The Sources of Extreme Ultraviolet and Soft X-Ray Backgrounds

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Abstract

Radiation in the extreme ultraviolet (EUV) and soft X-ray holds clues to the location of missing baryons, the energetics in stellar feedback processes, and the cosmic enrichment history. Additionally, EUV and soft X-ray photons help determine the ionization state of most intergalactic and circumgalactic metals, shaping the rate at which cosmic gas cools. Unfortunately, this band is extremely difficult to probe observationally due to absorption from the Galaxy. In this paper, we model the contributions of various sources to the cosmic EUV and soft X-ray backgrounds. We bracket the contribution from (1) quasars, (2) X-ray binaries, (3) hot interstellar gas, (4) circumgalactic gas, (5) virialized gas, and (6) supersoft sources, developing models that extrapolate into these bands using both empirical and theoretical inputs. While quasars are traditionally assumed to dominate these backgrounds, we discuss the substantial uncertainty in their contribution. Furthermore, we find that hot intrahalo gases likely emit an $\mathcal{O}(1)$ fraction of this radiation at low redshifts, and that interstellar and circumgalactic emission potentially contribute tens of percent to these backgrounds at all redshifts. We estimate that uncertainties in the angular-averaged background intensity impact the ionization corrections for common circumgalactic and intergalactic metal absorption lines by $\approx 0.3$–1 dex, and we show that local emissions are comparable to the cosmic background only at $r_{\text{prox}} = 10$–100 kpc from Milky Way–like galaxies.

Key words: cosmic background radiation – cosmology: theory – diffuse radiation – galaxies: ISM – intergalactic medium – quasars: general

1. Introduction

The extreme ultraviolet (EUV) through soft X-ray represents a slice of the electromagnetic spectrum that is difficult to observe in astronomical spectra. Not only must it be observed from above Earth’s atmosphere, but for extragalactic sources, much of this slice is absorbed by the Galaxy. Yet because most transitions to ground Rydberg states of ions fall in this band and, hence, most cooling emissions, the EUV/soft X-ray extragalactic background holds clues to the location of missing baryons, the energetics in stellar feedback processes, and the cosmic enrichment history. The lack of observations in this band complicates inferences from observable ionic transitions because these backgrounds often shape the ion ratios of diffuse astrophysical gases.

Active galactic nuclei (AGNs), or more specifically, the brightest of these, quasars, are thought to be the dominant extragalactic source for radiation in the EUV and soft X-ray, especially at $z \lesssim 3$ (Meiksin & Madau 1993; Madau et al. 1999; Faucher-Giguère et al. 2008; Haardt & Madau 2012). However, quasars’ spectral energy distributions (SEDs) have only been measured at frequencies redward of $\sim 25$ eV (e.g., Telfer et al. 2002), and current theoretical models are likely not successful enough to motivate extrapolations to the soft X-ray. Thus, models for quasar spectra extrapolate with a single power law between the EUV and soft X-ray, even though the quasar SED is certainly more complex (Bechtold et al. 1987; Laor et al. 1997; Done et al. 2012).

Quasars are not the only source that may contribute substantially to this critical waveband: X-ray binaries (XRBs), cooling gases ($10^3$–$10^5$ K) in the interstellar medium (ISM) of galaxies and the circumgalactic medium (CGM) that surrounds them, and virialized halo gas may also substantially contribute. Indeed, XRBs tend to dominate galactic X-ray emissions at $\gtrsim 1$ keV, while at lower energies, radiative cooling from the hot ISM in galaxies is thought to become important (Grimes et al. 2005; Tüllmann et al. 2006; Owen & Warwick 2009; Mineo et al. 2012b; Lehmer et al. 2015). This hot gas is the result of feedback from supernovae, massive star winds, and radiation pressure (McKee & Ostriker 1977; Chevalier & Clegg 1985; Strickland et al. 2000). A significant fraction of this feedback could also be radiated in the surrounding CGM in addition to the hot ISM (e.g., McQuinn & Werk 2018). Similarly, intrahalo gas that has been shocked by virialization can also be important, especially with decreasing redshift as more massive, and hence hotter, systems form.

Many fields of study are reliant on models for the metagalactic ionizing background. Such models are used in essentially all calculations of the ionization state of photoionized gas in the intergalactic medium (IGM) and CGM (for a recent review, see McQuinn 2016; Tumlinson et al. 2017), and they are used to set the ionization state of gas in cosmological simulations (and, hence, shape the rate at which simulated gas cools). However, previous ionizing background models only considered the contribution of quasars in the EUV and soft X-ray, making the typical simplifying assumptions to extrapolate from observed bands (Haardt & Madau 1996; Faucher-Giguère et al. 2009; Haardt & Madau 2012). Even if the background is dominated by quasars, these models may not apply near galaxies (where they are most used), since many UV and X-ray sources are (circum) galactic in nature (Cantalupo 2010; Gnedin & Hollon 2012).

This paper estimates the contribution of all source classes that we are aware of that may emit substantially in the EUV and soft X-ray, in the process estimating the plausible range of $z \sim 0$ and 2 UV background angular-averaged specific

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3 Starlight is an important contribution at 1–4 Ry in some models (and dominant at lower energies), with its relative importance depending on how efficiently these photons can escape from galaxies.
intensities, $J_\nu$. Section 2 estimates the emissivities of various EUV and soft X-ray sources. Using these estimates, we model the relative contribution of these sources to the ionizing background in Section 3. Section 4 discusses the impact of the uncertainties in the background on the ionization of highly ionized metals. Finally, for galactic sources, we estimate the size of the local enhancement expected around each galaxy in Section 5.

2. Modeling the Sources

This section describes all known sources that emit substantially in the UV and soft X-ray, developing models for their specific emissivity across redshift. These calculations are then fed into calculations of the background $J_\nu$ in Section 3.

2.1. AGNs

Quasars—highly luminous AGNs—are likely the most emissive sources in the EUV and soft X-ray. Yet their emissivity in this band is highly uncertain. The UV observations of quasar emissions can only be used to reliably estimate the mean SED to wavelengths as short as several hundred Å (e.g., Telfer et al. 2002). A break is observed in the mean SED at $\lambda \sim 1000$ Å, with the spectrum softening blueward of this break. This break is commonly attributed to the innermost temperature of the quasar’s accretion disk (“the Big Blue Bump”; Shakura & Sunyaev 1973) and the transition of quasar spectra to Compton upscattered radiation from a corona (e.g., Czerny & Elvis 1987). However, thin accretion disk–plus–corona models have limited success at describing quasar spectra in the UV (Laor et al. 1997; Davis et al. 2007), which may be partly cured by invoking inhomogeneous temperatures (Dexter & Agol 2011) and opacity effects (Czerny & Elvis 1987). Additional tuning must be added to achieve power law–like emission in the soft X-ray, as is observed (Bechtold et al. 1987; Laor et al. 1997). The disk emission almost certainly needs to be Compton upscattered by material distinct from the traditional coronae. This could be accomplished by an optically thick region around the disk interior at temperatures of $\sim 0.2$ keV (Done et al. 2012).

Because of these open issues, UV background models have used simple power laws estimated from quasar stacks, rather than theoretically motivated templates, to extrapolate to shorter wavelengths. These power laws fit stacked spectra blueward of the break at $\sim 1000$ Å and redward of the highest energy where the SED can be reliably estimated ($\sim 500$ Å). There is a limited dynamic range over which the power law is fit. The Lusso et al. (2015) stacked SED is the solid turquoise curve in Figure 1, with the cyan region highlighting the estimated $1\sigma$ errors. We have normalized the SED to the $z = 0$ specific emissivity at 1 Ry as described below.

