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Probing intergalactic radiation fields during cosmic reionization through gamma-ray absorption

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ABSTRACT

We discuss expectations for the absorption of high-energy gamma-rays by $\gamma\gamma$ pair production with intergalactic radiation fields (IRFs) at very high redshifts ($z \sim 5$–20), and the prospects thereof for probing the cosmic reionization era. For the evolving IRF, a semi-analytical model incorporating both Population II and Population III stars is employed, which is consistent with a wide variety of existing high-z observations including quasi-stellar object spectral measurements, *Wilkinson Microwave Anisotropy Probe* Thomson depth constraints, near-infrared source count limits, etc. We find that the ultraviolet IRF below the Lyman edge energy with intensities in the range of a few times 10^{-19} erg cm^{-2} s^{-1} Hz^{-1} sr^{-1} can cause appreciable attenuation above ∼12 GeV at $z \sim 5$, down to ∼6–8 GeV at $z \gtrsim 8$–10. This may be observable in the spectra of blazars or gamma-ray bursts by the *Fermi* Gamma-ray Space Telescope or next-generation facilities such as the Cherenkov Telescope Array, Advanced Gamma-ray Imaging System or 5@5, providing invaluable insight into early star formation and cosmic reionization.

Key words: gamma-ray burst: general – galaxies: active – galaxies: high-redshift – intergalactic medium – cosmology: theory.

1 INTRODUCTION

Some time after the epoch of cosmic recombination at redshift $z \sim 1100$, the bulk of the intergalactic gas in the Universe must have been somehow reionized by $z \sim 6$, as indicated observationally from the spectra of high-z quasi-stellar objects (QSOs) and the polarization of the cosmic microwave background (CMB). However, the sources, history and nature of this cosmic reionization process are still largely unknown, as most of this redshift range has yet to be explored through direct observations. Because the first stars and galaxies in the Universe must have formed during this period, the primary suspect is photoionization by ultraviolet (UV) radiation from such objects, potentially involving metal-free, Population (Pop) III stars. Alternative possibilities include mini-quasars, supernova remnants and dark matter decay. Besides providing us with clues to such processes in the early Universe, cosmic reionization also profoundly affects the ensuing formation of stars and galaxies, so elucidating this era is one of the most pressing issues in cosmology today (see Barkana & Loeb 2001; Ciardi & Ferrara 2005; Fan, Carilli & Keating 2006; Choudhury 2009 for reviews).

In the majority of scenarios for reionization of hydrogen in the intergalactic medium (IGM), the main protagonists are UV photons with energies above the Lyman edge ($\epsilon \geq \epsilon_{\rm LE} = 13.6$ eV). Although those with lower energies do not contribute to photoionization, they are also crucial since (i) they give indications as to the strength and nature of the ionizing radiation, (ii) those in the Lyman–Werner band ($\epsilon = 11.2$–13.6 eV) can photodissociate H_2 molecules and suppress early star formation (e.g. Ciardi & Ferrara 2005) and (iii) Lyα photons ($\epsilon = 10.2$ eV) can strongly affect the H I spin temperature and the associated cosmological 21-cm signatures (e.g. Furlanetto, Oh & Briggs 2006). Thus, having some observational means to probe the evolution of UV intergalactic radiation fields (IRFs)[1] in the cosmic reionization era would be of

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[1] Although often referred to as 'extragalactic background light' for lower z, here we avoid the term 'background' since IRFs can be highly inhomogeneous in the reionization era, especially for $\epsilon \geq \epsilon_{\rm LE}$, even though it turns out to be more or less uniform for the spectral regime relevant to $\gamma\gamma$ absorption.

paramount importance, complementing existing observations that probe the neutral or ionized gaseous components of the IGM. However, direct detection of this diffuse emission from very high z is extremely difficult if not impossible.[2]

