Updated analysis of near-infrared background fluctuations

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ABSTRACT
The power spectrum of Near InfraRed Background (NIRB) fluctuations measured at 3.6 μm by Spitzer shows a clustering excess over the known galaxies signal that has been interpreted in terms of early (z ∼ 13), accreting (direct collapse) black holes (DCBH) or low-z intrahalo light (IHL). In addition, these fluctuations correlate with the cosmic X-ray background (CXB) measured at (0.5-2) keV, supporting the black hole explanation. This has been questioned by the recent detection of a correlation between the two CIBER 1.1/1.6 μm bands with the 3.6 μm Spitzer one. This correlation is hardly explained by early DCBHs that, due to intergalactic absorption, cannot contribute to the shortest wavelength bands. Here we show that the new correlation is caused instead by a Diffuse Galactic Light (DGL) component arising from Galactic stellar light scattered by dust. The black hole interpretation of the excess remains perfectly valid and, actually, the inclusion of DGL allows less demanding (by up to about 30%) requirements on the DCBH abundance/mass.

Key words: cosmology: diffuse radiation-dark ages; reionization, first stars – infrared:galaxies – galaxies: high-redshift – X rays: diffuse background

1 INTRODUCTION
On angular scales ∼ 100 arcsec (corresponding to multipole number ℓ ≲ 10^5) the power spectrum of the source-subtracted Near InfraRed Background (NIRB) fluctuations has an amplitude that exceeds by ∼ 100 times the signal expected from all galaxies below the detection limit and first stars. The origin of such “clustering excess” (i.e. due to correlations in the sources spatial distribution) has now represented a puzzle since its discovery (Kashlinsky et al. 2005, 2007; Matsumoto et al. 2011; Kashlinsky et al. 2012; Cooray et al. 2012a; Zemcov et al. 2014; Seo et al. 2015; Yue et al. 2013a). Two scenarios have been proposed to interpret the clustering excess. The first advocates the contribution from intrahalo light (IHL), i.e. relatively old stars stripped from their parent galaxies following merging events. These stars therefore reside in between dark matter halos and constitute a low-surface brightness haze around galaxies. The IHL is expected to come mostly from low redshifts (1 + z ∼ 1.5) systems (Cooray et al. 2012a; Zemcov et al. 2014).

The second scenario is instead based on the presence of a class of early, highly obscured accreting black holes of intermediate mass (∼ 10^4–6 M⊙) at z ∼ 13 (Yue et al. 2013b, 2014, Cooray et al. 2012a). As a suitable mechanism to produce such objects does exist – the so called Direct Collapse Black Holes (DCBH, for a concise overview of the problem see Ferrara et al. 2014), and the interpretation of the supermassive black holes observed at z = 6 seemingly requires massive seeds (Volonteri & Bellovary 2011), such hypothesis seems particularly worth exploring.

Both scenarios successfully explain the observed clustering excess, albeit with apparently demanding requirements. In fact, if the excess is to be explained by intrahalo light, then a large fraction of the stars at low-z must reside outside systems that we would normally classify as “galaxies” (Zemcov et al. 2014). On the other hand, in the DCBH scenario the abundance of seed black holes produced until z ∼ 13 must represent a sizeable fraction of the estimated present-day black hole abundance, as deduced from local scaling relations (Kormendy & Ho 2013) and recently revised by Comastri et al. (2013). However, it is important to outline that both scenarios are not in conflict with any known observational evidence.

The two scenarios, however, differ strongly for what concerns the interpretation of the observed cross-correlation between 3.6 μm NIRB fluctuations and those measured at (0.5-2) keV in the cosmic X-ray background (CXB) by Cappelluti et al. (2013). While accreting black holes naturally produce X-ray emission, no obvious similar mechanism can be identified for intrahalo stars, thus making difficult to explain the observed cross-correlation.
The DCBH scenario might have its own problems. They could possibly arise from the recent measurement of NIRB fluctuations at 1.1 and 1.6 μm obtained by CIBER\(^1\) Zemcov et al. (2014) showed that these fluctuations do correlate with those observed at 3.6 μm by Spitzer, thus suggesting a common source. If confirmed, this could possibly represent a problem for DCBHs as their formation must stop, based on a number of physical arguments discussed in Yue et al. (2014), after \(z \approx 13\). Intergalactic absorption at wavelengths shorter than the Ly\(\alpha\) line would then prevent DCBH to contribute at 1.1 and 1.6 μm.

