Population III and the near-infrared background excess

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ABSTRACT
We make a critical assessment of models that attribute the recently detected near-infrared background “excess” (NIRBE) to the redshifted light from Population III objects. To supply the required 25 keV/baryon at redshift 9, Pop III massive stars must form with an efficiency exceeding 30% in all “minihalos” with virial temperatures above a few hundred kelvins: to avoid excessive metal pollution, most of the baryons once in Pop III stars must end up in intermediate-mass black holes (IMBHs). Gas accretion onto such IMBHs must either be inhibited or lead to early miniquasars with steep UV/X-ray spectra, in order not to overproduce the present-day unresolved soft X-ray background. In the latter case (NIRBE dominated by “X-ray quiet miniquasars”), the total mass density of IMBHs at $z \sim 9$ must be $\gtrsim 50$ times higher than the mass density of supermassive black holes observed today in the nuclei of galaxies. A stellar-dominated NIRBE is less economical energetically: $\gtrsim 5\%$ of all baryons in the universe must be processed into Population III stars. We survey various aspects of the Population III hypothesis for the NIRBE, and show that the ionizing photon budget required to account for the NIRBE is much larger than that required to explain the high electron scattering optical depth measured by the WMAP satellite.

Key words: cosmology: diffuse radiation – galaxies: formation – intergalactic medium

1 INTRODUCTION

Independent measurements based on COBE/DIRBE and IRTS/NIRS data provide evidence for an excess isotropic emission of extragalactic origin in the wavelength band 1.2 to 4 $\mu$m (Dwek & Arendt 1998; Gorjian et al. 2000; Wright & Reese 2000; Wright 2001; Cambresy et al. 2001; Matsumoto et al. 2004). The inferred flux appears too bright to be accounted for by the integrated light from faint galaxies, and shows a spectral discontinuity from the resolved optical background at $\sim 1\mu$m (Wright & Reese 2000; Cambresy et al. 2001; Matsumoto et al. 2004). A similar conclusion is obtained from the analysis of near-infrared background (NIRB) fluctuations on angular scales ranging from half a degree (DIRBE) to sub-arcmin (2MASS), namely that normal galaxies cannot account for the observed angular power spectrum (Kashlinsky & Odenwald 2000; Kashlinsky et al. 2002). It has been suggested that the observed NIRB spectral excess and its brightness fluctuations may be the signature of the redshifted UV light from Population III (zero-metallicity) star formation at $z \sim 10$ (Santos et al. 2002; Salvaterra & Ferrara 2003; Magliocchetti et al. 2003; Kashlinsky et al. 2004; Cooray et al. 2004). Alternative possibilities involve Eddington-limited emission from an early population of accreting miniquasars (Cooray & Yoshida 2004), or, perhaps less exotically, flux missed by standard photometry in the outer, lower surface brightness parts of galaxies (Bernstein et al. 2002).

In this paper we assess the merits of Pop III objects as the root cause of the NIRB excess (NIRBE). We show that the energetic requirements are uncomfortably high, and discuss the astrophysical implications of an early epoch of massive Pop III star formation.

2 A POP III MODEL FOR THE NIRBE

2.1 Simple energetics

In the near IR, out of $\sim 35$ nW m$^{-2}$ sr$^{-1}$ of integrated flux from 1 to 4 $\mu$m, about $I_J = 13.5 \pm 4.2$ nW m$^{-2}$ sr$^{-1}$ are contributed by the Cambresy et al. (2001) DIRBE measurement in the J-band at 1.25 $\mu$m. This number is quite uncertain, as it depends on zodiacal light subtraction (Kelsall et al. 1998;

1 Throughout this paper we will quote surface brightness values integrated over the bandwidth, rather than the more common brightness per logarithmic bandwidth.
This corresponds to an observed excess energy density of 

\[ u_J = 10^{-15} \text{ ergs cm}^{-3}. \]  

(1)

Assume, for simplicity, that all this energy was emitted as Lyα radiation\(^2\) by very massive Pop III stars with a narrow redshift distribution centered around \( z = 9 \). This is the redshift at which the data requires a rapid transition from Pop III to normal Population II stars (Salvaterra & Ferrara 2003): a spectral jump in the NIRB then occurs at the redshifted wavelength \((1 + z)1216 \text{ Å}\). The energetics would be even more severe if the sources responsible for the NIRBE were broadly distributed in the range \( z = 9 - 20 \) (say), or if the initial stellar mass function (IMF) was not dominated by very massive stars. The comoving Lyα energy density radiated at \( z = 9 \) is then

\[ U_\alpha = (1 + z)u_J = 10u_J, \]  