The effective power-law index of the quasar stacks, $\alpha_{QSO}$ (see Equation (1)), that analyzes the estimate varies significantly, with Telfer et al. (2002) finding $\alpha_{QSO} = 1.57 \pm 0.17$ for their radio-quiet sample, Shull et al. (2012) and Stevans et al. (2014) finding $\alpha_{QSO} = 1.4 \pm 0.2$, and Lusso et al. (2015) finding $\alpha_{QSO} = 1.7 \pm 0.6$, with their larger error owing to analysis differences described below. These observations show rough consistency (although they are discrepant with the lower-luminosity sample of Scott et al. 2004, which finds $\alpha_{QSO} = -0.6 \pm 0.4$). Lastly, photoionization calculations for the broad UV lines in these spectra favor somewhat softer spectra with $\alpha_{QSO} \approx 2$ (Baskin et al. 2014; Lusso et al. 2015).

Lusso et al. (2015) pointed to several factors that result in differences in the estimated $\alpha_{QSO}$ from stacking. Especially for quasars at $z \gtrsim 1$, estimates for the stacked SED must correct for H1 absorption from the IGM (with the Lyman series affecting $\lambda < 1216$ Å and Lyman continuum $\lambda < 912$ Å). The differences in how this correction is done lead to some of the discrepancies in the reported values and their uncertainties. In addition, where the $\sim 1000$ Å break wavelength is placed affects the final slope, and many samples do not have much spectral coverage of this break. Finally, broad-line features are present in the stacks, so different choices are made for how to fit the continuum underneath the lines.

A justification often given for extrapolating with a single power law into the soft X-ray is that the spectral indices of Type 1 AGNs required in the EUV are similar to the spectral index needed to extrapolate to the soft X-ray band, as well as the power-law index found in the soft X-ray (Laor et al. 1997). However, in both the UV and soft X-ray, individual systems show broad dispersion in their allowed index (although individual system inferences are difficult in the UV owing to IGM absorption). In addition, within the range of allowed mean spectral indices, there is no reason why there cannot be a softening followed by a hardening (indeed, a soft spectrum followed by a hotter corona spectra is seen in models such as that of Done et al. 2012) or vice versa (in the stacked SED, some quasars should be harder and hence become more dominant at bluer wavelengths, hardening the spectrum).

Figure 1 shows the empirical estimates and extrapolation of quasar emissivity at $z \sim 0$. For our calculation, we use quasar emissivities reported at 1 Ry from Khaire & Srianand (2015) that are consistent with the mean Ly$\alpha$ forest transmission (Fumagalli et al. 2017). These emissivities are extrapolated...
from the g-band luminosity function with the relation 
\[ \log \epsilon_g = \log \epsilon_{g12} + 0.487 \] (Boyle et al. 2000; Croom et al. 2004; Haardt & Madau 2012; Khaire & Srianand 2015), and since the mean SED is much better known between these wavelengths—and the normalization is essentially calibrated to match robust constraints at 1 Ry from the Lyα forest—this extrapolation should not contribute significant uncertainty.

We extrapolate from this emissivity at 1 Ry with a power-law spectrum parameterized as

\[ J(\nu) = J_0 \left( \frac{\nu}{\nu_{1 \text{Ry}}} \right)^{-\alpha_{\text{QSO}}} . \]  

We vary \( \alpha_{\text{QSO}} \) between 1.1 and 2.3, the 1σ error bar of Lusso et al. (2015), a range shown by the dashed curves in Figure 1. However, one cannot extrapolate all the way to \( \approx 1 \text{ keV} \) with this spectrum unless it has \( \alpha_{\text{QSO}} \approx 1.7 \) (Laor et al. 1997) to be compatible with soft X-ray background measurements discussed in Section 3. We taper our spectrum starting at 100 eV so that it converges to the same point at 800 eV as if \( \alpha_{\text{QSO}} = 1.7 \). While our choices here are somewhat arbitrary, we believe they provide a reasonable guess for the allowed range of quasar specific emissivities (motivated by both the error on UV extrapolations and the large theoretical uncertainty in the spectral form).

Above 800 eV, we assume that the spectrum scales with a spectral index of \( \alpha = 0.5 \). While 800 eV is on the lower side of the observations for where the harder coronal emission dominates, finding 1–2 keV (Laor et al. 1997), this spectral index is characteristic of the coronae of radio-loud quasars and somewhat harder than that found for radio-quiet ones (although H I absorption additionally acts to harden their spectra; Laor et al. 1997). The selected slope of \( \alpha = 0.5 \) is a good fit to the slope found in the more detailed models for this component in Haardt & Madau (2012) and also to \( z = 0 \) soft X-ray background measurements. However, our tapering to a single curve at \( > 800 \text{ eV} \), which is done to match the background intensity measurements in the soft X-ray, should underestimate the uncertainty in \( \epsilon_g(z) \) at these energies. We justify not attempting to quantify the uncertainty \( > 800 \text{ eV} \) because these higher energies are less important for this study.

2.2. XRBs

The X-ray emission from galaxies is thought to be dominated by XRBs at \( > 1 \text{ keV} \). The galactic XRB emission from high-mass XRBs (HMXBs) should trace the star formation rate (SFR), as their formation lags star formation episodes by just tens of Myr, and low-mass XRBs (LMXBs) should trace stellar mass, as their is can lag star formation by many Gyr. These correlations have been confirmed observationally (Grimm et al. 2003; Ranalli et al. 2003; Gilfanov et al. 2004; Hornschemeier et al. 2005; Lehmer et al. 2010; Boroson et al. 2011; Mineo et al. 2012a; Zhang et al. 2012). We use these correlations to relate the cosmic XRB emissivity with redshift to the observed SFR density and stellar mass density. We approach the XRB contribution to the EUV/soft X-ray from both a theoretical and an empirical standpoint, considering two models.

**Empirical model**—In this model, all X-ray emission traces either the SFR or the stellar mass (Lehmer et al. 2010). LMXBs are likely as important as their high-mass counterparts in the average galaxy at \( z \approx 0 \), though at \( z \gtrsim 1 \) and in star-forming galaxies, HMXBs dominate the X-ray emission from XRBs. We allow the relationship between SFR and X-ray emission to account for temporal trends that result from such things as increasing cosmic metallicity. For HMXBs, we use the redshift-dependent relation constrained in Dijkstra et al. (2012), parameterized as

\[ L_{X,0.5-8} / \text{SFR} = [L_{X,0.5-8} / \text{SFR}]_{z=0} (1 + z)^{3/2}, \]

where \( L_{X,0.5-8} \) is the 0.5–8 keV X-ray luminosity. Dijkstra et al. (2012) found \( 0 < b < 1.3 \), anchoring to the Mineo et al. (2012a) best fit of \( [L_{X,0.5-8} / \text{SFR}]_{z=0} = 2.6 \times 10^{39} \text{ erg s}^{-1} (M_\odot \text{ yr}^{-1})^{-1} \). For the cosmic SFR density, we use the fit in Haardt & Madau (2012) derived from rest-frame optical and UV observations. For LMXBs, we use a correlation between total stellar mass and X-ray luminosity, \( L_{X,0.5-8} / M_{\star} \sim 9 \times 10^{28} \text{ erg s}^{-1} \) (Gilfanov et al. 2004; Lehmer et al. 2010). We use Wilkins et al. (2008) for the cosmic stellar mass density as a function of redshift.

