Data from (non-) attenuation of gamma rays from blazars and gamma ray bursts (GRBs) give upper limits on the EBL from the UV to the mid-IR that are only a little above the lower limits from observed galaxies. New data on attenuation of gamma rays from blazars now lead to statistically significant measurements of the cosmic gamma ray horizon as a function of source redshift and gamma ray energy that are independent of EBL models. These new measurements are consistent with recent EBL calculations based both on multiwavelength observations of thousands of galaxies and also on semi-analytic models of the evolving galaxy population. Such comparisons account for (almost) all the light, including that from galaxies too faint to see.
Galaxies in every corner of the universe have been sending out photons, or light particles, since nearly the beginning of time. Astronomers are now beginning to read this extragalactic background light.

By Alberto Domínguez, Joel R. Primack and Trudy E. Bell

Extragalactic Background Light

The extragalactic background light (EBL) includes all the light from all the galaxies that have ever shined. It began to accumulate when the first stars and galaxies formed, roughly 200 million years after the big bang, and new galaxies add their light all the time. Still, because space is so vast (and expanding), this light is dim and diffuse. The cosmic microwave background (CMB) is another radiation field that also pervades the universe. The CMB, however, does not grow with time; rather it was formed all at once, about 400,000 years after the big bang.
Cosmic Extragalactic Backgrounds

Herschel far-IR  Spitzer mid-IR  HST-optical/UV

0.850-1.2mm

0.850-1.2mm

in the future: ALMA, CCAT..

Extragalactic Background Light (EBL)

\( \nu S_\nu \) (nW m\(^{-2}\) Hz\(^{-1}\))

Big Bang

stars + black holes

black holes

Chandra/XMM –X-ray

Frequency [Hz]

Wavelength

\( \nu \)

S_\nu

\( (\text{nW m}^{-2}\text{ Hz}^{-1}) \)
Extragalactic Background Light (EBL)

- The usual plot of $\lambda I_\lambda = dI/d \log \lambda$ vs. $\log \lambda$ shows directly the ENERGY DENSITY $\rho_\lambda = (4\pi/c) \lambda I_\lambda$ in the EBL:

  \[ 1 \text{ nW/m}^2/\text{sr} = 10^{-6} \text{ erg/s/cm}^2/\text{sr} = 2.6 \times 10^{-4} \text{ eV/cm}^3 \]

- Total EBL $\Omega_{EBL}^{obs} = (4\pi/c) I_{EBL}/(\rho_{\text{crit}} c^2) = 2.0 \times 10^{-4} I_{EBL} h_{70}^{-2}$

- The estimated $I_{EBL}^{obs} = 60-100$ nW/m$^2$/sr translates to

  \[ \Omega_{EBL}^{obs} = (3-5) \times 10^{-6} \] (about 5% of $\Omega_{CMB}$)

- Local galaxies typically have $E_{\text{FIR}}/E_{\text{opt}} \approx 0.3$, while the EBL has $E_{\text{FIR}}/E_{\text{opt}} = 1-2$. Hence most high-redshift radiation was emitted in the far IR.
more luminous and massive galaxies are (much) more obscured: for starbursts and (U)LIRGs a de-reddening of the UV-emission does not succeed: the central starburst is behind a ‘black screen’ and the UV emission comes from a lower obscuration component; even de-reddened Hα fails by about a factor of 10; ULIRGs/starbursts often have ‘post-starburst’ UV/optical SEDs while the real starburst is completely hidden

Sanders & Mirabel 1996, Meurer et al. 1999, Wuyts et al. 2011
EBL Evolution Calculated from Observations Using AEGIS Multiwavelength Data

\[ j_i(\lambda, z) = \int_{M_2}^{M_1} \frac{\Phi(M_K, z)f_i T_i(M_K, \lambda)}{dM_K} + \]
\[ + \int_{M_3}^{M_2} \frac{\Phi(M_K, z)m_i T_i(M_K, \lambda)}{dM_K} + \]
\[ + \int_{M_4}^{M_3} \frac{\Phi(M_K, z)b_i T_i(M_K, \lambda)}{dM_K} \]

Luminosity function observed K-band, Cirasuolo+ 09

Spectral energy distributions
SWIRE template library, Polletta+ 07

Spectral-type fractions

\[ \lambda I_\lambda(z) = \frac{c}{4\pi} \int_{z}^{z_{\text{max}}} j_{\text{total}}(\lambda(1+z)/(1+z'), z') \left| \frac{dt}{dz'} \right| dz' \]
The AEGIS Survey...

...is unlocking the secrets of galaxy and large-scale structure formation over the last 9 billion years.

AEGIS is targeted on a special area of the sky, called the Extended Groth Strip (EGS), that has been observed with the world's most powerful telescopes on the ground and in space, from X-rays to radio waves.

