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ON THE NATURE OF THE SOURCES OF THE COSMIC INFRARED BACKGROUND

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ABSTRACT

We discuss the interpretation of the cosmic infrared background (CIB) anisotropies detected by us recently in the *Spitzer*/IRAC-based measurements. The fluctuations are approximately isotropic on the sky, which is consistent with their cosmological origin. They remain after the removal of fairly faint intervening sources and must arise from a population that has a strong CIB clustering component with only a small shot-noise level. We discuss the constraints the data place on the luminosities, epochs, and mass-to-light ratios of the individual sources producing them. Assuming the concordance ΛCDM cosmology, the measurements imply that the luminous sources producing them lie at cosmic times <1 Gyr and were individually much brighter per unit mass than the present stellar populations.

Subject headings: cosmology: observations — cosmology: theory — diffuse radiation — early universe

1. INTRODUCTION

If the early universe contained significantly more luminous populations than the present, such as is thought to be the case with the very first metal-free stars (see review by Bromm & Larson 2004), these populations could have produced a significant contribution to the cosmic infrared background (CIB) with potentially measurable structure (Santos et al. 2002; Salvaterra & Ferrara 2003; Cooray et al. 2004; Kashlinsky et al. 2004; see Kashlinsky 2005a for recent review). In an attempt to uncover the CIB fluctuations from early populations, we have analyzed deep images obtained with the *Spitzer* Infrared Array Camera (IRAC; Kashlinsky et al. 2005, hereafter KAMM1), which led to the detection of significant CIB fluctuations that remained after subtracting sources to faint flux levels. In a companion paper (Kashlinsky et al. 2007, hereafter KAMM2), we present analysis from deeper and larger fields using the GOODS/*Spitzer* data (Dickinson et al. 2003), which confirms our earlier findings and extends them to fainter levels of removed galaxy populations and larger angular scales.

In this Letter we discuss the cosmological implications of the recent measurements of the CIB fluctuations from early populations obtained by us (KAMM1; KAMM2). These measurements imply that the signal must come from cosmic sources that have a significant clustering component but a low shot-noise contribution to the power spectrum. Given the amplitude of the CIB flux expected from these populations in the concordance ΛCDM cosmology ($\gtrsim 1$ nW m^{-2} sr^{-1}), we show that these sources must have very faint individual fluxes of $\lesssim 10$–20 nJy in order not to exceed the measured levels of the remaining shot noise. Furthermore, these populations had to have had a mass-to-light ratio significantly below that of the present-day stellar populations in order to produce the required CIB fluxes in the short cosmic time available (<1 Gyr) from the available baryons. Finally, we discuss the prospects for their individual detection with future space missions. We use the AB magnitude system, so flux per frequency ν of magnitude m is $S_\nu(m) = 3631 \times 10^{-0.4m}$ Jy; diffuse flux in units of nW m^{-2} sr^{-1} is defined as νI_ν, with I_ν being the surface brightness in units of MJy sr^{-1}.

2. MAGNITUDES AND EPOCHS OF THE SOURCES OF THE CIB FLUCTUATIONS

In their analyses, KAMM1 and KAMM2 used a total of five different fields with deep *Spitzer*/IRAC observations of up to 24 hr per pixel. All the observed fields are located at high Galactic and ecliptic latitudes and are free of significant zodiacal emissions at all IRAC channels and of cirrus at the IRAC channels 1–3 (3.6–5.8 μm). Individual galaxies and other sources were removed until a fixed level of the shot noise from the remaining sources was reached. The power spectrum of the remaining diffuse emission showed a residual shot-noise component on small angles and a significant excess due to clustering of faint/distant sources at scales $\gtrsim 0'.5$. Within the errors, all fields cleaned to the same shot-noise level showed the same excess fluctuations, consistent with their cosmological origin (see Fig. 1 of KAMM2). At 8 μm there is significant pollution by the Galactic cirrus, and at 5.8 μm the larger instrumental noise leads to relatively large errors in the large-scale fluctuations. Here we concentrate on the interpretation of the data at 3.6 and 4.5 μm in terms of the luminosities, the epochs, and the nature of the cosmological sources contributing to these fluctuations.

