Metagalactic Ultraviolet Flux from Cosmic Structure Formation

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Abstract. The contribution to the ultraviolet background (UVB) from thermal emission due to gas shock heated during cosmic structure formation is assessed with an updated version of Press-Schechter (Sheth & Tormen 1999) formalism. The calculation is consistent with empirical estimates based on the observed properties of galaxies and the observed cosmic star formation history. The bulk of the radiation turns out to be produced by objects in the mass range $10^{11-13} M_\odot$, i.e. large galaxies and small groups. When compared to more conventional components (QSOs, stellar) it is found that near 1 Ry, thermal emission is comparable to stellar contributions and amounts to about 10%, 20% and 35% of the total flux at redshifts of 3, 4.5 and higher, respectively; more importantly, near the ionization threshold for He II, the thermal contribution is comparable to the QSO intensity already at redshift $\sim 3$ and dominates at redshifts above 4. In addition, thermal photons alone are enough to produce and sustain He II reionization already at $z \approx 6$. Finally, the observed Gunn-Peterson effect at high redshifts ($3 \leq z \leq 6$) constrains the escape fraction of ionizing photons from galaxies to less than a few percent.

Key words. cosmology: large-scale structure of universe — radiation mechanism: thermal — shock waves

1. Introduction

Neutral hydrogen in the intergalactic medium (IGM) produces a forest of resonant Lyα absorption lines in the spectra of high-redshift quasars. The connection of these features to the structure formation process has been now firmly established using N-body/hydrodynamic numerical simulations (Cen et al. 1994; Zhang et al. 1995; Miralda-Escude et al. 1996). There is consensus that the observed IGM temperature results from a balance between photoionization heating and adiabatic cooling due to the Hubble expansion. Such photoheating is provided by the extragalactic ultraviolet background (UVB) whose nature, origin and evolution have, therefore, been subject to considerable investigation.

At low redshifts, the ionization balance is consistent with a pure power-law UVB. Traditionally QSOs have been considered as the main sources of ionizing photon. However, a number of recent results are at odds with this. Kim et al. (2001) find the break in the redshift evolution of absorbers at lower redshifts than predicted by numerical simulations using a standard QSO ion-
izing background (Haardt & Madau 1996), hinting at an incomplete description of the UVB. This led Bianchi et al. (2001, B01 hereafter) to recompute the UVB as a superposition of contributions from QSOs and galaxies.

Similarly, high resolution simulations using a cold dark matter model and a standard QSOs ionizing background, produce Ly-α forest lines with a minimum width significantly below that observed (Theuns et al. 1998; Bryan et al. 1999). This has prompted several suggestions for additional heat sources, including photo-electric dust heating (Nath et al. 1999), radiative transfer effects (Abel & Haehnelt 1999), or Compton heating by X-ray background photons (Madau & Efstathiou 1999).

The situation around redshift $z \sim 3$ is more complicated. There is a general trend for the optical depth at the He$^+$ edge to increase with redshift (e.g. Heap et al. 2000; Songaila 1998) reports an abrupt change of the C iv /Si iv ratio at $z \approx 3$, often interpreted as a hardening of the ionization spectrum due to a sudden He ii reionization. This is corroborated by the detection of patchy He ii Ly-α absorption at similar redshifts. However, more recent VLT/UVES (Kim et al. 2002) and Keck/HIRES (Boksenberg et al. 2004) studies find no such discontinuity around $z \approx 3$, and even suggest that C iv /Si iv is not a good indicator of the He ii ionization state.

Here we report on recent findings about another source of UVB ionizing photons, namely thermal emission from shock-heated gas in collapsed cosmic structures. We show that the ionizing photons emitted by this process make a non negligible fraction of the metagalactic flux, that the resulting spectrum is hard and copious He ii ionizing photons are produced. In fact this process may well dominate the production of such hard photons at $z > 4$.

2. Model

We consider the mean ultraviolet ionizing flux produced by QSO, stellar and thermal components. After estimating the mean volume emissivity of each component as a function of redshift, as described below, we solve for the cosmological radiative transfer equation (Peebles 1993). The effective optical depth, $\tau_{\text{eff}}$, due to the presence of intervening neutral gas, is computed by assuming a distribution of absorbers as a function of H i column density and redshift (Paresce et al. 1980). The dependence on $N_{\text{HI}}$ is determined from counts of Lyα absorption lines in QSOs spectra; a power-law evolution with redshift such that $\tau_{\text{eff}} \sim (1+z)^{\gamma}$, is further assumed (Zuo 1993). We use $\gamma \approx 3.4$ in the redshift range $1.5 < z < 4$ (Kim et al. 2001), and, based on the strong evolution for $\tau_{\text{eff}}$ as implied by recent spectra of high redshift QSOs (Becker et al. 2001; Fan et al. 2002) we adopt $\gamma = 5.5$ for $z > 4$.

