Olbers’ Paradox and the Age of the Universe

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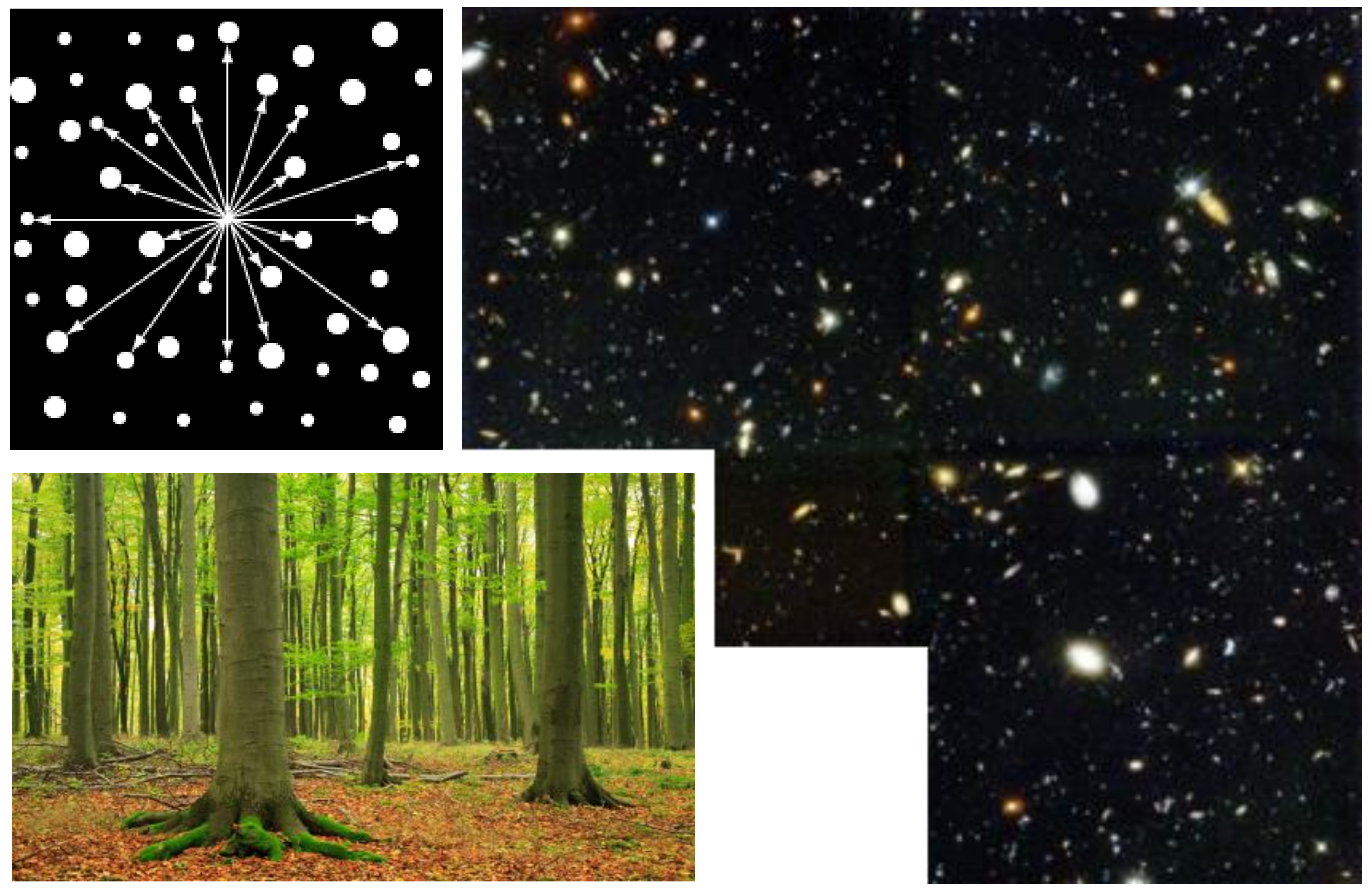

