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Cosmic Infrared Background ExpeRiment (CIBER): A probe of Extragalactic Background Light from reionization

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Abstract. The Cosmic Infrared Background ExpeRiment (CIBER) is a rocket-borne absolute photometry imaging and spectroscopy experiment optimized to detect signatures of first-light galaxies present during reionization in the unresolved IR background. CIBER-I consists of a wide-field two-color camera for fluctuation measurements, a low-resolution absolute spectrometer for absolute EBL measurements, and a narrow-band imaging spectrometer to measure and correct scattered emission from the foreground zodiacal cloud. CIBER-I was successfully flown in February 2009 and July 2010 and four more flights are planned by 2014, including an upgrade (CIBER-II). We propose, after several additional flights of CIBER-I, an improved CIBER-II camera consisting of a wide-field 30 cm imager operating in 4 bands between 0.5 and 2.1 microns. It is designed for a high significance detection of unresolved IR background fluctuations at the minimum level necessary for reionization. With a FOV 50 to 2000 times larger than existing IR instruments on satellites, CIBER-II will carry out the definitive study to establish the surface density of sources responsible for reionization.

Keywords. diffuse radiation, large-scale structure of universe, infrared: general

1. Introduction

The optical and UV radiation from sources present during reionization is now present in the near-infrared with a small, but non-negligible, contribution to the Extragalactic Background Light (EBL). Searches for this radiation based on absolute photometry have proven problematic due to confusion with the Zodiacal foreground. Instead of the absolute background, in Cooray *et al.* (2004), we proposed to develop a near-infrared sounding rocket experiment, CIBER, to conduct a deep search for extragalactic background fluctuations from the epoch of reionization associated with first-light galaxies.

The EBL spectrum contains all radiative information from the reionization epoch (Santos *et al.* 2003; Kashlinsky *et al.* 2004; Fernandez & Komatsu 2006; Cooray *et al.* 2009). We expect that the EBL contains diffuse signatures of reionization, such as Ly-α background radiation redshifted to near-IR wavelengths today. Remnants of these first stars, black holes in the form of miniquasars, will also contribute to the EBL (Cooray & Yoshida 2004).

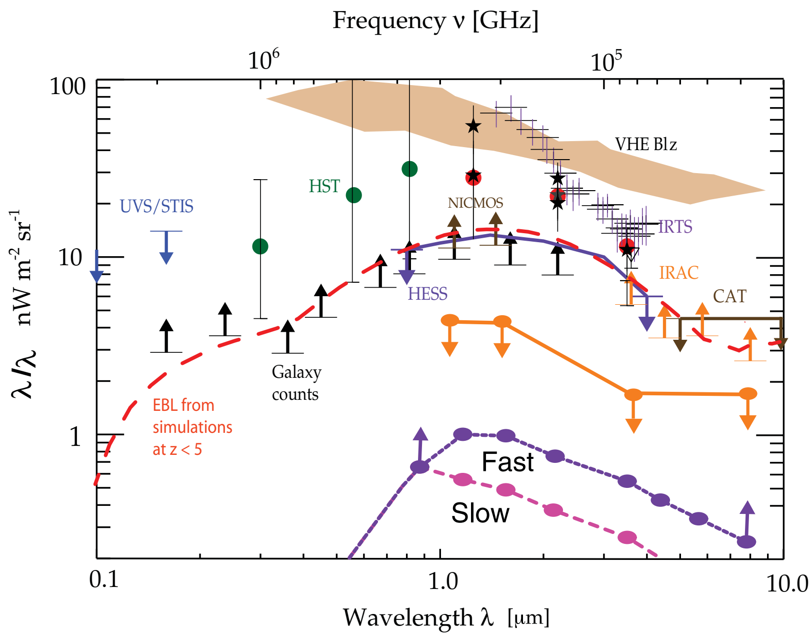

Figure 1. Summary of EBL observations at infrared and optical wavelengths, showing upper limits, reported residuals after subtraction of local foregrounds, reported detections with absolute photometry (DIRBE and IRTS), and integrated galaxy counts (lower limits). The large experimental scatter at 1.2 μm is notable, with Zodiacal removal suspected as a prime source of systematic error (Dwek et al. 2005). A recent upper limit based on TeV absorption using HESS (Aharonian et al. 2006) contradicts the excess reported by several authors at 1-2 μm. The indirect EBL measurements with TeV spectra, however, do not provide consistent results since a previous independent estimate suggests a higher background (the region labeled VHE Blz; Schroedter 2005). The long-dashed line shows the integrated galaxy light associated with galaxies formed at $z < 5$ based on a semi-analytical model (Primack *et al.* 2008). The dotted and dashed lower lines show the estimated EBL from $z > 6$ for fast and slow reionization histories, lower limits since the calculation is based on the minimum UV luminosity density needed to reionize and maintain the ionized state of the intergalactic medium (Chary & Cooray 2011). The light grey upper limits show constraints on the first-light EBL from reported fluctuations in deep Spitzer and NICMOS images.

