The Low Surface Brightness Universe, IAU Col. 171
ASP Conference Series, Vol. 170, 1999
J. I. Davies, C. Impey and S. Phillipps, eds.

The HST/LCO Measurement of the Optical Extragalactic Background Light

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Abstract.
We present the first detection of the mean flux of the optical extragalactic background light (EBL) at 3000, 5500, and 8000Å, derived from coordinated data sets from *HST* and Las Campanas Observatory. To isolate the extragalactic component, we have measured and subtracted the flux from foreground sources explicitly. In addition to detections in all three bands, we identify the minimum surface brightness contributed by resolved galaxies ($23 < V < 28$ AB mag) using a non-standard method of aperture photometry to which these data are uniquely suited. Individually resolved galaxies account for $\sim 30\%$ of the mean EBL coming from galaxies fainter than $V = 23$ AB mag. Taking into account the effective surface brightness detection limits of the deepest galaxy counts, and the results of LSB surveys at low redshift, the EBL we detect can be explained by galaxy populations already cataloged.

1. Introduction

The Extragalactic Background Light (EBL) is the integrated light from all extragalactic sources, both resolved and unresolved. The cosmological significance of the EBL was first appreciated in the 1700's, when expectations of a infinite, static Universe, uniformly filled with stars, led astronomers to puzzle over the fact that the nighttime sky is dark. The apparent conflict posed by the darkness of the night sky became known as Olbers' paradox. While it is now easily explained by the expansion of the Universe, the finite speed of light, and, most importantly, the finite lifetimes of stars, Olbers' paradox stands as an excellent illustration of the power of background measurements to test our model of the Universe. With new 10m–class telescopes and HST, the limits of resolved–source detection are being extended to ever fainter levels; however, a measurement of the EBL remains an invaluable complement to the source–count approach. Low surface brightness objects at low redshift and the majority of the galaxy luminosity function at high redshift are all easily missed both in surface brightness limited galaxy counts and in redshift surveys. In addition, photometry and even identification of faint galaxies becomes uncertain near detection limits. The EBL is immune to these surface brightness selection effects.

On a practical note, because the *HST*/WFPC2 field of view is only 5 arcmin^2, galaxies brighter than $V = 23$ AB mag are not statistically well sampled in these data. Our measurement of the EBL is therefore defined as the flux

https://doi.org/10.1017/S0252921100054543 Published online by Cambridge University Press

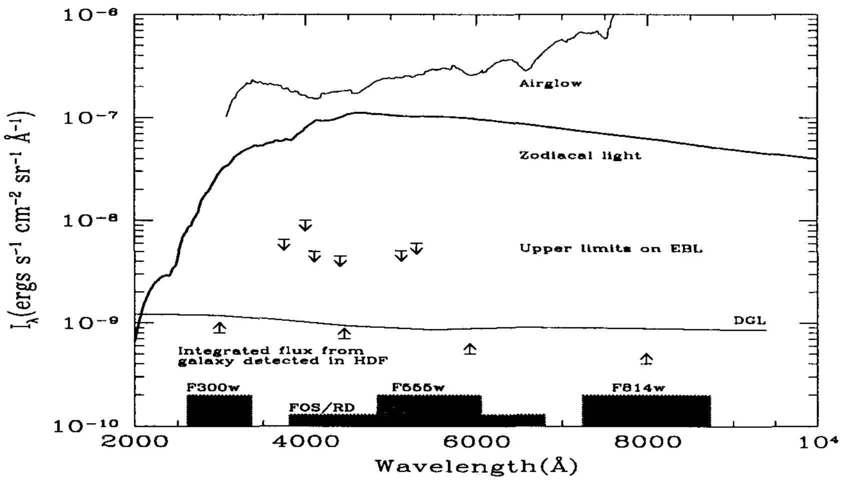

Figure 1. The relative surface brightness of airglow, zodiacal light, and diffuse galactic light (DGL) compared to upper limits for the EBL from previous investigations and the cumulative surface brightness of sources with $V > 23$ AB mag in the Hubble Deep Field (Williams et al. 1996). All foregrounds are shown at the flux levels we identify in this work. Hatched regions show the *HST*/WFPC2 and FOS band-passes.

from resolved and unresolved galaxies fainter than $V = 23$ AB mag. We use the abbreviation EBL23 as a reminder of this bright magnitude cut-off. This result can be combined with ground-based counts at brighter magnitudes to obtain the total EBL.