An indirect but powerful means of probing diffuse radiation fields is through photon–photon ($\gamma\gamma$) absorption of high-energy gamma-rays (e.g. Gould & Schreder 1967; Stecker, deJager & Salamon 1992). Gamma-rays with energy E emitted from extragalactic sources will be absorbed during intergalactic propagation by interacting with photons of the diffuse radiation field with energy ϵ to produce electron–positron pairs ($\gamma + \gamma \rightarrow e^+ + e^-$), as long as there is sufficient opacity for energies satisfying the threshold condition $E\epsilon(1 - \cos\theta) \geq 2m_e^2c^4$, where θ is the incidence angle of the two photons. The observed spectra of the gamma-ray sources should then exhibit corresponding attenuation features, from which one can effectively infer or limit the properties of the diffuse radiation. This method has been utilized in recent TeV observations of blazars by ground-based Cherenkov telescopes to set important constraints on the extragalactic background light in the near-IR to optical bands at relatively low z (Aharonian et al. 2006; Albert et al. 2008).

As first discussed by Oh (2001; see also Rhoads 2001), UV IRFs with sufficient intensities to cause IGM reionization are also likely to induce significant $\gamma\gamma$ absorption in gamma-ray sources at $z \gtrsim 6$ at observed energies in the range of a few to tens of GeV. However, these estimates (i) were made before *Wilkinson Microwave Anisotropy Probe* (*WMAP*) observations indicating an early start of reionization and were limited to $z \leq 10$ and (ii) did not include the possibility of metal-free Pop III stars, which may have been active during the first epochs of star formation and are more prodigious UV emitters compared to normal stars.[3] The recent launch of the *Fermi* satellite[4] with the Large Area Telescope (LAT) operating in the ∼0.1–100 GeV domain motivates us to re-evaluate the $\gamma\gamma$ absorption opacity at very high z, incorporating more recent observational and theoretical developments concerning the cosmic reionization era.

For this purpose, we employ updated versions of the semi-analytical models of Choudhury & Ferrara (2005, 2006), which self-consistently describe inhomogeneous reionization of the IGM, accounting for both Pop II and Pop III stars and their radiative and chemical feedback effects. With only a few free parameters, they are able to fit a wide variety of high-z observational data. Using the evolving IRFs as predicted by these models, the $\gamma\gamma$ opacity is evaluated for the redshift range z = 5–20. We also briefly assess the detectability of the resultant absorption features in high-z sources such as blazars or gamma-ray bursts (GRBs) with current and future gamma-ray facilities, and the consequent implications.

2 INTERGALACTIC RADIATION FIELD MODEL

The salient features of our semi-analytical models are as follows (see Choudhury & Ferrara 2005, 2006, 2007; Choudhury, Ferrara & Gallerani 2008; Choudhury 2009 for more details). (1) Adopting a lognormal distribution of IGM inhomogeneities (Mirada-Escudé, Haehnelt & Rees 2000), the ionization and thermal histories of the neutral, H II and He II phases of the IGM are tracked simultaneously and self-consistently. (2) The formation and evolution of dark matter haloes are described by a Press–Schechter-based approach. (3) Three types of radiation sources are considered: (i) metal-free Pop III stars with a Salpeter initial mass function (IMF) in the mass range 1–100 $M_\odot$, with spectra according to Schaerer (2002) and including nebular and Lyα emission lines (see Salvaterra & Ferrara 2003); (ii) low-metallicity ($Z = 0.02\,Z_\odot$) Pop II stars with spectra according to Bruzual & Charlot (2003), otherwise being the same as Pop III and (iii) QSOs with power-law spectra and emissivity based on the observed luminosity function at $z < 6$, considering only those above the break luminosity (Choudhury et al. 2008). (4) Pop II and Pop III stars form from gas in virialized haloes with efficiencies $\varepsilon_{*,\mathrm{II}}$ and $\varepsilon_{*,\mathrm{III}}$, respectively, and the corresponding escape fractions of ionizing photons from the host haloes are parametrized by $f_{\mathrm{esc,II}}$ and $f_{\mathrm{esc,III}}$. Included self-consistently are the consequent effects of radiative feedback that suppresses star formation in sufficiently small haloes, as well as a 'genetic' merger-tree-based treatment of chemical feedback that induces the transition from Pop III to Pop II star formation (Schneider et al. 2006).