This model’s second ingredient is the XRB SED. Above 300 eV, the SED of galactic X-ray emission has been constrained observationally. For the SED, we stack the spectrum of four star-forming galaxy SEDs observed from 0.3 to 3 keV with Chandra/REFLEX-Newton (Wik et al. 2014; Lehmer et al. 2015; Yukita et al. 2016). The stack is computed by averaging the specific luminosity per unit SFR of each galaxy, \( L_X(\nu)/\text{SFR} \). However, the spectrum of XRBs is not constrained below 300 eV. To extrapolate, we model the XRB spectrum as a simple power law in specific luminosity with \( \alpha_{\text{empirical}} = 0.7 \) (using the same conventions as with \( \alpha_{\text{QSO}} \) in Equation (1)). This slope is based on the scaling of stacked X-ray emission—not just the four we use for our empirical spectrum (Rephaeli et al. 1995; Swartz et al. 2004).

The solid curves in Figure 2 and later Figure 3 show the resulting specific emissivity at \( z = 0 \) for the stacked SED and \( \alpha_{\text{empirical}} = 0.7 \) models. Even among the four stacked galaxy spectra, there is ~1 dex scatter in \( L_X(\nu)/\text{SFR} \), owing largely to scatter in the number of ultraluminous X-ray sources. An extremely crude estimate of the error on the mean stack is shown by the highlighted regions in Figure 2, which is the standard deviation of the four spectra divided by \( \sqrt{N_{\text{gal}}} - 1 \).

We note that much of the emission below 1 keV is likely from hot gas in the ISM and not XRBs. Most XRB emission is found to decline below 1 keV rather than have a flat power law, as our extrapolation assumes (because of their intrinsic spectrum and H I absorption), and the \( < 1 \text{ keV} \) appears to be due to more diffuse sources, as discussed in Section 2.4. Thus, our \( \alpha_{\text{empirical}} = 0.7 \) model may be better conceived as an amalgam of XRB and hot ISM emission, where hot ISM takes over at lower energies and has a power-law–like spectrum. We discuss the realism of this power-law extrapolation for ISM emission in Section 2.4. In addition, the bounds we place on supersoft sources in Section 2.3 also are relevant to potential soft emissions from LMXBs.

**Fragos+++ (2013) model**—We use the XRB population synthesis model of Fragos et al. (2013). It uses the XRB population synthesis simulations StarTrack (Belczynski et al. 2008),

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4 Increasing metallicity is expected to decrease the number of XRBs because metallicity increases mass loss from stellar winds, affecting binary separations, and because higher-metallicity stars have larger radii, which increases Roche lobe overflow (Linden et al. 2010). There is also observational evidence for X-ray flux scaling inversely with metallicity (Brophy et al. 2016).

5 The total SFR density that is often estimated is likely less appropriate because star formation energized behind gas and dust is unlikely to produce EUV and soft X-ray photons that can escape.
respectively, using the luminosity bounds from Chen et al. (2015). The highlighted bands around the red solid and blue dashed curves are, respectively, the standard deviation estimated from the four stacked galaxies and the quoted uncertainties in Fragos et al. (2013). The teal and pink shaded areas represent the allowed emissivity for SSSs with blackbody temperatures of 3 \times 10^5 and 5 \times 10^5 K, respectively, using the luminosity bounds from Chen et al. (2015). The respective dashed curves represent this emission with attenuation from a 10^{-2} \text{eV} \text{cm}^{-2} \text{rad}^{-1}.

2.3. Supersoft X-ray Sources

Supersoft X-ray sources (SSSs) are observed systems with blackbody spectra that peak in the soft X-ray and are theorized to be compact binary systems with a white dwarf accreting from either a main-sequence star or a red giant, and this accretion ignites on the surface (Kahabka & van den Heuvel 1997; Greiner 2000). Accretion onto white dwarfs should be generic, and such accretion is necessary in a major progenitor scenario of Type Ia supernovae. Models find that the accretion should be thermally stable with rates of \dot{M} \sim 10^{-7} \dot{M}_\odot \text{yr}^{-1} (Nomoto et al. 2007). With such \dot{M}, accreting white dwarfs should emit substantially in the 0.1–0.7 keV band. The SSS could increase ISM photoheating rates enough to explain the higher temperatures inferred from photoionized ISM observations compared to models (Woods & Gilfanov 2013).

However, the number of SSSs that have been detected is 1–2 orders of magnitude below expectations from population synthesis models (Chen et al. 2014, 2015). The lack of sources could be because of obscuring H I columns around these sources (although see Nielsen & Gilfanov 2015; Woods & Gilfanov 2016), if dynamically unstable mass loss for giant stars occurs differently from that in current models (Chen et al. 2015) or the nature of accretion onto these systems is different (Cassisi et al. 1998). Observations are sensitive to SSSs with a more massive white dwarf primary, so the smaller primaries (which are more important at lower energies) could still be present at forecast abundances.

Here we assume that stable accretion onto undetected (i.e., less massive) white dwarfs is occurring, and we attempt to place an upper bound on the total ionizing emissions. We assume that the spectrum of these objects follows a blackbody with an effective temperature ranging between 3 \times 10^5 and 5 \times 10^5 K, characteristic of the lower-mass primaries that would go undetected in previous soft X-ray searches (Greiner 2000).

For long-term thermally stable accretion onto a white dwarf in the stable hydrogen-burning regime, the ideal donor star is a 2 \text{M}_\odot main-sequence star (Chen et al. 2014). It follows that the luminosity of SSSs is expected to peak at stellar ages of approximately 1 Gyr (the lifetime of a 2 \text{M}_\odot main-sequence star) and drop off steeply at ages > 1 Gyr in the soft X-ray (Chen et al. 2015); thus, globally, their emissions should peak at roughly z \sim 1.8, approximately 1 Gyr following peak cosmic SFR.

6 The 4 Ry emission drops off less steeply but still peaks at 1 Gyr.
To estimate the contribution of SSSs, we constructed the shape of the emissivity function from the shape of the cosmic SFR density and shifted this evolution by 1 Gyr.\(^7\) We normalized the upper bound to the emission from SSSs by setting the integrated $\geq 4$ Ry luminosity from SSSs to equal the He II–ionizing luminosity of the a025qe15 model in Chen et al. (2015; which used binary population synthesis models to predict the stellar age-specific luminosity). In this model, the criterion for stable mass loss for binaries with giant donors (a critical mass ratio) is adjusted to better agree with the late-time soft X-ray flux of elliptical galaxies, which is overpredicted with the more standard prescription. Their other two models that adjust the critical mass criterion to satisfy the X-ray limits increase this critical mass ratio and thus show lower luminosities. However, their model without this prescription overpredicts the observational constraints in the X-ray. We normalize to the He-ionizing model rather than to the soft X-ray predictions because the soft X-ray energies fall in the tail of the blackbody; thus, the normalization would be sensitive to the assumed spectrum.

Figure 2 shows the allowed emissivity of SSSs, where the teal and pink shaded areas represent the allowed emissivity for SSSs with blackbody temperatures of $3 \times 10^5$ and $5 \times 10^5$ K, respectively. Although, unlike Chen et al. (2015), we use a single temperature for our spectral model, the limited range of temperatures consistent with stably accreting white dwarfs and allowed by observational constraints in the soft X-ray justifies this approximation. The dashed curves show the attenuation of this emission from a column of $10^{20}$ and $3 \times 10^{20}$ cm$^{-2}$. These models show upper bounds skimming the lower bounds of quasars at $\sim 100$ eV. Our bound on SSSs allows a potential contribution that is as much as an order of magnitude above our empirical XRB model, barring any absorption.