Fig. 1a (top left): Olbers’ paradox: if galaxies are distributed uniformly on average, and the Universe goes on forever, then every possible line of sight must end on a galaxy! **Fig. 1b** (bottom left): In exactly the same way, every line of sight in a large forest must end on a tree. **Fig. 1c** (right): The Hubble Deep Field (1995), an image obtained by pointing the Hubble Space Telescope at one of the emptiest parts of the sky and collecting light for ten days. Extending the period of observation does not reveal significantly more galaxies. The Universe is mostly dark empty space!

Introduction

How can the sky be dark at night, if the Universe is infinitely big and uniformly filled with sources of light? (Fig. 1) This question has become known as Olbers’ paradox after the Prussian doctor who wrote about it in 1823, although he was not the first to notice it, and did not resolve it [1]. First to state the paradox clearly was Kepler in 1610. Replying to Galileo, who had observed thousands of new stars through the newly invented telescope, Kepler retorted that then, “in an infinite Universe the stars would fill the heavens as they are seen by us!” His conclusion was that the Universe must be *finite*. (This resolution still survived as late as 1917, in the form of Shapley’s “island Universe” model.) Others, including Olbers and the Swiss astronomer de Chėseaux before him in 1744, decided that the night sky must be darkened by some sort of absorbing medium. At least a dozen other explanations were offered over the centuries, some (like fractals and curved space) anticipating developments in modern physics [1].

The first *correct* resolution to Olbers’ paradox came not from a scientist but a poet, Baltimore’s Edgar Allan Poe. In his prose poem *Eureka* (1848), Poe realized that the finite speed of light means that when we look farther away, we also look farther back in time. Thus it may be that most of the light sources in the Universe are so far away that their light *has not yet had time to reach us*. Not only was Poe’s basic insight correct, but it can also be turned on its head: we can use observations of the exact level of darkness of the night sky to deduce the age of the Universe. That is our objective in this project.

Theory

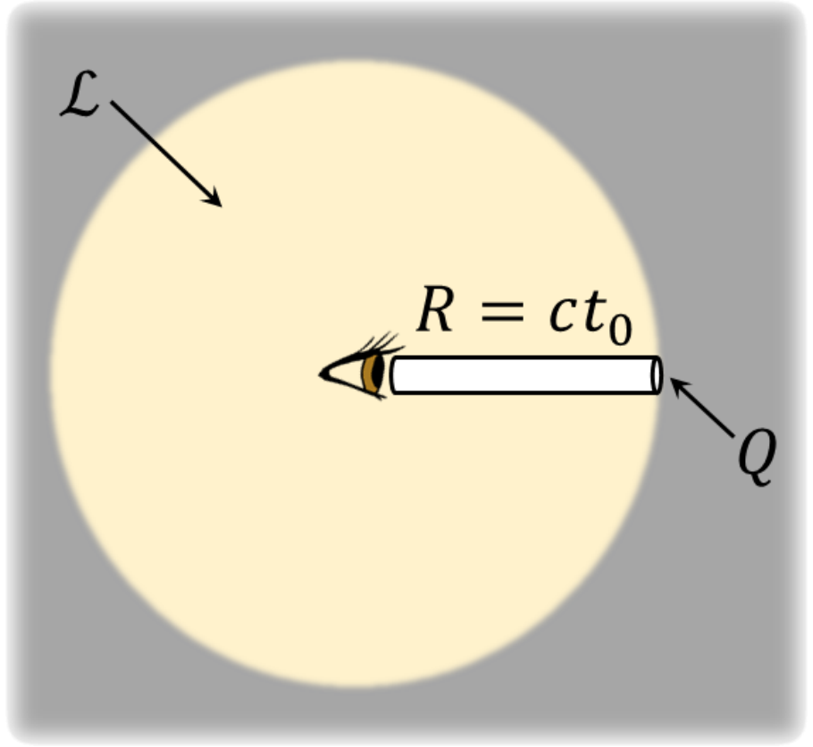

Fig. 2: Simple model of the Universe as a ball of glowing gas

We model the Universe for argument’s sake as a sphere filled with luminous gas (Fig. 2). Its radius---the farthest that we can see---is the distance that light has traveled for the entire history of the Universe: $R = ct_0$ (where c is the speed of light and t_0 the age of the Universe). The *luminosity density* of this gas is

