A MODEL FOR INTERGALACTIC DUST AND ITS IMPACT ON THE EXTRAGALACTIC BACKGROUND LIGHT

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Olbers' Paradox

Olbers and de Chéseaux were astronomers who questioned the cause of the darkness of the night sky. They postulated that the reason we cannot see the all of the stars in the universe because there is an absorbing medium between the earth and faraway stars. However, any medium that absorbs light will re-emit that light at a lower energy; therefore, an absorbing medium cannot be the sole reason for the darkness of the night sky. The accepted resolution of Olbers' paradox involves the finite age of the universe (and to a lesser extent, cosmic expansion) [1]. However, our research shows that Olbers and de Cheseaux were not entirely wrong; dust in the Intergalactic Medium (IGM) does not block the EBL, but does shift it to longer wavelengths.

Extragalactic Background Light Model

In order to study the dampening of extragalactic background light (EBL) due to dust, we must first establish the quantity of light that is observable. To do so, we create a model of the EBL's intensity at all wavelengths.

We first visualize the light that reaches the Earth as originating from a series of spherical shells that are increasingly far away. Light originating from each of these shells will be redshifted by the same amount; Figure 1 below depicts such a spherical shell model.

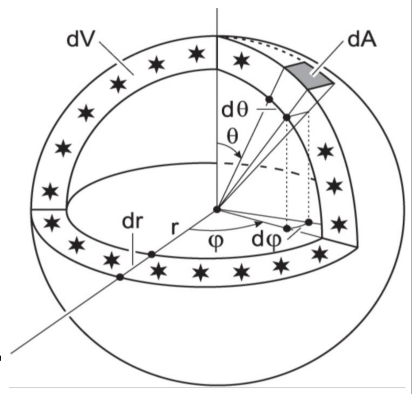


Fig. 1: Spherical Shell Model [1]

We work in the context of standard relativistic cosmology with Hubble constant H_o and matter and dark energy densities Ω_m and Ω_Λ (both defined relative to the critical density $\rho_{\rm crit} = 3H_0^2/8\pi G$). We assume that galaxies are distributed with a number density $n(z)$ in cm^{-3}, and that they emit their light with a spectral energy distribution (SED) $F(\lambda, z)$ in erg s^{-1} Å^{-1} that depends both on wavelength λ at emission and source redshift z. Then the spectral intensity of all the galaxies out to z_f (the redshift at which galaxies first formed) is given by [1]

$$I_\lambda(\lambda_o) = \frac{c}{4\pi H_o}\int_0^{z_f} \frac{n(z)F(\lambda,z)(1+z)^{-3}}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}\,dz \qquad (1)$$

Eq. (1) gives the total intensity as observed at λ_0. This is a sum over contributions from many galaxies at different source wavelengths $\lambda = \lambda_0/(1+z)$. It does not, as yet, account for absorption by the IGM.

Fig. 2 shows a plot of Eq. (1) (red line) for a model with $n(z) = n_0 =$ const. and $F(\lambda, z)$ corresponding to a combination of four Planck blackbody functions, normalized to the observed galaxy luminosity density $\mathcal{L}_0 \equiv n_0 L_0$ at $z = 0$, where L_0 is galaxy luminosity (see [2] for details).

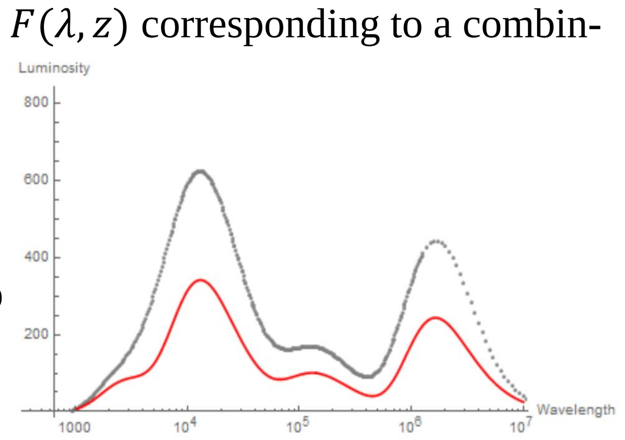


Figure 2: EBL Intensity with a four-blackbody SED

The four peaks in this model are associated physically with starlight and its re-emission by dust in normal galaxies (peaks two and four) and secondarily with starlight and its re-emission by dust in starburst galaxies at high redshifts (peaks one and three).

