COSMIC INFRARED BACKGROUND FROM POPULATION III STARS AND ITS EFFECT ON SPECTRA OF HIGH-\textit{z} GAMMA-RAY BURSTS

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ABSTRACT

We discuss the contribution of Population III stars to the near-IR (NIR) cosmic infrared background (CIB) and its effect on spectra of high-\textit{z}, high-energy gamma-ray bursts (GRBs) and other sources. It is shown that if Population III is composed of massive stars, the claimed NIR CIB excess will be reproduced if only \(\sim 4\%\) of all baryons went through these stars. Regardless of the precise amount of the NIR CIB due to them, they likely left enough photons to provide a large optical depth for high-energy photons from distant GRBs. Observations of such GRBs are expected following the planned launch of NASA’s GLAST mission. Detecting such damping in the spectra of high-\textit{z} GRBs will then provide important information on the emissions from the Population III epoch, and the location of this cutoff may serve as an indicator of the GRBs’ redshifts. We also point out the difficulty of unambiguously detecting the CIB part originating from Population III in spectra of low-\textit{z} blazars.

Subject headings: cosmology: theory — cosmology: observations — diffuse radiation — gamma rays: bursts — gamma rays: theory

1. INTRODUCTION

Zero-metallicity, Population III (hereafter P3) stars are thought to have preceded the normal metal-enriched stellar populations, but because they would be located at high \(z\), they are inaccessible to direct observations by current telescopes. If massive, they are expected to have left a significant level of diffuse radiation shifted today into the infrared, and it was suggested that the cosmic infrared background (CIB) contains a significant contribution from P3 in the near-IR (NIR), in both its mean level and anisotropies (see review by Kashlinsky 2005 and references therein). This has recently received strong support from measurements of CIB anisotropies in deep Spitzer Infrared Array Camera (IRAC) images (Kashlinsky et al. 2005). If P3 stars are responsible for even a fraction of the claimed NIR CIB, they would provide a high comoving density of photons all the way to the P3 era. In this Letter, we analyze the effects of such photons on the spectra of high-\textit{z}, high-energy gamma-ray bursts (GRBs) and blazars, which will be observed with the upcoming Gamma-Ray Large Area Space Telescope (GLAST) LAT instrument to 300 GeV. We show that the entire CIB excess (NIRBE) can be explained if only \(\sim 4\%\) of the baryons have gone through P3 stars. This would result in \(\sim 0.1(1+z)^3\) photons \textit{cm}^{-3} whose present-day energy is between 1 and 4 \textit{m}\textit{m}. Such photons would provide a large optical depth due to photon-photon absorption for GRBs (and other sources) at energies that will be probed with GLAST. Detecting this spectral damping in forthcoming GRB observations will provide an important test of the P3-era parameters.

2. CIB FROM POPULATION III

At wavelengths \(\geq 10 \textit{m}\textit{m}\), the total flux produced by the observed galaxies matches the levels of the CIB within its uncertainties, but in the NIR the claimed levels of the CIB are substantially higher than the net fluxes produced by galaxies out to flux limits where this contribution saturates (see review by Kashlinsky 2005 for details). Figure 1 shows the CIB excess levels (filled circles) over the net flux from galaxies observed in deep surveys (open symbols); the legend discusses the details. The excess is significant at \(1 \textit{m}\textit{m} \leq \lambda \leq 4 \textit{m}\textit{m}\), the range we term NIR, and its bolometric flux is

\[
F_{\text{NIRBE}} = 29 \pm 13 \text{ nW m}^{-2} \text{ sr}^{-1},
\]

\[
F_{\text{CIB excess}}(\lambda \geq 10 \text{ \textit{m}\textit{m}}) \leq 10 \text{ nW m}^{-2} \text{ sr}^{-1}
\]  \(\text{Kashlinsky 2005}\). At \(\lambda \geq 10 \text{ \textit{m}\textit{m}}\), we evaluated the upper limits that are shown in Figure 1 and described in the legend. The wavelengths \(\geq 10 \text{ \textit{m}\textit{m}}\) contribute little, so we adopt the value of \(F_{\text{NIRBE}}\) in what follows.