$$\mathcal{L} \approx \frac{\rho_{\rm lum}}{3M_\odot/L_\odot} = 3\times10^{-33}\,{\rm W/m^3}\ , \qquad (1)$$

where $\rho_{\rm lum} = 0.005\rho_{\rm crit}$ is the average density of luminous matter in the Universe, $\rho_{\rm crit} \equiv 3H_0^2/(8\pi G)$ is the critical density that distinguishes flat from curved space, H_0 is the Hubble expansion rate and G is Newton’s gravitational constant [1]. The ratio $M_\odot/L_\odot$ is the Sun’s mass-to-light ratio and the factor of 3 in the denominator reflects the fact that an average star is about 1/3 as luminous as the Sun. Imagining ourselves at the center of the ball and looking toward the edge through a column of length R, we observe an *intensity* (or luminosity per area) given by

Fig. 3a (left): Dr. Overduin and K. Glazer at the Towson University observatory with Optical Guidance Systems 0.4m Ritchey–Chrétien reflecting telescope and Santa Barbara Instruments Group ST7E CCD detector; **Fig. 3b** (right): K. Glazer (left) and C. Edwards (right) analyzing images of the Hubble Deep Field with Dr. Storrs (center).

$$Q = \mathcal{L}R = \mathcal{L}ct_0 \approx 30\ {\rm nW/(m^2\ sr)}\ , \qquad (2)$$

where we have assumed the accepted value for $t_0 = 14$ Gyr and divided by 4π to express our result in conventional units of intensity per steradian (sr). This is our theoretical prediction for the total intensity of the Extragalactic Background Light (EBL) over near-optical wavelengths (from the ultraviolet to the infrared). Despite the simplicity of our model, it agrees well with recent experimental determinations of this quantity, $Q = 36 \pm 11$ nW/(m^2 sr) [2] and $Q = 24 \pm 4$ nW/(m^2 sr) [3], giving us confidence that Poe was right and we do understand, quantitatively as well as qualitatively, why the sky is dark at night.

Observation

To test Eq. (2) we set out to measure Q (Fig. 3a) with a 16-inch telescope and CCD detector (Fig. 3a). For maximum sensitivity we used an R-band filter (wavelength $\lambda = 658 \pm 138$ nm). Only about 10% of the EBL lies in this band [3], so the net EBL intensity we looked to detect was $Q_R \approx 0.1Q \approx 3$ nW/(m^2 sr).

We observed the Hubble Deep Field (HDF), an empty patch of sky 3 arcmin wide in Ursa Major (RA=$12^{\rm h}\ 36^{\rm m}\ 49.4^\circ$, Dec=$+62^\circ$ 12’ 58” in J2000 coordinates). To minimize sky brightness, we timed our observations near the new moons on May 26 and June 23, 2017. We were fortunate to have clear weather on May 26 and again on June 25. The image in Fig. 4 was taken on May 26, but the numbers we discuss below come from our analysis of 3 images from June 25: a 15-min exposure at 9:29 pm and two 30-minute exposures beginning at 9:48 pm and 10:53 pm EDT. We calibrated these images, first by taking a series of 2-min “darks” to model thermal noise in the CCD, scaling to the same exposure time as the images and subtracting; and second, by taking a series of 1-sec “flats” to model variations in detector sensitivity and telescope throughput, normalizing to an average value of one, and dividing our images by the result. We checked that the resulting images did overlap with the HDF by converting to B1950 coordinates and locating four foreground stars on the relevant Palomar Sky Survey Plate, E-674 (Fig. 4).