Interestingly, integrated individual galaxy counts appear to fall short of the EBL measured with absolute photometry at near-infrared wavelengths (Fig. 1). For instance in the 1-3 μm band, galaxies contribute an intensity of $\sim$10 nW/m^2 sr (Madau & Pozzetti 2000). In contrast, measurements of the extragalactic background light (EBL) by DIRBE and the IRTS at the same wavelengths range from 10 nW/m^2 sr at 3.6 μm (Levenson & Wright 2008) to up to 60 nW/m^{2}sr at 1.2 μm (Cambresy *et al.* 2001; Matsumoto *et al.* 2005). It is highly unlikely that this whole difference is associated with sources during reionization, since such a large intensity requires unphysical requirements on star-formation (Madau & Silk 2005).

Though the total luminosity produced by sources responsible for reionization is uncertain, a lower limit can be placed assuming a minimal number of photons to produce and maintain reionization, given existing information on reionization, rest-frame UV luminosity functions of galaxies at $z > 6$, stellar mass estimates for galaxies at $z \sim 6$, among others (Chary & Cooray 2011). Such minimal reionization scenarios produce an EBL $\sim$ 1 nW/m^2 sr, a level undetectable by current absolute photometry measurements which, after dedicated space-borne measurements, show large discrepancies. As the

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spectral signature in EBL from reionization contains integrated emission from all sources, including fainter ones undetectable with JWST, it captures the exact reionization history and provides more information than other known probes of reionization, including CMB and 21-cm background. This spectral feature could be resolved in the future with absolute photometric measurements in narrow spectral bands between 1-2 μm with an out-of-Zodi EBL explorer at distances around 5 AU (Cooray *et al.* 2009).