(2)

corresponding to 25 keV per cosmic baryon. Zero-metallicity stars in the range \( 80 < n_e < 500 \text{M}_\odot \text{ cm}^{-3} \) emit \( N_\gamma = 70,000 - 90,000 \) photons above 1 ryd per stellar baryon over a lifetime of \( t_{\text{ms}} = 2 - 3 \times 10^6 \text{ yr} \) (Schaerer 2002). In the following, we will adopt a mid-range value of \( N_\gamma = 80,000 \) ionizing photons per stellar baryon. In the Case B approximation, a fraction 0.7 of these is converted into Lyα. The total mass density of baryons that needs to be processed by \( z = 9 \) into Pop III stars to produce the NIRBE is then simply estimated as

\[ \rho_* = \frac{m_p U_\alpha}{0.7N_\gamma E_\alpha} \approx 2.7 \times 10^8 \text{M}_\odot \text{ Mpc}^{-3}, \]  

(3)

where \( m_p \) is the proton mass and \( E_\alpha = 10.2 \text{ eV} \) is the energy corresponding to the Lyα transition. Note that this mass density depends only weakly on the IMF of massive \((> 80 \text{M}_\odot)\) Pop III stars. Dividing \( \rho_* \) by the critical density one gets\(^3\)

\[ \Omega_* = 0.002 = 0.045 \Omega_b, \]  

(4)

i.e. at least 5% of all baryons in the universe must be converted into Pop III stars (see also Santos et al. 2002). This is energetically and astrophysically daunting. It means Pop III star formation at early times must be comparable with the mass density in stars observed today, \((2.3 \pm 0.3) \times 10^{-3}\) (for a Kennicutt IMF; Cole et al. 2001).

\(^2\) This is energetically advantageous, since most of the power of massive Pop III stars is emitted above 1 ryd, and in Case B recombination approximately 50% of this energy is re-emitted as Lyα.

\(^3\) Throughout this paper we adopt a flat ΛCDM background cosmology with parameters \((\Omega_\Lambda, \Omega_M, \Omega_b, n, \sigma_8, h) = (0.3, 0.7, 0.045, 1, 0.9, 0.7).\)

### 2.2 Star formation efficiency

The minimum mass scale for the gravitational aggregation of cold dark matter particles is negligibly small. In the Press-Schechter formalism, the mass fraction in dark matter halos above mass \( M \) at redshift \( z \) can be written as

\[ F(> M | z) = \text{erfc} \sqrt{\frac{\delta_c(z)}{2\sigma_M(z)}}, \]  

(5)

where \( \sigma_M(z) \) is the linear theory rms density fluctuation smoothed with a ‘top-hat’ filter of mass \( M \) at redshift \( z \), and \( \delta_c(z) \) is the critical threshold on the linear overdensity for spherical collapse at that redshift (Press & Schechter 1974). Baryons, however, respond to pressure gradients and need to contract and cool in order to fragment into stars. It is useful here to identify two mass scales: (1) a molecular cooling mass \( M_{\text{HI}} \) above which gas can cool via roto-vibrational levels of \( \text{H}_2 \) and contract, \( M_{\text{HI}} \approx 10^4[(1 + z)/10]^{-3/2}\text{M}_\odot \) (virial temperature in excess of 200 K; Machacek et al. 2003); and (2) an atomic cooling mass \( M_{\text{H}} \) above which gas can cool efficiently and fragment via excitation of hydrogen Lyα, \( M_{\text{H}} \approx 10^4[(1 + z)/10]^{-1/2}\text{M}_\odot \) (virial temperature above 10^5 K). Figure 1 shows the fraction of the total mass in the universe that is in collapsed dark matter halos with masses greater than \( M_{\text{HI}} \) and \( M_{\text{H}} \) at the epochs of interest here. Let us define a star formation efficiency \( f_s \) as the fraction of collapsed baryons that cool and form Pop III stars,

\[ f_s = \frac{\Omega_*}{\Omega_b g F(> M_{\text{H}}[9])}. \]  

(6)

Here \( g \leq 1 \) is a correction factor accounting for the fact that the gas fraction (gas mass/virial mass) in “minihalos” condensing due to \( \text{H}_2 \) cooling may be lower than the universal cosmic value \( \Omega_b/\Omega_M \). In the absence of a UV photodissociating flux and of ionizing X-ray radiation, three-dimensional simulations of early structure formation yield gas fractions \( g = 0.6 - 0.7 \) (Machacek et al. 2003). The same simulations also show that the amount of cold, dense gas available for star formation exceeds 20% only for halos above \( 10^8 \text{M}_\odot \).

