

A New Era in Extragalactic Background Light Measurements: The Cosmic History of Accretion, Nucleosynthesis and Reionization

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Executive Summary

What is the total radiative content of the Universe since the epoch of recombination? The extragalactic background light (EBL) spectrum captures the redshifted energy released from the first stellar objects, protogalaxies, and galaxies throughout cosmic history. It is a key constraint on all models of galaxy formation and evolution, and provides an anchor that connects global radiation energy density to star formation, metal production, and gas consumption. Yet, we have not determined the brightness of the extragalactic sky from UV/optical to far-infrared wavelengths with sufficient accuracy to establish the radiative content of the Universe to better than an order of magnitude.

The first-generation of EBL measurements established that the far-infrared background is energetically as important as the optical/near-IR background, revealing the importance of dust in high redshift galaxies. As a function of wavelength, a cosmic consistency test can be performed by comparing the integrated light from all galaxies resolved by both ground and space-based observatories to the EBL intensity. Any discrepancies suggest the presence of new, diffuse sources unresolved by telescopes. The possibilities for new discoveries with profound implications for astronomy range from recombination signatures during reionization, unexpected sources such as primordial blackholes, photons from decay of elementary particles, to a new component to the interstellar medium of the Milky Way.

Among many science topics, a precise measurement of the EBL spectrum from optical to far-IR wavelengths, will address the following questions:

- What is the total energy released by stellar nucleosynthesis over cosmic history?
- Was significant energy released by non-stellar processes?
- Is there a diffuse component to the EBL anywhere from optical to sub-millimeter?
- When did first stars appear and how luminous was the reionization epoch?

Zodiacal dust in the Solar System is the main foreground that limits precision EBL measurements at optical and near-IR wavelengths, while interstellar dust in the Galaxy limits measurements at far-infrared wavelengths. Therefore, EBL measurements must be considered over the next decade in parallel with techniques and observing methods that further our understanding of zodiacal and Galactic dust. Absolute EBL measurements to an astrophysically interesting precision can be achieved by wide field imaging from the outer Solar System either at a distance of 5 AU or above the ecliptic plane where the zodiacal foreground is reduced by more than two orders of magnitude. Such an imaging opportunity could be conceived as part of a mission to the outer Solar system.

The high energy (GeV/TeV) source community will benefit from this program as a precise measurement of the EBL spectrum allows the intrinsic spectra of AGN at TeV energies to be established which will in turn, provide a better understanding of their time variability and the acceleration of relativistic electrons responsible for the high energy emission. The planetary scientists and dynamicists will benefit from precision measurements of the zodiacal dust cloud as details of its origin and the source of zodiacal dust are still hotly debated. A detailed characterization of our zodiacal cloud will provide critical information required to fine-tune imaging studies of extra-Solar terrestrial planets and exo-zodiacal clouds in nearby stars.

Introduction: A complete understanding of the total energy content of the Universe across the entire electromagnetic spectrum is still lacking. While at radio wavelengths the cosmic microwave background (CMB) produced by primordial photons has been well studied over the last quarter century, with a detailed characterization of CMB fluctuations with two satellite missions (COBE and WMAP), the same cannot be said of the backgrounds that peak at both optical/near-IR and far-IR (submm) wavelengths. At optical and near-IR wavelengths the absolute EBL is a measure of the energetics of unobscured star formation in the Universe [1], while at far-IR wavelengths the EBL gives a measure of the photon content reprocessed by dust, both in galaxies and between galaxies [2]. Thus, the near-IR EBL has been suggested as a way to identify first sources that reionized the Universe while the sub-mm EBL reveals the star-formation history enshrouded by dust [3].