The four free parameters of the model are $\varepsilon_{*,\mathrm{II}}, \varepsilon_{*,\mathrm{III}}$, η_{esc} that fixes both $f_{\mathrm{esc,II}}$ and $f_{\mathrm{esc,III}}$, and finally λ_0, related to the mean free path of ionizing photons due to H I in high-density regions.[5] These are ascertained so as to simultaneously reproduce a large set of high-z observational data: (i) redshift evolution of Lyman limit absorption systems; (ii) effective optical depths of the IGM for Lyα and Lyβ from QSO spectra; (iii) electron scattering optical depth τ_e from *WMAP* third-year results (Spergel et al. 2007);[6] (iv) temperature of the mean IGM; (v) cosmic star formation history and (vi) limits on J-band source counts from NICMOS HUDF. In the fiducial, best-fitting model,[7] H reionization begins rapidly at $z \sim 15$, initially driven by Pop III stars, and is 90 per cent complete by $z \sim 8$. Thereafter it is slowed down by feedback effects and taken over by Pop II stars at $z \sim 7$, finally reaching completion by $z \sim 6$ (see fig. 2 of Choudhury 2009). The cosmic star formation rate (SFR) is always dominated by Pop II stars and is at the level of 0.05–0.08 $M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$ for $z \sim$ 6–8 (fig. 2b of Choudhury 2009), in line with that deduced from observed GRB rates (e.g. Salvaterra et al. 2008; Kistler et al. 2009).

Shown in Fig. 1 is the volume-averaged intensity of the IRF as calculated from this model, which declines monotonically with z following the evolution of the SFR. We caution that at $z \gtrsim 6$ before intergalactic H II regions have completely overlapped, the IRF is expected to be inhomogeneous and fluctuating along different lines of sight, particularly strongly for $\epsilon \geq \epsilon_{\mathrm{LE}}$. However, it is also evident that ionizing photons are strongly absorbed by the neutral IGM and the mean IRF spectrum cuts off very sharply above ϵ_{LE}, so that this portion has negligible effects on the $\gamma\gamma$ opacity (Madau & Phinney 1996; Oh 2001; Rhoads 2001). On the other hand, UV radiation with $\epsilon < \epsilon_{\mathrm{LE}}$ has much longer mean free paths in the IGM, and the

[2] Earlier indications of a large contribution from Pop III stars to the local near-infrared (near-IR) background are now disfavoured from J-band source count limits (Salvaterra & Ferrara 2006).

[3] Note that $\gamma\gamma$ absorption measurements in low-z blazars have set strong constraints against a large contribution from Pop III stars to the local near-IR background (Aharonian et al. 2006; see also Raue, Kneiske & Mazin 2009).

[4] See web site http://fermi.gsfc.nasa.gov.

[5] The adopted cosmological parameters are $h = 0.73$, $\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$, $\Omega_b h^2 = 0.022$, $\sigma_8 = 0.74$, $n_s = 0.95$ and $\mathrm{d}n_s/\mathrm{d}\ln k = 0$ (Spergel et al. 2007).

[6] The fiducial model gives $\tau_e = 0.07$, consistent with the fifth-year results as well (Dunkley et al. 2009).

[7] The relevant parameters are $\varepsilon_{*,\mathrm{II}} = 0.1$, $\varepsilon_{*,\mathrm{III}} = 0.02$, $f_{\mathrm{esc,II}} = 0.0578$ and $f_{\mathrm{esc,III}} = 0.54$.