From equation 4 and Figure 1, it is obvious that if the whole J-band excess is caused by Pop III stars, then one needs to invoke high star formation efficiencies, \( f_s \approx 0.3 \), in all halos above the molecular cooling mass. Pop III star formation that was limited only to halos above the atomic cooling mass could make a significant contribution to the NIRBE only for \( f_s \sim 1 \), which is implausible. Our estimate of \( f_s \) agrees with that of Santos et al. (2002) but is higher than the value of 10% derived by Salvaterra & Ferrara (2003) for a very top-heavy IMF. While comparatively high efficiencies appear to be needed for globular clusters to survive gas expulsion and remain gravitationally bound (Goodwin 1997), it is not clear how such large values may be reached in metal-free gas restricted to relatively inefficient \( \text{H}_2 \) cooling. It is also surprising that negative radiative, mechanical, and chemical “feedback” effects would not be choking off the formation of such a large number of Pop III stars, given the fragile nature of these molecules (Haiman et al. 2000; Ricotti et al. 2002; Scannapieco et al. 2002).
If this were the case, reprocessing of ionizing radiation in the volume-averaged hydrogen results of 1-d radiation hydrodynamical calculations of the minihalos into the IGM is in contrast with the recent reprocessing of ionizing-photon escape fraction, photons must be absorbed in the densest molecular clouds on timescales much shorter than the stars’ main sequence lifetimes: the photoevaporative flows leave dark halos with a clumping factor from the background baryon density is 

\[
\Omega_h \approx 3,500 \text{ Lyman continuum photons per baryon in the universe. Here } n_b = 2.5 \times 10^{-7} \text{ cm}^{-3} \text{ is the mean cosmological baryon density today. The assumption that most of this radiation gets absorbed and converted into Lyα within the host halo then implies that every baryon in the halo that was not converted into stars must recombine on average } N_{\text{rec}} = N_x f_x/(1 - f_x) \approx 35,000 \text{ times over the lifetime of a Pop III star cluster. The volume-averaged hydrogen recombination timescale for halo ionized gas at temperature } 10^4 \text{ K with mean overdensity } \delta = 200 \delta_{200} \text{ relative to the background baryon density is}
\]

\[
t_{\text{rec}} \approx 3 \times 10^6 \text{ yr} \left(\frac{1+z}{10}\right)^{-3} \delta_{200}^{-1} C_h^{-1},
\]

where \( C_h \equiv \langle n_e^2 \rangle / \langle n_p \rangle^2 \) takes into account the degree of clumpiness of photoionized halo gas (here \( \langle n_p \rangle \) is the mean number density of ionized hydrogen in the halo). Then from \( N_{\text{rec}} = (t_{\text{rec}}/t_{\text{acc}}) \approx (1 + z)/10^3 \delta_{200} C_h, \) one derives a clumping factor \( C_h \sim N_{\text{rec}}, \) i.e. the Lyman continuum photons must be absorbed in the densest molecular clouds around the sites of star formation (see also Santos et al. 2002). A small ionizing-photon escape fraction, \( f_{\text{esc}}, \) from minihalos into the IGM is in contrast with the recent results of 1-d radiation hydrodynamical calculations of the evolution of H ii regions around Pop III stars (Whalen et al. 2004). These show that the ionization fronts exit the halo on timescales much shorter than the stars’ main sequence lifetimes: the photoevaporative flows leave dark halos with a low gas content and produce escape fractions \( f_{\text{esc}} \gtrsim 0.95. \)

If this were the case, reprocessing of ionizing radiation into Lyα would still occur in the low-density IGM (Santos et al. 2002; Haardt & Madau 1996). Note that Case B recombination predicts approximately 10% of the Lyα luminosity to be reprocessed into redshifted Hα line emission at 6.5 μm.