What is the total energy released by nucleosynthesis over cosmic history? Our attempts to resolve the EBL into individual galaxies rely on deep observations which measure the contributions of faint sources. At far-infrared wavelengths where source confusion due to the large point spread function is an issue, we predominantly rely on stacking homogeneous populations of galaxies detected at other passbands to measure the contribution of faint, hitherto undetected sources. Both these techniques suggest that $\sim 85\%$ of the integrated galaxy light arises from galaxies at $z < 1.5$ corresponding to the peak in the star-formation history and the rapid growth of stellar mass in galaxies.

However, integrated galaxy light estimates typically fall well short of the absolute EBL values. For instance at $3.6 \mu\text{m}$, the galaxies contribute an intensity of $\sim 9 \text{ nW m}^{-2} \text{ sr}^{-1}$ [4]. In contrast, the EBL measured by DIRBE at the same wavelength is $(13.3 \pm 2.8) \text{ nW m}^{-2} \text{ sr}^{-1}$ [5]. Similarly, at FIR wavelengths, the stacking at $160 \mu\text{m}$ reveals a galaxy contribution of $(13.4 \pm 1.7) \text{ nW m}^{-2} \text{ sr}^{-1}$ [6] while the DIRBE measured EBL is $(25 \pm 7) \text{ nW m}^{-2} \text{ sr}^{-1}$ [7]. It is therefore unclear if there is a significant component of the EBL that arises from star-formation and AGN activity which are hidden from traditional deep, pencil-beam surveys, particularly at $z > 1.5$. Such a revelation would dramatically change our understanding of the peak of cosmic star-formation and indicate the presence of massive, quiescent (or dust obscured) galaxies at $z > 1.5$ which are missed in traditional, Lyman-break galaxy selections.

Furthermore, a discovery of hidden star-formation and stellar mass, would help address the difficulties associated with keeping the intergalactic medium in the Universe ionized between $z \sim 3 - 6$. Current models require a non-Salpeter, top-heavy IMF [8] in galaxies at $z > 2$ to reconcile estimates of star-formation rates and stellar mass density estimates and for maintaining the ionized state of the IGM.

The EBL spectrum also contains all radiative information from the reionization epoch [9]. Diffuse signatures are expected in terms of Ly- α background radiation redshifted to near-IR wavelengths today. While individual galaxies contributing to such a background during reionization will be most likely resolved by JWST, due to their large clumping factors, any backgrounds that scatter to a larger extent especially in an under dense region will contribute to the EBL [10], but most likely not be detected by JWST. Whether the epoch of dust formation quickly followed reionization or whether that epoch was substantially delayed since the appearance of first stars hold clues to star and galaxy formation. A careful analysis of the sub-millimeter background combined with galaxy counts and fluctuations of the EBL at near-IR from JWST and future IR missions can address this question.

