Exploring the Non-thermal Universe with Gamma Rays
On the occasion of the 60th birthday of Felix Aharonian
Barcelona, November 6 - 9, 2012

EBL
Extragalactic Background Light

Joel Primack & Alberto Domínguez

Collaborators:
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Fourth International Fermi Symposium, Monterey, CA
October 28 – November 2, 2012
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 blazers now lead to statistically significant measurements of the cosmic gamma ray horizon (CGRH) 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 all the light, including that from galaxies too faint to see. Catching a few high-redshift GRBs with Fermi or low-threshold atmospheric Cherenkov telescope (ACT) arrays could provide important new constraints on the high-redshift star formation history of the universe.
If we know the intrinsic spectrum, we can infer the optical depth $\tau(E,z)$ from the observed spectrum. In practice, we typically assume that $dN/dE|_{\text{int}}$ is not harder than $E^{-\Gamma}$ with $\Gamma = 1.5$, since local sources have $\Gamma \geq 2$. More conservatively, we can assume that $\Gamma \geq 2/3$. 

\[ \frac{dN}{dE}|_{\text{obs}} = \frac{dN}{dE}|_{\text{int}} \exp\left[-\tau(E,z)\right] \]
Local EBL Observations

\[ \Gamma \geq 1.5 \]
\[ \Gamma \geq 2/3 \]
Evolution Calculated from Observations Using AEGIS Multiwavelength Data


\[ j_i(\lambda, z) = j_i^\text{faint} + j_i^\text{mid} + j_i^\text{bright} = \]

\[ = \int_{M_1}^{M_2} \Phi(M_K, z) f_i T_i(M_K, \lambda) dM_K + \]

\[ + \int_{M_2}^{M_3} \Phi(M_K, z) m_i T_i(M_K, \lambda) dM_K + \]

\[ + \int_{M_3}^{M_4} \Phi(M_K, z) b_i T_i(M_K, \lambda) dM_K \]

Luminosity function observed K-band, Cirasuolo+ 09

Spectral energy distributions SWIRE template library, Polletta+ 07

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

Best SED Fits

Worst SED Fits

Domínguez+ 11
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 ≥ 2

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

Domínguez+11
Local Luminosity Density

\[ j \text{ [erg s}^{-1} \text{ Mpc}^{-3} \text{ Hz}^{-1}] \]

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

- this work
- Soifer & Neugebauer +91
- Kochanek+ 01
- Bell+ 03
- Wyder+ 05
- Serjeant & Harrison 05
- Jones+ 06
- Takeuchi+ 06
- Huang+ 07
- Cameron+ 09
- Montero-Dorta & Prada 09

Dominguez+11
Local EBL Observations vs. Domínguez+11

Propagating errors in SED fits and redshift extrapolation

\[ \Gamma \geq 1.5 \]
\[ \Gamma \geq \frac{2}{3} \]

\[ \lambda_{\lambda} \text{[Jy]} \] vs. \[ \lambda \text{[\mu m]} \]
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) uses the current (WMAP5) 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
Galaxy Formation in $\Lambda$CDM

- 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 SNe 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 91; Kauffmann+93; 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 12 (discussed here)
Some Results from our Semi-Analytic Models

\[ z=0 \text{ Luminosity Density} \]

\[
\frac{dE}{d\nu} = \beta(1 + z)^{\alpha} = \beta \left( \frac{\nu}{\nu_0} \right)^{\alpha}.
\]

\[ \int_{\nu_0}^{\nu} d\nu = \int_{0}^{\nu_0} \beta \left( \frac{\nu}{\nu_0} \right)^{\alpha} d\nu = \frac{\beta}{1 + \alpha} \nu_0^{1 + \alpha}.
\]

\[ \int_{0}^{\nu_0} d\nu = \frac{\beta}{1 + \alpha} \nu_0^{1 + \alpha}.
\]

\[ E_{\text{EBL}} = \int_{\nu_0}^{\infty} \beta \left( \frac{\nu}{\nu_0} \right)^{\alpha} d\nu = \frac{\beta}{1 + \alpha} \nu_0^{1 + \alpha}.
\]

Gilmore, Somerville, Primack, & Domínguez (2012)
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

Propagating D+11 errors in SED fits and redshift extrapolation

Table 1. The integrated flux of the local EBL in our models (WMAP5 with evolving and fixed dust parameters, and the C/ΛCDM 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/ΛCDM</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>

Gilmore, Somerville, Primack, & Domínguez (2012)
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.

Gilmore, Somerville, Primack, & Domínguez (2012)
Increasing distance 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 assume that $dN/dE|_{\text{int}}$ 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
With our SAM based on current WMAP5 cosmological parameters and Spitzer (Rieke+09) dust emission templates, all high redshift blazars have spectral indexes $\Gamma \geq 1.5$, as expected from nearby sources.

(Of course, Felix can make them much harder!)