### 2.4 Metal enrichment

Non-rotating Pop III stars in the mass window \( 140 \lesssim m_* \lesssim 260 \text{ M}_\odot \) will disappear as pair-instability supernovae (PISNe; Bond et al. 1984), leaving no compact remnants and polluting the universe with heavy elements. Stars with \( 40 < m_* < 140 \text{ M}_\odot \) and \( m_* > 260 \text{ M}_\odot \) are predicted instead to collapse to IMBHs; the mass of metals (mostly oxygen) ejected by PISNe is approximately equal to \( m_* / 2 \) (Heger & Woosley 2002). Therefore if stars giving birth to PISNe were responsible for the NIRBE, they would overenrich the universe to a mean metallicity, \( \langle Z \rangle = \Omega_Z / \Omega_b = 0.5 \Omega_L / \Omega_b \approx 0.025, \) in excess of solar already by redshift 9 or so. Even allowing for only partial mixing of the ejecta, it is difficult to see how all these metals could remain undetected: the unusual nucleosynthetic signature of PISNe would appear in the metal abundances of second-generation stars, while absorption studies of the Lyα forest at \( z \sim 3 \) would reveal cosmic metallicities far in excess (by \( \gtrsim 2 \) orders of magnitude) of the observed values (Schaye et al. 2003). A similar argument has recently been used to strongly constrain the possible contribution of PISNe to the reionisation of the universe (Daigne et al. 2004).

### 2.5 Miniquasars

As already pointed out by Santos et al. (2002), if distant Pop III stars make a significant contribution to the NIRBE, then perhaps the most conservative hypothesis is to assume that most of the baryons once in Pop III stars ended up in IMBHs. If these seed holes were able to increase their initial mass via gas accretion and shine as miniquasars, and a significant fraction of the radiated energy was emitted above and close to the hydrogen Lyman edge, then they – and not their metal-free stellar progenitors – would dominate the UV background flux (Madau et al. 2004). Let us denote with \( f_{\text{UV}} \) the fraction of the bolometric power radiated by miniquasars that is emitted as hydrogen-ionizing radiation with mean energy \( \langle E \rangle. \)

Then the number of Lyman continuum photons produced per accreted baryon is \( N_\gamma = \eta m_p c^2 f_{\text{UV}}/\langle E \rangle, \) where \( \eta \) is the radiative efficiency. Accretion via a thin disk predicts most IMBHs at early times to be rapidly rotating with radiative efficiencies exceeding 10-15% (Volonteri et al. 2005). If the shape of the emitted spectrum from miniquasars followed the mean spectral energy distribution of

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\( \text{Figure 1. Solid lines: Total mass fraction in all collapsed dark matter halos above the molecular cooling and the atomic cooling masses, } M_{\text{H}} \text{, as a function of redshift. Dashed line: NIRB (nW m}^{-2} \text{s}^{-1}) \text{ due to redshifted Lyα emission from Population III stars at redshift } z \text{ (for } f_\alpha = 0.3, \ y = 0.65, \ N_x = 80,000, \text{ and } F(> M_{\text{H}}|z), \text{ see text for details).} \)

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\( \text{It has been suggested that the relative abundances in extremely metal-poor Galactic halo stars may show evidence for PISN enrichment below metallicities } [\text{Fe/H}] = -3 \text{ (Qian & Wasserburg 2002). The inferred fraction of baryons in the universe processed into PISN progenitors is, however, only } \lesssim 10^{-4} \text{ (Oh et al. 2001), approximately 500 times lower than the value needed to explain the NIRBE (see eq. 3).} \)
the quasar sample in Elvis et al. (1994),\(^5\) then \(f_{\text{UV}} = 0.3\) and \(\langle E \rangle = 3\) yr. One then estimates \(N_s \approx 10^6 n_{10.15}\), more than 10 times larger than the typical value for Pop III stars. Under the assumption that all these photons were converted into Lyo radiation at \(|z| = 9\), the total mass density that must be accreted onto IMBHs to explain the NIRBE is

\[
\rho_{\text{acc}} = \frac{m_p U_\alpha}{0.7 N_s F_\alpha} \approx 2 \times 10^7 \eta_{0.15} M_\odot \text{Mpc}^{-3}. \quad (8)
\]