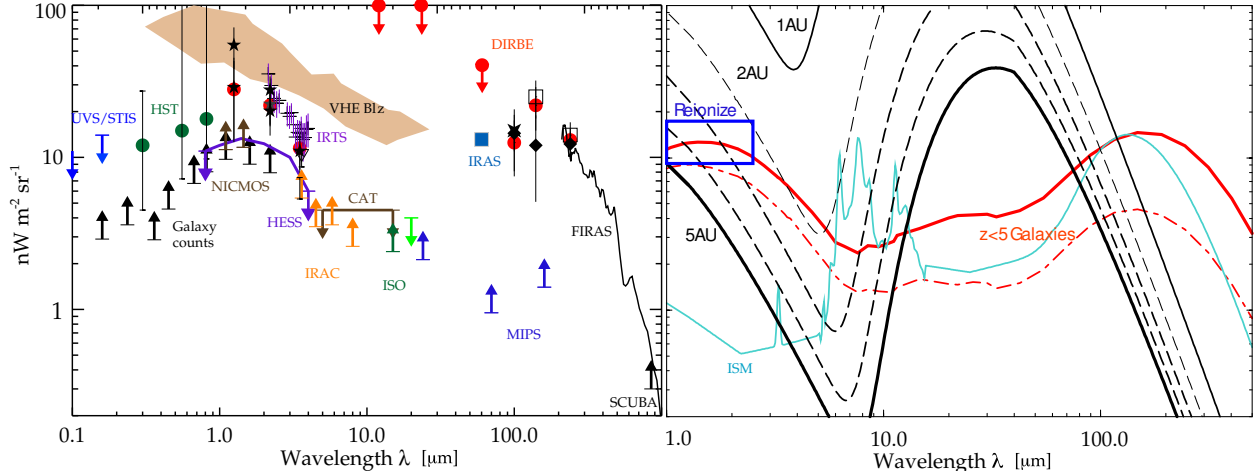


Figure 1: *Left panel:* The total optical to far-IR EBL measured from a combination of absolute photometry (ie. HST, DIRBE, IRTS, and FIRAS) and with indirect techniques (GeV/TeV blazar spectra and resolved/stacked galaxy counts) [6]. *Right panel:* The scattered light and thermal emission (black lines) at 1 AU to 5 AU from the Sun, for the zodiacal cloud with a radial density profile of $r^{-3/2}$. The line labeled ISM is the Galaxy emission towards a typical low-dust field. The curves in red show two predictions for the integrated light from $z < 5$ galaxies in semi-analytical models normalized to observed galaxy counts. The blue box labeled “Reionize” shows the wavelength range of interest for EBL measurements targetting diffuse emission from reionization, such as redshifted Lyman- α . At a distance of 5 AU, absolute photometry measurements can be carried out to determine the EBL spectral signature from reionization, without any significant zodiacal foreground as at 1 AU.

Was significant energy released by non-stellar processes? The dust torii surrounding active galactic nuclei leads to a secondary contribution from AGN to the EBL at longer wavelengths, providing a way to study the role played by AGN in galaxy formation and evolution. Contributions to the EBL spectrum are also expected from first stars and primordial blackholes in the form of miniquasars during reionization [11] and diffuse emission from haloes of galaxies and clusters. The reionization of the diffuse intergalactic medium will be accompanied by radiative recombination radiation with Lyman- α line from collisional excitation. An exciting possibility is a diffuse background from elementary particle decays. Neutralinos that decay to gravitinos and photons with mass splittings in the order of eV, instead of the usual MeV products, could lead to a photon background at IR wavelengths [12]. The lifetimes would be greater than 10 Gyrs and the photons would cluster similar to dark matter at late times instead of tracing luminous sources at halo centers.

In the future, sub-millimeter wavelength absolute and fluctuation measurements can also be used to constrain any spectral distortions to the CMB associated with most mechanisms of energy generation during reionization. In the wavelength range 100 μm to 1000 μm broad recombination lines from cosmological H and He before dark ages are also expected with intensities at the level of 10^{-5} $\text{nW m}^{-2} \text{sr}^{-1}$ [13].

State of the field: In Figure 1 (left panel) we summarize EBL intensity measurements between optical and far-IR wavelengths using absolute photometry, the integrated galaxy light from galaxy counts (lower limits), or with the TeV spectra of high redshift sources

(usually upper limits). The latter comes through the absorption seen in TeV spectra of blazars as high energy photons pair produce off of infrared background photons.

As is clear from Figure 1, we have not come close to achieving any reasonable estimate of the EBL spectrum over three decades in wavelength from $0.1 \mu\text{m}$ to $100 \mu\text{m}$ which is in stark contrast to the progress achieved at X-ray energies between $\sim 2\text{--}10 \text{keV}$. The few attempts at absolute measurements involve DIRBE on COBE in several bandpasses between $1.25 \mu\text{m}$ and $240 \mu\text{m}$ [7], IRTS, a small JAXA mission, between 1 and $4 \mu\text{m}$ [14], and FIRAS above $200 \mu\text{m}$ [15]. Because DIRBEs confusion limit was 5th magnitude at $2.2 \mu\text{m}$, all recent EBL measurements using DIRBE require subtraction of stellar light using ancillary measurements, such as 2MASS [5]. While the HST has been used for optical [16] and UV [17] EBL measurements, the instrument was not designed for absolute photometry and required a careful subtraction of instrument emission and baselines (e.g. dark current) and those measurements are subject to large uncertainties. Between $\sim 10 \mu\text{m}$ to $100 \mu\text{m}$, there is a dearth of accurate measurements and the EBL is loosely constrained from GeV/TeV source spectra, ISO/Spitzer, and with large upper limits from DIRBE.