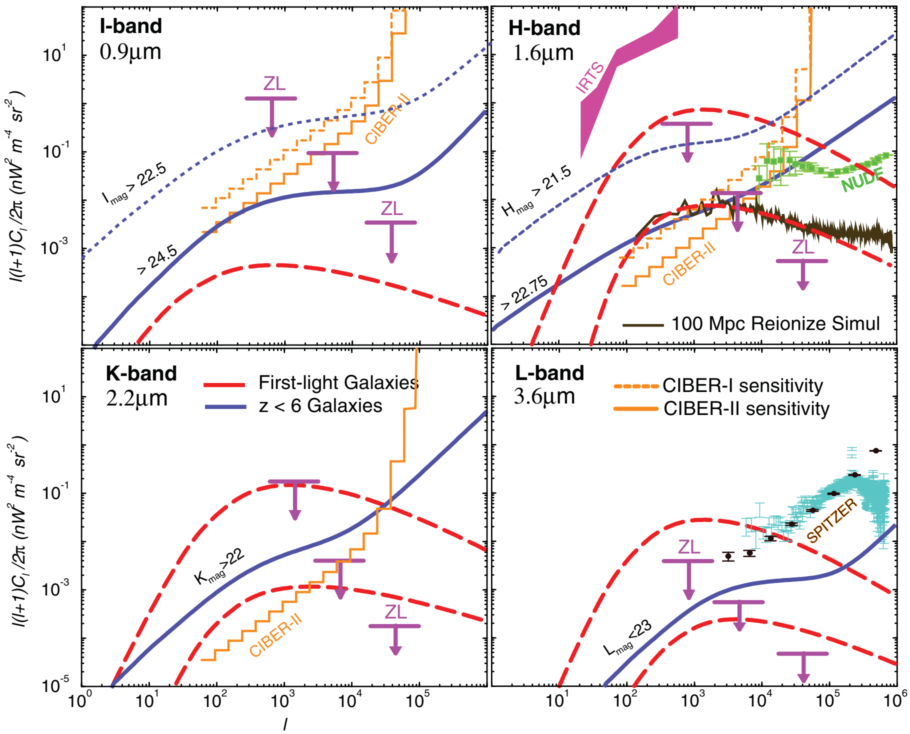

Figure 2. Spatial power spectrum of EBL fluctuations in standard IR bands. The long-dashed curves show the power spectra of fluctuations from first-light galaxies forming over the redshift interval $8 < z < 15$. The top long-dashed line shows the case where fluctuations are normalized to *Spitzer* measurements (Kashlinsky *et al.* 2008). The bottom long-dashed line shows the minimal signal necessary to produce reionization. Light grey points show *Spitzer* measurements by Kashlinsky *et al.* while black points show residuals from Cooray *et al.* after subtracting faint, blue dwarfs detected in deep HST ACS images. The thick-solid curves give estimated fluctuations from known galaxies, as a function of magnitude cutoff, based on a galaxy distribution model based on the halo appoach (Cooray & Sheth 2002; Cooray 2006) matched to existing clustering data (e.g., Sullivan *et al.* 2007). The galaxy cutoff taken for CIBER is 25% pixel removal using deep ancillary source catalogs. CIBER-II (thick-solid line) has a lower residual local galaxy foreground due to its smaller pixel size compared with CIBER-I (small-dashed line). The stair-steps in three panels shows the binned statistical sensitivity of CIBER-I and CIBER-II instruments in a single 50s observation. Zodiacal light is known to be spatially uniform, shown by the upper limits. The fluctuations in the upper-right panel are the EBL fluctuations resulting from a 2048^3 particle, large volume (100 Mpc) numerical simulation of reionization completed by the Princeton group (Trac & Cen 2007) with a combination of both Pop II and Pop III stars in first-light galaxies, as analyzed by the UCI team. The shape of fluctuations is model independent and shows the overall bump at $\ell \sim 1000$ in agreement with the analytical model.

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Even in the relatively recent times since reionization it appears there may be an under accounting of galaxies. The current star-formation in Lyman-break galaxies (LBGs) at $z \sim 6$ (Bouwens *et al.* 2006) falls about a factor of 6 to 9 below the minimum required to maintain an ionized IGM given canonical estimates for the clumping factor of the gas and the escape fraction of ionizing photons from galaxies. The upper limits on the ultraviolet luminosity function suggests a negative evolution with increasing redshift, in the sense that galaxies at the bright end of the UV luminosity function at $z \sim 6$ were fainter in the ultraviolet. The implication is that the contribution from star-formation in faint galaxies, below the detection threshold of current surveys, is higher than has been estimated. The *Spitzer* stellar mass estimates suggest a top-heavy IMF for high redshift galaxies (Chary 2008), suggesting a different stellar population in those galaxies than in the local Universe. If current galaxy surveys under account for galaxy evolution or miss populations, the deficit may be uncovered in a careful study of the EBL.

A first-light galaxy EBL component from reionization and any contribution from faint sources at $z \sim 6$ unresolved by existing deep, pencil surveys can be uncovered using a careful study of background fluctuations (Cooray *et al.* 2004). The technique involves the measurement of the angular power spectrum via an anisotropy study, similar in method to well-established techniques for studying CMB anisotropy. First-light galaxies have predictable clustering, determined by the growth of dark matter perturbations in ΛCDM cosmology, and will produce EBL fluctuations with a characteristic spatial power spectrum. Zodiacal light is known to be spatially uniform on arcminute scales. What is uncertain is the amplitude of fluctuations since it depends on the astrophysics of reionization and the importance of, say, fainter sources at $z \sim 6$ to 8 that are responsible for maintaining reionization. A fluctuation measurement has the potential to detect a first-light galaxy component to the EBL at much fainter levels than can be probed with absolute photometry.

Since our work on CIBER began (Cooray *et al.* 2004; Bock *et al.* 2006), *Spitzer* IRAC has carried out a study of EBL clustering anisotropy. After a deep removal of both point sources, and deconvolving emission from the extended PSF, Kashlinsky *et al.* (2005; 2007) claim detection of first-light galaxy fluctuations based on a deviation from a shot-noise power spectrum on the largest angular scales.

Some doubt may be cast on the interpretation of first sources due to the angular scales and wavelengths covered by IRAC. Due to IRAC's small field of view, the power spectrum from high-z objects must be carefully separated from fainter, unresolved foreground galaxies (Cooray *et al.* 2007; Chary *et al.* 2008). In addition, fluctuation measurements have been made at shorter near-IR wavelengths in narrow, but very deep, NICMOS images (Thompson *et al.* 2007). The images again show a fluctuation signal (Fig 2). The spectrum of fluctuations measured between *Spitzer* IRAC and HST NICMOS appears to be approximately flat, and the authors state it does not correspond to the shape expected for $z > 8$ sources (Thompson *et al.* 2007), but rather to a low redshift population unresolved in both *Spitzer* and HST.

Considering the difficulty of the measurement, we believe the amplitude between NICMOS and *Spitzer* is quite uncertain. We also note that narrow fields such as GOODS and NICMOS UDF are affected by cosmic variance, especially at $z > 6$, where the correlation length of halos responsible for reionization is greater than the field size. These caveats do not rule out the possibility that the *Spitzer* fluctuations, at least at some fractional level, reveal a first-light component. The initial results are clearly exciting, and have important implications on galaxy formation, but IR background fluctuations must be further studied at shorter wavelengths, where the signatures from reionization are expected to dominate.

