EBL with GRB and Blazars

Joel Primack
with Rudy Gilmore, Alberto Dominguez, & Rachel Somerville
The EBL is very difficult to observe directly because of foregrounds, especially the zodiacal light. Reliable lower limits are obtained by integrating the light from observed galaxies. The best upper limits come from (non-) attenuation of gamma rays from distant blazars, but these are uncertain because of the unknown emitted spectrum of these blazars.

This talk concerns both the optical-IR EBL relevant to attenuation of TeV gamma rays, and also the UV EBL relevant to attenuation of gamma rays from very distant sources observed by Fermi and low-threshold ground-based ACTs.

Just as IR light penetrates dust better than shorter wavelengths, so lower energy gamma rays penetrate the EBL better than higher energy, resulting in a softer observed gamma-ray spectrum from more distant sources.
PILLAR OF STAR BIRTH
Carina Nebula in UV Visible Light

Thursday, March 25, 2010
PILLAR OF STAR BIRTH
Carina Nebula in IR Light

Longer wavelength light penetrates the dust better

Longer wavelength gamma rays also penetrate the EBL better
If we know the intrinsic spectrum, we can infer the optical depth \( \tau(E, z) \) from the observed spectrum. In practice, we assume that \( \frac{dN}{dE}|_{\text{int}} \) is not harder than \( E^{-\Gamma} \) with \( \Gamma = 1.5 \), since local sources have \( \Gamma \geq 2 \).
Three approaches to calculate the EBL:

**Backward Evolution**, which starts with the existing galaxy population and evolves it backward in time -- e.g., Stecker, Malkan, & Scully 2006. Dangerous!

**Evolution Inferred from Observations** -- e.g., Kneiske et al. 2002; Franceschini et al. 2008; Dominguez, Primack, et al. in prep. using AEGIS data.

**Forward Evolution**, which begins with cosmological initial conditions and models gas cooling, formation of galaxies including stars and AGN, feedback from these phenomena, and light absorption and re-emission by dust.

All methods currently require modeling galactic SEDs. **Forward Evolution** requires semi-analytic models (SAMs) based on cosmological simulations.
A problem with this approach is that high-z galaxies are very different from low-z galaxies.

Lower limits, from the Hubble Deep Field

Baseline Model:
galaxy luminosities evolve as $(1+z)^{3.1}$ for $0 < z < 1.4$, no evolution $1.4 < z < 6$, zero luminosity for $z > 6$.

Fast Evolution:
galaxy luminosities evolve as $(1+z)^4$ for $0 < z < 0.8$, as $(1+z)^2$ for $0.8 < z < 1.5$, no evolution $1.5 < z < 6$, zero luminosity for $z > 6$. 
Evolution Inferred from Observations

T. M. Kneiske et al.: Implications of cosmological gamma-ray absorption. I. 2002

Lower limits, from the Hubble Deep Field

Optical Galaxies

Total

Luminous IR Galaxies

Assumed Star Formation Rate (solid curve)
Evolution Inferred from Observations

Model EBLs

Evolution Inferred from Observations

Assumed Star Formation Rates

Lower limits, from the Hubble Deep Field

Thursday, March 25, 2010
If local IR emissivity of galaxies observed by IRAS does not evolve with cosmic time.
Evolution Inferred from Observations Using AEGIS Multiwavelength Data

Alberto Dominguez et al. (in prep.)

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

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

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

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

Luminosity function observed K-band, Cirasuolo+ 09

Spectral energy distributions SWIRE template library, Polletta+ 07

Spectral-type fractions

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

Either assume SED types are constant, or else make extreme assumptions to bound the uncertainty.
When we first tried doing this (Primack & MacMinn 1996), 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 my report here is based on a semi-analytic model (SAM) using 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.