To measure the intensity, we used the astronomical image analysis software IRAF to measure the mean “data number” D (in counts/pixel) in the empty parts of each image (Fig. 3b). We fitted the resulting values to a quadratic function of time and extrapolated to find a minimum value, corresponding to the darkest time of night. This was $D_0 = 7000$ counts/pixel. Each count is, on average, triggered by 10 ± 4 photons (reflecting the quantum efficiency of the CCD chip and the gain of the readout electronics), so we collected $n = 70{,}000 \pm 30{,}000$ photons/pixel.

To convert from photon count to *luminosity*, we divided by exposure time and multiplied by the energy $E = hc/\lambda$ of each photon:

$$L = \frac{n}{t}\frac{hc}{\lambda} = \frac{(70{,}000\pm30{,}000\ {\rm px^{-1}})(2.0\times10^{-25}{\rm Jm})}{(1800\ {\rm s})(660\pm140)\times10^{-9}{\rm m}} = (1.2 \pm 0.6)\times10^{-17}\ {\rm W/pixel}\ . \quad (3)$$

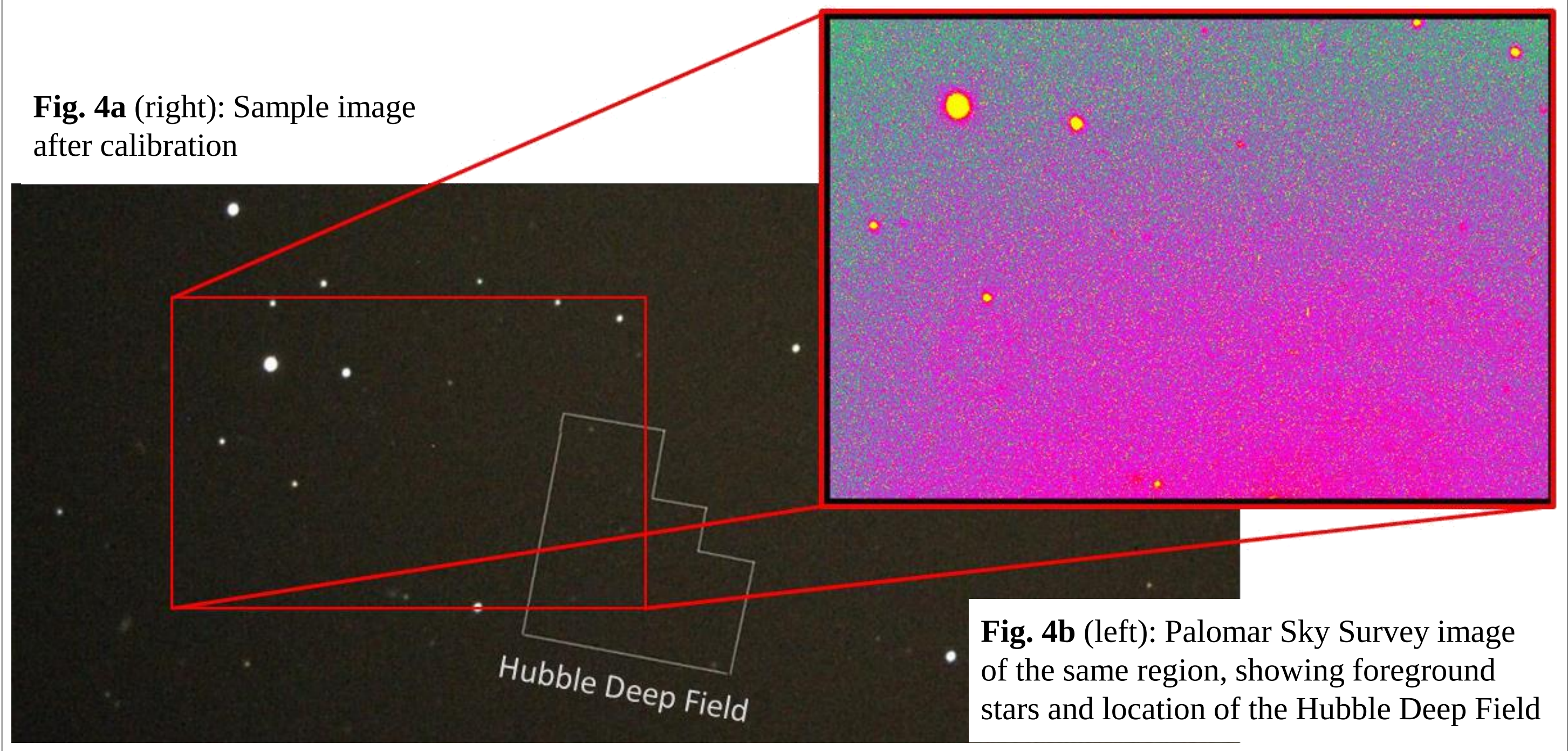

Fig. 4a (right): Sample image after calibration

Fig. 4b (left): Palomar Sky Survey image of the same region, showing foreground stars and location of the Hubble Deep Field

To convert from luminosity to *intensity*, we divided by the telescope aperture area $A = \pi(d/2)^2$ and by the CCD plate scale $\sigma = (0.63\ {\rm arcsec})^2$/pixel. Converting to conventional angular units, we finally obtained

$$Q_{\rm obs} = \frac{\left[(1.2\pm0.6)\times10^{-17}\,\frac{\rm W}{\rm px}\right]\left[\frac{(206{,}265\ {\rm arcsec})^2}{\rm sr}\right]}{\pi\left(\frac{0.41\ {\rm m}}{2}\right)^2\left[\frac{(0.63\ {\rm arcsec})^2}{\rm px}\right]} = 10{,}000 \pm 5000\ {\rm nW/(m^2\ sr)}\ . \quad (4)$$