Each telescope contributes its own key information to create a complete portrait of every galaxy. By looking out far into space and back in time, AEGIS literally shows us galaxies in all their glory that are emerging from infancy into adulthood. More...
Le PHARE code for fitting the SWIRE templates in FUV, NUV, B, R, I, Ks, IRAC1, 2, 3, 4 and MIPS24

χ² SED Fitting

Best SED Fits

Worst SED Fits

Domínguez+ 11

Quiescent

Star-forming

Starburst

AGN-type
**SED-Type Evolution**

**Local fractions, z<0.2:**

Goto+ 03, morphologically classified from Sloan converted to spectral classification using results from Galaxy Zoo

- Skibba+ 09 ~6% blue ellipticals
- Schawinski+ 09 ~25% red spirals

**Results:**

- 35% red-type galaxies
- 65% blue-type galaxies

**High-redshift universe, z>1:**

Two approaches:

1. Keep constant the fractions of our last redshift bin (Fiducial Model), or
2. Quickly increase starburst population from 16% at $z = 0.9$ to 60% at $z \geq 2$

We find that the differences in the predicted EBL are small except at long wavelengths, affecting attenuation only for $E \geq 5$ TeV.

Maximum uncertainty due to photometry and fit errors

Domínguez+11
Local EBL Observations

vs. Domínguez+11
& Gilmore+12

Propagating errors in SED fits and redshift extrapolation

Alberto Domínguez
When we first tried doing this (Primack & MacMinn 1996, presented at Felix Aharonian’s first Heidelberg conference), both the stellar initial mass function (IMF) and the values of the cosmological parameters were quite uncertain. After 1998, the cosmological model was known to be $\Lambda$CDM although it was still necessary to consider various cosmological parameters in models. Now the parameters are known rather precisely, and our latest semi-analytic model (SAM) used the current (WMAP5/7/9) cosmological parameters. With improved simulations and better galaxy data, we can now normalize SAMs better and determine the key astrophysical processes to include in them.

Remaining uncertainties include whether the IMF is different in different galaxies (possibly “bottom-heavy” in massive galaxies), feedback from AGN, the nature of sub-mm galaxies, and the star formation rate at high redshifts.
Present status of $\Lambda$CDM “Double Dark” theory:

- cosmological parameters are now well constrained by observations

- mass accretion history of dark matter halos is represented by ‘merger trees’ like the one at left
SAM Galaxy Formation

- gas is collisionally heated when perturbations ‘turn around’ and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law)
- massive stars and SNae reheat (and in small halos expel) cold gas and some metals
- galaxy mergers trigger bursts of star formation; ‘major’ mergers transform disks into spheroids and fuel AGN
- AGN feedback cuts off star formation

White & Frenk 1991; Kauffmann+1993; Cole+94; Somerville & Primack 99; Cole+00; Somerville, Primack, & Faber 01; Croton et al. 2006; Somerville +08; Fanidakis+09; Guo+2011; Somerville, Gilmore, Primack, & Domínguez 2012 & Gilmore +2012 (discussed here); Porter, Somerville, Primack 2014ab
ground sources, including stars, ISM emission and sunlight reflected about half the total IR background is likely being resolved. The far-IR background peak, and the author acknowledges that only counts data from Berta et al. (2010) set only a weak lower limit on those from the experiment to find bright counts, which were in disagreement with explained by the former’s use of data from the balloon-based FOCA. The measurement from Gardner, Brown & Ferguson (2000) are considerably higher than in our models compared with data can be found in SGPD12. In our models, instruments such ISOCAM, IRAC and MIPS provide data in the survey of the galaxies in the local universe, and surveys with the (6dF) and the 2MASS have provided us with an accurate accounting of the light associated with extended sources in simple aperture from the background, and it is possible to miss 50 per cent or more is fraught with difficulty in untangling the faint galactic fringes. As expounded by Bernstein (2007), photometry of faint galaxies evolution of the luminosity density in our universe, and integrated counts of galaxies. Direct measurements provide an absolute measurement of the background light without regard to the sources responsible, but require subtraction of foreground sources and it is present in the Milky Way and our Solar system in order to isolate the extragalactic signal. Integration of galaxy counts (galaxies per unit sky area at a given magnitude) is a way to set firm lower limits on the EBL, although the degree to which these measurements from faint sources will converge mathematically if the slope of the EBL, although the degree to which these measurements from faint sources will converge mathematically if the slope of the EBL, although the degree to which these measurements from faint sources will converge mathematically if the slope of the EBL, although the degree to which these measurements from faint sources will converge mathematically if the slope of the EBL, although the degree to which these measurements from faint sources will converge mathematically if the slope of the EBL, although the degree to which these measurements from faint sources will converge mathematically if the slope of the EBL, although the degree to which these measurements from faint sources will converge mathematically if the slope of the EBL, although the degree to which these measurements.
Some Results from our Semi-Analytic Models
Evolving Luminosity Functions

B-band

K-band

An advantage of the SAM approach is that it is possible to compare predictions and observations at all redshifts and in all spectral bands.