There is still uncertainty whether the IMF evolves, possibly becoming “top-heavy” at higher redshifts (Fardal et al. 2007, Dave 2008), and uncertainty concerning the nature of sub-mm galaxies and the feedback from AGN.
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

Springel et al. 2005

Wechsler et al. 2002
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 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

Some Results from our Semi-Analytic Models

z=0 Luminosity Density

Number Counts in b, i, 3.6 and 24 μm Bands

Somerville, Gilmore, & Primack (in prep.)
Gilmore et al. (in prep): WMAP5 cosmology, dust templates of Rieke et al. (2009)


Dominguez-Diaz et al. (in prep.)

Franceschini et al. (2008)

Figure 1: Left: The local EBL in several different models of galaxy evolution; see key in figure. Upward-pointing arrows show lower limits on the EBL from galaxy number counts, and other symbols show direct measurements; see [3] for details on these data.

Right: Results from [7], showing the attenuation factors \( e^{-\tau} \) as a function of gamma-ray energy for the indicated source redshifts. The blue-dashed line is for the WMAP1 model also shown on the left; the red dash-dotted line is a model with suppressed star formation in small dark-matter halos that produces less background light and gamma-ray attenuation.

Local Extragalactic Background Light

Gamma-ray bursts (GRBs) could be powerful candles for testing the UV background through gamma-ray absorption effects. The GRBs detected by the Fermi LAT to date are in the energy and redshift regime necessary to begin placing meaningful limits on the intervening UV flux density, and they demonstrate that emission at a rest-frame energy of \( > 60 \) GeV occurs in a significant fraction of bursts.

In our paper on modeling detection of GeV emission from GRBs [8], we found that Fermi should detect a small number of \( > 10^4 \) GeV photons per year, while a single detection by a ground-based instrument such as MAGIC-II could yield tens to thousands of counts, although such serendipitous events occur at a low rate \(< 0.3 \) yr\(^{-1}\). Having additional ACTs will increase that rate. Our model [8] was based purely on historical data from CGRO and Swift.

Our goal as a follow-on to this project is to incorporate the GRB data from the Fermi LAT to build a more sophisticated model of emission and instrumental detection rates. The observation by Fermi of GRB 080916C suggests, for instance, that GeV emission tends to arrive later than lower energy (keV and MeV) flux [16], and may therefore be part of a different spectral component. The findings of this analysis could have important implications for the observing strategies used in attempts to detect GRBs from the ground with current telescopes as well as future ACT arrays such as AGIS, as the sensitivity of these telescopes to GRBs is strongly dependent on spectra and also the arrival time of the...
Gilmore et al. (in prep.); WMAP5 cosmology, dust templates of Rieke et al. (2009)
Gilmore et al. (2009); WMAP1 cosmology
Dominguez et al. (in prep.)

Upper Limits from QSO 3C279 (z=0.53) and Blazars

Thursday, March 25, 2010
Gamma Ray Attenuation Predictions vs. Observational Limits

Primack, Gilmore, & Somerville 09
Our models are based on varying the SFR, ionizing light escape fraction from galaxies, and UV from AGN. Our models include radiative transfer through the IGM.
Modelling gamma-ray burst observations by Fermi and MAGIC including attenuation due to diffuse background light

Rudy C. Gilmore,1* Francisco Prada2† and Joel Primack1

1Department of Physics, University of California, Santa Cruz, CA 95064, USA
2Instituto de Astrofísica de Andalucía, CSIC, Apdo. Correos 3004, E-18080 Granada, Spain

ABSTRACT
Gamma rays from extragalactic sources are attenuated by pair-production interactions with diffuse photons of the extragalactic background light (EBL). Gamma-ray bursts (GRBs) are a source of high-redshift photons above 10 GeV, and could be therefore useful as a probe of the evolving ultraviolet background radiation. In this paper, we develop a simple phenomenological model for the number and redshift distribution of GRBs that can be seen at GeV energies with the Fermi satellite and Major Atmospheric Gamma-ray Imaging Cherenkov Telescope (MAGIC) atmospheric Cherenkov telescope. We estimate the observed number of gamma rays per year, and show how this result is modified by considering interactions with different realizations of the evolving EBL. We also discuss the bright Fermi GRB 080916C in the context of this model. We find that the Large Area Telescope on Fermi can be expected to see a small number of photons above 10 GeV each year from distant GRBs. Annual results for ground-based instruments like MAGIC are highly variable due to the low duty cycle and sky coverage of the telescope. However, successfully viewing a bright or intermediate GRB from the ground could provide hundreds of photons from high redshift, which would almost certainly be extremely useful in constraining both GRB physics and the high-redshift EBL.
**Fermi** highest-energy photons from blazars and GRBs vs. redshift