Overall intensity in Fig. 2 is too low due to the simplifying assumption of constant luminosity density. For more realistic results, we incorporate galaxy evolution by allowing $\mathcal{L}(z)$ to evolve with redshift. Fitting to a suite of models (named 'Fossil', 'TVD', 'SA' and 'HS') by Nagamine et al. [3], we obtain the results shown in Fig. 3. Units here are continuum units or CUs (1 CU = 1 photon s^{-1} cm^{-2} Å^{-1} sr^{-1}). A good fit to observations and a reference model by Finke et al. [4] (gray line in Figs. 2,3 and 6) is obtained with peak temperatures 17000, 4800, 420, and 40 K respectively.

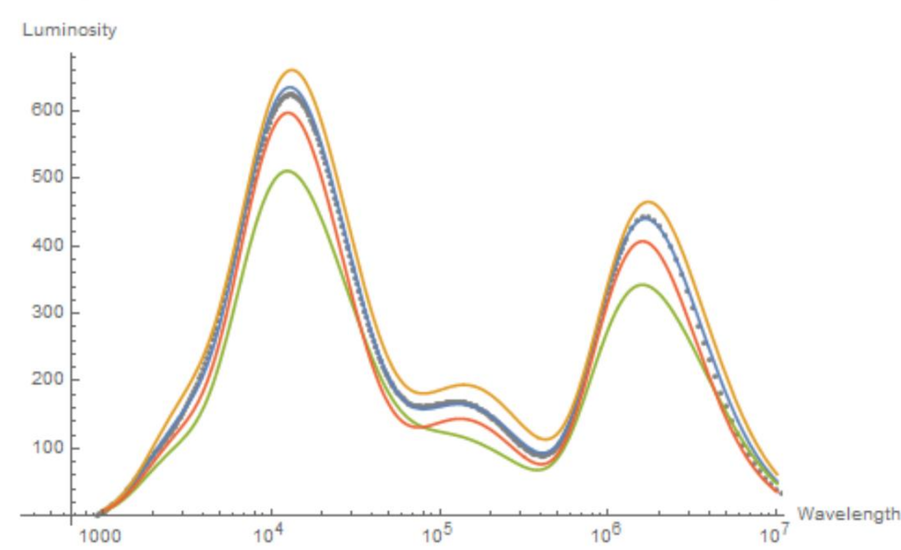


Figure 3: EBL Intensity with Galaxy Evolution

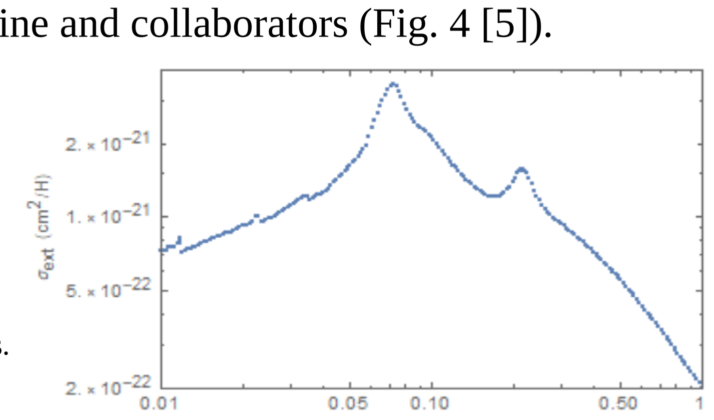
Out of these four models, the Fossil model most accurately matches the reference plot. We will use this function in our calculation for dust.

Dust Model

When light scatters from dust grains whose size is comparable to the wavelength, the dust will absorb some of the light's energy. This causes a dampening effect on the light, and the excited dust will give off its absorbed energy in the form of redshifted light.

Now that we have a model for EBL intensity without the effect of dust, we will apply a correction for dust extinction and find the impact of intergalactic dust on the EBL. The abundance of dust grains in the relevant size range has been established by Draine and collaborators (Fig. 4 [5]).

Fig. 4: Dust extinction as a function of wavelength in the interstellar medium (ISM) [5]. We assume that dust in the IGM has the same properties.