Gilmore, Somerville, Primack, & Domínguez (2012)
Some Results from our Semi-Analytic Models

Number Counts in UV, b, v, i, and z Bands

3.6, 8, 24 and 24, 70, 160, & 850 μm Bands

Worst failure is at 850 μm

Somerville, Gilmore, Primack, & Domínguez (2012)
EBL from our Semi-Analytic Models

Figure 4. The predicted $z=0$ EBL spectrum from our fiducial WMAP5 model (solid black) and WMAP5 + fixed dust parameters, and C/Λ1 CDM (dotted black) models, compared with experimental constraints at a number of wavelengths. D11 is shown for comparison in dashed–dotted red with the shaded area indicating the uncertainty region. Data: upward pointing arrows indicate lower bounds from number counts; other symbols are results from direct detection experiments. Note that some points have been shifted slightly in wavelength for clarity. Lower limits: the blue–violet triangles are results from HST and Space Telescope Imaging Spectrograph (STIS; Gardner et al. 2000), while the purple open triangles are from GALEX (Xu et al. 2005). The solid green and red triangles are from the Hubble Deep Field (Madau & Pozzetti 2000) and Ultra Deep Field (Dolch & Ferguson, in preparation), respectively, combined with ground-based data, and the solid purple triangle is from a measurement by the Large Binocular Camera (Grazian et al. 2009). In the near-IR J, H and K bands, open violet points are the limits from Keenan et al. (2010). Open red triangles are from IRAC on Spitzer (Fazio et al. 2004), and the purple triangle at 15 µm from ISO (Hopwood et al. 2010). The lower limits from Herschel number counts (Berta et al. 2010) are shown as solid red triangles. In the submillimetre, limits are presented from the BLAST experiment (green points; Devlin et al. 2009). Direct detection: in the optical, orange hexagons are based on data from the Pioneer 10/11 Imaging Photopolarimeter (Matsuoka et al. 2011), which are consistent with the older determination of Toller (1983). The blue star is a determination from Mattila et al. (2011), and the triangle at 520 nm is an upper limit from the same. The points at 1.25, 2.2 and 3.5 µm are based upon DIRBE data with foreground subtraction: Wright (2001, dark red squares), Cambrésy et al. (2001, orange crosses), Levenson & Wright (2008, red diamond), Gorjian et al. (2000, purple open hexes), Wright & Reese (2000, green square) and Levenson et al. (2007, red asterisks). In the far-IR, direct detection measurements are shown from DIRBE (Schlegel, Finkbeiner & Davis 1998; Wright 2004, solid red circles and blue stars) and FIRAS (Fixsen et al. 1998, purple bars). Blue–violet open squares are from IR background measurements with the AKARI satellite (Matsuura et al. 2011).

Table 1. The integrated flux of the local EBL in our models (WMAP5 with evolving and fixed dust parameters, and the C/Λ1 CDM model) and the model of D11. Units are nW m$^{-2}$ sr$^{-1}$.

<table>
<thead>
<tr>
<th>Wavelength range</th>
<th>WMAP5 (fiducial)</th>
<th>WMAP5 + fixed</th>
<th>C/Λ1 CDM</th>
<th>D11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical–near-IR peak (0.1–8 µm)</td>
<td>29.01</td>
<td>24.34</td>
<td>26.15</td>
<td>24.47</td>
</tr>
<tr>
<td>Mid-IR (8–50 µm)</td>
<td>4.89</td>
<td>5.16</td>
<td>5.86</td>
<td>5.24</td>
</tr>
<tr>
<td>Far-IR peak (50–500 µm)</td>
<td>21.01</td>
<td>22.94</td>
<td>24.08</td>
<td>39.48</td>
</tr>
<tr>
<td>Total (0.1–500 µm)</td>
<td>54.91</td>
<td>52.44</td>
<td>56.09</td>
<td>69.19</td>
</tr>
</tbody>
</table>

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© 2012 RAS
The evolution of the EBL with redshift is shown graphically in Fig. 5, in two ways: in physical and co-moving coordinates. The left panel shows that the EBL was much higher in the past, especially in the optical and near-IR and in the far-IR. The right panel shows how the present-day EBL was generated as a function of redshift. This EBL evolution must be taken into account in calculating attenuation of gamma rays from all but the nearest extragalactic sources.

Figure 5. The evolution of the EBL in our WMAP5 Fiducial model. This is plotted on the left panel in standard units. The right panel shows the build-up of the present-day EBL by plotting the same quantities in comoving units. The redshifts from 0 to 2.5 are shown by the different line types in the key in the left panel. (From Fig. 5 of [9].)