Accreting white dwarfs seem to be a natural consequence of stellar evolution—it should then follow that SSSs contribute substantially to the ionizing background. However, there is limited observational evidence to support their ubiquity. If SSSs are numerous, their observational elusiveness requires a limited mass range of accreting white dwarfs and a gas-poor environment (Woods & Gilfanov 2016) to respectively explain the lack of detections in the soft X-ray and the lack of ionized nebulae associated with these objects (although the lack of ionized nebulae may suggest that the bulk of their ionizing photons escapes their host galaxy).

2.4. Warm-Hot Gas in the ISM and CGM

The ISM is a mix of different gas phases, with this multiphase structure driven largely by stellar wind bubbles and supernova blastwaves (McKee & Ostriker 1977). The spectrum of radiation emitted by these bubbles and blastwaves depends on the resulting temperatures and ionization states of associated gases. Some of this emission escapes into intergalactic space, with the amount depending on the H I columns out of the host galaxy. Furthermore, some of the gas driven by these feedback processes vents from galaxies, potentially heating the CGM and leading to additional cooling emission that has less difficulty escaping from the galactic environs.

Radiation from warm-hot gas in the ISM can, in principle, be observed directly at $> 300$ eV. However, there is no robust determination of this ISM X-ray emissivity because no straightforward method exists for disentangling the ISM contribution from the XRB one. Mineo et al. (2012b) attempted to disentangle the ISM contribution by subtracting off flux from X-ray point sources, which are likely XRBs, finding that most of the observed flux remains at the lowest energies observed, with little above 1 keV. Using the remaining flux as an estimate for the ISM contribution, they measured the relation between ISM emission and SFR,

$$L_{X,0.5-2}/SFR \approx 8.3 \times 10^{38} \text{ erg s}^{-1} (M_\odot \text{ yr}^{-1})^{-1},$$

where $L_{X,0.5-2}$ is the 0.5–2 keV ISM luminosity.

Observationally, the shape of the average ISM SED is essentially unconstrained at $< 300$ eV, and the more diffuse emission from the CGM is unconstrained at all wavelengths. To model the spectral shape, we use the spectrum of gas cooling from some maximum temperature to a much lower temperature. The specific emissivity of a population of objects with this spectrum is then given by

$$\epsilon_F(T_{\text{max}}) = \rho_{\text{SFR}} \times [L_{\text{bol}}/SFR] \times \int_{T_{\text{min}}}^{T_{\text{max}}} dT \; e^{-1}_F T,\epsilon_T(\nu),$$

where $\epsilon_T(\nu)$ is the UV SFR, and $[L_{\text{bol}}/SFR]$ sets the normalization (which we develop models for shortly). We compute $\epsilon_T(\nu)$ using CLOUDY (Ferland et al. 2013) and assuming collisional ionization equilibrium.\(^8\) We choose $T_{\text{min}} = 10^4$ K, although our calculations are not sensitive to this choice. In addition, our calculations assume a single metallicity of $Z = 0.3 Z_\odot$ for $T_{\text{max}} = 10^6$ K and $Z = Z_\odot$ for $T_{\text{max}} = 3 \times 10^6$ K. However, since metal emission lines dominate the bolometric emission—what we normalize to—metallicity has little effect on the resulting spectrum.

We choose $T_{\text{max}}$ to have values of $1 \times 10^6$ or $3 \times 10^6$ K. The motivation for this spectral form is that gas tends to be shock heated to these temperatures by $10^7–10^9$ km s$^{-1}$ flows before cooling. At these temperatures, cooling times tend to be short, so there is not often a heating process to halt cooling from running away. (Since we assume a single maximum temperature, our calculation misses that decelerating blastwaves tend to shock gases to a range of temperatures.) In the CGM, our simple model has the additional motivation that gas may be cooling from the $10^6$ K virialized phase characteristic of star-forming galaxies.

This model assumes collisional ionization equilibrium (CIE) cooling, which is likely not a good approximation for ISM cooling. McQuinn (2012) used the Allen et al. (2008) models for unmagnetized supernova shocks to compute the spectrum of a supernova blastwave as it decelerates in a constant-density medium of density 1 cm$^{-3}$. This calculation includes the nonequilibrium ion abundances and consistently models the self-ionization of the shock. They found a spectrum that, on average, scales as $\alpha = 1.7$ between 10 eV and a cutoff at $\sim 1$ keV. Such a spectral index between $10^2$ and $10^3$ eV falls in

\(^7\) Describing this evolution with the more complex light curve in Chen et al. (2015) should not change the results over this 1 Gyr delayed model.

\(^8\) To understand the effect of ionizing backgrounds on our predictions, we have computed the ionization state with the Haardt & Madau (1996) model and $nT = 10^4$ and $100$ K cm$^{-3}$, thermal pressures justified in McQuinn & Werk (2018). We find that there is a negligible difference in the spectra, and thus the photoionization background does not have a significant effect on the resulting SED of the hot gas.
between the effective scaling of our two considered $T_{\text{max}}$ models.

Our normalization of the ISM and CGM emissivities uses the idea that the radiated energy is likely a significant fraction of the total feedback energy. We consider supernova feedback, although stellar winds can be comparable energetically (Leitherer et al. 1999). The bolometric luminosity per unit SFR—what sets the emissivity normalization in our models (Equation (3))—is

$$[L_{\text{bol}}]/[\text{SFR}] = f_{\text{esc}} f_{\text{rad}} f_{\text{SN}} E_{\text{SN}},$$

where $f_{\text{SN}}$ is the approximate fraction of stars expected to go supernova that we take to be $10^{-2}$, $E_{\text{SN}}$ is the approximate energy output per supernova that we take to be $10^{51}$ erg s$^{-1}$, $f_{\text{rad}}$ is the fraction of the feedback energy that is radiated, and $f_{\text{esc}}$ is the fraction that escapes the galaxy. Calculations find that $f_{\text{rad}} \approx 0.9$ in the local ISM surrounding supernovae if they are unclustered (Thornton et al. 1999), and that for clustered supernovae, this fraction can go down to $f_{\text{rad}} \approx 0.5$ (Sharma et al. 2014). Much of the energy that is not radiated in the ISM (or, if radiated, is reabsorbed) is likely radiated in the CGM where $f_{\text{esc}} \approx 1$: McKee & Werk (2018) argued that the large oxygen-VI (OVI) columns require $f_{\text{rad}} > 0.1$ in the CGM, and large values of $f_{\text{rad}}$ appear to be borne out in numerical simulations of the CGM (van de Voort & Schaye 2013; Fielding et al. 2017). Observations further suggest that the characteristic scale for the CGM emission extends many tens of kpc outside of the galaxy (Werk et al. 2014), so this diffuse emission would likely go undetected in soft X-ray images even if the gas reached sufficiently high temperatures to be seen in the soft X-ray. We note that this energetics-motivated model for CGM emission is similar to that of Miniati et al. (2004, except they assume emission at $T_{\text{vir}}$), as are our conclusions for the potential impact on $J_{\nu}$.

In our model of the CGM emission (though it can also be colder, less obscured ISM emission), we take the possible range for escaping emission to be $f_{\text{esc}} f_{\text{rad}} = 0.1–0.5$ and $T_{\text{max}} = 10^{6}$ K. This “CGM/ISM” model is shown by the green shaded region in Figure 3. This spectrum peaks at hundreds of eV and falls off below the X-ray measurements at $>300$ eV. However, we again note that falling below the X-ray measurements is not required, as this emission could be too diffuse to detect.