KAMM1 and KAMM2 show that the CIB fluctuations must come from cosmological sources, such as ordinary galaxies and the putative Population III. The former are defined as metal-rich stars with initial mass functions (IMFs) of a Salpeter-Scalo (Kennicutt 1998) type with masses $\sim 1\ M_\odot$. Population III is defined (loosely) as luminous sources that existed at, say, $z \gtrsim 10$ and that possibly were individually very massive and intrinsically very luminous. Data such as discussed here cannot resolve whether the sources contributing to the CIB were metal-rich (Fernandez & Komatsu 2006) or not, or whether the source of this radiation was stellar nucleosynthesis (Santos et al. 2002) or black hole accretion in the early universe (Cooray & Yoshida 2004). Population III epochs ($z \gtrsim 10$) may contain emissions by both stars and quasar-like objects (Kashlinsky & Rees 1983).

Any model aimed at explaining the CIB fluctuation results must reproduce three major aspects: (1) The sources producing the measured CIB fluctuations must be fainter than those removed from the data. (2) They must reproduce the observed excess CIB fluctuations at $\gtrsim 0'.5$, where $\delta F \simeq 0.07$–0.1 nW m^{-2} sr^{-1}. (3) The populations below the above cutoff must account not only for the correlated part of the CIB but must also reproduce the observed (low) shot-noise component of the signal. These aspects lead to the following:

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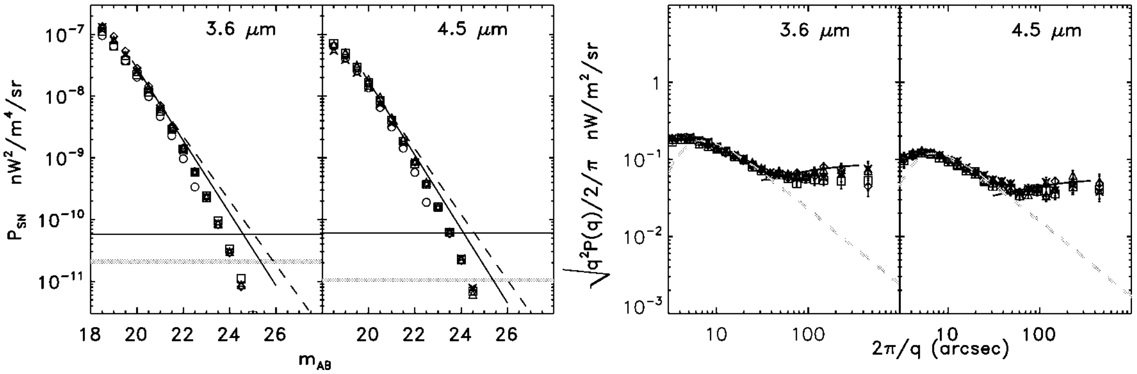

FIG. 1.—*Left*: Shot-noise power amplitude from the data compared to the values of P_{SN} estimated by integrating the counts. The solid lines show the levels of P_{SN} reached in the QSO 1700 analysis (KAMM1). The light shaded areas show the levels of P_{SN} reached in KAMM2. The symbols plot P_{SN} by integrating the counts evaluated for all five fields in Table 1 of KAMM2. The diamonds correspond to the Hubble Deep Field–North epoch 1 (HDF-N E1) region, the triangles to HDF-N E2, the squares to the Chandra Deep Field–South epoch 1 (CDF-S E1) region, and asterisks to CDF-S E2; the open circles correspond to counts for the QSO 1700 field. The solid line shows P_{SN} according to the fit to IRAC counts of Fazio et al. (2004) used in KAMM1; the dashed lines correspond to the IRAC count analysis from Savage & Oliver (2005). The counts are significantly incomplete due to confusion at the levels of P_{SN} reached with our analysis and therefore give a *lower* limit on the limiting magnitude. *Right*: CIB fluctuations from KAMM2 at the shot-noise levels shown with shaded regions in the left panel. The notations for the counts from the GOODS data are the same as in the left panels. The light-shaded dashed lines show the shot-noise fluctuations. The solid lines show the least-squares fits to the CIB fluctuations from sources at $z \gtrsim 6$ assuming ΛCDM model as described in the text.