Gamma ray attenuation due to $\gamma \gamma \rightarrow e^+ e^-$ is calculated by integrating the cross section times the proper density of background photons along the line of sight to the emitting redshift, and integrating over the scattering angle $\theta$, where $\theta = \pi$ corresponds to a head-on collision. The most probable scattering angle is $\theta \approx \pi/2$. If we assume $\theta = \pi/2$, then the characteristic wavelength $\lambda_{bg}$ of the background photons that will most strongly affect a gamma ray of energy $E_{\gamma}$ is given by $\lambda_{bg} = 1.2 \left( E_{\gamma}/\text{TeV} \right) \mu\text{m}$.

We have calculated gamma-ray attenuation as a function of the redshift of the source and the observed gamma-ray energy, from the evolving EBL determined both observationally and from our SAM calculations. This is shown in the left panel of Fig. 6.

A more general way to show the EBL attenuation is to plot the “Attenuation Edge” redshift where the optical depth $\tau$ reaches a certain value as a function of gamma-ray energy, which is presented in the right panel of Fig. 6 out to redshift 5 for $\tau = 1, 3, \text{and } 5$.
Increasing redshift causes absorption features to increase in magnitude and appear at lower energies. The plateau seen between 1 and 10 TeV at low $z$ is a product of the mid-IR valley in the EBL spectrum.
If we know the intrinsic spectrum, we can infer the optical depth $\tau(E, z)$ from the observed spectrum. In practice, we typically \textit{assume} that $\frac{dN}{dE}|_{\text{int}}$ is not harder than $E^{-\Gamma}$ with $\Gamma = 1.5$, since local sources have $\Gamma \geq 2$. More conservatively, we can assume that $\Gamma \geq 2/3$. 

Illustration: Mazin & Raue
Reconstructed Blazar Spectral Indexes

With our SAM based on WMAP5 cosmological parameters and Spitzer (Rieke+09) dust emission templates, all high redshift blazars have intrinsic spectral indexes $\Gamma \geq 1.5$, as expected from nearby sources.

(Of course, the spectrum could be harder than $\Gamma \geq 1.5$.)
Predicted Gamma Ray Attenuation

The Cosmic Gamma Ray Horizon (CGRH) is the observed gamma ray energy as a function of redshift $z$ where the attenuation is $1/e = 0.368$. The figure shows the predicted gamma-ray attenuation as a function of energy $E_\gamma$ (TeV) for different redshifts $z$. The curves are labeled with $z = 0.03$, $z = 0.1$, $z = 0.25$, and $z = 1.0$. The inset figure illustrates the cosmic gamma-ray horizon in redshift, with data points and error bars for various galaxies. The curves are labeled as follows:

- **WMAP5 Fiducial**
- **WMAP5 Fixed**
- **Domínguez+11**

The figure is adapted from Gilmore, Somerville, Primack, & Domínguez (2012).
With a 50 GeV threshold, we see to $z \approx 1.5-3$ with less than 1/e attenuation!

1/e attenuation!

1.5-3

Threshold

100 GeV

50 GeV

Threshold

Gamma energy (TeV)

Redshift

Cosmic Gamma-Ray Horizon

Gilmore, Somerville, Primack, & Domínguez (2012)
The first statistically significant detection of the cosmic γ-ray horizon (CGRH) that is independent of any extragalactic background light (EBL) model is presented. The CGRH is a fundamental quantity in cosmology. It gives an estimate of the opacity of the Universe to very-high energy (VHE) γ-ray photons due to photon-photon pair production with the EBL. The only estimations of the CGRH to date are predictions from EBL models and lower limits from γ-ray observations of cosmological blazars and γ-ray bursts. Here, we present synchrotron self-Compton models (SSC) of the spectral energy distributions of 9/15 blazars based on (almost) simultaneous observations from radio up to the highest energy γ-rays taken with the Fermi satellite. These SSC models predict the unattenuated VHE fluxes, which are compared with the observations by imaging atmospheric Cherenkov telescopes. This comparison provides an estimate of the optical depth of the EBL, which allows a derivation of the CGRH through a maximum likelihood analysis that is EBL-model independent. We find that the observed CGRH is compatible with the current knowledge of the EBL.
EBL modeling, which were derived from observed data. The EBL model described in Domínguez et al. (2011a) is plotted with a red-thick line. The shaded regions show the uncertainties from the darker blue lines and the statistical plus 20% of systematic uncertainties are shown with lighter blue lines. The CGRH calculated from upper limits at all wavelengths as $(1 + z)^{-3}$.