The contributions of QSOs and stars to the ionizing UV background adopted here are similar to those in B01. Basically the QSO emissivity assumes a luminosity function that follows the double power-law model of Boyle et al. (1988). For $z \leq 3$, we adopt the parameters given in Boyle et al. (2000). At $z > 3$, we include the exponential decline suggested by Fan et al. (2001). For the QSO spectrum in the ionizing UV range we use a simple power law, $j(\nu) \propto \nu^{-1.8}$ (Zheng et al. 1997).

For the stellar component, we assume a star formation rate that is constant from high redshifts to $z \approx 1$, then rapidly decreases to local values, as indicated by galaxy surveys in the rest-frame non-ionizing UV (Madau et al. 1998; Steidel et al. 1999). Synthetic galactic spectra (Bruzual A. & Charlot 1993; version 2001) are then used to calculate the emissivity of ionizing UV photons as a function of $z$. The absorption of radiation by the galaxy interstellar medium is modeled by a redshift-independent value for $f_{\text{esc}}$, the
fraction of Ly-continuum photons that can escape into the IGM.

Finally, for the emissivity from shocked intergalactic gas we assume such gas to be thermalized in virialized dark matter halos, which we describe with a Press-Schechter prescription [Sheth & Tormen 1999]. The dark matter density in virialized objects is computed according to the spherical collapse model; the ratio of baryons to dark matter is taken as the universal value, $f_b \approx 0.15$. The spectral thermal emissivity of the shocked gas in each halo is thus computed through the code by [Raymond & Smith 1977 version 1992; collisional regime is a good approximation for the plasma conditions]; we then estimate the thermal volume emissivity by adding up the contributions from all collapsed structures. We account for the finite cooling time of a halo, by introducing a term ensuring that the radiated energy does not exceed the thermal energy of the system. Finally, we take into account feedback effects by computing the increase in the cooling time caused by the injection of additional, feedback energy.

More details are presented in [Miniati et al. 2004]. We note that cooling process associated with thermal emission investigated here also leads to galaxy/star formation [White & Rees 1978]. In fact, [Miniati et al. 2004] also show that the estimated flux presented here, based on a Press-Schechter model, is in remarkable agreement with an empirical estimate based on the observed cosmic star formation history and the distribution of stellar mass as a function of halo virial temperature, as reconstructed from SDSS data from [Kauffmann et al. 2003].

3. Results

3.1. Photo-ionization Rates

Fig. 1 shows the evolution as a function of redshift, of the photo-ionization rates in units of $10^{-12}$ s$^{-1}$ defined as

$$\Gamma_{12}(z) = \frac{4\pi}{10^{-12} \text{s}^{-1}} \int_{\nu_s}^{\infty} \sigma_{\text{s}}(\nu) \frac{J(\nu, z)}{h_p \nu} d\nu (1)$$

for the various UV radiation components discussed above, together with measured values inferred from the observed Gunn-Peterson effect in high-z QSO spectra [McDonald & Miralda-Escudé 2001; Fan et al. 2002].

The left panel of Fig. 1 is relative to ionization of H I and contains a number of important features. First, although the emission from QSOs is able to produce the ionizing flux observed at $z \sim 2 - 3$, it falls short at higher redshifts, a well known fact. In our formulation, it results from the assumed rapid decline of the QSO number density for $z > 3$, as derived from the SDSS [Fan et al. 2001].

Second, a comparison of the measured values of $\Gamma_{12}$ and the stellar ionization rates assuming $f_{\text{esc}} = 1\%$ (dash curve) implies, according to our model, that $f_{\text{esc}}$ is smaller than a few %. Estimates of the UV background from the proximity effect are known to be larger than those obtained via theoretical models of the IGM opacity (i.e. the work of Fan et al we are using here), probably because of a bias of the QSO distribution towards the denser environments [Schirber & Bullock 2002] or because of systematic errors due to line blending [Scott et al. 2000].

Finally, the right panel of Fig. 1 shows the He II ionization rates. According to the plot, above 4 Ry stellar emission is thoroughly negligible (independent of $f_{\text{esc}}$) whereas thermal emission is comparable to QSOs at $z \sim 3$ but completely dominates the radiation flux at higher redshifts. This result is very important in terms of the IGM evolution and has not previously been noticed. It depends only weakly on feedback, but it does assume an escape fraction of the thermal photons from collapsed halos of order 1. As discussed in [Miniati et al. 2004] these conditions should be ensured for collisionally ionized gas within halos of virial temperature above $10^6$ K, that is for the halos that generate most of the thermal emission.
3.2. Softness parameter