1. The shot-noise component of the power spectrum from source counts dN/dm per magnitude interval dm is $P_{SN} = \int S^2(m)dN(m)$, with $S = \nu S_\nu$. To estimate the limiting magnitudes implied by the measured shot noise, we generated source counts for the observed fields with SExtractor (Bertin & Arnouts 1996). Figure 1 shows the remaining shot-noise levels in the KAMM1 and KAMM2 analyses and the count data. The intersection of the counts with the lowest shot-noise levels shows that the sources are eliminated to $m \gtrsim 25$–26, so the detected CIB fluctuations come from fainter sources. This magnitude limit at 3.6 μm corresponds to only $10^9\ h^{-2}(10^{-0.4(m-25.5)}\ L_\odot)$ emitted at 6000 Å at $z = 5$, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. If the counts contain extra populations in addition to those from Fazio et al. (2004), the magnitude limit will be fainter. Thus, KAMM1 and KAMM2 have removed a significant fraction of galaxies even at $z = 5$, and the CIB fluctuations must come from sources at higher z.

2. The clustering component of the CIB at $0'.5 \lesssim 2\pi/q \lesssim 5'$ requires $F_{CIB} \sim$ a few times nW m^{-2} sr^{-1} as noted by us earlier (KAMM1). The rms fluctuation in the CIB flux, $\delta F = [q^2P_2(q)/2\pi]^{1/2}$, on an angular scale $2\pi/q$ is related to the underlying three-dimensional power spectrum of the emitters' clustering, $P_3(k)$, the duration over which the flux was produced, Δt, and the rate of the CIB production rate, dF/dt, via the Limber equation (e.g., Kashlinsky 2005a):

$$\delta F = F_{CIB}\bar{\Delta}_F;\ \ \bar{\Delta}_F^2 \equiv \frac{\Delta t \int_{\Delta t} (dF/dt)^2 \Delta^2(qd_A^{-1})dt}{[\int_{\Delta t} (dF/dt)dt]^2}, \quad (1)$$

where $\Delta(k) = [k^2P_3(k)/2\pi c\Delta t]^{1/2}$ is the rms fluctuation in source counts over the cylinder of radius $2\pi/k$ and length $c\Delta t$. In the limit, when the CIB release rate is approximately constant, the relative CIB fluctuation, Δ_F, will be $\sim\langle\Delta^2(qd_A^{-1})\rangle^{1/2}$, with $\langle\ldots\rangle \equiv (\Delta t)^{-1}\int_{\Delta t}\ldots\ dt$. If dF/dt peaks at some cosmic epoch z_p, the relative fluctuation will be $\simeq\Delta(qd_A^{-1}(z_p))$.