Among the indirect methods, the large difference in EBL estimates from TeV spectra is due to uncertainty in the intrinsic measurements is subject to the assumed intrinsic shape of the high-energy emission spectrum, which is known to be time-dependent and vary from source to source. Furthermore, recent Fermi results of high energy blazars seem to suggest that the adopted gamma-ray spectrum of these blazars is much softer than previously thought. This translates directly to an error on the inferred EBL constraints. One attempt at constraining the near-IR EBL indirectly with TeV blazars [18] (line in Fig. 1 between 1 and $4 \mu\text{m}$) seems to suggest that we have essentially resolved almost all of the EBL with known galaxy counts. A second attempt [19] (shaded region in Fig. 1), consistent with large DIRBE EBL estimates, imply that we are far away from resolving the background, even with JWST due to source confusion.

In retrospect, if a precise measurement of the EBL at IR wavelengths were to be available, then instead of indirect limits on the IR EBL with TeV spectra with an assumed intrinsic spectrum, TeV sources detected in experiments such as HESS, VERITAS, and MAGIC can be used to pursue the primary goal of understand the astrophysics of high energy emission and AGNs. This requires that the EBL spectrum between 4 and $10 \mu\text{m}$ be determined directly as the attenuation of high energy photons is dependent on the shape of the spectrum in this small wavelength range where no measurements currently exist [20].

At far-IR wavelengths, cosmological surveys with Herschel are expected to resolve about 10% of the FIRAS EBL between $250 \mu\text{m}$ and $550 \mu\text{m}$, though the FIRAS EBL measurement itself is largely uncertain and must be improved in the future. In fact, due to the negative k-correction at sub-millimeter wavelengths, the EBL at $\sim 850 \mu\text{m}$ provides the strongest constraint on the fraction of star-formation at $z > 3$ which is obscured by dust. Similar to the situation with JWST, source counts from deep surveys expected with ALMA at wavelengths greater than $300 \mu\text{m}$ will only be useful in understanding the importance of discrete source populations if they are accompanied by EBL measurements.

Is there a diffuse component to the EBL? As discussed, the integrated galaxy counts fall short of the absolute EBL estimates measured by DIRBE at 2.2 and $3.6 \mu\text{m}$ where there is a minimum in the contribution of the scattered and thermal components of the zodiacal

light [21]. While it is possible that deep extragalactic survey counts miss flux from extended components, especially in ground-based infrared surveys, and the large difference around $1 \mu\text{m}$ based on IRTS is far more likely to be associated with residual zodiacal light [22], the current state of measurements do not exclude the possibility of a faint, diffuse near-infrared background of cosmological origin. The issue of cosmic variance is also key since the best measures of the 1.1 and $1.6 \mu\text{m}$ integrated galaxy light come from the NICMOS UDF [23], which spans an angular scale about ~ 6 Mpc, smaller than the clustering scale of typical $\sim 10^{12-13} M_{\odot}$ dark matter halos at $z > 3$. A mission outside the zodiacal cloud with a factor of 100 lower zodi foreground can resolve the current discrepancies and search for diffuse background components at very low levels. While Spitzer and HST have revealed the $z < 4$ universe in detail and JWST will detect higher redshift sources, future absolute EBL measurements between $0.5 \mu\text{m}$ and $2.5 \mu\text{m}$ in several narrow wavelength bandpasses with an uncertainty less than $0.5 \text{ nW m}^{-2} \text{ sr}^{-1}$ (a factor of ~ 30 to 50 improvement over DIRBE) will be necessary for this purpose.