Discussion

Our measured $Q_{\rm obs}$ is much larger than the predicted EBL intensity Q_R, but that is to be expected because this small extragalactic signal is overwhelmed by “noise” from much larger foreground sources. The largest of these is undoubtedly *light pollution* from street lamps, etc. Our observing site in Towson ranks at the bottom of the Bortle scale (class 8/9), implying an artificial night sky brighter than 18 magnitudes/arcsec^2 (Fig. 5). This alone contributes an intensity to the diffuse background light of at least $Q_{\rm poll} \approx 6000$ nW/(m^2 sr).

The three next-largest contributions are caused by *airglow* (light from air molecules in the Earth’s atmosphere that have been excited by cosmic rays), *starlight* scattered from dust in our own Galaxy, and *zodiacal light* (sunlight scattered off dust in the plane of the Solar System). These produce foreground signals of about $Q_{\rm air} \approx 3000$ nW/(m^2 sr), $Q_{\rm star} \approx 500$ nW/(m^2 sr) and $Q_{\rm zod} \approx 400$ nW/(m^2 sr) [4]. Subtracting, we find a small remainder that is consistent with the EBL intensity: $Q_{\rm ebl} = Q_{\rm obs} - Q_{\rm poll} - Q_{\rm air} - Q_{\rm star} - Q_{\rm zod} \approx 100 \pm 5000$ nW/(m^2 sr) $\approx Q_R$.

With the launch of the *James Webb* telescope in early 2019 [5], we may be able to resolve these quantities with higher precision, of order nW/(m^2 sr). We would then be able to *deduce the age of the Universe t_0 directly from our measured value of Q_{ebl}* using Eq. (2)---a remarkable fact that deserves to be better known.