2. CIBER-I

The CIBER instrument currently consists of two wide-field imagers to measure EBL fluctuations, a Low-Resolution Spectrometer (LRS) to probe the EBL via absolute photometry, and a Narrow-Band Spectrometer (NBS), to measure the brightness of the Zodiacal light by the Ca-II 854.2 Fraunhofer line (Bock *et al.* 2006). Two imaging cameras operate at 0.9 and 1.6 μm and probe EBL fluctuations over a wide 4 sqr. degree field of view, allowing measurements over the distinctive peak in the power spectrum at $\ell \sim 2000$ (0.1 degrees).

With the NBS, CIBER will also test the large EBL intensity ($\sim$50 nW/m^2 sr) reported by DIRBE and IRTS. The measurement is not limited by the sensitivity of the instruments, but primarily by the Zodiacal foreground and to a lesser extent by the astrophysical systematic errors in removing stars and scattered starlight, expected to be $\sim$ 2% of the Zodiacal brightness.

As the residual EBL spectrum closely resembles that of Zodiacal light (Dwek *et al.* 2005), there is the possibility of a large $\sim$25% error in the Zodi model used by both DIRBE and IRTS teams. The NBS has sufficient sensitivity and systematic error control to precisely measure the Zodiacal amplitude at 854.2 nm. This measurement can be extrapolated to the DIRBE 1.2 and 2.2 μm bands based on the Zodiacal spectrum measured by the LRS. We also propose several additional flights to observe multiple lines of sight through the Zodiacal cloud, measured between a span of 6 months, to vary the solar elongation angle. The observation windows are carefully chosen so these fields are within the DIRBE observations at the same time of year. If the DIRBE models are incorrect at the 20% level, this should become readily apparent, and the multiple observations are necessary to help us understand how the Zodi models should be corrected.

CIBER-I was launched from White Sands Missile Range in New Mexico on a Terrier-Black Brant sounding rocket on February 2009 and in July 2010. The vehicle performed as expected, and the payload achieved an apogee of 320 km in both flights. All flight events went according to plan and we hope to release our first science results within a year (a result based on CIBER-I involving the zodiacal light spectrum and the silicate absorption appears in the literature; Tsumura *et al.* 2010). With the second flight, we now have a first measurement of the EBL out to angular scales grater than 30 arcminutes at 1 and 1.6 μm with CIBER. This fluctuation analysis will test the claims of Kashlinsky *et al.* (2007) at shorter near-IR wavelengths. The results will be published over the coming year. CIBER-I has two more flights scheduled, with the next panned for February 2012.

3. CIBER-II

After the planned fourth flight in 2013, we plan a more capable camera designed to probe fluctuations down to the low level of minimal reionization fluctuations, with a factor of $\sim$ 10 improvement in sensitivity compared to that of CIBER-I (see Fig. 2). The CIBER-II camera consists of a 30 cm telescope operating simultaneously in four bands between 0.5 and 2.1 μm with each imaging the same 2 sqr. degree field of view. The four bands are matched to identify the spectral dependence of the reionization contribution from foreground and Zodiacal fluctuations. As is the case with CIBER-I, CIBER-II will image wide fields with existing deep coverage in optical and near-IR with *Spitzer* and ground-based instruments.

The cameras are designed for high sensitivity to surface brightness in the short amount of time available during a sounding rocket flight. In comparison with space-borne telescopes, CIBER-II measures fluctuations on large angular scales, on both sides of the expected peak in the power spectrum. These are also the angular scales best suited for distinguishing this signal from local galaxies, and systematic effects due to its distinctive power spectrum. By measuring large angular scales, potential problems with source removal are less serious than in a small deep measurement. CIBER-II is designed to have a very large instrumental FOV, the figure of merit relevant for measuring surface brightness, reaching the required raw sensitivity even in a short sounding rocket flight compared with the long integrations possible on a satellite. It is expected that CIBER-II will carry out the definitive study to establish the surface density of sources responsible for reionization and its results will complement number counts at $z > 6$ from JWST, especially at the bright end, to put a complete picture of reionization together. NASA has already approved two flights with CIBER-II in 2013 and 2014.

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Discussion

Madore: To reach 0.1 % accuracy on the EBL how large an area do you have to survey to beat cosmic variance?

Cooray: ZEBRA will cover 10 fields as a function of galactic latitude with each covering about 10 sq. degrees. 10 fields are adequate to beat the cosmic variance.