For hotter ISM gas with $T_{\text{max}} \approx 3 \times 10^{6}$ K, we tune the normalization to meet the observations, finding $f_{\text{esc}} f_{\text{rad}} = 0.01–1$. This “ISM” model is shown by the turquoise shaded region in Figure 3. Much of the ISM radiation is likely absorbed in the galaxy to produce such low $f_{\text{esc}} f_{\text{rad}}$: the blue dotted lines represent the H1 + He I transmissions for H I column densities ranging from $10^{18}$ to $10^{22}$ cm$^{-2}$. Large H I columns of $\sim 10^{22}$ cm$^{-2}$ are necessary to obscure the X-ray emission. Additionally, lower columns would obscure ISM models with smaller $T_{\text{max}}$.

For both the ISM and CGM models, we assume that the same range of $f_{\text{esc}} f_{\text{rad}}$ holds with redshift to compute $J_{\nu}$ in Section 3. As the properties of galaxies change, and it is thought that the escape of ionizing photons goes up with redshift, this might underestimate temporal trends, especially for $J_{\nu}$ at higher redshifts.

### 2.5. Virialized Hot Halo Gas

This section considers the emission from virialized gas in massive halos. We distinguish this scenario from the diffuse CGM gas previously considered in that, as cooling times get longer in larger systems, a roughly single-temperature hydrostatic virialized region forms, whereas the CGM emission is due to cooling gas and likely a range of temperatures. A second distinction is that the CGM emission is sourced by halos where most star formation occurs in the universe, $\sim 10^{12} M_\odot$ halos, whereas we will see that hot halo emission is due to systems at least an order of magnitude larger (and is powered by virialization and quasar feedback).

The hot-gas scenario should be thought of as being essentially the same as the warm-hot IGM emission that has been discussed extensively by prior studies as a source of the soft X-ray background (Cen & Ostriker 1999; Croft et al. 2001; Davé et al. 2001). While some of the diffuse emission likely comes from filamentary gas, most is likely to come from gas associated with halos as modeled in Pen (1999). There is 25% (15%) dark matter in $>10^{12} M_\odot$ halos at $z = 0$ (0.5) and 10% (5%) dark matter in $>10^{14} M_\odot$ halos. Filamentary gas is too diffuse (and possibly too unenriched) to compete with virialized regions even though it constitutes a somewhat larger mass fraction. The amplitude of this emission is more sensitive to how the associated gas is distributed around halos, which we discuss below.

Group and cluster virialized gas emits in the EUV and soft X-ray of massive halos via free–free and atomic line emissions, with the latter becoming more prominent in lower-temperature halos. The X-ray emission from virialized gas that has been measured for $\gtrsim 10^{15} M_\odot$ halos can be directly observed (Markevitch 1998; Arnaud & Evrard 1999; Della Ceca et al. 2000; Helsdon & Ponman 2000; Borgani et al. 2001; Holden et al. 2002; Mulchaey et al. 2003; Jeltema et al. 2008; Pratt et al. 2009), and we design our models to latch onto these observations. In particular, we use the models of Sharma et al. (2012) based on timescale considerations, which are able to fit the observed X-ray luminosity–temperature relation ($L_X–T_X$). In particular, McCourt et al. (2012) and Sharma et al. (2012) found (using simulations of a gravitationally stratified atmosphere in which cooling is initially in balance with heating) that in order for a halo to not be locally thermally unstable, leading to condensation and driving SFRs larger than observed, the cooling time must be at least 10 times the dynamical time. This bound on the density of gas in halos has been confirmed in simulations with more realistic feedback prescriptions (Gaspari et al. 2013). It also is consistent with observations (Sharma et al. 2012; Voit & Donahue 2015; Voit et al. 2018).

We use the Sharma et al. (2012) fiducial model, which uses a cooling time–to–dynamical time ratio of 10 (an upper limit on the core density and therefore on $L_X$) as an upper limit to our calculation and their lowest-luminosity model with a cooling time–to–dynamical time ratio of 100 as a lower limit. These models, which produce $L_X^{\text{Sharma}}$, generously bracket the spread in $L_X–T_X$ values seen in observations (see Figure 3 of Sharma et al. 2012). Indeed, a more detailed analysis likely could shave off factors of two in the uncertainty at both sides. Both of these models use an asymptotic gas density slope of $–2.25$ to solve a differential equation for the gas density profile (see Sharma et al. 2012). We identify $T_X$ with $T_{\text{vir}}(M_{\text{halo}})$, the virial
temperature of a halo of mass $M_{\text{halo}}$, calculated assuming an isothermal sphere (Barkana & Loeb 2001).9

For the spectral form of this emission, $\ell(\nu) \equiv L_\nu/\int d\nu L_\nu$, we use a composite CLOUDY spectrum that is made up of a series of CLOUDY “coronal equilibrium” models with several discrete temperatures. These CLOUDY models assume collisional ionization equilibrium (Ferland et al. 2013) and a hydrogen density of $10^{-4}$ cm$^{-3}$—the virial density of halos in spherical collapse at $z = 0.2$. We use the solar abundance ratios of Grevesse et al. (2010) with an overall metallicity of $Z = 0.3 Z_{\odot}$, in accord with the typical metallicity in intracluster and CGM measurements (Mantz et al. 2017; Prochaska et al. 2017). Changing to $Z = 0$ (or, to a lesser extent, turning on an ionizing background or decreasing the density we assume) results in the emission lines disappearing in the spectra but does not significantly change our results.

The temperatures of these models are computed over a large range of virial temperatures. The models in the composite spectrum are then weighted in accordance with the Sheth–Tormen halo mass function (Sheth & Tormen 1999), $dn/dM_{\text{vir}}$, at a given redshift such that

$$\epsilon_\nu = \int_{M_{\text{min}}}^{\infty} dM \frac{dn}{dM} L^M(\nu),$$

where $L^M(\nu)$ is the frequency-dependent luminosity of the halo gas of a given halo mass, set equal to $L^\text{Sharma}_X \chi L^\text{cloudy}(\nu)$. We set $M_{\text{min}} = 10^{13} M_{\odot}$ here, but smaller values would not change our results for $\epsilon_\nu$ and $J_\nu$ (as discussed below) at $z = 0$.

Our fiducial model, shown as the red shaded region in Figure 4, is this calculation for the $z = 0$ emissivity of halo gas, with the region bracketing the two $T_X-L_X$ models of Sharma et al. (2012) described above. The cyan and gold shaded regions show this calculation above higher minimum masses, as discussed in the following paragraph. If we treat the observed spread as an indication of measurement error (or, e.g., biases owing to missing the most diffuse components), then the band indicates the level of uncertainty. Interestingly, these estimates for virialized gas emission exceed our lower bounds for quasar emission between several tens and a few hundred eV. In contrast to the $z = 0$ emissivity, the observed background comes from a range of redshifts, and when this is considered, we find in Section 3 that quasars are still likely to be the dominant source due to the declining abundance of massive halos at increasing redshift.

Most of the $z = 0$ emission from virialized gas comes from small clusters. Figure 4 also shows calculations that only allow for emission above halos with masses of $10^{14}$ (cyan) and $10^{15}$ $M_{\odot}$ (gold), respectively. We find that the EUV and soft X-ray emission from this gas is dominated by $M \gtrsim 10^{13} M_{\odot}$ at $z = 0.1$.

Lower-mass halos cool very efficiently and so have lower gas densities. In the Sharma et al. (2012) models, the gas in the most massive halos essentially traces the dark matter but becomes cored at lower masses with a large fraction not fitting within in the virial radius for $M \lesssim 10^{13} M_{\odot}$. We caution that at $M \gtrsim 10^{13} M_{\odot}$, representing the cooling emission with a virialized atmosphere may be fraught, and the CGM calculations described previously likely have more bearing.

