The Extragalactic Background Light and the γ–Ray Opacity of the Local Universe

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Abstract

The extragalactic background light (EBL) in the UV to far–infrared wavelength region is the repository of all energy releases in the universe since the epoch of recombination. It is also a source of opacity for TeV γ–ray sources. We briefly review the observational status of the EBL and discuss the uncertainties in its intensity at different wavelengths. The constraints on the EBL are used to place limits on the TeV opacity of the local universe.

1. Introduction

The detection of the diffuse extragalactic background light (EBL), defined here as the background light in the 0.1 to 1000 μm range, presents an extremely difficult challenge for astronomers. Unlike the cosmic microwave background, the EBL has a priori no distinct spectral characteristics. Its measurement requires the determination of the absolute sky brightness in the presence of emissions from the telescope, the instruments, the Earth's atmosphere, and stray light from bright local sources (Earth, Sun, Moon). In addition to these technical difficulties in obtaining the absolute sky intensity, the detection of the EBL requires the removal of bright sources of foreground emission including resolved sources (stars, star–forming regions) within our Galaxy, and diffuse sources such as scattered and emitted light from interplanetary dust (IPD) particles (zodiacal dust), interstellar dust, and unresolved stars. Finally, any residual emission surviving the foreground removal process must pass strict positivity and isotropy tests to be considered of cosmological origin (Hauser et al. 1998).

Limits and detections of the EBL can be obtained using a variety of methods: (1) direct sky measurements; (2) measurements of fluctuations in the intensity of the background; (3) galaxy number counts, which provide lower limits on its intensity; and (4) observations of TeV γ–ray emitting blazars. An extensive review on the search for and the detection of the cosmic infrared background (CIB,

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defined as the EBL between 1 and 1000 μm) with the Diffuse Infrared Background Experiment (DIRBE) and the Far Infrared Spectrophotometer (FIRAS) instruments on board the *Cosmic Infrared Background Explorer* (*COBE*) satellite, and a summary of the observational status of the EBL at UV and optical wavelengths were presented by Hauser & Dwek (2001).

2. Limits and Detections of the EBL

From nucleosynthesis arguments (e.g. Hauser & Dwek 2001), the EBL is expected to have an average intensity of about $\nu I_\nu \sim 10$ nW m^{-2} sr^{-1} over the 0.1 to 1000 μm wavelength region. The EBL is viewed through strong sources of foreground emission whose combined intensity has minima at $\lambda \sim 5$ and 300 μm. At shorter wavelengths ($\lambda \leq 4\mu$m) the foreground emission is dominated by scattered emission from zodiacal dust and Galactic starlight, each having a intensity of $\nu I_\nu \sim 100$ nW m^{-2} sr^{-1} at 2 μm in the direction of the Lockman Hole. Thermal emission from zodiacal cloud dominates the foreground in the $\sim$ 5–60 μm wavelength region with an intensity of $\nu I_\nu \sim 4 \times 10^3$ nW m^{-2} sr^{-1} between $\sim$ 15 and 30 μm in the same direction of the sky. At longer wavelengths, the EBL is primarily obscured by emission from zodiacal and interstellar dust. At 140 μm these two components contribute about equally to the foreground emission at a level of $\nu I_\nu \sim 20$ nW m^{-2} sr^{-1}.

Galactic starlight is an important contributor to the foreground emission at near infrared wavelengths ($\lambda \approx$ 1–5 μm), and the removal of this component from the DIRBE skymaps was discussed in detail by Arendt et al. (1998). The systematic uncertainties in the $\sim 1 - 5$ μm residuals were dominated by uncertainties in the model used to subtract the emission from unresolved stars. Since then significant efforts have been undertaken to improve the removal of the Galactic stellar emission component, resulting in the detection of the CIB at 1.25, 2.2, and 3.5 μm (Dwek & Arendt 1998, Wright & Reese 2000, Wright 2001a, Cambrésy et al. 2001, Arendt & Dwek 2002). Larger values for the CIB at these wavelengths were obtained by Cambrésy et al. (2001) and Matsumoto et al. (2000). The latter used the Kelsall et al. (1998) model to subtract the zodiacal foreground, whereas the former used a different model characterized by a larger contribution of the zodiacal dust cloud to the foreground emission (Wright 2001b).