Both for the individual spectral components and for the total spectrum, we have computed the redshift evolution of the spectral softness parameter, \( S_L \equiv \frac{J_{\text{HI}}}{J_{\text{HeII}}} \), where \( J_{\text{HI}} \) and \( J_{\text{HeII}} \) are the UVB intensities at the H I and He II Lyman limits respectively. These are shown in Fig. 2. Thermal emission is characterized by moderate values of \( S_L \), raising with redshift from \( \sim 10 \) to \( 100 \) and \( 80 \) to \( 300 \), respectively; the stellar component shows less evolution but with maximal \( S_L \) values above \( 1000 \) at \( z \gtrsim 3 \). The composite spectra (feedback case) \( S_L \) evolution resembles very closely that of QSOs, even at high redshift: this is somewhat fortuitous as at \( z \gtrsim 4 \) the UVB is dominated by the sum of stellar and thermal contribution. When compared with the available data, e.g. the recent study of Heap et al. (2000), our predicted values for \( S_L \) at redshift around \( z = 3.2 \) are close to the measurements of those authors. However, the reported change in the parameter \( S \) would not necessarily imply a “jump” of the same quantity at \( z \approx 3 \), as it would be due to the evolution of our composite spectrum; in particular to the decrease in the ratio of thermal to the QSO flux.

3.3. He II Reionization

The previous results hint at the intriguing possibility that He II reionization could have been powered by UV light from cosmic structure formation. For this to be the case, the production rate of ionizing photons has to satisfy the condition

\[
\Gamma \times \min(\tau_{\text{rec}}, \tau_{\text{Hubble}}) \geq 1.
\]

Here \( \tau_{\text{rec}} \approx 0.9/\bar{n}_{\text{gas}}\alpha(T)C \) is the recombination time, \( \alpha \) is the radiative recombination coefficient, and the clumping factor...
Fig. 2. Redshift evolution of the softness ratio $S_L$ for different emission cases: thermal, no feedback (dot); thermal, with feedback (thin solid); stellar (long dash); QSOs (short dash); total, no feedback (higher thick solid); total, with feedback (lower thick solid).

$C \equiv \langle n_p^2 / \langle n_p \rangle^2 \rangle > 1$ is meant to allow for the effects of density inhomogeneities inside the ionized region. Using a helium to hydrogen number ratio $y = 0.08$ and assuming a temperature of the reionized gas $T \approx 4 \times 10^4$ K, we find

$$\tau_{\text{rec}} = 5.3 \times 10^{15} C^{-1} \left( \frac{1 + z}{10} \right)^{-3} \text{ s}, \quad (3)$$

which is shorter than a Hubble time for $z \lesssim 4.5$. Thus, from Fig. 2 we find that at $z \approx 6$ thermal emission dominates the photoionization rates and alone provides $5.5 \times 10^{-17} \quad (10^{-16})$ He II photoionizations/s in the no-feedback (feedback) case. According to eq. (3), the He II recombination rate at the same redshift is $6.4 \times 10^{-17} C$ s$^{-1}$. Hence, it appears that structure formation can produce He II reionization around $z = 6$, without the contribution from any other process and essentially independently of the feedback prescription adopted.

Whether or not this possibility is fully compatible with all observational results is not clear at the moment and will be the subject of future investigations.

4. Summary

We have shown that UVB ionizing photons can be copiously produced by thermal emission from shock-heated gas in collapsing cosmic structures.

Thermal radiation is characterized by a hard spectrum extending up to photon energies of order $h \nu \sim k_B T$. This is well above the H I and He II ionization thresholds for virial temperatures above $10^5$ K. The bulk of the emission is produced by halos with temperatures between $10^6$ K and a few $\times 10^7$ K, corresponding to masses $10^{11-13} \ M_\odot$. We assume that most of the thermal radiation is able to freely escape into intergalactic space, which is justified for a gas that is collisionally ionized and at the temperature of these halos [Miniati et al. 2004].

We use simplified radiative transfer to compute the transmitted flux due to QSO, stellar and thermal emissions. Importantly, the resulting associated photoionization rates, when compared to measurements of the Lyman series Gunn-Peterson effect in the spectra of high redshift QSOs [Fan et al. 2002, Becker et al. 2001], imply an escape fraction of UV ionizing photons from galaxies, $f_{\text{esc}}$, below a few %. This result is in agreement with very recent and independent determinations of $f_{\text{esc}}$ carried out by Fernández-Soto et al. 2003, who set a 3$\sigma$ (statistical) upper limit $f_{\text{esc}} \sim 4\%$ for a sample of spectroscopically identified galaxies of redshift $1.9 < z < 3.5$ in the Hubble Deep Field.

With $f_{\text{esc}} \approx 1\%$, it turns out that near the H I ionization threshold, thermal emission is comparable to the stellar component and amounts to about 5-10%, 15-30% and 20-50% of the total at redshifts of 3, 4.5 and higher respectively. Near the ionization threshold for He II, the thermal contribution is much stronger. It is
comparable to the QSO input already at $z \sim 3$, and it dominates for $z > 4$. Thus, this contribution, with a typical softness parameter $S_L = 10 - 100$, is expected to play a major role in He II reionization. In principle structure formation alone provides enough photons to produce and sustain He II reionization at $z \sim 6$.

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