### 3. The Contribution of Different Sources to $J_\nu$

The summary of the emissivity calculations described in Section 2 is shown in Figure 5. We plot each of the sources’ specific emissivities at $z = 0.1$, 2.0, and 4.0. We use the quasar calculations described in Section 2.1, the XRB calculation of Section 2.2, the SSS calculation of Section 2.3, the ISM and CGM calculations as described in Section 2.4, the empirical galactic model with a power-law SED discussed in Section 2.2, and the virialized halo gas calculation as described in Section 2.5. The band encapsulating each model reflects the range of possible values that we motivated the use of.

Both the peak of the quasar emissivity and cosmic SFR (to which the XRB and CGM emissivity are tied) occur at $z = 2–3$, prompting a similar peak in each source’s emissivity near these redshifts. In contrast, the amount of free–free emission from virialized halo gas drops off rapidly with increasing redshift due to the abundance of $\gtrsim 10^{13} M_{\odot}$ halos decreasing quickly with redshift. While virialized gas is likely the most important source at most of the considered wavelengths at $z = 0$, quasars become the most important at $z = 2–4$. At higher redshifts than shown, models suggest that XRBs and perhaps hot ISM gas become the dominant source at 100–1000 eV (Mirabel et al. 2011; Pacucci et al. 2014; Madau & Fragos 2017).

The solution to the cosmological radiative transfer equation gives the background angular-averaged specific intensity at a

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9 We note that the Sharma models are computed for just free–free cooling, which could lead to differences at the lowest temperatures we consider where atomic cooling becomes important. However, the CGM models become more applicable in this limit.

10 Because the virial scale is an arcminute for an $M = 10^{13} M_{\odot}$ halo at $z = 0.5$, these sources of emission would not be included in X-ray point-source catalogs. Nearly every sight line on the sky intersects a $10^{13} M_{\odot}$ halo (McQuinn 2014).
particular energy as observed at $z_0$,

$$J_0 (z_0) = \frac{c}{4\pi} \int_{z_0}^{\infty} \frac{dz}{dz} \left( \frac{1 + z_0}{1 + z} \right)^3 \epsilon_o (z) e^{-\tau (z_0, z)}$$

where $\epsilon_o$ is the proper volume emissivity—what we modeled in Section 2 for various sources—$|dt/dz| = [H (z)(1 + z)]^{-1}$, and $\tau$ is the effective optical depth between $z_0$ and $z$ in a nonuniform IGM, given by

$$\tau (E_0, z_0, z) = \int_{z_0}^{z} dz' \int_{0}^{\infty} dN H i f (N H i, z')(1 - e^{-\tau_o (N H i)})$$

for randomly distributed absorbers, where $f (N H i, z')$ is the H I column density distribution and $\tau_o (N H i)$ is the optical depth at a particular energy through an absorber,

$$\tau_o = N H i \sigma_H i (\nu) + N H e n \sigma_H e n (\nu)$$

where $\sigma_X$ is the photoionization cross section of species $X$, and the He II column of a system $N H e n$ must be modeled in terms of $N H i$. We use Equation (A10) in Fardal et al. (1998) for the relationship between $N H e n$, $N H i$, and $\Gamma H i$ for a single temperature and density slab. We assume $10^5$ K and a density set by the model in Schaye (2001), in which an absorber’s column and density are related by assuming that the size of the absorber is the Jeans length and photoionization equilibrium.

The Schaye (2001) model agrees well with the simulations (Altay et al. 2011; McQuinn et al. 2011). Our calculations neglect He I continuum absorption and resonant lines, which contribute relatively small features in $J_\nu$ compared to the H I and He II continuum absorption that we include.\footnote{Because the mapping of $N H i$ to $N H e n$ depends on $J_\nu$, we must solve for $J_\nu$ iteratively. Additionally, we use the rates for our fiducial quasar model when calculating the generally subdominant contribution to $J_\nu$ from other source models.}

For $f (N H i, z)$, our calculations use the piecewise-in-$N H i$ fits of Prochaska et al. (2014), which use a parameterization of the form $f (N H i, z) = AN H i^{a} (1 + z)^{b}$. While the error bars over the range of columns probed are generally quoted at the tens of percent level, there are some factor of two discrepancies around $10^{16}$ cm$^{-2}$ (Prochaska et al. 2014). However, for the $z \sim 0$ background, the dilution from expansion and redshifting (which is perfectly captured) is more important than the continuum absorption of hydrogen. At $\gg 1$ Ry, where we focus, this is true not just at $z \sim 0$ but also at higher redshifts. Therefore, discrepancies in the column density distributions may indicate that there is room for as much as a factor of two difference from mean free path effects, but likely only at the lowest energies considered and moderate redshifts. Even a factor of two is smaller than the possible amplitude ranges in all of our source models. Thus, our modeling of absorption is not the dominant source of uncertainty.

Figure 5 shows $J_\nu$ at $z = 0$ for each of the sources shown in Figure 5. We also include two observational constraints from ROSAT: the constraint of Warwick & Roberts (1998), using the lowest energies where the extragalactic background can be estimated, is represented by the error bar at 250 eV, and the ROSAT PSPC data constraint of Georgantopoulos et al. (1996) is shown as the red bowtie starting at $\sim 500$ eV. By construction, both of these observational bounds are reasonably matched by the full range of quasar emissivity models.

Our calculations show that, even accounting for our estimated range of specific emissivities, quasars are the
dominant contributor to the EUV/soft X-ray background at energies $\lesssim 100$ eV. If the value of $\alpha_{\text{QSO}}$ is on the softer side, as observations may suggest, then the emission of hot halo gas in massive halos could be the more important contributor to the EUV background at energies upward of a couple hundred eV. Figure 6 suggests that galactic sources may be of secondary importance to these two sources where $E \geq 100$ eV, but the ISM and CGM may be second only to quasars at lower energies. Even though they are not the dominant sources of emission of the extragalactic background, they can dominate within the halos of galaxies (Section 5) and their contribution.

Potential background sources can be isolated using unresolved X-ray background measurements. In particular, the 1–2 keV resolved fraction of the X-ray background is 80% of the total in the Chandra deep fields (a total of 0.06 deg$^2$), and similar constraints have been found in larger fields (Hickox & Markevitch 2006). Thus, only $\approx 20\%$ of the X-ray background is due to diffuse sources like virialized halo gas. This bound suggests that the maximum virialized halo gas emission is a factor of $\sim 2$ below our maximum estimates. However, at 1–2 keV, the signal is dominated by rare $>10^{14} M_\odot$ halos (Figure 4), which may not fall in the Chandra field of view. A more detailed analysis is necessary to understand this constraint.

Figure 7 shows $J_\nu$ for the same sources at $z = 2$. Here quasars are undisputedly the dominant source of the EUV/soft X-ray background. No other source is likely to produce enough $>54$ eV photons to doubly ionize the He II if it is ionized at $z \sim 3$, as observations suggest (McQuinn 2016). The number of $M > 10^{13} M_\odot$ halos steeply declines with increasing redshift; thus, the contribution of virialized hot halo gas at $z = 2$ is negligible in comparison to the contribution of both quasars and galactic sources. The overall increase in the background intensity from $z = 0$ to 2 follows from the rise of both the cosmic SFR and quasar luminosity function.