The subtraction of the zodiacal dust emission was described in detail by Kelsall et al. (1998). The procedure modeled the variation in the sky intensity caused by the Earth's motion through the IPD cloud and the DIRBE scanning pattern (see the animation on *http://icrgate.icrr.u-tokyo.ac.jp/can/Symp2002/Presentations.htm*). The resulting IPD emission model is therefore insensitive to any isotropic emission component of the cloud. The uncertainties in the intensity of this zero level component were determined from the variance in its value. This variance was obtained by modeling the primary dust cloud with different geometrical configurations which produced about equally good fits to the observed variations in the sky brightness. Even though the model succeeded in the subtraction of 98% of the thermal emission form the zodi cloud, the residual emission was not a 3σ detection and was far from isotropic, preventing its identification as the CIB.

At mid–infrared (IR) wavelengths the CIB has a lower limit at 15 μm, obtained from galaxy counts obtained with the *Infrared Space Observatory* (*ISO*) satellite (Elbaz et al. 2001). At far–infrared wavelengths, the CIB has been detected at $\sim$ 200 to 1000 μm by Puget et al. (1996), Fixsen et al. (1998) and Lagache et al. (2000), at 140 and 240 μm by Hauser et al. (1998), and at 100 μm by Lagache et al. (2000). Hauser et al. reported the 140 CIB intensity derived using the DIRBE photometric calibration. A somewhat lower value (but consistent with the DIRBE calibration) is derived if the FIRAS photometric scale is used in the calibration.

Figure 1 summarizes select detection and limits on the CIB. The filled symbols represent lower limits on the EBL. The open symbols are nominal detections. Also shown in the figure are polynomial approximations to the EBL, the solid and dashed lines corresponding to the limits and detections represented by the solid and open symbols, respectively. A more complete discussion and depiction of the limits and detection of the EBL can be found in Hauser & Dwek (2001, Figure 5) and Arendt & Dwek (2003, astro-ph/0211184).

3. The TeV γ–Ray Opacity of the Universe

The EBL is a source of opacity for γ–rays in the 0.1 to 10 TeV (=10^{12} eV) energy range (Nikishov 1962, Stecker et al. 1992), which are attenuated by e^+e^- pair production. This effect allows, in principle, the determination of the EBL from the observations of TeV γ–ray sources, if their intrinsic spectra is known. The pair–production reaction peaks at energies given by $\lambda(\mu\text{m}) \approx 1.24$ E_γ(TeV). Figure 2 depicts the γ–ray opacities to sources at redshift of z=0.031 corresponding to the lower (solid line) and larger (dashed line) EBL shown in Figure 1. Also shown in the figure are the contributions of the different segments of the lower EBL (shown as a shaded bar diagram in Figure 1) to the total γ–ray opacity. The figure shows that the 0.2 to 2 TeV opacity is dominated by the optical and near–IR intensity of the EBL. The 17 TeV opacity is dominated by the mid–IR intensity of the CIB. If the 60 μm residual intensity at the level of 28

