} \log(1 + z)};
$$

$$
\alpha_{1100} = \alpha_{1100}^{z=0} + C_{\alpha_{1100} \log(1 + z)},
$$

(A2)

where $\gamma_{1500}$, $C_{\alpha_{1500}}$, $C_{\alpha_{1100}}$ are the redshift evolution parameters for each. For Ly$\alpha$, the direct constraint is at $z \approx 0.3$ and $z \approx 1$ when the line is in FUV and NUV bands, respectively (middle panel in Figure 2). We therefore parameterize its redshift evolution pivoted at these two redshifts:

$$
\text{EW}_{\text{Ly}\alpha} = C_{\text{Ly}\alpha} \log \left( \frac{1 + z}{1 + 0.3} \right) + \text{EW}_{\text{Ly}\alpha}^{z=0.3};
$$

where $C_{\text{Ly}\alpha} = (\text{EW}_{\text{Ly}\alpha}^{z=1} - \text{EW}_{\text{Ly}\alpha}^{z=0.3})/\log \left( \frac{1 + 1}{1 + 0.3} \right)$. (A3)

This is simply a linear function allowing the equivalent width to be positive (emission) or negative (absorption), and also allows change of sign over redshift (4th panel in Figure 7). The Lyman continuum escape fraction is defined to be a positive, logarithmic parameter. The GALEX data will provide direct constraints on the ionizing photons only at $z \approx 1$ in FUV, and $z \approx 2$ in NUV. We therefore have

$$
\log f_{\text{LyC}} = C_{\text{LyC}} \log \left( \frac{1 + z}{1 + 1} \right) + \log f_{\text{LyC}}^{z=2};
$$

where $C_{\text{LyC}} = (\log f_{\text{LyC}}^{z=2} - \log f_{\text{LyC}}^{z=1})/\log \left( \frac{1 + 2}{1 + 1} \right)$. (A4)

B. COVARIANCE OF THE UVB PARAMETERS

In Section 4.2.1 we use an MCMC method to sample the posteriors of our parameterized UV background emissivity and photon bias given the data, with the best fit parameters summarized in Table 1. Here in Figure B1 we visualize the marginalized posterior distribution for each parameter and their covariances using a triangle plot (using the corner package from Foreman-Mackey et al. 2014). We exclude $\log f_{\text{LyC}}^{z=1}$ and $\log f_{\text{LyC}}^{z=2}$ in this figure as the ionizing Lyman continuum at both $z = 1$ (constrained in FUV) and $z = 2$ (constrained in NUV) are not detected and almost entirely independent from other parameters (see Figure 5). One can see significant covariances between some of the parameters. For example, the redshift dependence of the 1500Å emissivity normalization $\gamma_{1500}$ is degenerate with that of the clustering bias $\gamma_{bz}$, with only their product tightly constrained by the data. Similar degeneracy can be seen for the 1500Å spectral slope $\alpha_{1500}$ and the frequency dependence of the clustering bias $\gamma_{bv}$.
Fig. B1.— Triangle plot of the posterior probability distribution for parameters in our UV background model. Diagonal panels show the marginalized posterior for each parameter; other panels show projected correlations between each combination of parameter pairs. The normalization $\epsilon_{1500}$ has a unit of ergs s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$. 