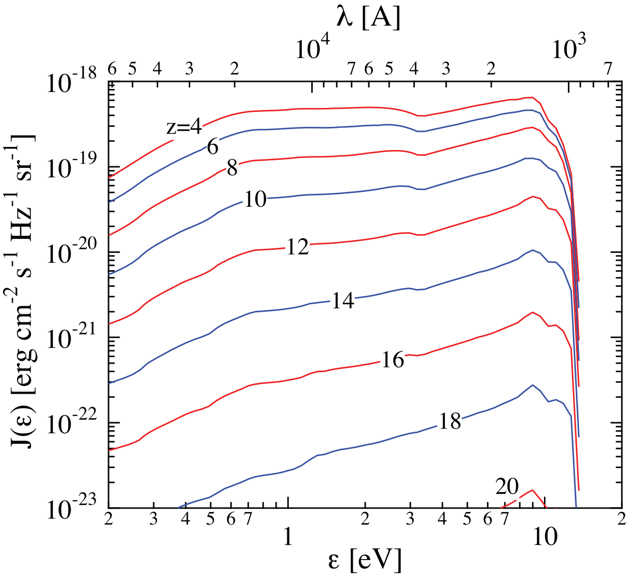

Figure 1. Volume-averaged intensity of the intergalactic radiation field $J(\epsilon)$ versus energy ϵ (or wavelength λ) at redshifts z as labelled for the fiducial model.

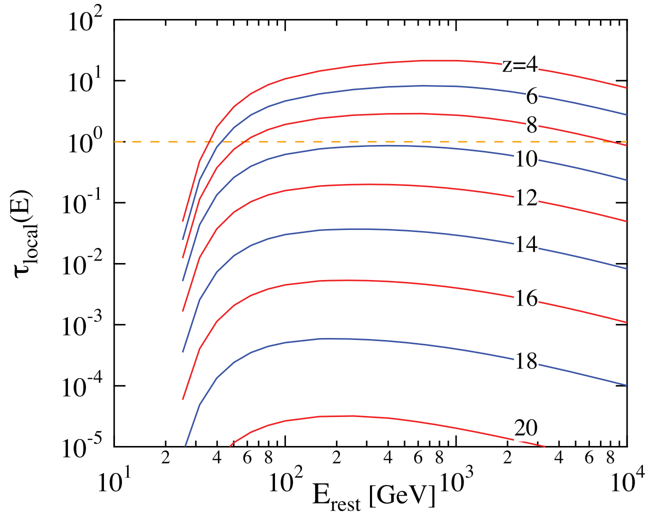

Figure 2. Local $\gamma\gamma$ optical depth $\tau_{\rm local}(E)$ versus rest-frame gamma-ray energy $E_{\rm rest}$ at redshifts z as labelled for the fiducial model. The contribution from the CMB is not shown.

notion of a nearly uniform and isotropic background may still be appropriate for this regime, which is also the most relevant for $\gamma\gamma$ absorption. Of particular note is the band $\epsilon = 10.2$–13.6 eV where the spectrum dips somewhat due to blanketing by the Lyman series lines, but which should nevertheless be very important for the $\gamma\gamma$ opacity.

Being optimized for the cosmic reionization era, the main shortcoming of the present model is that it does not account for Pop I stars or dust that can become important at lower z. Our IRF calculations are available only for $z \geq 4$, and may be somewhat less reliable near $z \sim 4$ as the comparison with observations has not been as thorough as for $z > 5$. A more complete model describing the evolution of the IRF at all redshifts awaits future studies.

