Measuring the Cosmic Star Formation Rate with Fermi-LAT

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Extragalactic Background Light

Background light from all the stars that have existed in the observable universe.
Background light from all the stars that have existed in the observable universe.

Two broad components: Direct Stellar emission, and stellar emission absorbed by dust and re-radiated in the infrared.

Extragalactic Background Light

Dominguez et al. (2011)
Gamma-ray absorption by EBL

EBL photons extinguish extragalactic gamma rays.

\[ \gamma_{\text{ebl}} + \gamma_{\gamma-\text{ray}} \rightarrow e^- + e^+ \]

Knowledge of the absorption effects due to EBL is necessary to infer the intrinsic spectra of extragalactic gamma-ray sources.

Gamma rays we see are attenuated by:

\[ F_{\text{obs}} = F_{\text{int}} \exp[-\tau_{\gamma\gamma}(E, z)]. \]

We want to create a model of the EBL to aid in our understanding of the \( \gamma \)-ray sources.
Background light from all the stars that have existed in the observable universe.

Two broad components:
Direct Stellar emission, and stellar emission absorbed by dust and re-radiated in the infrared.

LAT γ-rays absorb mainly direct stellar emission.

UV emission mainly produced by short-lived, high-mass stars.
FSRQs:
Have strong BLR

Internal $\gamma\gamma$ absorption

Stern & Poutanen (2010)
See also Reimer (2007)
Internal $\gamma\gamma$ absorption

With more data, no evidence for absorption at $<10$ GeV. Small ($\tau_{\gamma\gamma} \sim 1$) absorption at $\sim 10$ GeV (Stern & Poutanen 2014).

Our analysis: stacked residuals (adjusted for redshift) of best fit model for sources from Poutanen & Stern (2010). No evidence for absorption.

Similar conclusions by Costamante et al. (2017, in preparation).
Measuring EBL Absorption

150 BL Lac Objects

46 months (almost 4 years) of LAT data

Three redshift bins

“Pass 7” instrument response function

Ackermann et al. (2012)
Measuring EBL Absorption

![Diagram of EBL absorption measurements across different redshift bins.](image)
Measuring EBL Absorption

414 FSRQs
327 BL Lac Objects
741 total sources

101 months (~8.5 years) of LAT data

Twelve redshift bins

“Pass 8” instrument response function
Measuring EBL Absorption

PRELIMINARY

0.03 < z < 0.23

0.23 < z < 0.34

0.34 < z < 0.44

0.44 < z < 0.60

0.60 < z < 0.68

0.69 < z < 0.89

Finke et al. 2010

Dominguez et al. 2011
Measuring EBL Absorption

PRELIMINARY

$0.89 < z < 0.94$

$0.94 < z < 1.09$

$1.10 < z < 1.37$

$1.38 < z < 1.59$

$1.60 < z < 2.14$

$2.15 < z < 3.10$

Finke et al. 2010

Dominguez et al. 2011
The total number of photons emitted per unit energy per unit time blackbody is given by

\[ \epsilon j^{\text{stars}}(\epsilon; z) = m_e c^2 \epsilon^2 f_{\text{esc}}(\epsilon) \int_{m_{\text{min}}}^{m_{\text{max}}} dm \xi(m) \times \int_{z}^{z_{\text{max}}} dz_1 \left| \frac{dt_*}{dz_1} \right| \psi(z_1) \dot{N}_*(\epsilon; m, t_*(z, z_1)). \]

Initial Mass Function

Stellar evolution

Luminosity Density

dust extinction

star formation rate

expansion of universe

JF, Razzaque, & Dermer (2010).
Razzaque, Dermer, & JF (2009).
The total number of photons emitted per unit energy per unit time by a blackbody is given by

\[ \epsilon j^{\text{stars}}(\epsilon; z) = m_e c^2 \epsilon^2 f_{\text{esc}}(\epsilon) \int_{m_{\text{min}}}^{m_{\text{max}}} \text{d}m \, \xi(m) \times \int_{z}^{z_{\text{max}}} \text{d}z_1 \left| \frac{dt^*}{dz_1} \right| \psi(z_1) N_*(\epsilon; m, t_*(z, z_1)). \]

**Initial Mass Function**

**Stellar evolution**

**Luminosity Density**

**dust extinction**

**star formation rate**

**expansion of universe**

JF, Razzaque, & Dermer (2010).
Razzaque, Dermer, & JF (2009).
EBL Model

Initial Mass Function

\[ \epsilon \int_{\text{stars}}(\epsilon; z) = m_\epsilon c^2 \epsilon^2 f_{\text{esc}}(\epsilon) \int_{m_{\text{min}}}^{m_{\text{max}}} dm \xi(m) \]

\[ \times \int_{z_{\text{max}}}^{z} dz_1 \left| \frac{dt_\star}{dz_1} \right| \psi(z_1) \dot{N}_\star(\epsilon; m, t_\star(z, z_1)). \]

- dust extinction
- Stellar evolution
- Luminosity Density
- expansion of universe
- star formation rate
- SFRD [solar mass yr^{-1} Mpc^{-3}]

JF, Razzaque, & Dermer (2010).
Razzaque, Dermer, & JF (2009).
EBL Model

\[ u_{EBL}(\epsilon; z) = \int_{z}^{z_{\text{max}}} dz' j(\epsilon; z') \left| \frac{dt}{dz'} \right| \]

expansion of universe

luminosity density

EBL energy density

JF, Razzaque, & Dermer (2010).
Razzaque, Dermer, & JF (2009).
EBL Model

\[ \tau_{\gamma\gamma}(E, z_s) = c \int_0^{z_s} dz \left| \frac{dt}{dz} \right| \int_{\epsilon_{\text{min}}}^{\infty} d\epsilon \ n_{\text{EBL}}(\epsilon; z) \sigma_{\gamma\gamma}(E, \epsilon) \]

EBL number density

absorption cross section

expansion of universe

absorption optical depth

JF, Razzaque, & Dermer (2010).
Razzaque, Dermer, & JF (2009).
Do Markov Chain Monte Carlo fit to gamma-ray opacity data.