Gilmore, Somerville, Primack, & Domínguez (2012)
With a 50 GeV threshold, we see to \( z \approx 1.5-3 \) with less than \( 1/e \) attenuation!
Detection of the cosmic $\gamma$-ray horizon from multiwavelength observations of blazars

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Presented at the 4th Fermi Symposium in Monterey, CA

The Detection of the Cosmic $\gamma$-ray Horizon

Alberto Domínguez
(University of California, Riverside)
A one-zone synchrotron/SSC model is fit to the multiwavelength data excluding the Cherenkov data, which are EBL attenuated. Then, this fit is extrapolated to the VHE regime representing the intrinsic VHE spectrum. Technique similar to Mankuzhiyil et al. 2010.
There are 4 out of 15 cases where our maximum likelihood methodology could not be applied since the prediction from the synchrotron/SSC model was lower than the detected flux by the Cherenkov telescopes.

Two other cases where the statistical uncertainties were too high to set any constraint on E0. 

Domínguez+12
ABSTRACT  The light emitted by stars and accreting compact objects through the history of the universe is encoded in the intensity of the extragalactic background light (EBL). Knowledge of the EBL is important to understand the nature of star formation and galaxy evolution, but direct measurements of the EBL are limited by galactic and other foreground emissions. Here, we report an absorption feature seen in the combined spectra of a sample of gamma-ray blazars out to a redshift of $z \sim 1.6$. This feature is caused by attenuation of gamma rays by the EBL at optical to ultraviolet frequencies and allowed us to measure the EBL flux density in this frequency band.

The Imprint of the EBL in the Spectra of Blazars

Marco Ajello$^{1,2}$, Anita Reimer$^3$, Rolf Buehler$^1$
on behalf of the Fermi-LAT collaboration

Presented at the 4th Fermi Symposium in Monterey, CA
We look for the collective deviation of the spectra of blazars from their intrinsic spectra

- We use 46 months of P7V6 1-500 GeV data
- We define 3 redshift bins with 50 sources each:
  - \( z = 0 - 0.2, 0.2 - 0.5, 0.5 - 1.6 \)
- All BL Lacs are modeled with a LogParabola spectrum
- We perform a combined fit where:
  - The spectra of all sources are fit independently
  - The spectra of all sources are modified by a common \( e^{-b \cdot \tau(E,z)} \) term
- We evaluate 2 cases:
  1. Null hypothesis \( b=0 \) : there is no EBL
  2. Null hypothesis \( b=1 \) : the model predictions are correct

\[
F(E)_{\text{absorbed}} = F(E)_{\text{intrinsic}} \cdot e^{-b \cdot \tau_{\text{model}}}
\]
Measurement of Tau with Energy and Redshift

- We use the composite likelihood in small energy bins to measure the collective deviation of the observed spectra from the intrinsic ones.

- The cut-off moves in $z$ and energy as expected for EBL absorption (for low opacity models).

- It is difficult to explain this attenuation with an intrinsic property of BL Lacs:
  1. BL Lacs required to evolve across the $z=0.2$ barrier.
  2. Attenuation change with energy and redshift cannot be explained by an intrinsic cut-off that changes from source to source because of redshift and blazar sequence effects.

Best-fit EBL model
Best-fit intrinsic cut-off

Ackermann+12
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

Dominguez+12 + Ackermann+12

Cosmic γ-ray horizon [TeV] vs Redshift

1ES0806+524
Mkn501
PKS2005-489
Mkn421
PGS2155-304
1ES0806+524
1ES1218+304
1ES1101-232
PG1553+113
3C66A

Cosmic Gamma-Ray Horizon
Dominguez+12

Preliminary

Domínguez+ 11
Constraining the near-infrared background light from Population III stars using high-redshift gamma-ray sources

Rudy C. Gilmore

ABSTRACT The Fermi satellite has detected GeV emission from a number of gamma-ray bursts and active galactic nuclei at high redshift, \( z \geq 1.5 \). 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 \( 0.5 \) \( \text{M}_\odot \) 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 \( \mu \text{m} \).

Upper bounds on the redshift \( z = 6 - 9 \) 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 \((160 \text{ GeV} \text{ as emitted})\) instead of 13.2 GeV, in combination with the 5 most constraining \( z \geq 2 \) sources \((\text{Abdo+2010})\). The dotted lines show a case with a GRB at \( z = 7 \) and a highest energy observed photon at 15 GeV \((120 \text{ GeV} \text{ emitted})\).
New data on attenuation of gamma rays from blazars
- X-ray + Fermi + ACT SSC fits to 9 blazars (Dominguez+12)
- Fermi data on 150 blazars at $z = 0 - 1.6$ (Ackermann+12)
now lead to statistically significant measurements of the cosmic gamma ray horizon and EBL as a function 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 all the light, including that from galaxies too faint to see.

Catching a few high-redshift GRBs with Fermi or low-threshold atmospheric Cherenkov telescope arrays could provide important new constraints on the high-redshift star formation history of the universe.

Happy Birthday Felix!