Allowing for absorption in the IGM, Eq. (1) is amended to include an opacity term $\tau(\lambda, z)$ as follows:

$$I_\lambda(\lambda_o) = \frac{c}{4\pi H_o}\int_0^{z_f} \frac{n(z)F(\lambda,z)(1+z)^{-3}}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}\,e^{-\tau(\lambda_o,z)}dz \qquad (2)$$

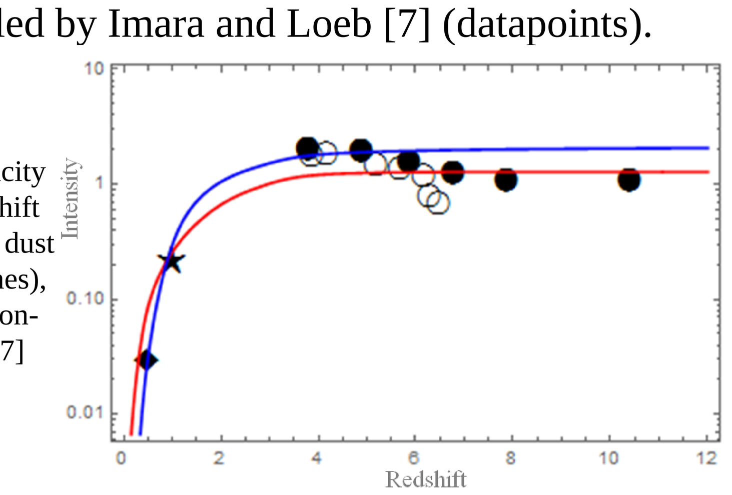
Opacity is obtained by integrating over the column of absorbing material out to redshift z as follows [6]

$$\tau(\lambda_o, z) = \int_0^z \xi\left(\frac{\lambda_o}{1+z'}\right)\tau_*(z')\frac{(1+z')^2}{H(z')/H_o}dz' \quad ,(3)$$

where $\xi(\lambda)$ is the extinction in dust relative to that in the B-band (4400 Å) and $\tau_*(z)$ is a phenomenological function allowing for evolution in the dust population with redshift.

We expect that the density of dust in the universe should follow that of stars, perhaps with some degree of "lag time", climbing steeply at low redshifts and then falling off gradually beyond $z{\sim}1$. By trial and error, we find two plausible candidate models with $\tau_{*,1}(z) = 0.35z^{5/2}/(1+z^5)$ and $\tau_{*,2}(z) = 0.35(e^z-1)/e^{2z}$. With these models, we obtain the opacity plots shown in Fig. 5 at $\lambda_0 = 3000$ Å (red and blue lines). Both provide an excellent fit to observational constraints compiled by Imara and Loeb [7] (datapoints).

Fig. 5: IGM dust opacity as a function of redshift for our two candidate dust evolution models (lines), with observational constraints at 3000 Å [7]



The resulting EBL intensities, incorporating both galaxy evolution and dust evolution (with either function), are then given by Eq. (2) as shown in Fig. 6.

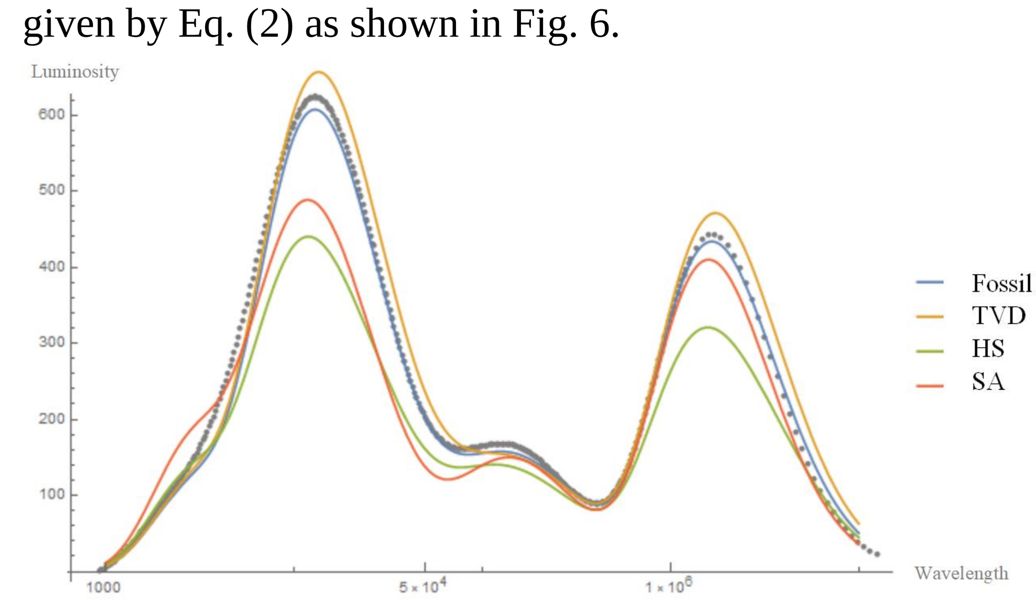


Fig. 6: EBL Intensity with extinction by the dusty IGM

EBL Extinction

Note that the total integrated EBL intensity (area under the curves in Fig. 6) does not change (energy conservation). Rather, dust extinction shifts the light toward longer wavelengths. Table 1 below shows the temperatures of each of the peaks, and the dampening effect of dust at each peak.