The CGRH feature (i.e., the Cherenkov observations span negative to positive values of log $E$) in the CGRH from 9 out of 11 blazars where our maximum likelihood methodology can be applied. We find that the CGRH derived from 9 out of 11 blazars (Mkn 501 and Mkn 421) are systematically higher because the optical depth for these cases becomes unity at energies larger than the energies observed from lower redshifts. This effect is expected to occur at energies larger than $300$ TeV.

Interestingly, galaxy emission, given the increasing behavior of the flux decrement given by the D11 model. The estimations from other EBL models such as Franceschini, Rodighiero & Vaccari (2008), and therefore no useful constraint can be derived. In both cases the synchrotron/SSC model does not seem to correctly fit the multiwavelength data. For the case of 1ES 2344+514 with slow flux variability timescale, a value $\tau_{\text{synch}}$ can be derived. For the case of 1ES 2344+514 with fast flux variability timescale, a value $\tau_{\text{SSC}}$ can be derived. However, for this case the uncertainties are larger than $\tau_{\text{synch}}$. In any flux state on 4 blazars (1ES 1959+650, W Comae, PG1553+113, 4C 39.21, 3C 66A), we find that the CGRH derived from 9 out of 11 blazars are in agreement within uncertainties with the EBL model by D11. We note that these EBL limits from Mazin & Raue (2007) are in agreement with the estimation by the D11 EBL model. The estimations from other EBL models such as Franceschini, Rodighiero & Vaccari (2008), and therefore no useful constraint can be derived. In both cases the synchrotron/SSC model does not seem to correctly fit the multiwavelength data. For the case of 1ES 2344+514 with slow flux variability timescale, a value $\tau_{\text{synch}}$ can be derived. For the case of 1ES 2344+514 with fast flux variability timescale, a value $\tau_{\text{SSC}}$ can be derived. However, for this case the uncertainties are larger than $\tau_{\text{synch}}$. In any flux state on 4 blazars (1ES 1959+650, W Comae, PG1553+113, 4C 39.21, 3C 66A), we find that the CGRH derived from 9 out of 11 blazars are in agreement within uncertainties with the EBL model by D11. We note that these EBL limits from Mazin & Raue (2007) rather than the newer results by Meyer et al. (2012) are in agreement within uncertainties with the EBL model by D11.

Our maximum likelihood procedure cannot be applied to any flux state on 4 blazars (1ES 1959+650, W Comae, PG1553+113, 4C 39.21, 3C 66A), and therefore no useful constraint can be derived. In both cases the synchrotron/SSC model does not seem to correctly fit the multiwavelength data. For the case of 1ES 2344+514 with slow flux variability timescale, a value $\tau_{\text{synch}}$ can be derived. For the case of 1ES 2344+514 with fast flux variability timescale, a value $\tau_{\text{SSC}}$ can be derived. However, for this case the uncertainties are larger than $\tau_{\text{synch}}$. In any flux state on 4 blazars (1ES 1959+650, W Comae, PG1553+113, 4C 39.21, 3C 66A), we find that the CGRH derived from 9 out of 11 blazars are in agreement within uncertainties with the EBL model by D11. We note that these EBL limits from Mazin & Raue (2007) are in agreement within uncertainties with the EBL model by D11. The estimations from other EBL models such as Franceschini, Rodighiero & Vaccari (2008), and therefore no useful constraint can be derived. In both cases the synchrotron/SSC model does not seem to correctly fit the multiwavelength data. For the case of 1ES 2344+514 with slow flux variability timescale, a value $\tau_{\text{synch}}$ can be derived. For the case of 1ES 2344+514 with fast flux variability timescale, a value $\tau_{\text{SSC}}$ can be derived. However, for this case the uncertainties are larger than $\tau_{\text{synch}}$. In any flux state on 4 blazars (1ES 1959+650, W Comae, PG1553+113, 4C 39.21, 3C 66A), we find that the CGRH derived from 9 out of 11 blazars are in agreement within uncertainties with the EBL model by D11. We note that these EBL limits from Mazin & Raue (2007) rather than the newer results by Meyer et al. (2012) are in agreement within uncertainties with the EBL model by D11.
DETECTION OF THE COSMIC $\gamma$-RAY HORIZON FROM MULTIWAVELENGTH OBSERVATIONS OF BLAZARS

Cosmic $\gamma$-ray horizon [TeV] vs. Redshift

Propagating D+11 errors in SED fits and redshift extrapolation

Furniss+ 2013: 3C66A z=0.33-0.41

3C66A corrected

PG1553+113

1ES0806+524

1ES1101-232

1ES1218+304

1ES2344+514

Mkn501

Mkn421

PKS2005-489

PKS2155-304
Here, we report an absorption feature seen in the combined spectra of a sample of opacity at $z = 1.05$ derived in A. A. Abdo et al. EBL models. The downward arrow derived combining the limits on the best-fit EBL models. The plot shows the measurement at $z \approx 1.0$, which is the average redshift of the most constraining redshift interval (i.e., $0.5 \leq z < 1.6$). The Fermi-LAT measurement was derived combining the limits on the best-fit EBL models. The downward arrow represents the 95% upper limit on the opacity at $z = 1.05$ derived in A. A. Abdo et al., Astrophys. J. 723, 1082 (2010).
A significant steepening in the blazars' spectra is detected.

