The Extragalactic Background Light: Implications for The Cosmic Star Formation History

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Dwek & Arendt 2005, in preparation
Lecture Outline

- The extragalactic background light (EBL):
  - What is it, how do we measure it, methods of determination, problems
- The subtraction of foreground emissions
  - zodiacal light, Galactic stars and ISM
- The nature of the near-IR EBL (NEBL)
  - residual zodi or extragalactic?
- Population III spectral imprint on the NEBL
- Is there any evidence for the Xgalactic nature of the EBL in the observed TeV spectra of blazars?

Summary
The Extragalactic Background Light (EBL) in Context of Other Backgrounds

\[ I_{\text{CMB}} = 1000 \text{ nW m}^{-2} \text{ sr}^{-1} \]

\[ I_{\text{EBL}} \approx I_{\text{CMB}} / 10 \]
Sources Contributing to the EBL

The EBL consists of the cumulative radiation emitted by all energy sources since the epoch of recombination

- **Exotic Sources**
  - decaying particles, primordial black holes, exploding stars, Pop III stars

- **Active Galactic Nuclei**
  - powered by gravitational energy release

- **Starlight**
  - powered by the release of nuclear energy
The Importance of the EBL

- It contains information on:
  - cosmic star/BH formation history
  - cosmic history of metal production
  - thermalization of X-rays & starlight by dust
- Opacity source for TeV photons
- Causal relation to X-ray and radio backgrounds
- Constrains the existence/evolution of exotic sources
Difficulties in EBL Measurements

- No unique spectral characteristics
- Strong foreground emission
  - Interplanetary dust
  - Reflected sunlight
  - Thermal emission
  - Interstellar dust
  - Galactic starlight
- Spectral windows at ~ 5 and 300 µm
Measuring the EBL

- Direct diffuse sky measurements
  - Absolute calibration (IUE, DIRBE, IRTS, HST)
  - Excellent stray light rejection
  - Removal of foreground emission
- Source counts
  - Lower limit on EBL
  - Converge to EBL intensity
- Fluctuation analysis
  - Requires knowledge of $dI(z)/dz$
- Search for absorption in the spectra of TeV blazars
  - Requires knowledge of the intrinsic blazar spectrum
COBE Orbit Characteristics

- Sun-synchronous 900 km orbit with a 103 min. period
- 99° inclination causes the orbit to precess by 1°/day
- Scans 1/2 sky each day
- Data was collected over a 10 moth period

Scan modes of COBE Instruments

- FIRAS
- DIRBE
- DMR
DIRBE Observed Sky

- **2.2 µm sky**
  - starlight, IPD emission, LMC, SMC

- **25 µm sky**
  - IPD emission (Zodiacal light)
  - Galactic ISM

- **240 µm sky**
  - Interstellar Dust emission, LMC, SMC
Taking out the “Gang” of Foreground Emission Components

- IS dust
- Galactic stars
- Zodiacal light
Zodi Light Variation

(1) Towards the ecliptic plane

(2) Towards the ecliptic pole
Observed Signatures of Zodiacal Light Emission

- high ecliptic latitudes
- mid ecliptic latitudes
- low ecliptic latitudes
Components of the Zodiacal Dust Model
Kelsall et al. 1998

- Smooth dust cloud
  - asteroidal cometary collisions
  - 5 different models

- Interplanetary dust bands
  - asteroidal breakup
  - toroidal band model
  - migrating band model

- Circumsolar ring
  - Inward flowing dust particles, resonantly trapped in earth’s orbit
Zodi Subtracted Sky

- 2.2 µm sky
  - starlight, LMC, SMC

- 25 µm sky
  - Galactic ISM

- 240 µm sky
  - Interstellar Dust emission, LMC, SMC
Zodi Subtracted Sky

- **2.2 µm sky**
  - starlight, LMC, SMC

- **25 µm sky**
  - Galactic ISM
  - 2% of previous level

- **240 µm sky**
  - Interstellar Dust emission, LMC, SMC
Starlight Model
Arendt et al. 1998

- Observed 2.2 µm sky
  - Zodi subtracted
  - bright sources blanketed

- Faint source model
  - Exponential disk
  - Spiral arms
  - Molecular ring
  - Stellar halo
  - Bulge
Satellite Subtracted Sky