Here, we show that the cross-correlation between CIBER and Spitzer bands does not represent a problem for the DCBH hypothesis, as very likely it arises from a well-known contaminant: Diffuse Galactic Light (DGL), i.e. dust scattered or thermally emitted light in the Milky Way.\(^2\) Zemcov et al. (2014) pointed out that DGL strongly contributes to the CIBER 1.1 and 1.6 μm auto-correlation power spectra on large scales. Motivated by this evidence, we show that the 1.1×3.6 μm and 1.6×3.6 μm cross-correlations at the largest scales (\(\gtrsim 15\)) can be purely ascribed to the DGL and that there is no tension between the high redshift DCBH scenario and CIBER observations. Actually, the sub-dominant contribution of DGL in the 3.6 μm band helps decreasing the DCBH abundance required to explain the clustering excess.

2 METHODS

In order to estimate the DGL component in the 3.6 μm auto-correlation power spectrum we proceed in the following way. First, we use the fact that on small scales (and in all bands) shot noise completely dominates the 1-halo and 2-halo clustering terms both in the auto- and cross-correlation power spectra. Therefore we can safely assume that at these scales

\[ C_l \approx C_{\text{SN}}, \]

and derive the value of \(C_{\text{SN}}\) by fitting the five CIBER data points at the smallest scales in the 1.1 μm and 1.6 μm auto-correlation power spectra, and in the 1.1(1.6)×3.6 μm cross-correlation ones. Results of the fit are reported in Table 1.

Similarly, on the largest scales the signal is dominated by the DGL component, so that

\[ C_l \approx C_{\text{DGL}} = A_{\text{DGL}} \left( \frac{l}{1000} \right)^\alpha, \]

Here we assume, following Zemcov et al. (2014); Mitchell-Wynne et al. (2013), that the DGL power spectrum has a power-law form with a fixed slope \(\alpha = -3.05\) for both the DGL auto-correlation and cross-correlation power spectra as derived by the combined fit of CIBER and Spitzer data.\(^3\) Mitchell-Wynne et al. (2013). Results of the fit of the six CIBER data points on the largest scales are also given in Table 1. We checked that our results do not change significantly when we let the value of \(\alpha\) vary within its 1σ errors (-3.05 ± 0.07). We further implicitly assume here that the DGL fluctuations at two wavelengths are perfectly correlated (i.e. unity correlation coefficient). This seems a reasonable assumption given that the three bands very closely spaced in wavelength. At this point we can derive the contribution of DGL to the 3.6 μm auto-correlation power spectrum as

\[ A_{\text{DGL}}^{bb} = \sqrt{A_{\text{DGL}}^{aa} \times A_{\text{DGL}}^{bb}} \]

which gives

\[ A_{\text{DGL}}^{bb} = (A_{\text{DGL}}^{ab})^2/A_{\text{DGL}}^{aa}. \]

In the previous expressions, \(b\) corresponds to the 3.6 μm band; \(a\) corresponds either to the 1.1 or 1.6 μm band. Note that the DGL is derived from the (1.1)1.6×3.6 μm cross-correlation power spectra in Zemcov et al. (2014). In this work Spitzer observations were analyzed using a shallower source subtraction depth (mag \(\approx 22\)) than in the original work by Cooray et al. (2012b), who instead used a deeper threshold (mag \(\approx 24\)). As a result, the 3.6 μm auto-power spectrum in Zemcov et al. (2014) is largely dominated by shot noise and no interesting signal is seen. For this reason we have decided to compare the derived auto-power spectrum with the 3.6 μm auto-power in Cooray et al. (2012b).

This should not introduce any artifacts, as the DGL component must be independent of the point source subtraction depth. Also, note that the DGL fitting has been derived for the same fields, thus eliminating possible effects introduced by the dependence of the DGL signal from Galactic coordinates.