2. Foreground Subtraction and Data Sets

The key to any background measurement is the successful subtraction of foreground contamination. Figure 1 shows the surface brightnesses of foreground sources along lines of sight where they are faintest — at Galactic latitudes greater than 65 degrees and ecliptic latitudes greater than 30 degrees. For comparison, upper limits from previous attempts to measure the EBL are also shown, along with lower limits from integrating the flux in resolved galaxies (i.e. galaxy counts). The cumulative flux from foreground sources is roughly 100 times the EBL flux.

The brightest and most problematic foreground source is the rapidly varying molecular and atomic line emission, airglow, produced by the Earth's own atmosphere. We have avoided this problem entirely by using HST to measure the total night sky flux from above the atmosphere. The dominant foreground contributing from above the Earth's atmosphere is sunlight scattering off of the large ($\geq 10\mu$m), rough, interplanetary dust grains which concentrate in the ecliptic plane. As the solar system is harder to escape than the Earth's atmosphere,

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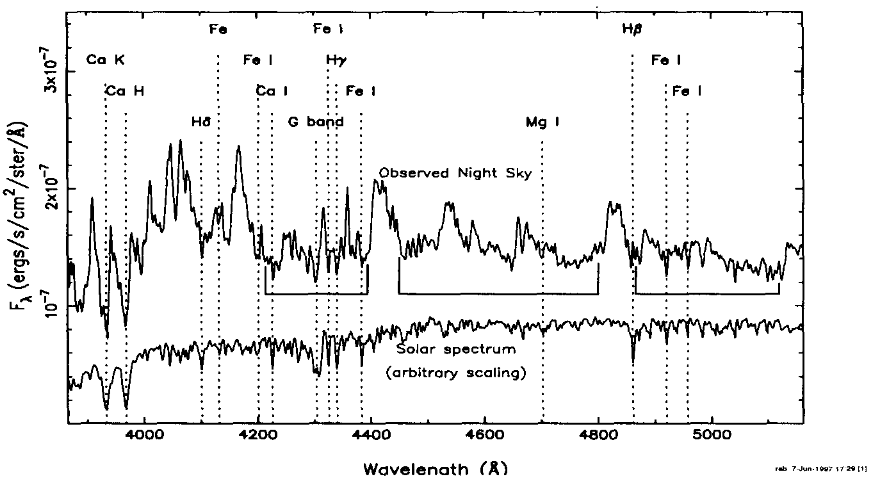

Figure 2. The observed night sky spectrum compared to a scaled solar spectrum. Solar absorption features due to ZL in the night sky spectrum are readily identified.

it is fortunate that the scattering involved is well described by Mie theory and is only weakly wavelength dependent, with scattering becoming more efficient by 5% per 1000Å with increasing wavelength. The mean zodiacal light flux can thus be identified by the strength of solar absorption features (Fraunhofer lines) which are preserved in its spectrum (see Figure 2).

Stars in our own Galaxy can be resolved and subtracted relatively easily with modern optical CCD detectors. However, interstellar dust scatters incident starlight, producing diffuse Galactic light at optical wavelengths. The dust column density and the interstellar radiation field strength, both of which determine the intensity of scattered DGL, are well correlated with the 100μm thermal emission from the dust along the line of sight. Our field was selected for its very low 100μm emission and therefore minimal DGL. The remaining low-level optical DGL can be estimated using simple scattering models, which are in good agreement with the empirical observations of the DGL from 2500–9000Å (see Witt et al. 1997 and references therein).

In this work, we isolate the EBL23 using three, simultaneous data sets: absolute surface photometry in 1000Å–wide bands centered at roughly 3000, 5500, and 8000Å from WFPC2; low ($\sim$ 300Å) resolution surface spectrophotometry at 4000—7000Å from the FOS; and moderate (2.0Å) resolution surface spectrophotometry from the Boller and Chivens spectrograph on the 2.5m duPont telescope at Las Campanas. The HST data are used to measure the mean flux of the total background, while the LCO data are used to measure the zodiacal light (ZL) by the method described above. We estimate foreground diffuse galactic light (DGL) using scattering theory and empirical correlations