To evaluate the range of the expected CIB flux from the sources producing the measured fluctuations, we adopt the ΛCDM model with $(\Omega, \Omega_{baryon}, \Omega_\Lambda, h) = (0.3, 0.044, 0.7, 0.71)$ and consider the epochs spanning $5 \leq z \leq 20$. The cosmic time at $z = 20$ is $\simeq 0.2$ Gyr, and the time between $z = 20$ and $z = 5$ is 1 Gyr. The scale $r_8 = 8\ h^{-1}$Mpc, with today's density contrast σ_8, subtends $\theta_8 \simeq 3'$–$4'$. The relative fluctuation in the projected two-dimensional power spectrum, Δ, on that angular scale θ_8, produced from sources located at a mean value of $\bar{z}$ and spanning the cosmic time Δt, would be $\Delta(\theta_8) \sim \sigma_8(1+\bar{z})^{-1}(r_8/c\Delta t)^{1/2} \simeq 0.02\sigma_8(\bar{z}/10)^{-1}(\Delta t/\mathrm{Gyr})^{-1/2}$, neglecting the amplification due to biasing. Biasing, due to sources forming out of rare peaks of the density field, will increase Δ (Kaiser 1984), and for reasonable bias factors (from $\sim$2 for systems collapsing at $z \sim 5$ to $\gtrsim$3 at $z \gtrsim 10$) one can gain amplification factors, A, in Δ from $\simeq$2 to $\gtrsim$4–5 between $z = 5$ and 20 (Kashlinsky 1991, 1998; Cooray et al. 2004; Kashlinsky et al. 2004). Thus, the arcminute-scale CIB fluctuations of $\delta F \sim 0.07$–0.1 nW m^{-2} sr^{-1} at 3.6 and 4.5 μm require the mean CIB from these sources to be $F_{CIB} \sim 4$–$5\langle A[(1+z)/6]^{-1}\rangle^{-1}(\Delta t/1\ \mathrm{Gyr})^{1/2}$ nW m^{-2} sr^{-1}. Assuming that the fluctuations are produced by low surface brightness systems at much lower z does not alter the required high value of their mean CIB contribution; e.g., taking $\Delta t = 5$ Gyr corresponding to the cosmic time between $z = 1$ and 20 gives $\Delta \simeq 0.02$ at $1'$, assuming no biasing. (As discussed below such sources would likely produce shot noise in excess of what we measure.) We can reach similar conclusions with the entire range of scales $\gtrsim 0'.5$ where we measure the clustering component of the CIB. The left panels of Figure 1 show the least-squares fits for F_{CIB}, assuming the ΛCDM model, from all the fields data at 3.6 and 4.5 μm. This gives $F_{CIB}\langle A[(1+z)/10]\rangle \gtrsim (4, 2.5)(\Delta t/1\ \mathrm{Gyr})^{-1/2}$ nW m^{-2} sr^{-1} at 3.6 and 4.5 μm, respectively.

We thus conservatively take the fiducial flux of $F_{CIB} = 1$ nW m^{-2} sr^{-1} as the minimal CIB flux at 3.6 and 4.5 μm required by the fluctuations, corresponding to the relative minimal CIB fluctuations of $\sim$7%. The results below can be rescaled to arbitrary F_{CIB}, but our general conclusions will be valid unless the CIB flux from sources producing the measured fluctuations is significantly *below* the above number. Although the net CIB fluxes may in principle be much higher, this *minimal* CIB level at 3.6 μm is smaller than the claimed CIB excess from DIRBE and *IRTS* measurements compared with that from galaxy counts (Dwek & Arendt 1998; Arendt & Dwek 2003; Matsumoto et al. 2005) and is consistent with the recent measurements of absorption in the spectra of fairly distant ($z = 0.13$–0.18) blazars at TeV energies (Dwek et al. 2005; Aharonian et al. 2006). However, such CIB levels should be measurable from the spec-

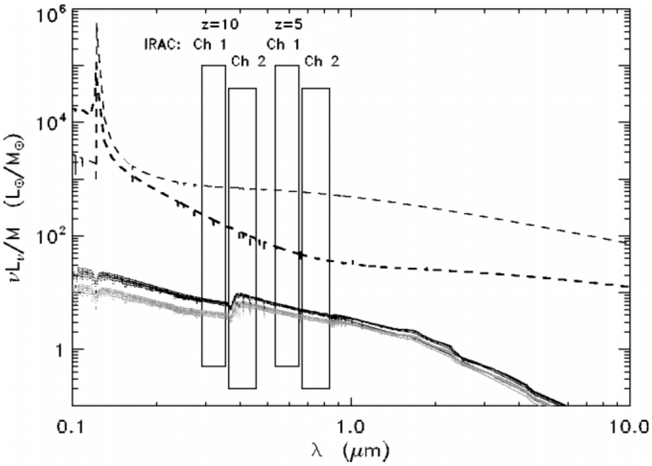

FIG. 2.—Rest-frame luminosity per unit mass plotted vs. wavelength for Population III spectra (from Santos et al. 2002; *dashed lines*) and "ordinary" stellar populations at 0.5 and 1 Gyr with a Salpeter-Scalo IMF [computed from PEGASE for metallicity $Z = 0$, 10^{-3}, 2×10^{-3}, 5×10^{-3}, 10^{-1} assuming constant burst of star formation; i.e., SFR $\propto \exp(-t/t_{\rm burst})$ with $t_{\rm burst} = 20$ Gyr]. $L_\odot = 3.8 \times 10^{33}$ ergs s^{-1} is the solar bolometric luminosity. The part of emission probed by the IRAC channels 1 (3.6 μm) and 2 (4.5 μm) at $z = 5$, 10 is shown with the marked regions.