3 RESULTS

We compare the curve \([A_{\text{DGL}}(l/1000)^\alpha + C_{\text{SN}}]l^2/(2\pi)\) and its 1σ variance with observations in Fig. 1. We find that both the CIBER measured auto-correlation power spectra and the cross-correlation power spectra could be nicely matched by the sum of shot noise and DGL without the need for additional components. Indeed, while some extra-power can be seen in CIBER data at 3000 \(\lesssim l \lesssim 2 \times 10^4\), such an bump is not seen in Mitchell-Wynne et al. (2013) where resolved sources are subtracted down to a much deeper limiting magnitude. Thus it is likely that this bump in CIBER data can be due to foreground sources not resolved in Zemcov et al. (2014) analysis.

As described in the previous Section, we estimate the contribution of the DGL to the 3.6 μm auto-correlation

\[ \begin{array}{|c|c|c|} \hline \text{power spectra} & \log(C_{\text{SN}}) & \log(A_{\text{DGL}}) \\ \hline 1.1 \times 1.1 \mu m & -6.11^{+0.007}_{-0.008} & -4.5^{+0.3}_{-1.2} \\ 1.6 \times 1.6 \mu m & -6.33^{+0.007}_{-0.01} & -4.6^{+0.3}_{-1.8} \\ 1.1 \times 3.6 \mu m & -7.69^{+0.006}_{-0.009} & -6.4^{+0.3}_{-1.1} \\ 1.6 \times 3.6 \mu m & -7.79^{+0.008}_{-0.009} & -6.4^{+0.3}_{-1.1} \\ \hline \end{array} \]

\(^1\) http://ciber.caltech.edu

\(^2\) Often the term DGL specifically refers to stellar light scattered by dust, while longer wavelength (\(\gtrsim 5\mu m\)) thermal emission from grains is referred to as the “Galactic cirrus”.

\(^3\) Note that the constraints are mainly provided by HST data.
NIRB fluctuations

Figure 1. Upper: The 1.1 (left) and 1.6 $\mu$m (right) CIBER auto-correlation power spectra (filled circles); the solid line shows the sum of the best-fit shot noise and DGL contribution, with the 1$\sigma$ variance indicated by shaded areas. Also plotted the HST power spectra from Mitchell-Wynne et al. (2015) (filled triangles); note that in the 1.1 $\mu$m panel the HST points are actually measured at 1.25 $\mu$m. Lower: Same as above for the cross-correlation power spectra.

We obtain a value for the DGL amplitude $\log(A_{\text{DGL}}) = -8.3^{+1.1}_{-3.3}$ and $\log(A_{\text{DGL}}) = -8.2^{+1.1}_{-3.5}$ from the 1.1 $\mu$m and 1.6 $\mu$m data, respectively. In the top panels of Fig. 4 we show the 3.6 $\mu$m fluctuation spectrum measured by Spitzer (Cooray et al. 2012b for the same field, and Kashlinsky et al. 2012 in a different field as comparison), along with the contribution from DGL and $z < 5$ galaxies (clustering and shot noise) as computed by following the methods in Helgason et al. (2012). The solid line shows the sum of these two components while the light shaded area indicates the 1$\sigma$ uncertainty.

Shot noise and DGL account quite well for the observed power on both large and small scales. However, the clustering excess is still clearly visible at intermediate scales, i.e. at $300 \lesssim l \lesssim 2 \times 10^4$. In principle, such extra power might be partially accounted by the large errors associated to the estimated DGL component. However, the maximally allowed DGL power spectrum largely overestimates the observed signal at $l < 2 \times 10^3$. Moreover, we recall that if the 3.6 $\mu$m fluctuations were purely due to the combination of low-$z$ galaxies and DGL signals, the observed 3.6 $\mu$m - CXB cross-correlation would remain unexplained.