- **2.2 µm sky**
  - bright and faint stars subtracted

- **25 µm sky**
  - Dominated by Galactic ISM
  - 2% of previous level

- **240 µm sky**
  - Interstellar Dust emission, LMC, SMC
Starlight Subtracted Sky

- 2.2 \( \mu m \) sky
  - bright and faint stars subtracted
  - linear scale

- 25 \( \mu m \) sky
  - Dominated by Galactic ISM

- 240 \( \mu m \) sky
  - Interstellar Dust emission, LMC, SMC
Residual Sky after ISM Subtraction

- 2.2 μm sky
- 25 μm sky
- 240 μm sky
Residual = EBL if it is positive AND isotropic

Systematic Uncertainties

- 1.25 \( \pm 21 \)
- 2.2 \( \pm 12 \)
- 3.5 \( \pm 6 \)
- 4.9 \( \pm 8 \)
- 12 \( \pm 140 \)
- 25 \( \pm 160 \)
- 60 \( \pm 27 \)
- 100 \( \pm 6 \)
- 140 \( \pm 7 \)
- 240 \( \pm 3 \)

positive but not isotropic
positive AND isotropic
Recent Detections and Limits on the EBL at the Near-IR Wavelengths

- **Dwek & Arendt (1998)**
  - 2.2 \( \mu \text{m} \) DIRBE stellar template + Kelsall zodi model

  - Subtracted stars brighter than 9 mag
  - extrapolated SKY model (the star count model of Wainscoat et al. 1992)
  - Subtracted a Kelsall-based zodi model using the strong no-zodi principle

  - Compared the histogram of the DIRBE pixel intensities to SKY model
  - Wright zodi model

- **Wright (2001)**
  - 2MASS (the Two Micron All Sky Survey) data to remove resolved Galactic stars + SKY to remove the unresolved stars
  - Wright zodi model

- **Cambresy et al (2001)**
  - 2MASS + Kelsall zodi model

- **Arendt & Dwek (2002)**
  - Multi-color DIRBE stellar template + Kelsall zodi model

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**2.2 \( \mu \text{m} \) Bright Stars Blanked**

Min | Max

2MASS image (16 mag)
Limits and Detections of the EBL
(Hauser & Dwek 2001)

![Graph showing CIB intensity and wavelengths with key data points labeled: Stellar 19-100 μm, Dust 11-58 μm, Dust 15±2 μm, and Total CIB intensity 36-120 μm.](image-url)
Galaxies were more Opaque in the Past

The luminosity density in the local universe
(Dwek et al. 1998)

$L_{IR}/L_{tot} \approx 0.30$

$\approx 1.3 \times 10^8 L_{\text{sun}}$

$\approx 0.5 \times 10^8 L_{\text{sun}}$

For the EBL

$L_{IR}/L_{tot} \approx 50/100 \approx 0.5$

$\nu L_{\nu} (\text{nW m}^{-2} \text{sr}^{-1})$

$\lambda (\mu \text{m})$
EBL Determination from Galaxy Number Counts

- Provide the EBL intensity from resolved galaxies
- Incomplete: low surface brightness galaxies may be missed
- Overlapping low-surface wings from galaxies can create a truly diffuse background
- Sensitivity and confusion limits
- Number counts provide useful limits on EBL

ISO FIRBACK @ 170 µm (Dole et al. 2001)
Building Up Galaxy Number Counts
(Dwek et al. 2002, using Chary & Elbaz (2001) galactic SEDs and input parameters)
EBL Intensity Due to Resolved Galaxies
(8 m diameter telescope)
The EBL at Near-IR Wavelengths (NEBL)

- Bernstein et al. 2002
- Matsumoto et al. (2004)
- Madau & Pozzetti 2000
- Totani et al. 2001
- Arendt & Dwek 2003
- Cambresy et al. 2001
- Wright 2001

![Graph showing the EBL at Near-IR Wavelengths (NEBL)]
The Strong No-Zodi Principle (Wright 2002)

- The 5 - 60 µm residual spectrum is very similar to that of the zodi
- It cannot be the EBL, otherwise we wouldn’t see any Xgal TeV sources
- Constrain zodi models to produce zero 25 µm flux at the ecliptic pole
The Nature of the 1-5 µm Excess Emission

- Zodiacal Light
  - an isotropic component could have escaped the DIRBE detection

- Cosmological
  - red-shifted galaxy (z ≈ 8)
  - luminosities too high
  - large CSFR
  - overproduction of metals
  - distinct spectral component (Pop III stars?)
The NEBL has a Zodi spectrum!