tra of gamma-ray bursts at $z \gtrsim 1$–2 detectable with the upcoming NASA's *GLAST* mission out to 300 GeV (Kashlinsky 2005b). *Spitzer* counts (Fazio et al. 2004) show that the remaining ordinary galaxies can contribute only $\simeq$0.15 nW m^{-2} sr^{-1} at 3.6 μm (KAMM1), and so explaining the CIB fluctuations with the remaining (extrapolated) *Spitzer* count sources requires an almost 100% fluctuation on arcminute scales.

3. The CIB in the populations producing the measured fluctuations significantly exceeds that from extrapolated IRAC counts (Fazio et al. 2004), and so the excess flux must come from fainter populations with a significant deviation from the extrapolated counts' slope (KAMM1). The measured fluctuations indicate a population with a relatively strong clustering component, which at the same time has low shot noise. This means that the sources must be individually faint. The shot noise from the remaining galaxies dominates the power spectrum of the CIB at $\lesssim 0'.5$, and its amplitude sets an *upper* limit on the shot-noise component of the sources contributing to the arcminute-scale CIB fluctuations. The amplitude of the shot-noise component is

$$P_{\rm SN} = \int_{>m} S(m)dF(m) \equiv S(\bar{m})F_{\rm tot}(>m),$$

where $dF(m) = S(m)dN(m)$ is the CIB from sources at the magnitude interval dm and $F_{\rm tot}(m)$ is the total flux from the remaining sources of $>m$ (Kashlinsky 2005a). The sources contributing to the clustering component of the fluctuations at arcminute scales must not exceed the level of the residual shot noise in the data of $P_{\rm SN} \simeq (2, 1) \times 10^{-11}$ nW^2 m^{-4} sr^{-1} at 3.6 and 4.5 μm. At 4.5 μm this shot-noise amplitude of $P_{\rm SN} = 10^{-11}$ nW^2 m^{-4} sr^{-1}, or $10(\lambda/3\ \mu{\rm m})^{-1}$ nJy nW m^{-2} sr^{-1}, would lead to sources contributing to the signal having mean fluxes less than 12 $(F_{\rm CIB}/{\rm nW\ m^{-2}\ sr^{-1}})^{-1}$ nJy or AB magnitudes $\bar{m} \geq 29 + 2.5 \log (F_{\rm CIB}/{\rm nW\ m^{-2}\ sr^{-1}})$. At 3.6 μm the shot-noise levels are a factor of $\simeq$2 larger, leading to $\bar{m}$ about 1 mag brighter. Important further information could be obtained in still deeper measurements by setting a lower limit on the shot-noise component of the sources contributing to the CIB fluctuations determined when the clustering component disappears or is substantially reduced.

3. DISCUSSION

More information on the nature of the populations of these faint sources can be obtained by considering the fraction of baryons that went through stars prior to $z \gtrsim 5$ ($\Delta t \lesssim 1$ Gyr) and that are needed to explain the level of the CIB required by our data. The net flux at frequency ν produced by the population with comoving luminosity density $\mathcal{L}$ is $F_{\rm CIB} = (c/4\pi)\int_{\Delta t} \mathcal{L}_{\nu'}(1+z)^{-1}dt$, where $\nu' = \nu(1+z)$. This requires the average comoving luminosity density at 0.36–0.45 μm$[10/(1+z)]$ of

$$\bar{\mathcal{L}} \simeq \frac{4\pi}{c} F_{\rm CIB}(\Delta t)^{-1}(1+\bar{z}) \simeq 1.2 \times 10^9\ L_\odot\ {\rm Mpc^{-3}} \times \frac{1\ {\rm Gyr}}{\Delta t}\,\frac{1+\bar{z}}{10}\,\frac{F_{\rm CIB}}{{\rm nW\ m^{-2}\ sr^{-1}}}. \tag{2}$$