4. The Effect of the Extragalactic Background on IGM and CGM Absorption-line Inferences

Photoionization models are used to infer the density and metallicities of intergalactic and circumgalactic absorption systems (e.g., McQuinn 2016; Tumlinson et al. 2017). As ions have electronic binding energies in the EUV and soft X-ray, their abundances are shaped by these radiation backgrounds. We have shown that the uncertainty in the spectrum of the background at these energies is considerable, suggesting commensurate uncertainties in the density and metallicity inferences. In this section, we apply our models to quantify the sensitivity of the most observable ions to the assumed ionizing background.

Previous attempts to make metallicity and density inferences from ionic absorption measurements use a metagalactic ionizing background model, such as that of Haardt & Madau (2012). When errors are quoted pertaining to the ionizing background choice, they are computed as the differences between historical models for these backgrounds, such as comparing how a calculation changes if it uses Haardt & Madau (1996) rather than Haardt & Madau (2012). The major differences between various historical models for the ionizing background are in improved constraints on IGM absorption and for the 1 Ry emissivity of quasars, not improved modeling of the spectrum of the sources. In contrast, our models allow us to quantify the principal source of uncertainty.

We use CLOUDY to compute the equilibrium column densities of several common metal ions in the UV, with our $J_\nu$ models as the input ionizing spectrum and assuming temperature equilibrium. We only consider the range of $J_\nu$ in our quasar models, using the lower and upper envelopes of the quasar intensity. We then compare the resulting columns to the columns with the Haardt & Madau (2012) $J_\nu$. These models implicitly assume that photoionization is dominant for all ionic species as the equilibrium temperature is $\sim 10^4$ K. (Collisional ionization is included, but since our calculations use the equilibrium temperature, these effects are generally small.) We vary the dimensionless ionization parameter, $U$, the ratio

**Figure 6.** Angle-averaged $z = 0$ specific intensity, $J_\nu$, of sources described in Section 2 and shown in Figure 5. The error bar at $E = 250$ eV is the soft X-ray background intensity ROSAT measurement by Warwick & Roberts (1998). The red bowtie shows the ROSAT PSPC observations from Georgantopoulos et al. (1996). Despite observations suggesting that $\alpha_{\text{QSO}}$ may be on the softer end, quasars likely dominate the background at energies $\lesssim 100$ eV. Between 1 and several hundred eV, virialized hot halo gas may become as important as quasars. Galactic sources such as XRBs, SSSs, the ISM, and especially the CGM can contribute at the tens of percent level.

**Figure 7.** Angle-averaged $z = 2$ specific intensity, $J_\nu$, of sources described in Section 2 and shown in Figure 5. At this redshift, quasars dominate the background throughout the EUV and soft X-ray. Virialized hot halo gas is much less important than at $z = 0$ due to the declining abundance of $M > 10^{13} M_\odot$ halos.
between the ionizing photon flux and the volume density of the gas. We choose \( \log_{10} U = -1, -2, \) and \(-3\), which approximately bracket the mean of values of \( U \) allowed by the data in Werk et al. (2014). For Haardt & Madau (2012), these correspond to densities of \( 8 \times 10^{-6} \) to \( 8 \times 10^{-4} \) cm\(^{-3}\), with larger \( \log_{10} U \) corresponding to lower densities. However, the precise density depends on the background model.

The dispersion from the range of models in select ions’ column densities is shown in Figure 8. Here we show the difference between the CLOUDY column densities computed with the lower and upper limits of our quasar \( J_e \) band and those of our CLOUDY calculations using the Haardt & Madau (2012) background model. (By only using the lower and upper parts of our band, we may underestimate the range of expected columns if there are complex trends with \( J_e \) in the ionic column.) The green bars represent the range of \( J_{QSO} \) in relation to the Haardt & Madau (2012) background model, \( \log N_{X,QSO} - \log N_{X,HM12} \).

The reason the midpoint of our errors is not centered at zero (the Haardt & Madau (2012) values) is likely due to our soft X-ray normalization being slightly lower than theirs. The larger \( \log U \) values are more applicable for the higher ionization state metal lines (e.g., Ne VII), and the smaller \( \log U \) values are more applicable for the low ionization state metal lines (e.g., Si IV). We set \( N_{HI} = 10^{15} \) cm\(^{-2}\) and the metallicity to \( Z = 0.3 Z_\odot \) in these calculations, but we note that these are easily rescaled at fixed \( U \) to higher column or more metal-rich systems. For the model with the Haardt & Madau (2012) ionizing background, we find that with \( \log U = -1 \), the logarithmic column densities are \( \{10.0, 13.8, 14.0, 14.9, 15.1, 14.4, 14.0\} \) for \([\text{Si IV}, \text{C IV}, \text{N V}, \text{O V}, \text{O VI}, \text{Ne VII}, \text{Ne VIII}]\); for \( \log U = -3 \), they are \( \{12.1, 13.7, 13.1, 14.0, 13.3, 11.5, 10.4\} \); and for \( \log U = -3 \), the column densities are \( \{11.7, 11.9, 10.2, 11.2, 9.5, 6.7, 4.9\} \). The dispersion in possible \( J_e \) results in up to an order of magnitude in the uncertainty in the calculated column densities for the highest ions (Figure 8).

While normalizing to a fixed \( U \) is standard practice in this field, normalizing to a fixed H I photoionization rate would better encapsulate the uncertainty in the ionization correction, as this fixes the background to the most constrained location, as Ly\(\alpha\) forest measurements nail down the H I photoionization rate. While the green errors in Figure 8 compare the differences at fixed \( U \), the cyan errors normalize the model that traces our upper envelope for the quasar \( J_e \) to a different \( U \) such that it matches the H I photoionization rate of the lower envelope of the \( J_e \) model. Because this normalization fixes the background at a lower energy (near 13.6 eV) compared to normalizing in \( U \), this more physical normalization can sometimes result in more uncertainty, especially for the low ions. Indeed, most of the low ions show \( \approx 0.3 \) dex variation. When fixing the H I photoionization rate, we find factors of 3–10 errors in the ionization correction for all considered ions, which in turn reflects factors of \( \approx 3-10 \) uncertainties in density and metallicity inferences from IGM and CGM absorbers.

5. Proximity Effects

The uncertainties in derived metal ion column densities in the previous section neglect the possibility that the ionization state of circumgalactic gas could be affected by the ionizing flux of the host galaxy. Within some radius, local galactic sources will dominate the cosmic EUV/soft X-ray background in ionizing photon flux. The low-to-mid-ionization states of metals tend to arise in \( 10^4 \) K gas, with their ionization states set predominantly by the photoionizing radiation background. Thus, knowledge of the UV background is critical for estimating the densities and metallicities of the clouds that these lower ions trace. For example, the inferred densities for these clouds using standard ionizing background models is an order of magnitude smaller than predicted by pressure equilibrium with the virialized phase (Werk et al. 2014, 2016; McQuinn & Werk 2018). Modifications to the UV background have been hypothesized as a potential solution, likely requiring a 1–2 order of magnitude enhancement from unknown sources at \( \approx 100 \) eV (Werk et al. 2016). In addition, because highly ionized metals are major coolants of gas in the CGM, order unity changes in their ionization fractions from local emissions translate to order unity changes in their cooling rates when the major coolants are predominantly photoionized, potentially impacting the rate at which galaxies are fed gas.
SSSs is expected to peak at stellar ages of about 1 Gyr, the SSS models show and X-ray sources. The fainter ISM band and the lower SSS curve represent the proximity region radius for a galaxy with an SFR of 1 M\odot yr\(^{-1}\) at z = 0.2 for our galactic and circumgalactic source models, defined as the radius where the background J\(_\nu\) is equal to the local contribution from galactic EUV and X-ray sources. The fainter ISM band and the lower SSS curve represent the
these models attenuated by a column of 10\(^{22}\) cm\(^{-2}\). Because the luminosity of SSSs is expected to peak at stellar ages of about 1 Gyr, the SSS models show the expected luminosity at z = 0.2 from a galaxy with an SFR of 1.27 M\odot yr\(^{-1}\) at z = 0.3 (1 Gyr prior to z = 0.2). This assumes that this toy galaxy’s star formation history follows the shape of the cosmic SFR density.