3 GAMMA-RAY ABSORPTION OPACITY

We first estimate the 'local $\gamma\gamma$ optical depth' at each z by the optical depth across a Hubble radius $l_{\rm H}(z) = c/H_0\,[\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda]^{1/2}$,

$$\tau_{\rm local}(z, E) = l_{\rm H}(z) \int_{\epsilon_{\rm th}}^{\infty} {\rm d}\epsilon\, n(\epsilon, z) \times \frac{1}{2}\int_{-1}^{1} {\rm d}\mu (1-\mu)\sigma_{\gamma\gamma}(E, \epsilon, \mu), \quad (1)$$

where $n(\epsilon, z)$ is the IRF photon number density per energy interval, $\mu = \cos\theta$, $\epsilon_{\rm th} = 2m_{\rm e}^2c^4/E(1-\mu)$ is the threshold energy, and $\sigma_{\gamma\gamma}(E, \epsilon, \mu)$ is the $\gamma\gamma$ pair production cross-section. For given E, $\sigma_{\gamma\gamma}$ rises sharply from $\epsilon = \epsilon_{\rm th}$, peaks at $\epsilon = 2\epsilon_{\rm th}$ and then falls off as ϵ^{-1}. Thus $\tau_{\rm local}$ roughly mirrors the IRF spectrum at each z, although its detailed features are smeared out. Displayed in Fig. 2 in terms of the rest-frame gamma-ray energy $E_{\rm rest}$, we see that the opacity may be significant out to $z \sim 10$ for $E_{\rm rest} \sim 10^2$–10^4 GeV.[8] Note the steep drop in $\tau_{\rm local}$ at $E_{\rm rest} < E_{\rm LE} \sim (m_{\rm e}c^2)^2/\epsilon_{\rm LE} \simeq 18$ GeV, corresponding to the sharp cut-off in the IRF spectrum above the Lyman edge. As pointed out by Oh (2001; see also Rhoads 2001), this is crucial in that it allows appreciable contributions to the total $\gamma\gamma$ opacity from higher z even when the IRF intensity is relatively weaker, and which should be uncontaminated from absorption at lower z. However, we also see that due to the declining IRF intensity together with the reduced path-length, the opacity from $z \gtrsim 10$ is likely to be quite small.

This can be seen more explicitly in Fig. 3 where we show the integrated $\gamma\gamma$ optical depths for different source redshifts z,

$$\tau(z, E) = \int_{z_{\rm min}}^{z} {\rm d}z' \frac{{\rm d}l}{{\rm d}z'} \int_{\epsilon_{\rm th}}^{\infty} {\rm d}\epsilon\, n(\epsilon, z') \times \frac{1}{2}\int_{-1}^{1} {\rm d}\mu (1-\mu)\sigma(E(1+z'), \epsilon, \mu), \quad (2)$$

where ${\rm d}l/{\rm d}z' = l_{\rm H}(z')/(1+z')$ and E is the observed gamma-ray energy at $z = 0$. As mentioned above, the lower limit of z integration that can be taken in our model is $z_{\rm min} = 4$; for additional absorption from the range $z = 0$–4, we can only consult other models at the moment (e.g. Kneiske et al. 2004, hereafter K04; Stecker et al. 2006;

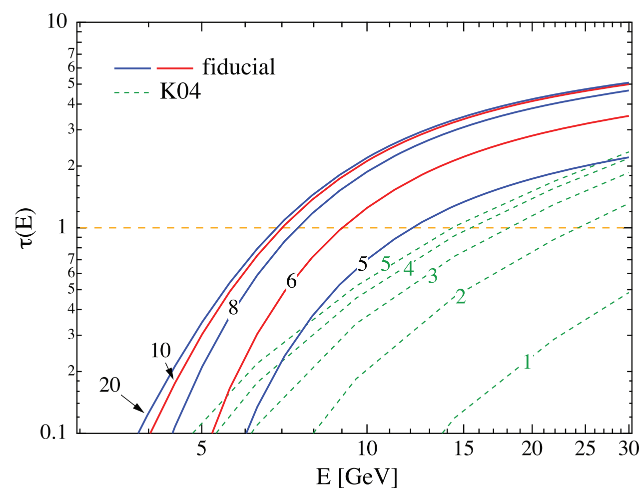

Figure 3. Integrated $\gamma\gamma$ optical depth $\tau(E)$ versus observed gamma-ray energy E for source redshifts z as labelled, for the fiducial model (solid curve) and K04's high stellar UV model (dashed curve).