Given the results on the DGL obtained so far, it is important to re-examine the DCBH scenario in Yue et al. (2013b) to assess whether DCBHs can simultaneously pro-
Figure 2. The 3.6 µm auto-correlation power spectra derived from (1.1) 1.6 µm auto-power spectra and (1.1)1.6 × 3.6 µm cross-correlation power spectra by assuming perfect correlations. Upper panels: sum of DGL and low-z galaxies contributions. Bottom: we add the DCBH contribution (thin lines are for DCBH only, thick lines are the sum) consistent with a mass density of active DCBHs of $4 \times 10^5 M_\odot \text{Mpc}^{-3}$ at peak (solid curves and corresponding shaded regions) or $2.7 \times 10^5 M_\odot \text{Mpc}^{-3}$ at peak (dashed curves with corresponding shaded regions). In each panel the filled circles (triangles) with error bars are data from Cooray et al. (2012b) (Kashlinsky et al. 2012).

We will consider two cases: (i) the fiducial model described in Yue et al. (2013b), with a mass density in active DCBHs $\rho_\bullet \approx 4 \times 10^5 M_\odot \text{Mpc}^{-3}$ at peak, and (ii) a reduced model in which the abundance is about 2/3 of the fiducial one, $\rho_\bullet \approx 2.7 \times 10^5 M_\odot \text{Mpc}^{-3}$. Note that the DCBH mass density $\sim M_{\text{BH}} \times n_{\text{BH}}$, so there are degeneracies between the $M_{\text{BH}}$ and $n_{\text{BH}}$. Here, we actually only vary the $M_{\text{BH}}$, while keeping other parameters as in the fiducial model. Results are shown in the bottom panels of Fig. 2. It is clear that the DCBH fiducial model can provide the required power...
stellar light scattered by dust. In particular, we have found that:

- The (1.1)1.6×3.6 µm cross-correlation power spectra can be fitted nicely by a DGL component that dominates the large scale NIRB fluctuations, and a shot noise component from the remaining low-z galaxies accounting for the small scale power.
- By assuming perfect correlations (unity correlation coefficient) at different wavelengths, the derived best-fitting DGL fluctuations dominate the 3.6 µm auto-correlation power spectra on scales \( l \lesssim 300 \). Between 300 \( \lesssim l \lesssim 2 \times 10^4 \) extra sources in addition to the DGL and the remaining low-z galaxies are required to interpret the “clustering excess”.
- If the 3.6 µm NIRB fluctuations are only from DGL + remaining low-z galaxies, the observed 3.6-CXB cross-correlation is hard to explain. Introducing the DCBH gives a much better fit of 3.6 µm auto-correlation power spectra, and naturally explains the 3.6-CXB cross-correlation. It also predicts the much decreased clustering term in NIRB-CXB correlations at \( \lesssim 1.6 \) µm.
- Finally, we point out that the DGL inclusion allows to decrease by up to about 30% the required DCBH abundance/mass.

We conclude that the DCBH scenario remains a viable interpretation of the puzzling NIRB clustering excess, making the NIRB a superb tool to investigate the pristine cosmic epochs in which the supermassive black hole seeds formed.

4 CONCLUSIONS

The DCBH scenario accounting for the observed “clustering excess” over known galaxies signal in the NIRB power spectrum has been questioned by the recent detection of a correlation between the two CIBER 1.1/1.6 µm bands with the 3.6 µm Spitzer one. This correlation is hardly explained by early DCBHs that, due to intergalactic absorption, cannot contribute to the shortest wavelength bands. We have shown that the new correlation is caused instead by a Diffuse Galactic Light (DGL) component arising from Galactic

Figure 3. (0.5 − 2.0) keV CXB − 3.6 µm IR cross-correlation power spectrum. Points are observations from \textit{Cappelluti et al.} (2013); dashed curves show the contribution from DCBHs; solid curves are the sum of DCBH and remaining \( z < 6 \) sources (AGNs, galaxies and hot gas, from \textit{Helgason et al.} 2014). Thick (thin) lines are for the fiducial (reduced) model with \( \rho_* = 4 \times 10^5 \, M_\odot \, Mpc^{-3} \) (\( \rho_* = 2.7 \times 10^5 \, M_\odot \, Mpc^{-3} \)) at peaks.

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