At far-infrared wavelengths, a component of diffuse EBL arising from dust in the IGM would be a significant problem for dark energy measurements using the next generation of supernova surveys. This grey-dust, which it has been argued would need to have extinction properties different from Galactic dust [24], would obscure the light from supernova and mimic the cosmological constant providing a floor to the uncertainty in measuring the equation of state $w(z)$.

When did first stars appear? Current theoretical models of reionization matched to Lyman-break galaxy luminosity functions out to redshifts of 7 at the bright-end suggest that first-light sources prior to full reionization contributed between 0.6 to $1 \text{ nW m}^{-2} \text{ sr}^{-1}$ to the total EBL light between $\sim 1 \mu\text{m}$ and $2 \mu\text{m}$. Their contribution to the lower wavelength optical background, however, is negligible as the light is redshifted beyond the optical. *This spectral signature in the optical to near-IR EBL should be a primary target for a dedicated mission to measure EBL at distances around 5 AU.*

If absolute measurements of the EBL spectrum can be achieved with errors better than $0.1 \text{ nW m}^{-2} \text{ sr}^{-1}$ between $0.8 \mu\text{m}$ and $2 \mu\text{m}$, we can in fact use the amplitude and shape of the spectral signature with JWST counts to determine when sources first turned on. The WMAP optical depth to electron scattering that is routinely quoted as when the reionization ended does not provide this information uniquely and the only other avenue to extract such information is the use of 21-cm background.

While absolute EBL spectrum is currently uncertain, fluctuations in the EBL can be used to study faint, unresolved sources. Measurements with HST and Spitzer, for the first time, have allowed first constraints to be placed on the surface density of faint, unresolved sources at intermediate to high redshifts using any observational windows available [25].

The limited range of angular scales provided by Spitzer and HST and planned studies during the Spitzer Warm Mission in a handful of deep, but narrow, fields complicate detailed inferences from clustering of unresolved fluctuations. Measurements that span out to several degree angular scales are necessary to separate cosmological sources of interest from those in the foreground, including tens of degree-scale correlations expected from both zodiacal and Galactic dust. The limitation due to small area is worse for current fluctuation measurements over the $1 \mu\text{m}$ to $2 \mu\text{m}$ wavelength range of interest where first-light galaxies peak, but some

limited improvements are expected with WFC3 on HST.

With the expected background from reionization estimated to be around 0.6 to 1.0 nW m⁻² sr⁻¹ between 1.0 μm to 1.6 μm, to detect few percent rms fluctuations expected at sub-degree angular scales, planned surveys must allow anisotropy measurements to reach a rms fluctuation level at or better than 0.05 nW m⁻² sr⁻¹ at 30 arcminute scales or the angular power spectrum $\ell^2 C_\ell / 2\pi$ at $\ell \sim 100$ to 1000 down to 10⁻³ nW² m⁻⁴ sr⁻².

Interpretation of Spitzer/WFC3 fluctuation measurements with deep surveys will be enhanced if these measurements are accompanied by multi-wavelength studies of clustering of resolved faint sources. New opportunities could be available in the next decade with facilities that will effectively allow wide, deep imaging at near-IR wavelengths. For those surveys to accurately determine a diffuse component and to complement deep galaxy counts from JWST, future space-based IR imaging must have imaging capabilities that span at least a square degree between 0.8 μm to 2.0 μm. The studies must be performed in deep imaging data with sources resolved down to a few hundred nJy level. A multi-wavelength strategy combining luminosity functions, clustering of resolved sources, and cross-correlation measurements against other cosmological tracers (e.g., 21-cm) can be used to extract astrophysical details of the unresolved population, including the redshift distribution and to connect source distribution to that of dark matter through approaches such as the halo model.