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Because for massive stars \(L \propto M\), the total flux produced by them is largely model independent (Rees 1978; Kashlinsky et al. 2004). Significant energy release by P3 stars is suggested from the recent measurement of CIB anisotropies in deep-exposure Spitzer data (Kashlinsky et al. 2005). Because P3 stars, if massive, would radiate at the Eddington limit, where \(L \propto M\), the total flux produced by them is largely model independent. We reproduce briefly the argument from Kashlinsky et al. (2004): Each star would produce flux \(L/4\pi d^2\), where \(d\) is the luminosity distance. Because for massive stars \(L \propto M\), the total comoving luminosity density from P3 stars is \(\sum n(L) dL \propto \Omega_{\text{baryon}} f_3(3H_H^2/8\pi G)\), where \(n(L)\) is their luminosity function and \(f_3\) is the mass fraction of baryons locked in P3 at any given time. In a flat universe, the volume per unit solid angle subtended by cosmic time \(dt\) is \(dV = c(1+z)d^2 dt\). Finally, these stars would radiate with an efficiency \(e\) (=0.007 for hydrogen burning). This then leads to a closed expression for the total bolometric flux from these objects:

\[
F_{\text{bol}} = \frac{3}{8\pi} \frac{c^5 G}{4\pi K_H^2} ((1+z)^{-1}) e f_3 \Omega_{\text{baryon}}
\]

\[
\approx 4 \times 10^7 z_5^3 e f_3 \Omega_{\text{baryon}} h^2 \text{ nW m}^{-2} \text{ sr}.
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\]
produced by any gravity-bound object, \( c^4 G \), distributed over the surface of the Hubble radius, \( R_{\text{H}} = c H_0^{-1} \), and the fairly understood dimensionless parameters. From Wilkinson Microwave Anisotropy Probe (WMAP) observations, we adopt \( \Omega_{\text{baryon}} h^2 = 0.0224 \) (Bennett et al. 2003), and since the massive stars are fully convective, their efficiency is close to that of hydrogen burning (Schaerer 2002), \( \epsilon = 0.007 \).

Requiring that P3 stars are responsible for the flux given by equation (1) leads to

\[
f_3 = (4.2 \pm 1.9) \times 10^{-3} z_3^{-1} 0.0224 0.007 \Omega_{\text{baryon}} h^2 \epsilon .
\]

Assuming \( z_3 \approx 10 \), this is somewhat less than the \( \gtrsim 5\% \) value suggested by Madau & Silk (2005) and considerably less than the \( \gtrsim 10\% \) value of Dwek et al. (2005). Within the NIRBE uncertainty, only \( \gtrsim 2\% \) of the baryons had to go through P3. This is not unreasonable considering that primordial clouds are not subject to many of the effects inhibiting star formation at the present epoch, such as magnetic fields and turbulent heating.

The only criterion for P3 formation seems to be that primordial clouds turning around out of the primordial density field have a virial temperature, \( T_{\text{vir}} \), that can enable efficient formation of and cooling by molecular hydrogen (Bromm et al. 1999; Abel et al. 2002). Assuming spherical collapse of Gaussian fluctuations and the \( \Lambda \text{CDM} \) model from WMAP observations (Bennett et al. 2003), the fraction of collapsed halos at \( z = 10 \) with \( T_{\text{vir}} \geq [400, 2000] \text{ K} \) is \( (2.6, 5) \times 10^{-4} \), in good agreement with equation (3), as can be derived from Figure 2 of Kashlinsky et al. (2004).

Equation (3) was evaluated from 1 to 4 \( \mu \text{m} \), but with significant CIB excess flux outside that range \( f_3 \) would increase. However, at wavelengths \( \approx 0.1-1 \mu \text{m} \), the high-\( z \) emissions would be below the Lyman break and would be reprocessed by the net contribution from OGs. The upper limits on the CIB excess there are discussed at length there (§ 5. Table 5, and following). Briefly, the net CIB flux is adopted from Cambréy et al. (2001) at 1.25 \( \mu \text{m} \), from Matsumoto et al. (2005) at 1.65 \( \mu \text{m} \), from Gorjian et al. (2000) and Matsumoto et al. (2005) at 2.2 \( \mu \text{m} \), from Dwek & Arendt (1998) and Wright & Reese (2000) at 3.5 \( \mu \text{m} \), and from Matsumoto et al. (2005) at 4 \( \mu \text{m} \). The flux from OGs is taken from Hubble Space Telescope counts out to 2.2 \( \mu \text{m} \) (open squares; from Madau & Pozzetti 2000) and from Spitzer IRAC counts at 3.6 and 4.5 \( \mu \text{m} \) (open diamonds; Fazio et al. 2004).

At \( \lambda \approx 10 \mu \text{m} \), no CIB excess was observed and the levels of CIB are consistent with the net contribution from OGs. The upper limits on the CIB excess there are shown where net flux from ordinary galaxies is known from measurements with the Submillimetre Common-User Bolometer Array (SCUBA). The CIB level at 450 and 850 \( \mu \text{m} \) from Madau et al. (2003), the fraction of collapsed halos at \( z = 10 \) with \( \gtrsim 1 \mu \text{m} \), and from Matsumoto et al. (2005) at 1.65 \( \mu \text{m} \), from Dwek & Arendt (1998) and Wright & Reese (2000) at 3.5 \( \mu \text{m} \), and from Matsumoto et al. (2005) at 4 \( \mu \text{m} \).