This is consistent with that expected by a 'minimal' EBL:

- i.e. EBL at the level of galaxy counts
- 4 models rejected above 3sigma

All the non-rejected models yield a significance of detection of 5.6-5.9 $\sigma$

The level of EBL is 3-4 times lower than our previous UL (Abdo+10, ApJ 723, 1082)
Cosmic Gamma-Ray Horizon Compared with EBL Models

![Graph showing the comparison of different models with EBL models. The graph plots the cosmic gamma-ray horizon, $E_0$ [TeV], against redshift. Various models are represented by different lines and markers, each with their respective error bars. The models include Ackermann+ 12, Domínguez+ 11, Stecker+ 06 Baseline, Franceschini+ 08, Kneiske & Dole 10, Finke+ 10 Model C, Gilmore+ 12 Fiducial, and Helgason+ 12. The graph highlights the impact of different levels of attenuation on the gamma-ray horizon.]

Alberto Domínguez
The other half of the universe?

A large previously unknown population of stars inhabits intergalactic space

By S. H. Moseley

The history of astronomy has largely been concerned with the study of discrete objects: planets, stars, and galaxies. From such observations, we have discovered the nature and evolutionary histories of these objects. It is only recently that the other half of the universe, Zemcov et al. (1) present results from a study of near-infrared background light that reveal that as many as half of all stars have been stripped from galaxies in their many collisions and mergers over the history of the universe. At galactic distances, the stars are faint but can be detected in ensemble through the spatial variations in the brightness caused by their spatial distributions. It is remarkable that such a major component of the universe could have been hiding in plain sight as an infrared background between the stars and galaxies.

Ancient observers saw the milky glow of our Galaxy and the smooth radiance of the zodiacal light. The development of telescopes resolved our Galaxy into a high density of faint stars. The zodiacal light, arising from light scattered from dust in our solar system, was found to be intrinsically diffuse. Other such backgrounds have been detected in the modern era: radio, x-ray, and, most famously, the cosmic microwave background (CMB). The radio and x-ray backgrounds have been resolved into faint sources that explain most of the sky brightness, but the CMB, the radiation from the surface of the universe, is a diffuse component that is hard to explain in terms of discrete objects.
Extragalactic background light (EBL) anisotropy traces variations in the total production of photons over cosmic history and may contain faint, extended components missed in galaxy point-source surveys. Infrared EBL fluctuations have been attributed to primordial galaxies and black holes at the epoch of reionization (EOR) or, alternately, intrahalo light (IHL) from stars tidally stripped from their parent galaxies at low redshift. We report new EBL anisotropy measurements from a specialized sounding rocket experiment at 1.1 and 1.6 micrometers. The observed fluctuations exceed the amplitude from known galaxy populations, are inconsistent with EOR galaxies and black holes, and are largely explained by IHL emission. The measured fluctuations are associated with an EBL intensity that is comparable to the background from known galaxies measured through number counts and therefore a substantial contribution to the energy contained in photons in the cosmos.

Table 1. Contributions to near-infrared EBL anisotropy and intensity.

<table>
<thead>
<tr>
<th>λ (µm)</th>
<th>1.1</th>
<th>1.6</th>
<th>2.4</th>
<th>3.6</th>
<th>3.6#</th>
<th>4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured δλI1.1</td>
<td>1.4±0.9</td>
<td>1.9±0.8</td>
<td>0.32±0.05</td>
<td>0.072±0.021</td>
<td>0.049±0.007</td>
<td>0.053±0.023</td>
</tr>
<tr>
<td>(nW m⁻² sr⁻¹)</td>
<td>1.4±0.7</td>
<td>1.9±0.8</td>
<td>0.32±0.05</td>
<td>0.072±0.021</td>
<td>0.049±0.007</td>
<td>0.053±0.023</td>
</tr>
<tr>
<td>deduced</td>
<td>7.0±4.0</td>
<td>11.4±5.4</td>
<td>2.2±0.4</td>
<td>0.65±0.19</td>
<td>0.44±0.06</td>
<td>0.37±0.16</td>
</tr>
<tr>
<td>IHL intensity</td>
<td>9.7±3.0</td>
<td>9.0±2.6</td>
<td>7.8±1.2</td>
<td>5.2±1.0</td>
<td>5.2±1.0</td>
<td>3.9±0.8</td>
</tr>
<tr>
<td>ratio of the</td>
<td>0.7</td>
<td>1.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>IHL and IGL</td>
<td>16.7±5.0</td>
<td>20.4±6.0</td>
<td>10.0±5.0</td>
<td>5.9±1.0</td>
<td>5.6±1.0</td>
<td>4.3±0.8</td>
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<td>intensities</td>
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<td>20.4±6.0</td>
<td>10.0±5.0</td>
<td>5.9±1.0</td>
<td>5.6±1.0</td>
<td>4.3±0.8</td>
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<tr>
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Local EBL Observations with Zemcov+14