[8] The contribution from the CMB (e.g. Stecker, Malkan & Scully 2006) also becomes important at $E_{\rm rest} \gtrsim 2$ TeV, but is irrelevant for our results below and not plotted in Fig. 2.

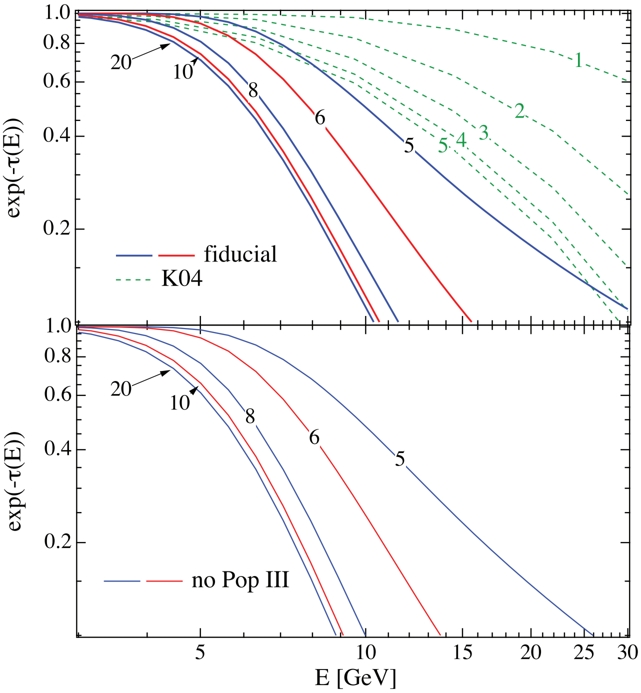

Figure 4. Spectral attenuation factor $\exp[-\tau(E)]$ versus observed gamma-ray energy E for source redshifts z as labelled. Upper panel: fiducial model (solid) and K04's high stellar UV model (dashed curve). Lower panel: model without Pop III stars.

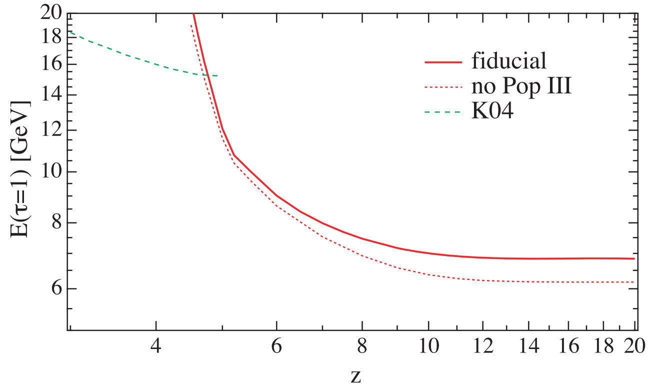

Figure 5. Observed gamma-ray energy E (where $\tau = 1$) versus redshift z for the fiducial model (solid curve), model without Pop III stars (dotted curve) and K04's high stellar UV model (dashed curve).

Razzaque, Dermer & Finke 2009; Gilmore et al. 2009). Overlaid here for comparison is K04's 'high stellar UV model', which gives their best description of QSO proximity effect measurements at $z \sim 2$–4.