Requires 23% of the Zodi light to be in an isotropic (undetected by DIRBE) component. This isotropic component will also affect the thermal component of the zodiacal light.

Fluctuation analysis (Matsumoto et al. 2004) suggests it is not isotropic, and similar to the excess EBL (Kashlinsky & Odenwald 2000)
Could the NEBL be Galactic?

Galaxy red-shifted to $z=8$

Local galaxy
Violates mid-IR upper limits set from observations of TeV blazars

Cambresy et al
Matsumoto et al
Wright, Rees, Gorjian

Kelsall zodi
Wright zodi
The NEBL Could be the Spectral Signature of the First Stars that Formed out of the Primordial Gas

- The NEBL could be produced by the first stars that formed out of the primordial gas (Pop III stars)
- Originally suggested by Bond, Carr, Hogan, Arnett to close the universe with baryonic matter
- Currently invoked as the source of photons needed to re-ionize the universe prior to $z \approx 8$
Intergalactic Medium (IGM)

Massive ($10^3 \, M_{\odot}$) Pop III star

SF efficiency $= 1/2.7 \approx 0.37$

Schematics of Population III star and its surrounding medium

- non-ionizing radiation
- nebular continuum & free-free
- recombination lines: Lyman-alpha, Balmer series

Ionization bounded H II region

$M_{\text{neb}} = 1.7 \times 10^3 \, M_{\odot}$

Intergalactic Medium (IGM)
Population III Source Spectrum

\[ M^* = 1000 \, M_{\sun} \]
\[ L^* = L_{\text{edd}} \times M^* = 3.3 \times 10^7 \, L_{\sun} \]
\[ T^* = 10^5 \, \text{K} \]
\[ t^* = 0.007 \frac{L^*}{M^*c^2} = 2 \times 10^6 \, \text{yr} \]
Stellar and nebular Energetics
(results of CLOUDY run)

Total luminosity = 10^3 L_{Edd} = 3.3 \times 10^7 L_{sun}

<table>
<thead>
<tr>
<th>Emission component</th>
<th>Fraction of total Lum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escaping stellar non-ionizing radiation</td>
<td>11%</td>
</tr>
<tr>
<td>Nebular emission</td>
<td>29%</td>
</tr>
<tr>
<td>continuum recomb</td>
<td>24%</td>
</tr>
<tr>
<td>free-free</td>
<td>5%</td>
</tr>
<tr>
<td>Recombination lines</td>
<td>60%</td>
</tr>
<tr>
<td>Lyman alpha</td>
<td>51%</td>
</tr>
<tr>
<td>Balmer series</td>
<td>9%</td>
</tr>
</tbody>
</table>
NEBL Created by Population III Stars

\[ \nu I'_\nu(\nu) = \left( \frac{c}{4\pi} \right) \int_{z_{\text{min}}}^{z_{\text{max}}} n_*(z) \left[ L'_\nu(\nu',z) + L^f(\nu',z) + L^{\text{lines}}(\nu',z) \right] \left| \frac{dt}{dz} \right| \, dz \]

\[ |\frac{dt}{dz}| = H_0^{-1} [(1+z)E(z)]^{-1} \]

\[ E(z) = \left[ \Omega_\Lambda + (1+z)^3\Omega_m \right]^{\frac{1}{2}} \]

\[ n_*(z) = n_0 \left( \frac{1+z}{1+z_{\text{min}}} \right)^{\alpha} \]

\( \Omega_m = 0.27 \quad \Omega_L = 0.73 \quad H_0 = 70 \)

no LOS absorption

alpha = -2.0

\( z_{\text{min}} = 6 \)

