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The extragalactic background light and the gamma-ray opacity of the universe

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ABSTRACT

The extragalactic background light (EBL) is one of the fundamental observational quantities in cosmology. All energy releases from resolved and unresolved extragalactic sources, and the light from any truly diffuse background, excluding the cosmic microwave background (CMB), contribute to its intensity and spectral energy distribution. It therefore plays a crucial role in cosmological tests for the formation and evolution of stellar objects and galaxies, and for setting limits on exotic energy releases in the universe. The EBL also plays an important role in the propagation of very high energy γ-rays which are attenuated en route to Earth by pair producing γ–γ interactions with the EBL and CMB. The EBL affects the spectrum of the sources, predominantly blazars, in the $\sim$10 GeV–10 TeV energy regime. Knowledge of the EBL intensity and spectrum will allow the determination of the intrinsic blazar spectrum in a crucial energy regime that can be used to test particle acceleration mechanisms and very high energy (VHE) γ-ray production models. Conversely, knowledge of the intrinsic γ-ray spectrum and the detection of blazars at increasingly higher redshifts will set strong limits on the EBL and its evolution. This paper reviews the latest developments in the determination of the EBL and its impact on the current understanding of the origin and production mechanisms of γ-rays in blazars, and on energy releases in the universe. The review concludes with a summary and future directions in Cherenkov Telescope Array techniques and in infrared ground-based and space observatories that will greatly improve our knowledge of the EBL and the origin and production of very high energy γ-rays.

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1. Introduction

The extragalactic background light (EBL), defined here as the emission in the 0.1–1000 μm wavelength region, is one of the fundamental observational quantities in cosmology. It comprises the integrated light from resolved and unresolved extragalactic sources, and the light from any truly diffuse background, excluding the cosmic microwave background (CMB). It is therefore the repository of all energy released by nuclear and gravitational processes since the epoch of recombination. A significant fraction of this radiation is shifted by cosmic expansion and by absorption and reradiation by dust into infrared (IR) wavelengths. Consequently, its intensity and spectral shape hold key information about the formation and evolution of galaxies and their stellar and interstellar contents throughout cosmic history. A strict lower limit on the EBL intensity is provided by the integrated light from resolved galaxies, hereafter referred to as the integrated galaxy light (IGL).

The EBL plays also an important role in the propagation of high energy γ-ray rays that are predominantly emitted by blazars, a subgroup of active galaxies hosting active galactic nuclei (AGN), whose relativistic jet is pointed towards the Earth. High energy photons emitted by blazars are attenuated by photon–photon interactions with the EBL, a process that can be used to set important limits on both, the intrinsic spectra of blazars and the intensity of the EBL in select energy and wavelength regions where these interactions are most prominent.

The EBL is intimately connected to the diffuse X-ray, radio, and supernova neutrino backgrounds. Deep X-ray surveys have resolved the X-ray background into point sources, most of which are dust enshrouded AGNs [186]. Up to 90% of the X-ray energy produced in individual AGN can be degraded and reradiated predominantly at mid-IR wavelengths (e.g. [106,47]). Consequently, the X-ray background can be used to predict the EBL intensity at at these wavelengths. Current estimates show that about 15% of the 24 μm EBL intensity is powered by AGN activity ([233,219] and references therein). Conversely, the connection between mid-IR bright sources and AGN can be used to estimate the contribution of obscured AGN to the X-ray background ([112,219] and references therein).

Massive stars that power the IR emission also emit radio free-free emission during the main sequence phase, and radio synchrotron emission during the supernova remnant phase of their

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evolution. The IR emission from star-forming galaxies is therefore correlated with the radio emission [164,75]. This correlation can be used to estimate the contribution of star-forming galaxies to the cosmic radio background [120,89,200].

Most of the EBL intensity is powered by massive stars that end their life as core collapse supernovae. The total EBL intensity can therefore be used to derive an estimate of the supernova rate and the resulting flux of supernova neutrinos [132,48]. The detectability of these neutrinos can be greatly enhanced by the proposed introduction of gadolinium in existing large water Cherenkov detectors (such as Super-Kamiokande) [49]. Gadolinium has a very high capture cross section for neutrons generated in $\bar{\nu}_e + p \rightarrow e^+ + n$, reactions, and can be introduced in the form of soluble trichloride ($GdCl_3$). Following the neutron capture, the Gd emits an 8 MeV γ-ray which produces relativistic electrons by Compton scattering. The Cherenkov radiation from these electrons is more easily detected than that produced in the cascade of the 2.2 MeV γ-ray generated by the capture of neutrons by free protons.

Several reviews have appeared in the literature, presenting a historical overview of the importance of the EBL, early estimates of its intensity, the quests for its detection, and its many astrophysical implications [124,137,156]. Since these reviews were written, significant advances have been made in studies of the EBL with the launch of UV (*Galex*) and IR space observatories (*Spitzer*, *Herschel*, and *Akari*). These observatories, together with ground-based telescopes, such as 2MASS, have provided new limits on the EBL ranging from UV to submillimeter wavelengths. Deeper galaxy number counts and new data analysis techniques of stacking astronomical images have narrowed the gap between the contribution of resolved galaxies and the true intensity of the EBL.