Use emcee routine (Foreman-Mackey et al. 2013).

Allow star formation rate density parameters (a, b, c, d) to vary:

$$\psi(z) = h \frac{a + bz}{1 + (z/c)^d}$$

all other parameters kept constant.

Similar method to Gong & Cooray (2013).
Star Formation Rate Result

PRELIMINARY

SFRD [solar mass yr$^{-1}$ Mpc$^{-3}$] vs. redshift
Star Formation Rate Result

Preliminary

SFRD [solar mass yr$^{-1}$ Mpc$^{-3}$]

Redshift

Star formed
Star Formation Rate Result

PRELIMINARY

SFRD \[ \text{[solar mass yr}^{-1} \text{ Mpc}^{-3}] \]

STAR FORMATION RATE RESULT

redshift

star formed

blazar
Star Formation Rate Result

SFRD \left[ \text{solar mass yr}^{-1} \text{ Mpc}^{-3} \right]

- measured with GRBs (Kistler et al. 2009)
- UV LF (Madau & Dickinson 2014)
- IR LF (Madau & Dickinson 2014)
We’ve used model fits to these results to make an independent measurement of the cosmic SFRD.

Allows us to constrain high-z SFRD more than previous γ-ray measurements (Gilmore 2012, Inoue et al. 2014).

Our results consistent with stars alone being able to reionize the universe (e.g. Madau et al. 1999, Kistler et al. 2009)

See also: talk by Kari Helgason today at 14:30 on luminosity density measurements

To do:

Different SFR parameterizations (e.g., Madau & Dickenson 2014)

Allow dust model to vary, with different parameterizations (Driver et al. 2008 dust model used so far)
EBL Model

\[
\epsilon j^{\text{stars}}(\epsilon; z) = m_e c^2 \epsilon^2 f_{\text{esc}}(\epsilon) \int_{m_{\text{min}}}^{m_{\text{max}}} dm \xi(m) \\
\times \int_{z}^{z_{\text{max}}} d\xi \int \left| \frac{dt_*}{d\xi} \right| \psi(z_1) \dot{N}_*(\epsilon; m, t_*(z_1, z_1)).
\]

\[
u_{\text{EBL}}(\epsilon; z) = \int_{z}^{z_{\text{max}}} d\xi j(\epsilon; \xi') \left| \frac{dt}{d\xi} \right|
\]

\[
\tau_{\gamma\gamma}(E, z_*) = c \int_{0}^{z_0} dz \left| \frac{dt}{dz} \right| \int_{\epsilon_{\text{min}}}^{\infty} d\epsilon n_{\text{EBL}}(\epsilon; z) \sigma_{\gamma\gamma}(E, \epsilon)
\]

JF, Razzaque, & Dermer (2010).
Razzaque, Dermer, & JF (2009).
Untangling Intrinsic Brightness and Extinction

To study the EBL with $\gamma$-rays ($\tau_{\gamma\gamma}$), we need to know $F_{\text{int}}$. How can we determine the intrinsic $\gamma$-ray flux?

$$F_{\text{int}} = F_{\text{obs}} \exp(-\tau_{\gamma\gamma})$$
Variability

Not a problem!

PRELIMINARY
γ-ray absorption and UV escape fraction

solid: $f_{\text{esc},H} = 0.0$

dashed: $f_{\text{esc},H} = 0.2$

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As we use the γ-ray spectrum for blazars exposed for over 9 years by the LAT, during which time sources exhibit changes in flux by several orders of magnitude, one might expect this to have an effect on the measured absorption. However, our analysis shows that this does not pose a problem. We performed a time resolved analysis in time bins derived from a Bayesian analysis similar to those used in the Third Hard Source Catalog (Ajello et al. 2017). In each time bin the intrinsic spectrum was modeled independently. The data from each time bin were used to constrain the EBL independently, and the results for all the time bins were combined; these results were virtually identical to what was found when using the exposure over the entire 9 years.

We expect our updated γ-ray EBL measurement to be submitted to a refereed journal later this year; however, extracting the maximum amount of information from this measurement requires a detailed modeling effort. The work described in this section has been funded by NASA Fermi GI grants, but these did not include funding for modeling work.

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3. EBL Model

Shortly after the launch of Fermi, the PI and his collaborators (Razzaque et al. 2009; Finke et al. 2010) created an EBL model that, despite its relative simplicity, does a good job of reproducing the observed γ-ray absorption optical depth of the universe (Fig. 1). This...
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**Cosmic Gamma-ray Horizon**

PRELIMINARY

\[ \tau_{\gamma\gamma} = 1 \]

- **This work**
- **3LAC (HEP)**
- **Finke+ 10 Model C**
- **Domínguez+ 11**
- **Helgason+ 12**