For comparison, the present-day luminosity density measured by the Sloan Digital Sky Survey at 0.32–0.68 μm is about an order of magnitude lower (Blanton et al. 2003). This indicates significantly more luminous populations contributing to the CIB fluctuations than is at present observed. The contribution to the density parameter by these sources is thus given by

$$\Omega_* = \frac{(\Gamma\bar{\mathcal{L}})|_{0.36-0.45\ \mu{\rm m}[10/(1+z)]}}{3H_0^2/8\pi G} \simeq 8.3 \times 10^{-3}\,\frac{F_{\rm CIB}}{{\rm nW\ m^{-2}\ sr^{-1}}} \times \frac{\Gamma}{\Gamma_\odot}\left(\frac{\Delta t}{1\ {\rm Gyr}}\right)^{-1}\frac{1+\bar{z}}{10}, \tag{3}$$

where Γ is the mass-to-light ratio. For comparison, the mean density in present-day stars is significantly lower at $\Omega_{*,z=0} \simeq 2 \times 10^{-3}$ (Fukugita et al. 1998; Cole et al. 2001), and much of the contribution to $\Omega_{*,z=0}$ comes from the late stellar Population I stars with solar metallicities. Strictly speaking, equation (3) assumes no reprocessing of baryons and may thus overestimate the required amount of luminous baryons in the case of short-lived massive stars, such as Population III, but it shows that it is energetically easier to produce the significant CIB levels implied by the *Spitzer* data in the cosmic time available with stars whose mass function is skewed toward $\Gamma \ll \Gamma_\odot$. (For populations made up of massive stars, it can be replaced with eq. [3] of Kashlinsky 2005b). If the CIB fluctuations are produced by populations containing a significant fraction of low-mass stars, which should still be burning today, they would require a large fraction of the present-day stars to have been produced at $z \gtrsim 6$–10.

To model the ordinary stellar populations, we have run stellar evolution models using the PEGASE code (Fioc & Rocca-Volmerange 1997), assuming a normal IMF with various metallicities and the ongoing star formation [i.e., star formation rate SFR $\propto \exp(-t/t_{\rm burst})$ with $t_{\rm burst} = 20$ Gyr]. For Population III we adopted the spectral energy distribution (SED) from Santos et al. (2002). Figure 2 shows the luminosity per unit mass in stars (Γ^{-1}), assuming the ordinary population to be less than 1 Gyr old [$\Gamma \sim (0.2$–$0.5)\Gamma_\odot$], and contrasts them with the expectations for massive Population III systems ($10^{-2}\Gamma_\odot$ to $10^{-3}\Gamma_\odot$). If the CIB fluctuation signal comes entirely from the Population III systems, equation (3) would give the minimal fraction of baryons locked in them, $\sim 0.15\%(F_{\rm CIB}/{\rm nW\ m^{-2}\ sr^{-1}})$. If the baryons are reused in stars, this fraction would be decreased. This number is in agreement with that of Kashlinsky (2005b) after scaling to the appropriate CIB levels: 0.14% $(F_{\rm CIB,\,bolometric}/{\rm nW\ m^{-2}\ sr^{-1}})(z/10)(\epsilon/0.007)^{-1}$, assuming the hydrogen-burning efficiency ϵ (such massive stars would be fully convective, with the overall efficiency reaching $\epsilon \gtrsim 3 \times 10^{-3}$; Schaerer 2002).

The sources satisfying the above constraints had masses in luminous matter of

$$M_* \sim 4\pi d_L^2 (1+z)^{-1} \Gamma S(\bar{m}) \lesssim 7 \times 10^5\ h^{-2}\ M_\odot \times \frac{\Gamma_{3.6\text{–}4.5\ \mu{\rm m}/(1+z)}}{5 \times 10^{-3}\Gamma_\odot} \frac{[S_\nu(\bar{m})]}{20\ {\rm nJy}} \left(\frac{1+z}{10}\right)^{1.6}, \tag{4}$$