In the case of accretion at the Eddington rate, the hole mass exponentiates over a Salpeter timescale, \(t_S = (4.5 \times 10^7 \text{yr}) \eta/(1 - \eta)\). By redshift 9, the mass density of Pop III holes could increase by as many as 6 e-foldings (taking \(\eta = 0.15\)), or about a factor 400. A miniquasar model for the NIRBE may then require an initial IMBH progenitor mass density of only \(\rho_s \approx 400 \times 50,000 M_\odot \text{Mpc}^{-3}\), \(\gtrsim 5000\) times lower than that given in equation (4). Note that our results differ from those presented by Cooray & Yoshida (2004). These authors fix the amount of Pop III star formation occurring at early times and then use the observed NIRBE to constrain the fraction of stellar mass converted into Eddington-limited seed IMBHs to be \(\lesssim 10\%\). To avoid overenrichment we take the seed hole fraction to be unity instead, and allow the mass density of Pop III holes to exponentiate via gas accretion, thus decreasing the amount of baryons that needs to be converted initially into Pop III stars.

The scenario described above is, in principle, an attractive solution to the NIRBE problem, as it is more economical energetically and does not demand very high star formation efficiencies down to minihalo masses. Still, plenty of cold gas must be made available at early times for IMBHs to accrete, driving the total mass density of IMBHs at \(z \sim 9\) to more than 50 times higher than the inferred mass density of supermassive black holes today (Yu & Tremaine 2002). The main issue, however, is that miniquasars powered by IMBHs are expected to be hard X-ray emitters. Hard X-ray photons produced in the \((0.5 - 2.0) (1 + |z|)\) keV band by our population of distant miniquasars would redshift without absorption and saturate the unresolved soft X-ray background (SXB). For a simple power-law \(F_\alpha \propto E^{-\alpha}\) with \(\alpha > 0\), the relative contribution to the NIRBE and the SXB is

\[
\frac{u_j}{u_{\text{SXB}}} \sim 0.5 \left( \alpha - 1 \right) / \left[ \left( \frac{5 \text{ keV}}{13.6 \text{ eV}} \right)^{1-\alpha} - \left( \frac{20 \text{ keV}}{13.6 \text{ eV}} \right)^{1-\alpha} \right]. \quad (9)
\]

The energy density associated with the unaccounted component of the present-day \(0.5 - 2\) keV SXB does not exceed \(u_{\text{SXB}} \approx 2 \times 10^{-18} \text{ ergs cm}^{-3}\) (Dijkstra et al. 2004), 500 times smaller than the NIRBE in the J-band. Equation (4) is consistent with the observations only for powerslaws steeper than \(\alpha \gtrsim 2.3\) (see also Salvaterra et al. 2005). While the photon energy distribution of putative high-z miniquasars is very uncertain, the spectra of ‘ultraluminous’ X-ray sources in nearby galaxies appear to require both a soft component (well fit by a cool multicolor disk blackbody with \(kT_{\text{max}} \approx 0.15\) keV, which may indicate IMBHs; Miller & Colbert 2004) and a non-thermal power-law component of comparable luminosity and slope \(\alpha \sim 1\). Even if miniquasars powered by accreting IMBHs were so “X-ray quiet” as to make a dominant contribution to the NIRBE while satisfying the SXB constraint, only a small fraction \(f_w\) of the energy released could be used to drive an outflow and be ultimately deposited as thermal energy into the IGM. Assuming rapid, homogeneous “preheating” at redshift 9 (Benson & Madau 2003), the conoving thermal energy density introduced in the IGM would be \(U_{\text{IGM}} = f_w U_\alpha\). At these early epochs, inverse Compton scattering would transfer all the energy released to the cosmic microwave background (CMB), producing a \(y\)-distortion to its spectrum, \(y = U_{\text{IGM}}/(4U_{\text{CMB}}) = 6 \times 10^{-4} f_w\). The COBE satellite measured \(y < 1.5 \times 10^{-5}\) (Fixsen et al. 1996), implying \(f_w < 0.025\).