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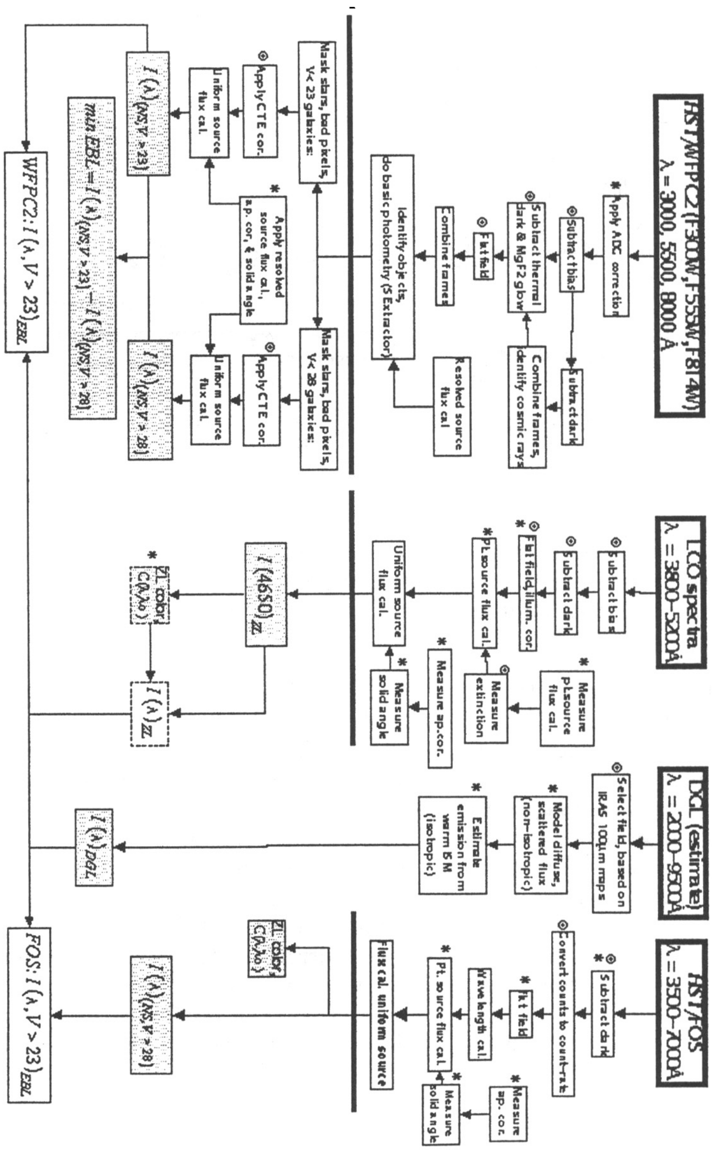

Figure 3. Flow chart of data reduction. Abbreviations are as follows: zodiacal light, ZL; diffuse galactic light, DGL; total night sky flux, NS; surface brightness, $I(\lambda)$; object cut–off at $V=23$, $I(\lambda)_{V>23}$; systematic errors, $*$; statistical errors, $\oplus$. The thick, horizontal bars divide pre-reduction from analysis. Bold type–face indicates original procedures, as opposed to STScI pipeline. Shaded boxes indicate results of individual data sets; dashed boxes show iterations in the ZL measurement; thick–lined boxes show final EBL23 results.

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between the optical DGL and thermal 100μm emission from the same dust. The HST observations were scheduled in three visits of six orbits each, with one month between visits. This allowed us to look for and confirm the expected modulation in the ZL with the Earth's orbital position, to look for possible off-axis scattered light with the satellite oriented at different roll angles, and to safe-guard against unidentified photometric anomalies with the instrument.

Observations from LCO and HST must be simultaneous to ensure that the ZL measured from the ground is exactly the contribution seen by HST. Also, the HST and LCO data sets must be calibrated to the same absolute scale with ~1% accuracy in order to detect the EBL. The basic data reduction, analysis, and method for combining data sets to detect the EBL23 is shown in the flow chart in Figure 3. When necessary to achieve the required accuracy, original reduction procedures were developed and STScI calibrations were augmented with our own solutions, as indicated in the flow chart. To eliminate stray light, HST observations were made only in the shadow of the Earth, with the Moon greater than 65 degrees from the optical axis of the telescope. We also selected the field to avoid $V > 7$ AB mag stars within 3 degrees.