Table 1: Effect of Dust Extinction (Fossil Model)

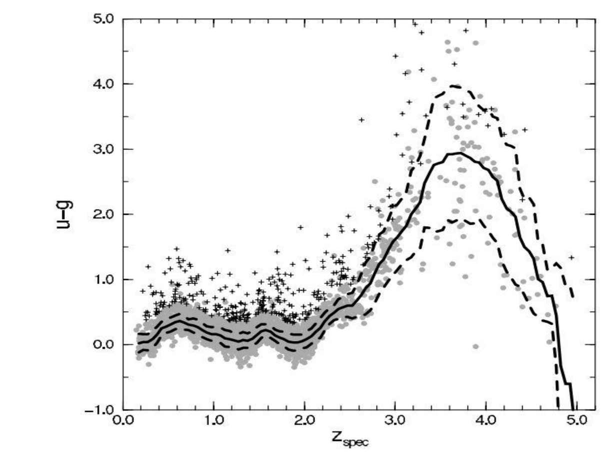
Peak Number	Peak Temperature	Decrease in Peak Intensity
2	4800 K	5%
3	420 K	6%
4	40 K	2 %

The peak that we care the most about is peak two. Not only has our model been normalized to this peak, but the temperature of peak two is 4800 K, corresponding 6030 Å (Wien's law). That is, intergalactic dust appears to reduce the intensity of the optical EBL by about 5%.

Quasar Reddening

Observationally, our main constraints on IGM extinction come from distant quasars. Observations of 3814 high-redshift quasars by the Sloan Digital Sky Survey [8] suggest that this extinction begins to cause significant reddening at $z \gtrsim 2$ (Fig. 7).

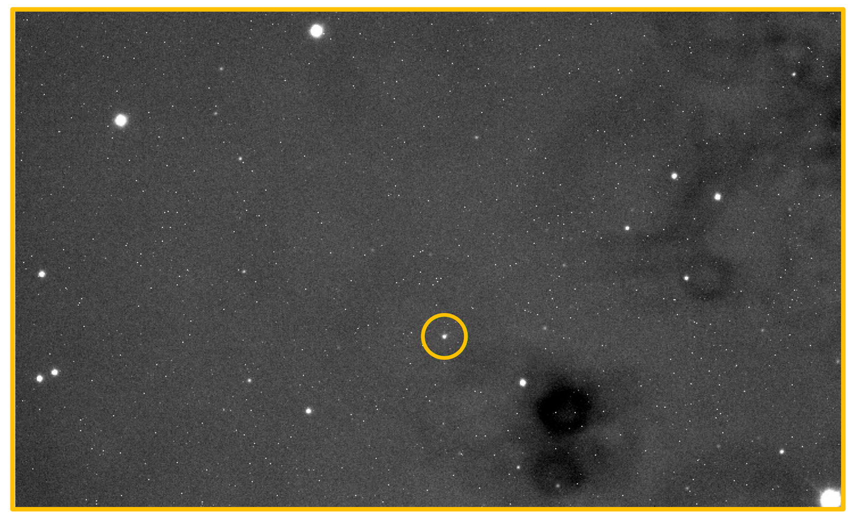
Fig. 7: Color index (u-g) as a function of redshift in the Sloan Digital Sky Survey [8]



To add an observational component to this project, we observed the most distant quasar accessible to our 16" telescope at Towson University, PG 1634+706 ($z = 1.337$).

We imaged PG 1634 in our telescope's red, green, and blue filters, and then used a python script to reduce our raw images. Fig. 8 below is the reduced image in the red filter, with our quasar outlined in the green circle.

Fig. 8: R-band image of quasar PG 1634, taken 30 Oct. 2018



Experimentally, we found that the flux ratio of the red and blue filters is 4, which is consistent with significant reddening by the IGM. Given the large uncertainties associated with the observation, we cannot draw definite conclusions from this one case. However, it is consistent with our theoretical models as outlined above.

Conclusions

We have shown that dust in the IGM reduces the intensity of the EBL at optical wavelengths by about 5%, with an uncertainty that remains to be established with future work. This result vindicates Olbers and de Chéseaux to a certain extent: they were not completely wrong about the reason why the sky is dark at night.

Acknowledgements

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References

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