Extragalactic Background Light
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From
Encyclopedia of Astronomy & Astrophysics
P. Murdin

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ISBN: 0333750888
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Extragalactic background light (EBL) is the integrated flux from all extragalactic sources, including those which are not individually detected. In keeping with the COSMOLOGICAL PRINCIPLE—that the universe should appear homogeneous and isotropic to a typical observer—the EBL is expected to have a uniform mean level on large angular scales over the sky.

The cosmological significance of the EBL was first recognized as early as the 1700s, when astronomers imagined the universe to be a static volume of space, uniformly filled with stars. In this cosmological picture, the number of stars at a distance, \( r \), increases as \( r^2 \), canceling the \( 1/r^2 \) fall-off in the apparent brightness of a single star and making the total flux from objects populating every shell of space a constant value. This view led HEINRICH WILHELM OLBERS and others to conclude that the nighttime sky should be as bright as the daytime sky. The dilemma presented by the fact that the sky is (relatively) dark at night became known as OLBERS’ PARADOX. This apparent conflict is now easily explained by the expansion of the universe, the finite speed of light and, most importantly, the finite lifetimes of stars. However, Olbers’ paradox stands as an excellent illustration of the power of background measurements to test our model of the universe.

Ironically, while the night sky is far from dark, extragalactic sources contribute less than 1% of the sky brightness from the ultraviolet (UV) to the infrared (IR). Terrestrial, zodiacal and Galactic sources produce foreground emission which dominates the sky flux, making the diffuse EBL very difficult to measure, but also causing strong bias against the individual detection of faint or low surface brightness galaxies and intergalactic stars. Measurements of the diffuse EBL are immune to surface brightness selection effects. The EBL therefore provides a complete census of the energy density in the universe, making it a very powerful constraint on models of STAR FORMATION and the baryonic content of the universe.

Sources of the EBL

The majority of the EBL at UV to IR wavelengths is produced by stars at all REDSHIFTS since the first stars formed. In the far-UV (\( \sim \)1000–1600 Å), Lyman continuum absorption by hydrogen in the intergalactic medium limits the objects contributing to the EBL to those at redshifts below \( z \sim 1600 \) Å/912 Å – 1 \( \sim 0.8 \). In addition, the UV light from galaxies is produced by the hot, massive stars, which are also responsible for most of the nuclear processing of hydrogen into helium and heavier elements (generally called ‘metals’). The far-UV EBL thus traces the global star formation and metal production rate in the last half of a Hubble time.

The sources of the EBL become more complicated at optical (3000 Å–1 \( \mu m \)) and IR (1–1000 \( \mu m \)) wavelengths because the light we detect in these bands originates from objects over a wider range of redshifts and, consequently, emitted wavelengths. The optical EBL includes the direct emission from STELLAR POPULATIONS out to redshifts of \( z \sim 10 \). The energy density from stellar populations peaks at 1–1.5 \( \mu m \) at most stellar ages, so that the optical EBL will include both older populations at low redshift and young populations at high redshift.

Finally, much of the stellar emission in the universe will be contribute to the far-IR background, both because the light from the earliest generations of stars (most distant stars) will be redshifted to longer wavelengths and because UV-optical photons will be absorbed by dust grains in the emitting galaxy and re-radiated as thermal emission at infrared wavelengths (\( \lambda \geq 10 \mu m \)). Dust attenuation of short-wavelength light is very efficient and may prevent more than 30% of the star formation in the universe from being directly detected at wavelengths shorter than 1 \( \mu m \).

Non-stellar emission, such as the gravitational potential energy from accreting black holes and emission from decaying particles, will also contribute to the EBL. It is also possible that a significant fraction of the baryons in the universe might reside in a primordial INTERGALACTIC MEDIUM of ionized gas which might be identified by its contribution to the EBL. While hot gas at a temperature of \( T \sim 10^6 \) K would emit x-rays, and cool gas (\( T \sim 10^4 \) K) would produce dramatic absorption features in quasar spectra, gas at a temperature of \( T \sim 10^5 \) K would be detectable only by its contribution to the EBL through redshifted HeII emission at 304 Å and Lyα at 1216 Å.

Measuring the EBL

Figure 1 shows the surface brightnesses of the foreground sources as a function of wavelength along lines of sight where these sources are faintest—at Galactic latitudes greater than 65° and ecliptic latitudes greater than 30°. For comparison, EBL detections and upper limits are shown in figure 2, along with models of the expected EBL and lower limits derived by summing the flux from resolved extragalactic sources (i.e. detected galaxies) and models of the EBL. At all wavelengths, the cumulative flux from foreground sources is roughly 100 times that of the EBL.

Ultraviolet (1000–2500 Å)

Because the atmosphere is opaque to photons with wavelengths shorter than about 3100 Å, UV observations must be made from rockets or from space. Early efforts to detect the far-UV background were inspired by the fact that the only bright foreground source documented at the time—ZODIACAL LIGHT—drops off sharply below 4000 Å and becomes insignificant below 2000 Å. However, the measurement was more difficult than expected and resulted by summing the flux from resolved extragalactic sources (i.e. detected galaxies) and models of the EBL. At all wavelengths, the cumulative flux from foreground sources is roughly 100 times that of the EBL.