\[ \lambda \Lambda [\text{nW m}^{-2} \text{sr}^{-1}] \]

\[ \lambda [\mu \text{m}] \]

Alberto Domínguez
The spatial fluctuations of the extragalactic background light trace the total emission from all stars and galaxies in the Universe. A multiwavelength study can be used to measure the integrated emission from first galaxies during reionization. Here we report arcmin-scale spatial fluctuations in GOODS-S with HST in five wavebands between 0.6 and 1.6 mm. This level of integrated light emission allows for a significant surface density of fainter primeval galaxies that are below the point-source detection level in current surveys.

See also: Seo et al. 2015, AKARI CIB Fluctuations, ApJ, 807, 140

The ultraviolet luminosity density and star-formation rate density from HST intensity fluctuations

Shown are luminosity function extrapolations and integrations down to MUV = −13. Our measured star formation rate densities (blue rectangle) are consistent with previous works at z = 8 to 10, however only extremely bright galaxies are directly detected. For reference we plot the theoretically expected relation between ultraviolet luminosity density and redshift to reionize the universe and/or to maintain reionization using an optical depth to reionization of \( \tau = 0.066 \pm 0.012 \) (Planck 2015). We take a gas clumping factor of \( C = 3 \) and show two cases where the escape fraction of galaxies is 6 and 20%.

fIHL, the intrahalo light fraction, as a function of halo mass

The dark and light shaded regions show the 95 and 68% ranges of fIHL from anisotropy measurements, and from an analytical prediction (Purcell+2007, blue). Intracluster measurements are shown as boxes (Gonzalez+2005), with 1σ errors. The red downward arrows denote the 95% confidence upper limit on fIHL estimated for Andromeda (M31) and our Milky Way (MW).

Ultraviolet luminosity density of the universe during the epoch of reionization

Ketron Mitchell-Wynne, Asantha Cooray, Yan Gong, Matthew Ashby, Timothy Dolch, Henry Ferguson, Steven Finkelstein, Norman Groggin, Dale Kocevski, Anton Koekemoer, Joel Primack & Joseph Smidt

2015

See also: Seo et al. 2015, AKARI CIB Fluctuations, ApJ, 807, 140
Updated analysis of near-infrared background fluctuations

Bin Yue, Andrea Ferrara, Ruben Salvaterra

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 scenario 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.

The Direct Collapse Black Hole (DCBH) scenario in Yue et al. 2014 MNRAS describes ~10^{5-6} M_☉ SMBH formation at redshifts z = 20 to 13.

Figure 3. (0.5 – 2.0) keV CXB – 3.6 μm IR cross-correlation power spectrum. Points are observations from 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 Helgason et al. 2014). Thick (thin) lines are for the fiducial (reduced) model with $\rho_\bullet = 4 \times 10^5 M_\odot\text{Mpc}^{-3}$ ($\rho_\bullet = 2.7 \times 10^5 M_\odot\text{Mpc}^{-3}$) at peaks.
uncertainty on the optical depth, obtained by fixing the intrinsic model, scales as 

Gilmore et al. (2012) SEDs at template approach that we use in this publication introduces errors in the EBL no larger than those resulting from $10^5$ of 630 points and 187 free parameters for the intrinsic 
tions of the weight $\lambda = 1.5$ $2.5 \times e^{-\lambda}$ from the di $l_f$ evol. 
0, 0. $\lambda$ results in an optical depth di $\lambda$ 4.1. EBL spectrum or from the di 

Subject headings: prevents us from ruling out an e production anomaly” at large optical depths, which has been used previously to place lower limits 

3.5 4 5 the EBL and seven local points constraining this model, (EBL), thus carries the 13 billion years’ radiation history preionized the universe. 