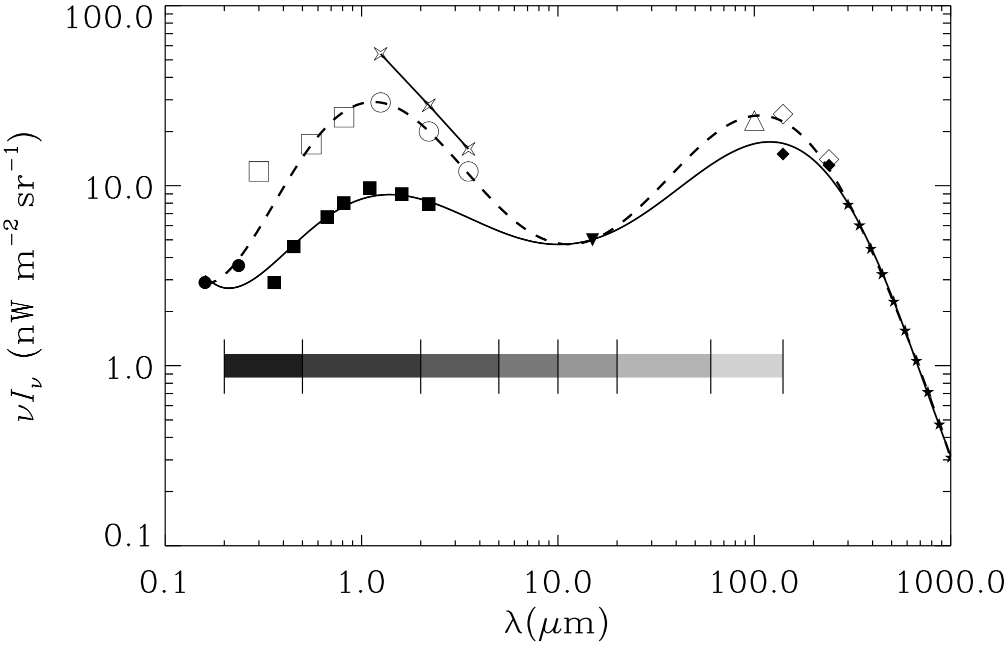

Fig. 1. Select limits and detections of the EBL: (1) filled circles–Gardner et al. (2000); (2) filled squares–Madau & Pozzetti (2000); (3) filled triangle–Elbaz et al. (2002); (4) filled diamonds–Hauser et al. (1998, FIRAS calibration); (5) filled stars: Fixsen et al. (1998); (6) open squares–Bernstein et al. (2002); (7) open circles–Wright (2001), Wright & Reese (2000); (8) open crosses–Cambrésy et al. (2001); (9) open triangle–Lagache et al. (2000); (10) open diamonds–Hauser et al. (1998, DIRBE calibration). The shaded bar diagram in the figure indicates different wavelength regions depicted in Figure 2. The solid and dashed lines are polynomial fits to the EBL represented by the filled and open symbols, respectively.

nW m^{-2} sr^{-1} (Finkbeiner et al. 2000) was of cosmological origin, it would result in a 17 TeV opacity of ~ 12. This would suggest that the intrinsic flux of Mrk 501 should be enhanced by a factor of $\sim \exp(12) \approx 10^5$ at this energy, resulting in a so–called IR–TeV "crisis" (Protheroe & Meyer 2000). However, the large value of the 60 μm residual reported by (Finkbeiner et al. 2000) is more likely to be due to an incomplete subtraction of foreground emissions than of a cosmological nature.

4. Summary

The past few years has seen major progress in the determination of the EBL over the 0.2 to 1000 μm wavelength region. However, the EBL detection at 0.3 to 0.8 μm (Bernstein et al. 2001) are only at the $\sim 2\ \sigma$ level. The near–IR detections are still uncertain because of the zero flux level of the zodiacal

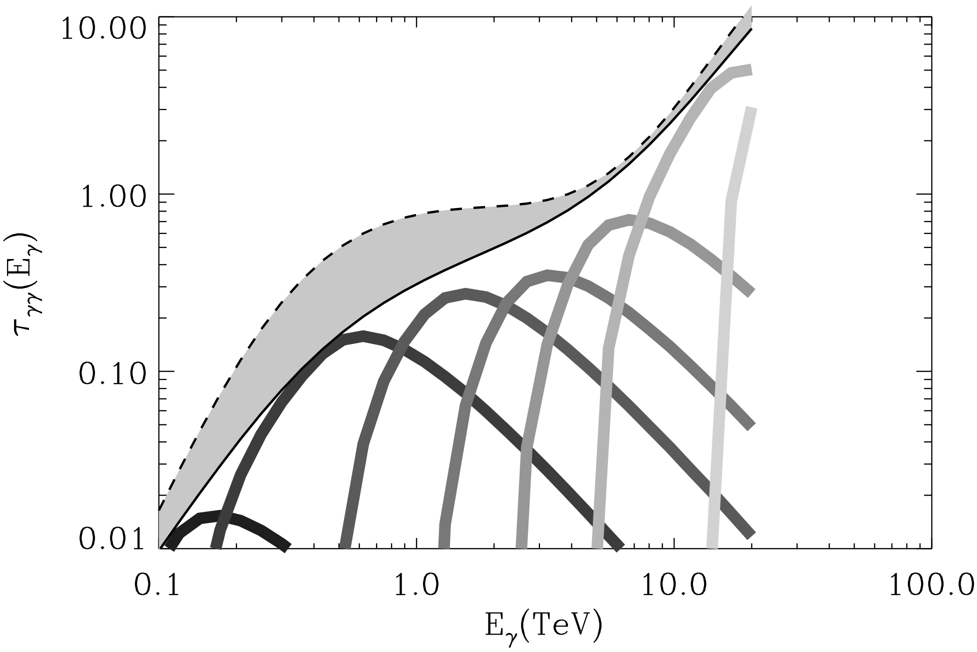

Fig. 2. The γ–ray opacity at redshift $z = 0.031$. The solid and dashed curved correspond to the opacity created by the respective EBL spectra shown in Figure 1. The shaded curves in the figure represent the contribution of the "minimal" EBL (solid line in Figure 1) in the different wavelength regions to the total opacity.

dust emission, and DIRBE–FIRAS calibration differences (although internally consistent) at 140 μm may have important implications for the > 20 TeV γ–ray opacity. At mid–IR wavelengths foreground emission from the zodiacal dust cloud prevents the detection of the CIB, and TeV astronomy may be the only means of determining the CIB at these wavelengths, if the intrinsic blazar spectrum were known.

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