Unlike the case with optical and near-IR data from space-based imagers, only a handful of attempts on fluctuation measurements exist at far-IR wavelengths [26]. This situation, however, is expected to soon change with wide-field imaging with instruments aboard Herschel. In fact, Herschel fluctuation measurements are necessary to study properties of sources that produce the bulk of the background light at sub-millimeter wavelengths. Given the recombination lines from cosmological H and He at redshifts prior to dark ages, with resolved sources removed, a detailed fluctuation study of the sub-millimeter background with a followup mission to Herschel could potentially be used to extract the detailed history of cosmological recombination (and any departures from standard physics) beyond the information provided by the CMB anisotropy spectrum.

What is the total radiative content of the Universe? We return to our central question. The reason that we do not yet know the answer to this question is essentially an issue of foregrounds in EBL measurements, namely stars, interstellar dust, interplanetary dust emission, at mid-infrared and far-infrared wavelengths, and sunlight scattered by interplanetary dust (zodiacal light), at optical and near-infrared wavelengths. Many DIRBE-based and IRTS-based results use a model of interplanetary dust scattering and emission [27], while others use an alternate model based on the principle that the zodiacal residual be zero at 25 μm at high ecliptic latitudes [28]. The HST results on the optical background subtract zodiacal emission based on the observed strength of reflected Fraunhofer lines from a ground-based measurement [16]. Unfortunately, zodiacal dust models are not unique and represent a leading source of systematic error. In the shortest DIRBE band, the difference between the two leading zodi models is somewhere between 50% to 100% of the EBL estimates (~ 20 to 40 nW m⁻² sr⁻¹) at near-IR wavelengths. *Simply repeating an absolute photometry experiment like DIRBE or IRTS will not improve current EBL measurements at wavelengths below 5 μm, unless supplemented with on-board absolute spectroscopy to monitor scattered Fraunhofer lines.*

Improvements in EBL measurements must come with a parallel improvement in our understanding of the zodiacal cloud, including the the structure of the zodiacal cloud and the distribution of zodiacal dust particles over their orbital elements. The structure and the density profile depend on sources of dust particles and sizes of the particles and it is still not established whether asteroidal or cometary dust dominate in the zodiacal cloud [29]. *In situ* measurements with Pioneer 10 indicate that dust density is dropping more rapidly than the $1/r$ radial behavior expected from the Poynting-Robertson force [30]. The zodiacal cloud itself contains unique science involving dynamics within the Solar system. The out-of-zodi EBL measurements (proposed below) and studies of the zodi velocity profiles, together with models of migration of dust, will help us to understand better the distribution of dust particles beyond Jupiter distance over their orbital elements and to estimate fractions and typical sizes of cometary and trans-Neptunian particles in the zone of the giant planets.

Priorities for 2010-2020 The absolute sky brightness is so strongly dominated by zodiacal light from visible to mid-infrared wavelengths that it is not possible to measure the EBL with confidence at distances of 1 AU with a 0.1% or better removal of zodi needed to detect the reionization spectral feature around $1 \mu\text{m}$ (Figure 1 right panel). The only way to measure the EBL with any useful accuracy between 5 and $50 \mu\text{m}$ is to conduct measurements outside the zodiacal cloud. There are two possibilities: traveling beyond Jupiter, or above the ecliptic plane. At distance of Jupiter, existing *in-situ* measurements with Pioneer 10 indicate a decrease in zodiacal light of two orders of magnitude, relative to the brightness at 1 AU. In addition to EBL measurements, on the way to the outer Solar System, measurements can be made to establish the dust density radial and azimuthal profiles. A measurement EBL and interplanetary dust distribution can be conceived either as a modest mission dedicated to this purpose or as a camera that piggy-backs on a Planetary mission to the outer Solar System.

As first steps towards this priority sounding rocket experiments can be pursued for absolute photometry. Methods of constraining the zodiacal light, e.g. using Fraunhofer lines as a spectral signature, have been developed and used successfully in the past. The time variation of zodi in three to six month intervals along the same lines of sight can be pursued to extract additional information.

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