H alpha contributes to 4.9 \( \mu \)m flux
The Cosmic Star Formation rate

$$CSFR = n^* \frac{M^*}{t^*} \sim (1 + z)^{-2}$$

Important implications for:
(1) collapse rate of dark matter (DM) haloes
(2) re-ionization
Is there any evidence for absorption in the observed gamma-ray spectrum of TeV blazars?
TeV Blazars as Probes of the EBL Intensity

- TeV gamma-rays are attenuated by the EBL
- Allow for the determination of EBL in a wavelength region (5 - 60 µm) dominated by emission from interplanetary dust
- Problem: Intrinsic source spectrum is unknown

**Peak cross section at energies:**

\[ \frac{E_{\gamma}(\text{TeV})E_b(\text{eV})}{\lambda_b(\mu m)} \approx 1 \text{ MeV}^2 \]

or

\[ \lambda_b(\mu m) \approx 1.24 E_{\gamma}(\text{TeV}) \]

\[ \gamma_b + \gamma_{EBL} \rightarrow e^+ + e^- \]
What is the Intrinsic blazar Spectrum?

Assume intrinsic spectrum is a power law.
Search for a "break in the spectrum".

Intrinsic blazar spectrum is much more complex.

Intrinsic spectrum is NOT a simple power law.
Spectrum can be explained with a Synchrotron Self-Compton model.

- Synchrotron peak
- Inverse Compton Peak
Determining the Blazar Spectrum for the EBL intensity and visa versa
What EBL to Use? (Dwek & Krennrich 2004)

UV/opt
  high, mid, low
near-IR
  high, low
far-IR:
  high, low

A family of 12 realizations of the EBL
The Optical Depth due to all EBL Realizations

\[ z = 0.03 \]
\[ H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \]
Intrinsic Blazar Spectra for EBL Realizations  
(Dwek & Krennrich 2004)

Some spectra show an “unphysical” upturn
An “Unphysical Upturn in the Intrinsic Spectrum of Mrk 501

The statistical F-test was applied to examine the significance of the upturn.

Significance of upturn depends on the uncertainty in the determination of the gamma-ray energy.

\[
\frac{dN}{dE} = \Phi E^{-\alpha - \beta \ast \log(E)} \times \exp\left[\frac{E}{E_0}\right]
\]

\[
\frac{dN}{dE} = \Phi E^{-\alpha - \beta \ast \log(E)}
\]
Viable Intrinsic Blazar and EBL Spectra

Constraints on gamma-ray production mechanisms
TeV Opacity due to the NEBL

$Z_{\text{min}} = 7, \quad Z_{\text{max}} = 15$

$Z_{\text{min}} = 9, \quad Z_{\text{max}} = 30$
Intrinsic Spectrum of H1426+428 ($z=0.129$)

$Z_{\text{min}} = 7, \ Z_{\text{max}} = 15$

$Z_{\text{min}} = 9, \ Z_{\text{max}} = 30$

NO evidence for absorption by Population III stars!!
Intrinsic Spectrum of PKS 2155 (z=0.13)

- Population III stars create an interesting break in the intrinsic source spectrum
- Need 120 GeV datum point to confirm trend
- Can acceleration models explain a spectral break at 300 GeV?

Zenithal min = 7, Zenithal max = 15
Zenithal min = 9, Zenithal max = 30
Summary

● The NIRS and DIRBE data show a definite excess in the diffuse sky emission over that expected from normal star-forming galaxies.

● The excess is best explained by residual zodi emission that escaped detection by DIRBE - however, fluctuation suggests its Xgal.

● HOWEVER, the excess emission could also be extragalactic in origin (NEBL).

● If so, the most likely candidates are Pop III stars that started forming at $z \approx 15-30$, and stopped forming at $z \approx 7-9$.

● The SFR needed is about 10x larger than that associated with normal galaxies.

● NO evidence for NEBL signature in the intrinsic spectrum of blazars - HOWEVER, PKS 2155 is an exciting object that needs further studies at lower energies ($\approx 100$ GeV).
The END
Thank you very much for listening
A spherical cow may be a good representation of reality, provided you have a sufficiently limited point of view.