The EXTRAGALACTIC BACKGROUND LIGHT, THE HUBBLE CONSTANT, AND ANOMALIES: CONCLUSIONS FROM 20 YEARS OF TEV GAMMA-RAY OBSERVATIONS 

J. Biteau$^1$ & D. A. Williams$^2$ 
Santa Cruz Institute for Particle Physics and Department of Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA 

Fig. 3.— EBL intensity at $z = 0$ as a function of wavelength. The best-fit spectra derived in this work are shown with light blue (gamma rays only, four-point spectrum) and blue points (gamma rays + direct constraints, eight-point spectrum). Lower and upper limits are shown with orange upward-going and darkbrown downward-going arrows, respectively. For comparison with the work of Ackermann et al. (2012) and H.E.S.S. Collaboration (2013f), the 1 $\sigma$ (stat. + sys.) contour of the best-fit scaled-up model (Gilmore et al. 2012) is shown as filled blue region, using a scaling factor of 1.13 as shown in Table 4.

Figure 10. Contribution to CIB from “normal” galaxies ($L < 10^{11} L_\odot$), LIRGs ($L < 10^{11-12} L_\odot$), and ULIRGs ($L < 10^{12-13} L_\odot$). Normal galaxies and LIRGs contribute equally to make up most of the intensity at $\lambda \lesssim 70 \mu$m, which is more sensitive to lower redshifts, while at longer wavelengths LIRGs and eventually ULIRGs contribute most to the signal. Also plotted are model predictions from Béthermin et al. (2010, Figure 13, bottom panel), with the LIRG and ULIRG predictions somewhat high. Although the model is a simple parametric fit to counts at multiple wavelengths, the high estimates for the LIRGs and ULIRGs lends weight to the suggestion that we are missing luminous, dust-obscured sources in our sample (Section 5.4.2).

Local EBL Observations

vs. Domínguez+11
& Gilmore+12

Propagating errors in SED fits and redshift extrapolation
ABSTRACT The Fermi satellite has detected GeV emission from a number of gamma-ray bursts and active galactic nuclei at high redshift, $z \approx 1.5$. We examine the constraints that the detections of gamma-rays from several of these sources place on the contribution of Population III stars to the extragalactic background light. Emission from these primordial stars, particularly redshifted Lyman $\alpha$ emission, can interact with gamma-rays to produce electron–positron pairs and create an optical depth to the propagation of gamma-ray emission, and the detection of emission at $>10$ GeV can therefore constrain the production of this background. We consider two initial mass functions for the early stars and use derived spectral energy distributions for each to put upper limits on the star formation rate density of massive early stars from redshifts 6 to 10. Our limits are complementary to those set on a high near-infrared background flux by ground-based TeV-scale observations and show that current data can limit star formation in the late stages of re-ionization to less than 0.5 $M_\odot$ yr$^{-1}$ Mpc$^{-3}$. Our results also show that the total background flux from Population III stars must be considerably less than that from resolved galaxies at wavelengths below 1.5 $\mu$m.

Upper bounds on the redshift $z = 6 - 10$ Pop-III SFRD in two possible scenarios with future Fermi GRBs, in the Larson IMF case. The solid lines show the limits from a GRB with the same redshift and spectral characteristics of GRB 080916C ($z = 4.35$), but with a highest energy observed photon of 30 GeV (160 GeV as emitted) instead of 13.2 GeV, in combination with the 5 most constraining $z \geq 2$ sources (Abdo+2010). The dotted lines show a case with a GRB at $z = 7$ and a highest energy observed photon at 15 GeV (120 GeV emitted).
The Cherenkov Telescope Array (CTA), a collaboration between more than 1,000 scientists from 31 countries, will consist of around 100 dishes in Paranal, Chile, on the grounds of the European Southern Observatory, and around 20 more in La Palma, Spain at the Roque de los Muchachos Observatory. — *Nature* 16 July 2015

Integral sensitivity for CTA from MC simulations, together with the sensitivities in comparable conditions (50 h for IACTs, 1 year for Fermi-LAT and HAWC) for some gamma-ray observatories.

Angular resolution for CTA, compared with some existing and future VHE gamma-ray observatories. The solid line provides the angular resolution of CTA obtained from events with ten or more images, the dashed line shows the angular resolution for events with only two images.
Conclusions

New data on attenuation of gamma rays from blazers

- Fermi data on 150 blazars at $z = 0 - 1.6$ (Ackermann+12)
- X-ray + Fermi + ACT SSC fits to 9 blazars (Dominguez+13)
- ACT blazars & EBL evolution model (Biteau&Williams15)

now lead to statistically significant measurements of the cosmic gamma ray horizon and EBL as functions of source redshift and gamma ray energy. These new measurements are consistent with recent EBL calculations based both on multiwavelength observations of thousands of galaxies and also on semi-analytic models of the evolving galaxy population. Such comparisons account for (almost) all the light at UV to mid IR wavelengths, including that from galaxies too faint to see.

Measurements of near-IR EBL fluctuations could indicate light from high-redshift galaxies and/or direct-collapse SMBHs.

Catching a few high-redshift GRBs with Fermi or low-threshold atmospheric Cherenkov telescope array (CTA) could provide important new constraints on the epoch of reionization $z > 6$. 