We compare the angular-averaged intensity from local galactic sources (i.e., ISM, XRBs, and SSSs) to that from the global background to determine the “proximity radius”: the distance from a galaxy where local and background sources contribute equally to the radiation. The proximity radius for a galaxy is given by

\[
r_{\nu, \text{prox}} = 103 \text{kpc} \left[ \frac{(10^{39} \text{ erg s}^{-1})}{(10^{-3} \text{ erg s}^{-1} \text{ cm}^{-2})} \right]^{1/2},
\]

where L\(_\nu\) is the local galactic specific luminosity. We have evaluated the equation at a J\(_\nu\) characteristic of our ionizing background calculations and for an L\(_\nu\) at the maximum of what we find in our galactic source models. Thus, we conclude that the proximity region is unlikely to extend beyond \(~\sim\)100 kpc, a smaller extent than inferred for many absorbers in the CGM, and especially the OVI smaller extent than inferred for many absorbers in the CGM, and especially the OVI

Figure 9 shows our full calculations for the proximity radii for a galaxy with SFR of \(~\sim\)1 M\odot yr\(^{-1}\) varies between 10 and 100 kpc. Taking the median of our bands or the observed X-ray luminosities would suggest \(~\sim\)10–30 kpc, a small fraction of the total CGM, but scaling as (SFR)\(^{1/2}\). Thus, proximity radiation changes the nature of cooling gas that resides fairly close to galaxies but does not affect the bulk of the halo gas with an extent of \(~\sim\)100 kpc. Thus, local sources are unlikely to be dominant for the vast majority of absorbers in many CGM samples, such as those of Tumlinson et al. (2011) and Stocke et al. (2013), whose absorbers mainly reside at 30–150 kpc. That being said, assuming the radiation escapes, proximity emission can substantially affect gas ionization near galaxies and, therefore, it can change the CGM gas cooling rate for the ions that are sensitive to the radiation with energies in the range shown in Figure 9.

This conclusion is consistent with the geometric arguments of McQuinn & Werk (2018) that showed that \(r_{\text{prox}} \lesssim 100\) kpc, assuming that the proximity region sources are also the dominant source of the background. Our calculations add the likely dominant background from quasar emissions, which reduces this radius further beyond the McQuinn & Werk (2018) estimates.

6. Conclusions

We have modeled the sources of the extragalactic background in the EUV and soft X-ray. In addition to the contribution from quasars, we included emissions that have so far been neglected in widely used background models: XRBs, the warm-hot interstellar and circumgalactic gas of star-forming galaxies, and virialized halo gas from groups and clusters. Our models are calibrated against the latest observational measurements to bracket the possible range of contribution from each of these sources. Note that these estimated ranges should be thought of as rough guidelines rather than rigorous bounds.

In agreement with previous studies, we find that quasars are likely the most important contributor to the ionizing background.\(^{13}\) However, we also show that their contribution to the observationally elusive 20–500 eV band can vary by up to a factor of 10 for plausible extrapolations into this band using power laws derived in the far-UV and soft X-ray. Furthermore, the evidence that the quasar SED is a single power law, as assumed in previous background studies, is weak.

If quasars contribute at the lower envelope of our estimated J\(_\nu\) range, we find that emissions from the galactic ISM/CGM, virialized halo gas in groups/clusters, and possibly supersoft sources may contribute significantly to the background.

1. The ISM contribution originates from cooling gas within stellar wind bubbles and supernova blastwaves. While a large fraction of the ISM emission is absorbed by H I within the galaxy, a significant amount of stellar feedback energy is likely dumped as lower-temperature gas and further away from obscuring H I in the ISM, venting into the CGM, where it is more easily radiated away. If most of the energy in stellar feedback is converted into background radiation, we find that the combined ISM/\(^{12}\) See the appendix in McQuinn & Werk (2018) for generic arguments that the proximity region must have an extent less than \(\lesssim\)100 kpc.

\(^{13}\) With the caveat that stellar emissions—which we do not model here—are likely to be important at <50 eV, with many models suggesting that they contribute up to a factor of 2 level and are possibly dominant at z \(\gtrsim\) 4 (e.g., Haardt & Madau 2012).
CGM contribution is roughly equal to the lower bound on quasars in the energy range 20–50 eV.

2. We also find that, at $z = 0$, emissions from hot virialized gas in groups/clusters can be as important as quasars at energies of $\sim 100$–1000 eV. This contribution falls off in importance at higher redshifts owing to the decreasing abundance of groups and clusters and the increasing number density of quasars.

3. Supersoft sources are often invoked as a huge unknown contribution at $\sim 100$ eV, although there is little empirical evidence for such a population. By deriving a stringent bound from luminosity predictions of SSSs from previous models, we show that unseen supersoft sources could maximally contribute tens of percent to the background at $\sim 100$ eV.

Disentangling the physics of circumgalactic gas with absorption-line spectra requires accurate modeling of the EUV and soft X-ray backgrounds. Previous studies have estimated the effect of uncertainties in these backgrounds by comparing inferences obtained from different historical background models—for example, the Haardt & Madau (1996) and Haardt & Madau (2012) models. As an application of our work, we have used our range of $J_\nu$ models to quantify this uncertainty more rigorously. We bracketed the effect of the ionizing background on the inferred column densities of ions commonly identified in UV absorption-line studies of the CGM. We showed that uncertainties in the average quasar spectrum alone are sizable, enough to introduce a few tenths of dex differences in the abundances of the most observationally important ions and up to 1 dex in the inferred column densities for the highest observationally relevant ionization states. These differences likely translate into comparable uncertainties in the densities and metallicities constrained by these ions.

The uncertainties in metal ionization corrections are even larger if local sources—e.g., XRBs and warm-hot ISM/CGM gases—contribute significantly. We estimated the EUV/soft X-ray proximity radius of a star-forming galaxy—the radius at which local emissions become equal to the extragalactic background. We found that this proximity radius is between $r_{\text{prox}} \approx 10$ and 100 kpc, assuming an SFR of $1 \text{ M}_\odot \text{ yr}^{-1}$, with $r_{\text{prox}} \approx 100$ kpc for choices that maximize the potential galactic luminosity (and only at $E < 100$ eV). Thus, local emission is unlikely to be the dominant source of ionization for the absorbers in most extragalactic CGM samples.

Future observations and theoretical work have the potential to further constrain emission processes that contribute sizably to the EUV and soft X-ray backgrounds. With a factor of 2–3 improved sensitivity, diffuse soft X-ray background measurements would reach most of our model space for hot halo emission. In analogy to the $\gamma$-ray, where angular anisotropy analyses have constrained the blazar, millisecond pulsar, and galactic contributions (Ackermann et al. 2012), a future soft X-ray space telescope could measure the angular anisotropy to constrain source models. Low-redshift clusters and groups are rare and have large arcminute extents, whereas (abundant) galactic sources will contribute a smoother signal in angle. Finally, future CGM observations and modeling have the potential to better constrain the density and thermal structure of this medium and, hence, its cooling emissions.

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