As we could infer from Fig. 2, our model predicts appreciable opacity at observed energies $E \lesssim 12$ GeV for sources at $z \gtrsim 5$, with notable differences out to $z \sim 8$. However, the relative effects of further absorption from $z \gtrsim 8$ may be practically indiscernible. Nevertheless, the spectral attenuation feature itself should be observable in high-z gamma-ray sources by current or future gamma-ray facilities, and possibly distinguishable in the range $z \sim 5$–8 for sufficiently bright objects (Section 4). Owing to the drop in $\gamma\gamma$ opacity at $E_{\rm rest} < 18$ GeV (Fig. 2), the differences in absorption in this z range are caused *in situ* by the evolution of UV IRFs just below the Lyman edge energy, including the crucial Lyα and Lyman–Werner bands. We also recall that in this model, Pop III stars continued to be significant contributors to the UV IRF down to $z \sim 7$, where they are comparable with Pop II stars for ionizing photons. Measurements of these effects would thus provide an important check of current models of cosmic reionization in its latter stages, as well as a unique and invaluable probe of evolving UV IRFs in the sub-Lyman edge regime during the era of early star formation (Section 4).

In Figs 4 and 5, respectively, we plot the spectral attenuation factor $\exp[-\tau(E)]$ and the observed energy $E(\tau = 1)$ where the optical depth is unity. Here the fiducial results are compared with those of an alternative model[9] that does not include Pop III stars, in which reionization is driven only by Pop II stars and occurs relatively late at $z \sim 6$ (similar to the late reionization model of Gallerani et al. 2008). The fact that Pop II stars are less efficient sources of ionizing photons compared to Pop III stars mandates a larger SFR, more intense IRF for $\epsilon < \epsilon_{\rm LE}$ and hence larger $\gamma\gamma$ opacity. However, since the SFR at $z \lesssim 6$ is observationally constrained, notable differences appear only at $z \gtrsim 8$, which should be challenging to distinguish in practice. Thus gamma-ray absorption may not be a sensitive probe of the reionization history itself. We have also investigated various other models, e.g. those with more realistic prescriptions for radiative feedback that fit the current high-z observations nearly equally well, and found that they generally do not lead to large differences. Conversely, being constrained by existing data, our predictions may be considered reasonably robust, at least within the framework of our model. Nevertheless, we caution that relaxing some of the present assumptions, e.g. regarding the stellar IMF or the QSO contribution, may yet allow a wider range of possibilities. Note that although some other recent models (e.g. Gilmore et al. 2009; Razzaque et al. 2009) predict somewhat less absorption at $z \sim 5$–6, they are not directly comparable with ours as their focus is on the $z < 6$ Universe (e.g. Gilmore et al. 2009 do not attempt to fit the Lyα effective optical depths at $z \gtrsim 5.5$ as we do).

4 DISCUSSION

The fact that $\gamma\gamma$ absorption is sensitive to photons with energies below the Lyman limit rather than the ionizing radiation (Section 2) actually points to a unique probe of the cosmic reionization epoch that complements measurements of QSO Gunn–Peterson troughs or CMB polarization anisotropies, which probe the neutral and ionized components of the IGM, respectively. On one hand, observationally deducing the global UV emissivity and hence the cosmic SFR from the latter two is problematic due to uncertainties in the inhomogeneity of the IGM (clumping factor) and the escape fraction of ionizing photons from the host galaxies (Madau, Haardt & Rees 1999; Wyithe et al. 2010). On the other hand, the direct census of the high-z UV luminosity density from deep, near-IR surveys are affected by the uncertain integrated contribution of faint galaxies below the telescope detection limit (e.g. Bouwens et al. 2007). Observing $\gamma\gamma$ absorption in high-z sources may allow more robust measurements of the evolution of the (sub-Lyman edge) cosmic UV emissivity, and in combination with other data, possibly the determination of the escape fraction and/or the IGM clumping factor as well. These inferences are general and independent of any particular model for reionization, but will be investigated in more quantitative detail in the near future. Likewise, the implications for

[9] The relevant parameters are $\varepsilon_{*,\rm II} = 0.1$ and $f_{\rm esc,II} = 0.0928$. The model gives $\tau_{\rm e} = 0.06$, marginally consistent with the fifth-year *WMAP* constraints.

constraining Lyα or H_2-dissociating radiation from $\gamma\gamma$ absorption will be discussed in future work.