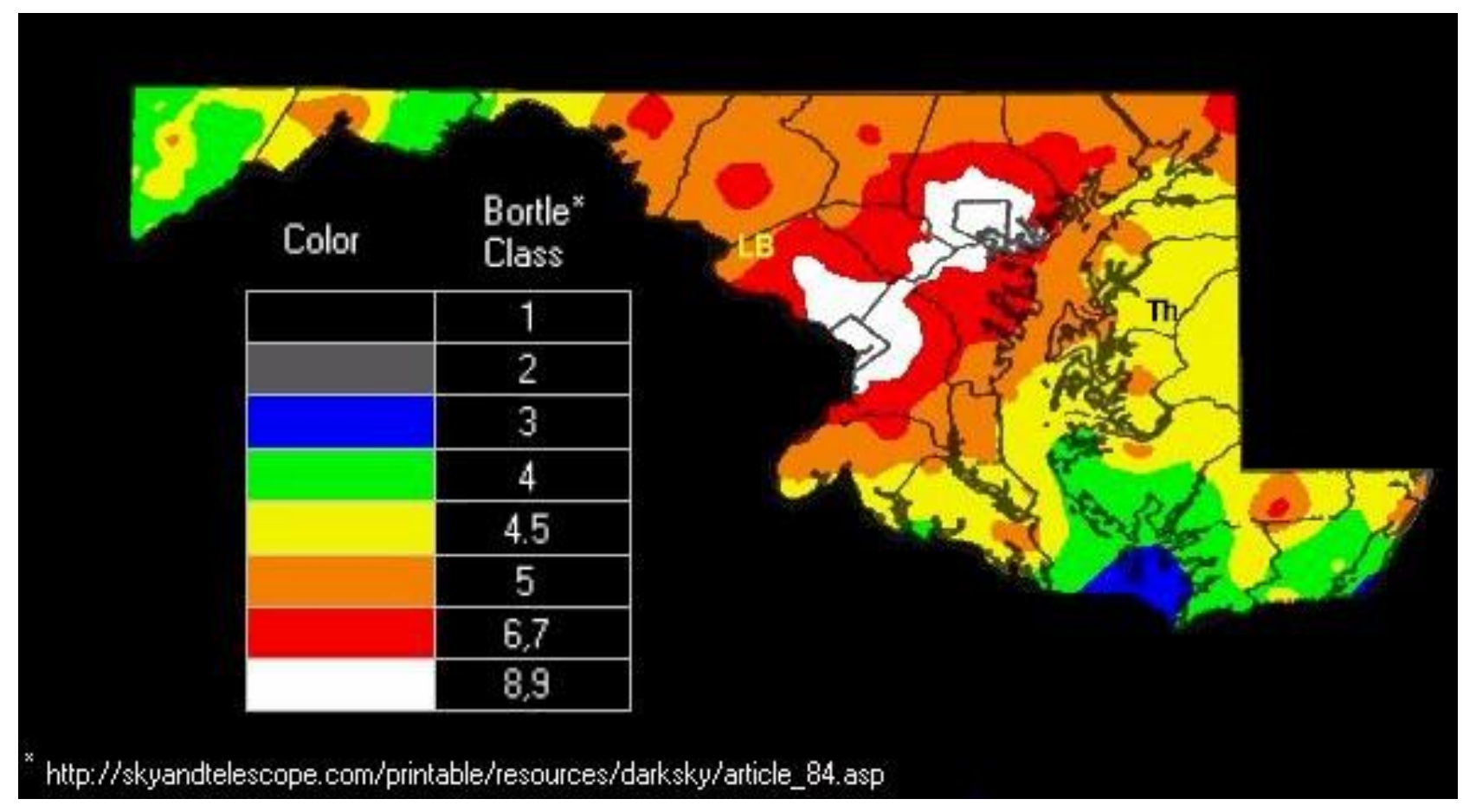

Fig. 5: Map of light pollution in Maryland according to the Bortle scale. The white regions are the Washington, DC and Baltimore/Towson areas.

Acknowledgments

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References

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