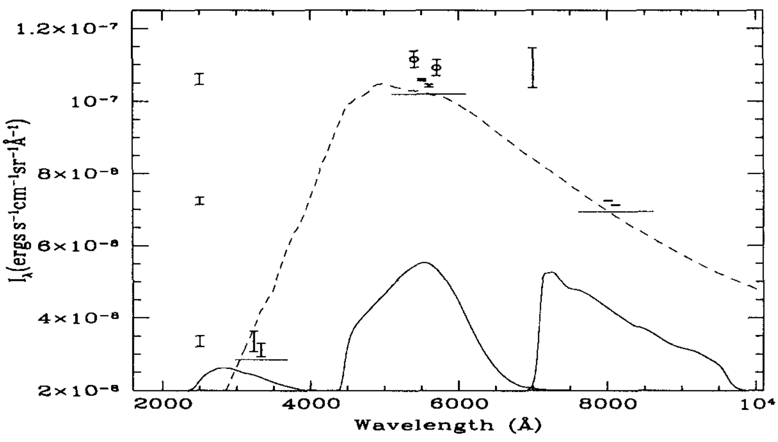

Figure 4. Total sky flux from WFPC2 (dots) and FOS (circles), November and December (offset +100Å) data sets. The 2% difference in flux results from changes in ZL due to Earth's motion. Dashed line shows ZL spectrum. Horizontal bars show ZL convolved with WFPC2 filters. Sky flux at $\lambda > 4000$Å is $\sim$ 95% ZL. Error bars on all points indicate 1σ RMS errors. Floating error bars at 2500Å show systematic uncertainties for WFPC2 result; the error bar at 7000Å shows the FOS uncertainty. Solid lines show WFPC2 band-passes.

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3. Results on the EBL

From each WFPC2 CCD image, we obtain a measurement of the night sky flux. As expected, we find variations in the sky flux between visits due to the varying ZL contribution at different times of year. We find no significant difference between the results from the three WFPC2 chips, and no indication of stray light or photometric anomalies between visits. Final statistical errors are less than 1% in the two redder pass-bands. The statistical error in the measurement at 3000Å is dominated by the accuracy with which we can subtract instrumental backgrounds, which are almost as bright as the total sky flux at this wavelength. Systematic errors are also of order 1%, and are dominated by the aperture correction and point source calibration. The results are shown in Figure 4. The total systematic errors plotted reflect 90% probability limits. FOS results have a much large systematic uncertainty ($\sim 5\%$), due to uncertainty in the aperture solid angle and point spread function, and non-uniform sensitivity across the detector, which affects surface brightness results much more than point source measurements. The WFPC2 and FOS results are discussed in detail in Bernstein et al. 1999a.

We took spectra of blank sky within the *HST*/WFPC2 field of view using the Boller and Chivens spectrograph at Las Campanas Observatory simultaneously with the November HST observations. We have used those spectra to measure the absolute flux of the ZL at 4650Å with a precision of 0.8%, and a systematic uncertainty of $< 1\%$, using the method outlined in §2. That measurement is discussed in Bernstein et al. 1999b.

The optical DGL was estimated using a simple non-uniform, back-scattering model, $I_\lambda = j_\lambda \, \omega_\lambda \, \tau_\lambda \, S(g,b)$, in which $S(g,b)$ is the scattering phase function in terms of Galactic latitude, b, and the average phase function of the dust, g (Jura 1979). The optical depth, τ_λ, and the surface brightness of the interstellar radiation field, j_λ, are empirically determined. The effective albedo, ω, and phase function, g, are based on extensive laboratory tests and modeling by Draine & Lee (1980) and are in excellent agreement with both optical and IR observations. The predicted DGL for our field (galactic latitude $b \geq 50°$, 150° from the galactic center) is in good agreement with prediction from scaling relations between the optical and UV scattering and the 100μm thermal emission from the galactic dust (see Witt et al. (1997) for a discussion of models and a review of results). The contribution from DGL is small enough that uncertainty in this estimate is an insignificant source of error for our final result.

Combining the HST and LCO results with a model of the DGL, we obtain the detections of the EBL23 shown in Figure 5. The errors are dominated by two systematic effects: unavoidable limitations in the flux calibration of independent data sets to the same absolute scale; and uncertainty in the color of the ZL, which we combine with our absolute ZL flux measurement at 4650Å to obtain the ZL flux at each WFPC2 band.

In the spirit of integrating galaxy counts to estimate the EBL from detected galaxies, we have identified the minimum EBL23 by a simplified aperture photometry method. In brief, we measure a single "sky" value using the whole CCD frame and measure source fluxes within apertures that are 8 times larger than those used for source photometry in, for example, the HDF catalog (see Williams et al. 1996). We find that for galaxies within two magnitudes of our