3. OPTICAL DEPTH TO PHOTON-PHOTON ABSORPTION AT HIGH ENERGIES AT HIGH \( z \); APPLICATION TO FORTHCOMING GRB MEASUREMENTS

If P3 stars at early epochs produced even a fraction of the claimed NIRBE, they would supply abundant photons at high \( z \). The present-day value of \( I_1 = 1 \text{ MJy sr}^{-1} \) corresponds to a comoving number density of photons per logarithmic energy interval, \( d \ln E_1 = (4\pi c) (I_1 h_{100}^{-1}) = 0.6 \text{ cm}^{-3} \), and if these photons come from high \( z \), then \( n_1 \propto (1 + z)^3 \). These photons also had higher energies in the past, \( \approx 0.1-0.3 \times (1 + z) \text{ eV} \), providing an abundance of absorbers for sufficiently energetic photons at high redshifts via \( \gamma\gamma \rightarrow e^+ e^- \) (Ahmazier & Berestetskiy 1965, § 32.2; Nikishov 1962). Stecker & de Jager (1993) have pioneered considerations of how \( \gamma\gamma \) absorption can constrain the present-day CIB from high-energy spectra of low-\( z \) blazars. Madau & Phinney (1996) and Salamon & Stecker (1998) have considered the effects of evolving normal galaxy populations on potential future intermediate-\( z \) \((\gtrsim 0.5) \) blazars. However, as shown in § 2, P3 stars are likely to have provided a far more abundant source of photons at high \( z \) to interact with high-energy gamma-ray photons.

GRBs are the obvious objects whose high-energy emissions would be damped by absorption from the NIRBE photons. This effect was difficult to detect with the Energetic Gamma-Ray Experiment Telescope (EGRET) because of its low sensitivity. Observations by EGRET have detected only six GRBs, with one of them being a record-energy 18 GeV photon (Hurley et al. 1994). A successor to the Compton Gamma Ray Observ-
In this section we show that the cross section for Thomson scattering, being electromagnetic in nature, has a cross section on the order of that for Thomson scattering, and that the NIRBE photons originated from P3 at redshifts higher than that of the GRBs, so that $n_z \propto (1+z)^4$. In this case, the optical depth due to photon-photon absorption is

$$
\frac{d\tau_{GRB}(E)}{dz} = R_H \frac{1+z}{\Omega_m(1+z) + (1-\Omega_m)(1+z)} \int_{-1}^{1} dx \int_{E_{\text{min}}}^{E_{\text{max}}} \sigma(E) n_{\gamma,\text{CIB}} \left( \frac{E'}{1+z} \right) \frac{dE'}{E'},
$$

where $n_{\gamma,\text{CIB}}$ is the present-day photon density corresponding to the observed CIB excess. Figure 2 shows the resultant optical depth and contributions to it from different $z$. We adopted $E_{\text{max}} = 1.24$ eV ($1 \mu$m) and the form of $n_{\gamma,\text{CIB}}$ corresponding to the solid line in Figure 1.

The onset of $\tau > 1$ occurs rapidly at $E \simeq [m_e^2 c^4/(1 \text{ eV})] \times (1+z)^{-2} \sim 130(1+z)^{-2}$ GeV. Either the GRB spectra at these energies should be strongly damped, or there had to be only negligible energy releases from the P3 era. Given the high values of $\tau$, this would still hold even if the P3 era produced only a small part of $F_{\text{NIRBE}}$, but it assumes that the latter has a Lyman cutoff redshifted to $\sim 1 \mu$m today. If the P3 era extended to lower $z$, the Lyman cutoff would occur at an observer wavelength $\sim 0.1 \mu$m and GRB spectra would be damped at pro-
portionally lower $E$. Thus, the location of this cutoff may also serve as an indicator of the GRBs’ redshifts. With the advertised LAT energy resolution of better than 10% at $E \approx 1$ GeV, one could determine GRB redshifts from the damping by P3 photons to better than $\sim 5\%$.

How robust is this result? First, photons due to optical counts of galaxies at much later times do not affect the GRB spectra much, because $\tau \sim \sigma_n R_H$ at low $z$ and they contribute $n_e(z = 0) \sigma_n R_H$ of roughly a few, as Figure 1 shows. Furthermore, unlike the P3 photons, for which $n_e \propto (1 + z)^3$, those contributed by galaxies would produce a still smaller contribution at earlier times compared with P3. Second, even if the NIRBE is not entirely cosmological, Figure 2 shows that P3 emissions should still lead to a very large optical depth, which scales as $\tau \propto F_{\text{NIRBE}}$. Thus P3 stars would likely be the dominant contributors to the optical depth to GRBs at high energies. Finally, the magnitude of $\tau$ at a given bolometric CIB flux should not be sensitive to the CIB-excess spectrum, because the (already narrow) range of 1–4 $\mu$m available to damp GRBs at high $z$ is further decreased by $(1 + z)$.