### 2.6 IMBHs in galaxy halos

We are therefore led to consider the possibility of a large population of IMBHs “wandering” in galaxy halos and unable to accrete significant amounts of material over a Hubble time. As the NIRBE would now be dominated by their stellar progenitors, the total mass density of remnant IMBHs, \(\approx 0.05\), would exceed the mass density of the supermassive variety found today in the nuclei of most nearby galaxies, \(\Omega_{\text{IMBH}} = (2.1 \pm 0.3) \times 10^{-5}\) (Yu & Tremaine 2002), by 3 orders of magnitude. The abundance of IMBHs – assuming they behave similarly to collisionless dark matter particles – is a function of the environment, being higher (positively biased) within a massive galaxy bulge that collapsed at early times, and lower (antibiased) within a dwarf galaxy collapsing at the present–epoch. This effect can be quite easily quantified within the extended Press–Schechter formalism, and is expected to be weak for progenitor halos of mass \(M_{\text{h12}}\) collapsing at \(z = 9\) and merging at later times into a “Milky Way” halo (Madau & Rees 2001). As the host of IMBHs aggregate hierarchically into more massive systems, dynamical friction against the visible and dark matter background will favor accretion of larger mass subunits and infalling satellites with low initial angular momenta: their cores will merge and undergo violent relaxation. Most IMBHs will not sink to the center and will be left wandering in galaxy halos (Madau & Rees 2001; Volonteri et al. 2003; Islam et al. 2003), where they can most easily escape detection.

### 3 DISCUSSION

The Pop III hypothesis for the NIRBE has appeared often in studies of the extragalactic background light, the first stars and their importance for reionization, the duration and extent of metal-free star formation (Kashlinsky 2004). It is only fair to point out that the very existence of this excess is open to question, because of the difficulty of accurately subtracting the contribution of bright foregrounds. After surveying many aspects of the Pop III model for the NIRBE, it is hard to reach any firm conclusion regarding its tenability, the unknown initial mass function of Pop III stars being one.
of the many adjustable theoretical parameters. Most previous studies have emphasized the possibility that both the NIRB fluctuations and mean levels may provide direct information on the epoch of the first stars. While a pregalactic contribution to the NIRB at a level of a few nW m$^{-2}$ sr$^{-1}$ cannot be ruled out, we offer here an assessment of the main weaknesses of the Pop III hypothesis. For a given amount of material converted into stars or accreted onto black holes, a factor $1 + z$ is lost to cosmic expansion in the total background light observed at Earth when converting from observed to radiated (comoving) luminosity density. An early epoch of production of the NIRBE thus makes the energetic requirements even more extreme. A very top-heavy stellar IMF helps with the energy budget but overenriches the universe with heavy elements unless most baryons once in Pop III stars end up in IMBHs. A fine tuning of the IMF is then required to avoid the PISNe mass window. Radiatively efficient accretion onto such a large population of IMBHs will, however, easily overproduce the SXB.

The recent detection by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite of a large optical depth to Thomson scattering, $\tau_\gamma = 0.17 \pm 0.04$, suggests that ionizing sources were already very abundant at redshifts $z > 10$ (Spergel et al. 2003). If the universe is suddenly reionized at redshift $z_r$, the Thomson scattering optical depth to $z_r$ is $\tau_\gamma = \int_{t(z)}^{t(z_r)} \sigma_T n_e(t) c dt$, where $\sigma_T$ is the Thomson cross section and $n_e(t)$ is the proper free-electron density. The mean number of recombinations per hydrogen atom in the IGM since redshift $z_r$ is $N_{rec} = \int_{t(z)}^{t(z_r)} dt / \tau_{rec}$. As long as the temperature of the IGM remains constant, $T = 10^4$ K, with redshift, $N_{rec}$ can be written as a function of $\tau_\gamma$ alone (Dijkstra et al. 2004) as

$$N_{rec} = \frac{\alpha_B(T) C_{IGM}}{\sigma_T n_e} \tau_\gamma \approx C_{IGM} (\tau_\gamma/0.08), \quad (10)$$

where $\alpha_B$ is the recombination coefficient. Here $C_{IGM}$ is the clumping factor of the diffuse IGM at high redshift and is expected to be of order unity (we purposely exclude halo gas in our definition of $C_{IGM}$, as the consumption of ionizing radiation by halo gas is accounted for by the escape fraction $f_{esc}$). To keep intergalactic gas ionized, one then needs the production of $N_{rec} = (1 + N_{rec}) / f_{esc}$ Lyman continuum photons per atom in the IGM. A J-band excess at a level of a few nW m$^{-2}$ sr$^{-1}$, interpreted as redshifted Ly$\alpha$ from redshift 10, implies the emission of approximately 4,500 H-ionizing photons per atom in the universe. Even for ionizing-photon escape fractions of order a percent or so, the ionizing photon budget required to account for the NIRBE is clearly much larger than that required to explain the WMAP results.

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