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Figure 1. The flux from foreground sources is shown for lines of sight at Galactic latitudes greater than 65° and ecliptic latitudes greater than 30°, where foregrounds are faintest. The curve marked by short dashes at 0.3–1 µm shows the airglow contribution to ground-based observations: below 0.3 µm, the atmosphere is opaque; above 1 µm, the atmosphere is too bright for background observations. The solid curve shows zodiacal light, with the scattered component peaking around 0.6 µm and the thermal component peaking around 10 µm. The short-long dashed curve shows thermal emission from interstellar (Galactic) dust, with strong emission features around 3, 6, 8 and 10 µm. Scattered light at UV to optical wavelengths from the same dust is marked by a dot–dashed curve. The long dashed curve shows thermal emission from interstellar gas (see text). The dotted curve shows the flux from discrete Galactic stars fainter than V = 6.0 mag. The dot–short dashed curve shows the cosmic microwave background radiation (2.73 K).

Figure 2. Measurements of the surface brightness of the EBL from the UV to the IR are indicated by filled dots and by the dark, solid curve. Upper limits are indicated with downward arrows. Upward arrows indicate lower limits to the EBL from the integrated flux of detected sources (galaxy counts). The hatch-marked region shows the range predicted by various models based on UV–optical source detections when dust obscuration is included (see Dwek et al. (1998) for details).

Rapid progress around 1980, with the advent of UV detectors with better resolution and greater sensitivity. Results in the last few decades have consistently shown that the majority of the UV background originates within the Galaxy, with only a small component being isotropic and therefore possibly extragalactic. The majority of the Galactic contribution is diffuse, dust-scattered starlight. The scattered flux can be estimated based on the intensity of the thermal emission from the same dust, which identifies the column density of dust, and simple scattering models incorporating empirically and theoretically determined dust properties. The previously poor agreement between modeling efforts now seems well explained by evidence that interstellar dust is strongly forward scattering. The scattered UV flux therefore depends on the scattering angle between the line of sight and the incident starlight from the center and plane of the Galaxy. Line emission from [O III] 1663 Å and O III] 1663 Å has also been detected in correlation with the column density of neutral hydrogen, as have H2 fluorescence (1550–1650 Å), two-photon, bound–free and free–free continuum emission, and Lyα (1216 Å) and Hα line emission, all from warm (T = 10⁵ K), high-latitude gas. The intensity of these components is proportional to the cosecant of the Galactic latitude, which approximates the path length through smoothly distributed gas.

Measurements and limits in the last 10 yr have converged towards EBL fluxes in the range 2–5 nW m⁻² sr⁻¹, with a minimum estimate of 1 nW m⁻² sr⁻¹ from the cumulative flux in detected sources. Emission from galaxies is apparently responsible for the majority of this flux, while quasars and active galactic nuclei are estimated to contribute less than 0.2 nW m⁻² sr⁻¹ and flux from any intergalactic medium is limited to less than 0.2 nW m⁻² sr⁻¹ between 912 and 1216 Å.

Optical (3000 Å–1 µm)
The Earth’s own atmosphere was the greatest impediment to early efforts at measuring the optical EBL. Atmospheric emission (airglow) is not only at least 100 times brighter than the EBL but also can vary by several per cent on timescales of minutes, as can atmospheric extinction. These effects make it nearly impossible to correct for atmospheric emission and extinction to the required accuracy. The only demonstratedly successful method for dealing with the atmosphere is to avoid it by conducting measurements of the EBL from space. The dominant foreground source contributing from beyond Earth’s atmosphere is sunlight scattering off of the large (≥ 10 µm), rough, interplanetary dust grains which concentrate in the ecliptic plane. This scattered zodiacal light is also at least 100 times brighter than the flux of the EBL, even at ecliptic latitudes of |b| > 35°. As the solar system is harder to escape than the Earth’s atmosphere, it is fortunate that the scattering involved is well described by Mie scattering theory and is only weakly wavelength dependent, with scattering becoming more efficient by ~5% per 1000 Å toward longer wavelengths. The mean zodiacal light flux
Any warm body emits thermal radiation, including in the UV, rapid progress has been made with the sky coverage. The most ambitious and successful IR system depends on spectral modeling using multiwavelength detectors. From space, observations of the IR EBL must therefore be made from telescopes, the Earth’s atmosphere and the Earth itself. Annual variation of the sky brightness in all directions to discrete sources, such as the Pioneer 10 Explorer, obtained data not only from above the atmosphere but from beyond the zodiacal dust cloud at a distance of 3 AU from the Sun. While it avoided both airglow and zodiacal light, the Explorer’s poor resolution made the subtraction of even discrete Galactic sources (i.e. stars) very difficult. As in the UV, rapid progress has been made with the advent of high-resolution detectors above the atmosphere aboard the Hubble Space Telescope. Detections of the EBL at 3000, 5500 and 8000 Å have recently been reported based on coordinated HST imaging (see HUBBLE DEEP FIELDS) and ground-based spectroscopy.