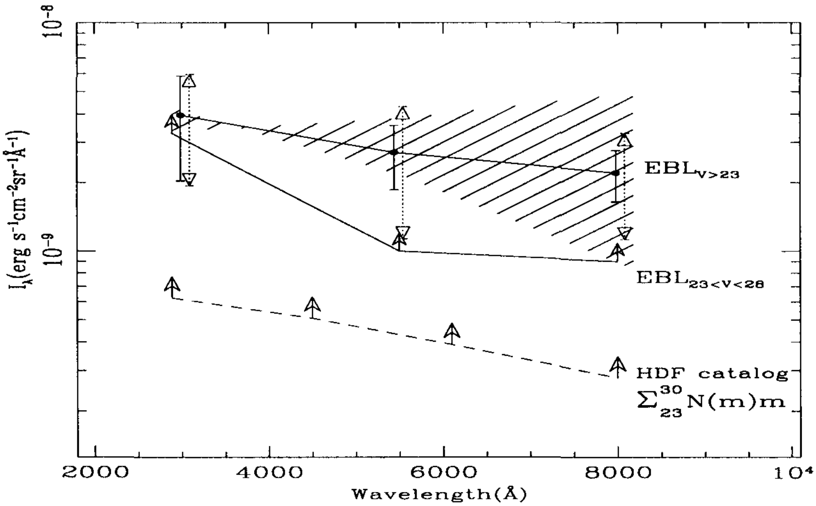

Figure 5. The detected EBL23 — EBL from galaxies with $V >$ 23 AB mag. Solid error bars show 1σ RMS errors; dotted error bars show systematic uncertainties. The hatch-marked region shows uncertainty from ZL subtraction. The dashed line connects integrated galaxy counts from the HDF. The solid line connects the minimum EBL23 values we identify from galaxies $23 < V \leq 28$ AB mag.

detection limit, roughly 50% of each galaxy's flux lies outside of the standard-sized apertures used by FOCAS or similar photometry packages. In addition, we estimate that an extragalactic sky pedestal is created by the overlapping wings of *resolved* galaxies and contributes roughly 2×10^{-10}ergs s^{-1} cm^{-2} sr^{-1} Å^{-1} to the sky level. This is a significant component and is undetectable except by absolute surface photometry. We therefore identify a minimum EBL23 from *detected* galaxies as shown in Figure 5. Previous estimates of the flux from resolved galaxies fainter than $V = 23$ AB mag are at least 50% too low as a result of the above effects (e.g. Pozzetti et al. 1998).

4. Discussion

The EBL23 is more than four times the flux recovered in standard galaxy photometry of galaxies with $23 < V < 30$ AB mag (e.g. HDF catalog, Williams et al. 1996). However, photometry errors clearly play a significant role in this difference, as the flux we recover from simplified aperture photometry of galaxies with $23 < V < 28$ accounts for $\sim$ 50% of the EBL23 we detected. Noting that luminosity functions of LSBs at low redshift contribute an additional 30–50% to the local luminosity density, and noting that even galaxies with *normal* central surface brightnesses (i.e. $\mu_V \sim 21.5$) are undetectable in the HDF at redshifts $z \gtrsim 0.5$, we conclude that the EBL23 we detect can be explained by galaxies which are well observed in the local universe. No exotic explanations are re-

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quired. The total EBL, including the flux from galaxies *brighter* than $V = 23$, is shown in Figure 6.

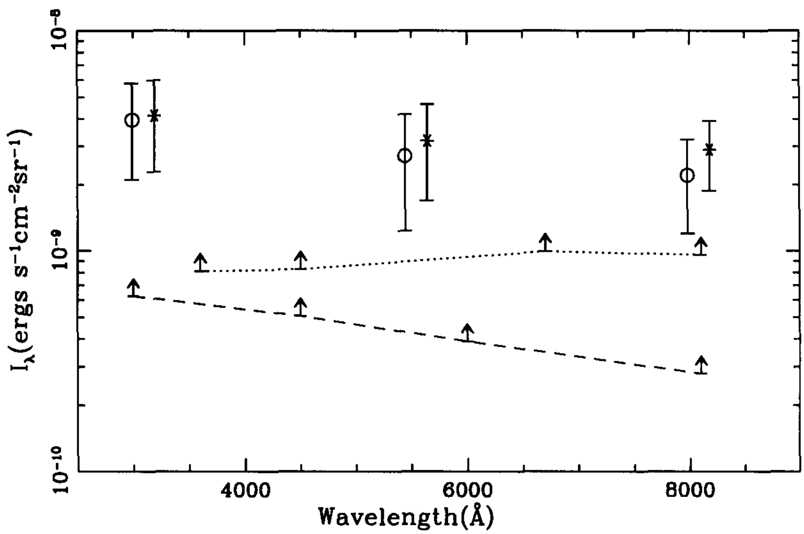

Figure 6. Open circles show the EBL23 from galaxies with $V >$ 23 AB mag. Error bars show 2σ statistical errors, encompassing nearly the same range as the 90% confidence interval due to systematic errors. Lower limit arrows connected by a dashed line mark the integrated flux in the HDF catalog. Lower limit arrows connected by a dotted line mark the flux in HDF counts plus ground-based counts for $V < 23$ AB mag. Asterisks show the total EBL: EBL23 from sources with $V > 23$ AB mag, plus the integrated ground-based counts at $V < 23$ AB mag.

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