where the luminosity distance was approximated as $d_L \simeq 3.2(1+z)^{1.3}\ h^{-1}$ Gpc. Such Population III sources, with only approximately less than a few times $10^5\ M_\odot$ in stellar material, would be below the detection threshold in the high-z Lyman dropout searches of Bouwens et al. (2005) and Willis & Courbin (2005) considered by Salvaterra & Ferrara (2006). In any case, theoretical predictions of the luminosity function of Population III sources are necessarily model-dependent as they depend on the assumptions of the small-scale power and its evolution, as well as the microphysics governing the various feedback effects during the collapse of the first halos. The Press-Schechter–type (Press & Schechter 1974) prescriptions may break down for the slope and regime of power spectra on the relevant scale (Springel et al. 2005), and the feedback mechanisms due to the H_2 destruction by the Lyman-Werner bands' radiation (Haiman et al. 1997) likely suppress star formation in a complicated halo-mass–dependent way.

To resolve the faint sources responsible for the CIB fluctuations, their individual fluxes must exceed the confusion limit usually taken to be $\alpha \geq 5$ times the flux dispersion produced by these emissions (Condon 1974). Lower flux sources will be drowned in the confusion noise; of course, this is precisely where CIB studies would take off. If such sources were to contribute the CIB required by our data, at 3.6 μm they would have to have an average surface density of $\bar{n} \sim F_{\rm CIB}^2/P_{\rm SN} \sim 2$ ${\rm arcsec^{-2}}\ (F_{\rm CIB}/{\rm nW\ m^{-2}\ sr^{-1}})^2\ (P_{\rm SN}/10^{-11}\ {\rm nW^2\ m^{-4}\ sr^{-1}})^{-1}$. To avoid the confusion limit and resolve these sources individually at, say, the 5 σ level ($\alpha = 5$), one would need a beam area $\omega_{\rm beam} \leq \alpha^{-2}/\bar{n} \sim 0.017\ (F_{\rm CIB}/{\rm nW\ m^{-2}\ sr^{-1}})^{-2}\ {\rm arcsec^2}$ or a circular radius $\lesssim 0.07(F_{\rm CIB}/{\rm nW\ m^{-2}\ sr^{-1}})^{-1}$ arcsec. This is not in the realm of the current instruments, but the *James Webb Space Telescope* could be able to resolve these objects (Gardner et al. 2006). Extrapolation of this argument to shorter λ is model-dependent, as it would assume both the SED of these sources (to predict their magnitudes at $\lambda < 3\ \mu$m) and their z (to predict the location of their Lyman break and whether or not they are observable at $\lambda < 3\ \mu$m). In any case, at 1.1 and 1.6 μm confusion is not reached until $m_{\rm AB} \gtrsim 28$ (Thompson et al. 2005). If the first stars produced dusty environments, their far-IR luminosities will be substantial, and these sources should be visible at wavelengths redshifted today to millimeter and submillimeter bands. In that case, they may be resolvable with the Atacama Large Millimeter/submillimter Array,[3] whose submillimeter resolution is better than 0″.02.

Finally, the fluctuations are unlikely to come from low-luminosity low-z normal galaxies. Such galaxies must have a surface density $\bar{n} \gtrsim 3 \times 10^7\ {\rm deg^{-2}}$ with the 3.6 and 4.5 μm fluxes $\lesssim$10–20 nJy. Unless they are significantly fainter than this limit, emissions from star-forming systems should have comparable fluxes at shorter λ out to the 4000 Å break for passively evolving populations or to the Lyman cutoff at $\simeq$0.1 μm for star-forming galaxies. Galaxy counts now extend to $m \simeq 30.5$ (2 nJy) at 0.67 μm and to 29 (10 nJy) at 1.6 μm (Madau & Pozzetti 2000) and are over an order of magnitude below the required value of $\bar{n}$ at the faintest magnitudes. This would exclude star-forming galaxies as faint as 2 nJy at $0.67\ \mu{\rm m}(1+z)^{-1}$ at $z \lesssim 5.7$ and passively evolving populations out to 10 nJy at $1.6\ \mu{\rm m}(1+z)^{-1}$ at $z \lesssim 3$. We note, however, that this analysis cannot exclude "abnormal" populations at low z.

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[3] See http://www.alma.nrao.edu/.

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