Infrared (1 μm–1000 μm)

Any warm body emits thermal radiation, including telescopes, the Earth’s atmosphere and the Earth itself. Observations of the IR EBL must therefore be made from space with cryogenically cooled detectors. From space, thermal emission comes from dust trapped in the solar system and in the Galaxy. Subtraction of these foregrounds depends on spectral modeling using multiwavelength observations and geometrical modeling based on all-sky coverage. The most ambitious and successful IR measurement to date was undertaken with the Cosmic Background Explorer (COBE), launched in 1989. Prior to COBE, progress was made using short-lived, rocketborne telescopes and satellites intended for observations of discrete sources, such as the Infrared Astronomical Satellite (IRAS).

Zodiacal light from scattering dies off at a wavelength of a few microns, but thermal re-emission of absorbed sunlight from the same dust peaks around 10 μm. This thermal emission is recognizable from the motion of the Earth in its orbit through the zodiacal dust. The annual variation of the sky brightness in all directions can be modeled empirically and subtracted. Once the thermal zodiacal component is removed, some individual Galactic sources can be resolved and subtracted. Flux from unresolved, discrete Galactic sources can be determined at each wavelength based on detailed statistical models of Galactic sources and their spatial distribution. The diffuse emission from interstellar dust is brightest at around 100 μm. This component can be estimated and subtracted at wavelengths longer than 100 μm by scaling the zodiacal light-subtracted, 100 μm observations using a temperature model of the dust.

The COBE observations produced 3σ detections at 140 and 240 μm and 2σ upper limits at 100 μm and shorter.

Testing the big picture

The difference between the cumulative flux in optically detected sources and the detected optical EBL indicates that roughly 50% of the flux from individual sources is beyond the spectroscopic detection limit of current redshift surveys (see figure 2 and also GALAXY REDSHIFT SURVEYS). Recent results show that the difference may be partially explained by low surface brightness objects which are not included in standard catalogs and missed flux in low surface brightness regions of the objects which are catalogued. At longer wavelengths, however, the individual sources which produce the IR EBL have not been completely identified and may be powered by stellar or non-stellar sources. More generally, upper limits, lower limits and detections of the EBL all seem to indicate that the energy density in extragalactic sources is roughly constant over 4 orders of magnitude in wavelength (0.1–1000 μm). This spectral shape alone is a very interesting constraint on our models of the universe. The mean EBL at any wavelength is a complicated function of emission rates from stars, dust extinction, evolution of galaxies and the initial mass function and evolution of the stellar populations themselves. Meaningful interpretation of the EBL therefore requires modeling these variables as a function of redshift. Such models—which characterize our picture of the universe—are constructed from observations of resolved sources as a function of redshift.

One method for modeling the EBL is based on measurements of the rest-frame UV emission of individual galaxies, which indicates the star formation rate as a function of redshift and subsequently the EBL as a function of wavelength. Uncertainties in the dust attenuation of UV and optical light in the emitting galaxies limit the accuracy of these models. Other uncertainties include the stellar initial mass function and spectral energy distributions, which together identify the number of stars forming with a given mass and the spectral output from those stars. Models of the EBL based on this method need to include significant (≥30%) dust obscuration and re-radiation in order to provide reasonable agreement with observations of the infrared EBL. This necessity indicates that star formation regions at all redshifts are largely dust enshrouded and optically dark.
The conversion rate of neutral hydrogen gas into stars as a function of redshift can be inferred from the statistics of absorption features in quasar spectra. This provides another method of modeling the EBL. As with the models based on UV rest-frame emission, the dominant uncertainty in these models is the fraction of optical light attenuated by dust and the characteristic temperature of the dust. As metals are produced through nucleosynthesis in the same hot, young stars whose output dominates the EBL, the mean EBL also can be predicted by the total metal mass density in the local universe. Clusters of galaxies are a convenient place to measure metal density, because any metals which may be ejected from galaxies will be trapped in the cluster potential. The rate of metal production can also be traced by absorption features caused by intervening systems in quasar spectra as a function of redshift. The total metal enrichment in the universe as identified by either method agrees with the total EBL energy density detected to date to within a factor of 2–5.

After more than 25 yr of work in the field, measurements or well-quantified upper limits have been found for the EBL over the full wavelength range from the UV to the IR. To within the measurement and modeling uncertainties, the results at all wavelengths produce a generally self-consistent picture of the total star formation rate in the universe, the total metals produced in stars and the total energy output from nucleosynthesis. Additionally, at wavelengths shorter than 1 µm, the diffuse background can be accounted for by sources which are well understood and largely present in surveys of individually detected galaxies. Efforts to better quantify the EBL UV and mid-IR wavelengths are underway in the form of new satellite missions and programs to identify the sources of the IR background.

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