Figure 2 shows that the optical depth from P3 is very high, $\tau \gtrsim (10^{2} -10^{4}) [F_{\text{NIRBE}}/(30$ nW m$^{-2}$ sr$^{-1}])$, which, when combined with the sudden onset of the optically thick regime, would lead to an identifiable damping by the P3 photons. The damping will affect progressively lower energy parts of the rest-frame GRB spectra as one moves to higher $z$. At these energies, the GRB emission is likely produced by the inverse Compton and synchrotron self-Compton components and is expected to be high (or even dominant) for the typical Lorentz factors involved

4. Is Population III Detectable with Low-$z$ Blazars?

Although spectra of more and more distant blazars are now being measured with new instruments, such as the High Energy Stereoscopic System, these blazars are still too close for unambiguous detection of P3 emissions. The furthest blazars with known spectra are at $z \approx 0.13–0.18$, and the spectra extend to $\mathcal{E} < 3$ TeV (Dwek et al. 2005; Aharonian et al. 2005). The right panel of Figure 2 shows the optical depth of a blazar at $z = 0.18$ produced by the $\gamma$-$\gamma$ absorption (1) due to observed galaxies, (2) due to NIRBE from the Diffuse Infrared Background Experiment (DIRBE) and the Infrared Telescope in Space (IRTS), and (3) omitting the IRTS-based point at 1.65 $\mu$m and assuming the lower end of the DIRBE-based results. Even if the entire NIRBE is correct and originates from P3, the additional damping from it is small and is more pronounced only at $\mathcal{E} > 1$ TeV, where measurements and interpretation are difficult. This is because P3 contributes to the background over a short range of wavelengths longward of $\approx 1$ $\mu$m. If P3 stars were to contribute only a fraction of the NIRBE, their emissions will not contribute appreciably to the observed spectra of $z \sim 0.1–0.2$ blazars but would be seen in the high-$z$ GRBs. If GLAST collects a large sample of blazars and other active galactic nuclei at $z \approx 1$, then, as Figure 2 shows, they can also be used to probe the emissions from the P3 era.

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2 See http://www.mpi-hd.mpg.de/HESS.
ERRATUM: “COSMIC INFRARED BACKGROUND FROM POPULATION III STARS AND ITS EFFECT ON SPECTRA OF HIGH-$z$ GAMMA-RAY BURSTS” (ApJ, 633, L5 [2005])

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In the above-mentioned Letter, one of the lines in the right panel of Figure 2 requires a small correction. The dotted line corresponding to the cosmic infrared background (CIB) from ordinary galaxies only should be as shown in the corrected Figure 2 below. The dotted line shown in the published version of the figure has an extra optical depth at $\mathcal{E} \lesssim 300$ GeV effectively arising from a UV excess. This minor error does not affect any of the conclusions of the Letter.

Also, the first sentence in the last paragraph of page L7 contains a typographical error and should read: “The onset of $\tau > 1$ occurs rapidly at $\mathcal{E} \gtrsim m_e^2 c^4/(1\text{ eV})(1 + z)^{-2} \sim 261(1 + z)^{-2}$ GeV.”

![Corrected Figure 2](image-url)

**Fig. 2.—**Left: Plot of $\delta t/dz$ vs. $z$ for GRB photon energies shown in the panel. Solid, dotted, dashed, dash-dotted, and dash–triple-dotted lines correspond to increasing values of $\mathcal{E}$. Middle: Net $\tau$ vs. the GRB photon energy for the GRB redshifts shown in the panel. Solid, dotted, short-dashed, dash-dotted, dash–triple-dotted, and long-dashed lines correspond to increasing values of $z$. The range of redshifts was chosen to avoid overlap between GRBs and the P3 era; the latter is assumed to have ended by $z = 10$. Only the NIRBE from Fig. 1 shown with the thick gray solid line is assumed in the calculations. This assumption is fairly safe at larger $z$, as this component gets progressively larger than the ordinary galaxies’ emissions, but at $z = 1$ the latter can still contribute (Madau & Phinney 1996). Right: Optical depth to photon-photon absorption for a source at $z = 0.18$. Line styles correspond to those in Fig. 1. The dotted line assumes only ordinary galaxies measured in deep counts and that their photons originated at $z \geq 0.18$. Thick gray lines correspond to the NIRBE: the solid line assumes both the DIRBE- and IRTS-based claims at the central points of the measurements, and the dashed line assumes the “minimal” NIRBE with only the DIRBE-based points (i.e., the 1.65 $\mu$m point is omitted) and the CIB levels corresponding to the lower end of the error bars in Fig. 1.