We now briefly address whether the effects discussed above are observable in real sources with current or future gamma-ray instruments. For blazars, the most prominent and numerous extragalactic sources of GeV gamma-rays, the highest redshift confirmed so far is $z \sim 3$ (Hartman et al. 1999; Abdo et al. 2009b). However, objects similar to the most powerful known blazars such as 3C454.3 with apparent luminosities $L \sim 10^{49}$ erg s^{-1} should be detectable by *Fermi* out to $z \sim$ 8–10 if they exist at such redshifts (e.g. Romani et al. 2004). According to the latest blazar evolution models (Inoue & Totani 2009), it may be plausible for *Fermi* to detect some blazars above $z \sim 6$ during its survey period, for which deep, pointed observations may indeed reveal the IRF absorption features described above.

GRBs are also promising as they are known to occur at $z > 6$ (Kawai et al. 2005; Greiner et al. 2009), at least up to $z \sim 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009), and perhaps out to the very first epochs of star formation in the Universe (e.g. Bromm & Loeb 2006; Salvaterra et al. 2008). Although the spectral properties of GRBs in the GeV domain are still rather uncertain, previous detections by *CGRO*/EGRET (Hurley et al. 1994) and the recent detection of GRB 080916C at $z = 4.35$ by *Fermi* (Abdo et al. 2009a)[10] demonstrate that at least some GRBs have luminous emission extending to >10 GeV, which can also be expected theoretically (e.g. Zhang & Mészáros 2001; Asano, Inoue & Mészáros 2009). A burst similar to GRB 080916C may still be detectable at several GeV by *Fermi*/LAT at $z \lesssim 7$, and even out to higher z if the spectrum was somewhat harder. Even better for this purpose would be proposed ground-based telescopes with much larger effective area and multi-GeV energy threshold, such as the Cherenkov Telescope Array (CTA),[11] Advanced Gamma-ray Imaging System (AGIS)[12] or the 5@5 array (Aharonian et al. 2001). Together with measurements of Lyα damping wings (McQuinn et al. 2009) and possibly radio dispersion (Ioka 2003; Inoue 2004), future, broad-band observations of very high-z GRBs should open new windows on to the cosmic reionization epoch.

Even if IRF-induced spectral features are detected, a generic problem for $\gamma\gamma$ absorption studies is distinguishing them from spectral cut-offs intrinsic to the source. In this regard, spectral variability should offer an important clue. Both blazars and GRBs are highly variable gamma-ray emitters, and in general, changes in physical conditions of the source that cause variations in flux should also be accompanied by variations of the intrinsic cut-off energy, whether it is due to injection of freshly accelerated particles, changes in the magnetic fields, internal radiation fields, bulk flow velocity, etc. In contrast, cut-offs of IRF origin should be stable in time and independent of the variability state of each object. Acquisition of time-resolved spectra should thus allow the deconvolution of the two effects. Another indication should come from statistical studies of a sufficient sample of measurements. IRF-related cut-offs should occur at similar energies for sources at similar z, and also exhibit a systematic evolution towards lower energies for higher z, whereas there is no strong reason to expect such trends for intrinsic cut-offs. Both the above strategies motivate the construction of future, high-sensitivity multi-GeV facilities such as CTA, AGIS and 5@5, which should be powerful tools to probe the evolution of UV IRFs in the cosmic reionization era through $\gamma\gamma$ absorption in very high-z sources.

[10] For $z = 4.35$ and $E = 13.2$ GeV, our fiducial model gives $\tau_{\gamma\gamma} \simeq 0.4$, consistent with the actual detection of a photon at this energy from GRB 080916C.

[11] See web site http://www.cta-observatory.org.

[12] See web site http://www.agis-observatory.org.

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