![Graph showing Fermi Constraints on the Gamma-ray Opacity of the Universe](image)

**PRELIMINARY**

**Fermi** Constraints on the Gamma-ray Opacity of the Universe (in prep.)

Thursday, March 25, 2010
Using high-energy 11-month photon data set collected by Fermi from distant blazars and GRBs we have (i) constrained the opacity of the universe to rays in the ∼10–100 GeV range and coming from various redshifts up to $z \approx 4.35$; and (ii) ruled out an EBL intensity as high as predicted by Stecker et al. (2006) in the optical–ultraviolet range at more than 4σ in five independent sources, thereby resulting in a > 5σ rejection significance level in total. Our most constraining results come from blazars J1504+1029, J0808-0751 and J1016+0513 with $(z, E_{\text{max}})$ combinations of $(1.84, 48.9 \text{ GeV})$, $(1.84, 46.8 \text{ GeV})$ and $(1.71, 43.3 \text{ GeV})$, respectively. The two most constraining GRBs are GRB 090902B and GRB 080916C, both of which rule out the Stecker et al. (2006) EBL models in the UV energy range at more than 3σ level.
Halos and galaxies: results from the Bolshoi simulation.

Anatoly A. Klypin\textsuperscript{1}, Sebastian Trujillo-Gomez\textsuperscript{1}, and Joel Primack\textsuperscript{2} \textsuperscript{1}NMSU, \textsuperscript{2}UCSC

ABSTRACT

Lambda Cold Dark Matter (ΛCDM) is now the standard theory of structure formation in the Universe. We present the first results from the new Bolshoi dissipationless cosmological ΛCDM simulation that uses cosmological parameters favored by current observations, which imply one-third fewer $10^{12}h^{-1}M_\odot$ dark matter halos than the WMAP1 (2003) parameters used in the Millennium simulations. The Bolshoi simulation was done in a volume $250\ h^{-1}\ \text{Mpc}$ on a side using 8 billion particles with mass and force resolution adequate to follow subhalos down to a completeness limit of $V_{\text{circ}} = 50\ \text{km s}^{-1}$ maximum circular velocity. Using merger trees derived from analysis of 180 stored time-steps we find the circular velocities of satellites before they fall into their host halos. Using excellent statistics of halos and subhalos ($\sim 10$ million at every moment and $\sim 50$ million over the whole history) we present accurate approximations for statistics such as the halo mass function, the concentrations for distinct halos and subhalos, abundance of halos as function of their circular velocity, the abundance and the spatial distribution of subhalos. We find that at high redshifts the concentration falls to a minimum of about 3.8 and then rises slightly for higher values of halo mass, a new result. We present approximations for the velocity and mass functions of distinct halos as a function of redshift. We find that while the Sheth-Tormen approximation for the mass function of halos found by spherical overdensity is quite accurate at low redshifts, the ST formula over-predicts the abundance of halos by nearly an order of magnitude by $z = 10$. We find that the number of subhalos scales with the circular velocity of the host halo as $\sqrt{V_{\text{host}}}$, and that subhalos have nearly the same radial distribution as dark matter particles at radii 0.3-2 times the host halo virial radius. The subhalo velocity function $N(> V_{\text{sub}})$ behaves as $V_{\text{circ}}^{-3}$. Combining our and Via Lactea-II results, we find that inside the virial radius of halos with $V_{\text{circ}} = 200\ \text{km s}^{-1}$ the number of satellites is $N(> V_{\text{sub}}) = (V_{\text{sub}}/58\ \text{km s}^{-1})^{-3}$ for satellite velocities in the range $4\ \text{km s}^{-1} < V_{\text{sub}} < 150\ \text{km s}^{-1}$. Finally, we use an abundance-matching procedure to assign $r$-band luminosities to dark matter halos as a function of halo $V_{\text{circ}}$, and find that the luminosity-velocity relation is in remarkably good agreement with the observed Tully-Fisher relation for $V_{\text{circ}}$ in the range 50-200 km s$^{-1}$. 
The Bolshoi simulation
ART code
250Mpc/h Box
LCDM
s8 = 0.83
h = 0.73
8G particles
1kpc/h force resolution
1e8 Msun/h mass res
dynamical range 262,000
time-steps = 400,000

NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time
<10^{-3} of the Bolshoi Simulation Volume
The Millennium-I Run (Springel+05) was a landmark simulation, and it has been the basis for ~300 papers. However, it and the new Millennium-II simulations were run using WMAP1 (2003) parameters, and the Millennium-I resolution was inadequate to see many subhalos. The new Bolshoi simulation (Klypin, Trujillo & Primack 2010) used the WMAP5 parameters (consistent with WMAP7) and has nearly an order of magnitude better mass and force resolution than Millennium-I. We have now found halos in all 180 stored timesteps, and we have complete merger trees. We are working with Darren Croton, Rachel Somerville, Lauren Porter and Andrew Benson on semi-analytic models of the evolving galaxy population based on Bolshoi, which should give better EBL predictions.
Mass Function of Distinct Halos

Velocity Function of Distinct Halos at $z = 0, 2, 3, 5, 6.5$

Subhalos follow the dark matter distribution except in the inner regions of cluster and galaxy halos

NOTE: figures are from Klypin, Trujillo, & Primack, arXiv: 1002.3660

Tully-Fisher Relation

Clusters

Galaxies

Thursday, March 25, 2010
The distribution of mass around 3 massive halos ($M_{\text{FOF}} = 10^{11} h^{-1} M_{\odot}$) at redshift $z = 8.8$. Each panel shows 1/2 of the dark matter particles in cubes of 1 $h^{-1}$ Mpc size. The center of each cube is the exact position of the center of mass of the corresponding FOF halo. The effective radius of each FOF halo in the plots is 150 – 200 $h^{-1}$ kpc. Circles indicate distinct halos and subhalos identified by the spherical overdensity algorithm BDM. The radius of each circle is equal to the virial radius of the halo. In panel (b) FOF linked together a chain of halos which formed in long dense filaments. This happens often. The numbers in the top-left corner of each panel show the ratio of FOF mass to that of SO. The Sheth-Tormen mass function agrees well with the abundance of halos with FOF masses, but these do not correspond to halos that will host forming galaxies as BDM halos do. Getting this right is important in understanding the new HST/WFC3 data on high-redshift galaxies, and also the reionization of the universe.

Bolshoi simulation - Klypin, Trujillo & Primack 2010 - Appendix B
Wide area + Ultra-deep Observations can be used to more accurately constrain the UV LF at $z \sim 7-8$

UV Luminosity Functions

50 $z \sim 7$ galaxies, 25 $z \sim 8$ galaxies

Bouwens et al. 2010
Conclusions

Data from (non-)attenuation of gamma rays from AGN and GRBs gives upper limits on the EBL from UV to mid-IR that are $\sim 2x$ lower limits from observed galaxies. These upper limits now rule out some EBL models and purported observations, with improved data likely to provide even stronger constraints.

EBL calculations based on careful extrapolation from observations and on semi-analytic models are consistent with these lower limits and with the gamma-ray upper limit constraints.

Such comparisons “close the loop” on cosmological galaxy formation models, since they account for all the light, including that from galaxies too faint to see. They can constrain star formation models, including variations in the stellar initial mass function (IMF).