The *Fermi* Gamma-Ray Space Telescope, operating between 200 MeV and 300 GeV, and ground-based air Cherenkov detectors (H.E.S.S., MAGIC, and VERITAS) operating in the ~50 GeV–100 TeV range have broadened the energy window for the studies of γ-ray sources. These advances have led to the detection of new GeV and TeV γ-ray sources and provided new data for determining their intrinsic spectra. Reviews of these subjects were presented by Weekes [237] and Hinton and Hofmann [129]. More recently, Dermer [77] presented a review of the *Fermi* catalog of γ-ray sources and the physics of the production of relativistic particles and γ-rays from these sources. Table 1 presents a glossary to the acronyms of the observatories and instruments referred to in this review.

These developments provide the main impetus for this review. We first present, in Section 2, the basic formulae describing the attenuation of photons by pair producing interactions with other photons. We then show how this attenuation will affect γ rays traversing a radiation field characterized first by a pure black body, representing the stellar emission component of the EBL, and then by a more realistic EBL that includes the dust emission component. This attenuation can, in principle, be used to determine the intensity of the attenuating radiation field if the intrinsic source spectrum is known. In Section 3 we survey the type of γ-ray sources that are used in these studies, their spectral characteristics, the physical mechanisms for generating their spectra, and constraints on their spectral shape imposed by general physical principles. In Section 4 we summarize measurements and limits on the EBL intensity determined by direct measurements and by adding the light from resolved galaxies. Models for the EBL intensity and its evolution with redshift are summarized in Section 5. In Section 6 we summarize the constraints on the EBL intensity derived from γ-ray observations of blazars, emphasizing the different assumptions made on the intrinsic blazar spectra to derive these limits. EBL models predict the γ-ray opacity of the universe at different energies, and in Section 7 we compare these model predictions with blazar observation. Throughout this review it was tacitly assumed that the production of γ-rays takes place exclusively in the sources. In Section 8 we consider alternative scenarios of γ-ray production that could have important implications for EBL limits, namely, that a significant fraction of the observed γ-rays could be produced en route to Earth. The role of the EBL in setting limits on exotic energy releases in the universe is briefly discussed in Section 9. A summary and future prospects for the fields of γ-ray and EBL research is given in Section 10.

Table 1
Glossary of abbreviations of spacecrafts,[a] telescopes, and instruments.

Abbreviation	Full name
Akari	Infrared imaging satellite (ASTRO-F)
BLAST	Balloon-borne Large-Aperture Submillimeter Telescope
COBE	Cosmic Background Explorer
DIRBE	Diffuse Infrared Background Experiment
FIRAS	Far Infrared Absolute Photometer
CTIO	Cerro Tololo Inter-American Observatory
GALEX	Galaxy Evolution Explorer
Herschel	Herschel Space Observatory
PACS	Photodetector Array Camera
SPIRE	Spectral and Photometric Imaging Receiver
HST	Hubble Space Telescope
WFPC2	Wide Field Planetary Camera
NICMOS	Near IR Camera and Multi-Object Spectrometer
IRTS	Infrared Telescope in Space
ISO	Infrared Space Observatory
ISOCAM	ISO Camera
JCMT	James Clerk Maxwell Telescope
SCUBA	Submillimeter Common User Bolometer Array
NTT	New Technology Telescope
Spitzer	Spitzer Space Telescope
IRAC	Infrared Array Camera
MIPS	Multiband Imaging Photometer
Subaru	Optical, near-IR telescope
Pioneer	Interplanetary spacecraft
WMAP	Wilkinson Microwave Anisotropy Probe
2MASS	Two Micron All Sky Survey
CTA	Cherenkov Telescope Array
Fermi	Fermi Gamma-Ray Space Telescope
H.E.S.S.	High Energy Stereoscopic System
IACT	Imaging Air Cherenkov Telescope
MAGIC	Major Atmospheric Gamma-Ray Imaging Cherenkov Telescope
Milagro	Gamma-ray and cosmic-ray telescope
VERITAS	Very Energetic Radiation Imaging Telescope Array System

[a] Spacecraft names are presented in italics, and their instruments are indented.

2. The EBL and the attenuation of gamma-ray photons

2.1. The EBL

The differential specific flux at wavelength λ_0, $dF_\nu(\lambda_0)$, received from radiative sources within a comoving volume element $dV_c(z)$ at redshift z at wavelength λ is given by (e.g. [185]):

$$dF_\nu(\lambda_0) = (1+z)\frac{\mathcal{L}_\nu(\lambda, z)\, dV_c(z)}{4\pi\, d_L(z)^2} \tag{1}$$

where $\mathcal{L}_\nu(\lambda, z)$ is the comoving specific luminosity density of the sources, d_L is their luminosity distance, and the $(1+z)$ factor arises from the decrease in energy of the emitted photons due to the redshift, and $\lambda_0 = (1+z)\lambda$.

The specific comoving intensity of the EBL per unit solid angle, $\delta\Omega$, at redshift z_0 and wavelength λ_0 is given by an integral over all energy releases over cosmic history:

$$\begin{aligned} I_\nu(\lambda_0, z_0) &= \int_{z_0}^{\infty} (1+z)\frac{\mathcal{L}_\nu(\lambda, z)}{4\pi\, d_L(z)^2}\frac{dV_c(z)}{\delta\Omega} \\ &= \left(\frac{1}{4\pi}\right)\int_{z_0}^{\infty} \mathcal{L}_\nu(\lambda, z)\left|\frac{c\,dt}{dz}\right| dz \end{aligned} \tag{2}$$