How Bright Was the Big Bang?

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It is generally believed that in the epoch prior to the formation of the first stars, the Universe was completely dark (the period is therefore known as the Dark Ages). Usually the start of this epoch is placed at the photon decoupling. In this work we investigate the question whether there was enough light during the dark epoch for a human eye to see. We use the black body spectrum of the Universe to find the flux of photon energy for different temperatures and compare them with visual limits of brightness and darkness. We find that the Dark Ages actually began approximately 5 million years later than commonly stated.

I. INTRODUCTION

The current model of the origin and the evolution of the Universe is known as the hot Big Bang theory. It states that the Universe started with a period of exponentially fast acceleration known as inflation. After the inflation the (largely empty) Universe was repopulated with all kinds of particles (reheating) and continued to expand at a gradually slowing rate. As the Universe enlarged both the density and temperature decreased, giving rise to various important processes such as the creation of asymmetry between matter and antimatter, the formation of baryons from the excess of quark over the antiquarks and the subsequent formation of light nuclei. All this happened while the Universe was not more than a few minutes old and had a temperature of more than a billion kelvins. At this point electrons would still not bind to the nuclei, and hence the Universe was filled with free electrons, making it opaque to electromagnetic radiation as the photons would be scattered by the electrons. The Universe would continue to cool and after 378 000 years, when the temperature was about 4000 K, the electrons started to combine with the nuclei to form atoms. This event is called recombination. Shortly after the recombination the decoupling of photons happened, where photons became free to travel through space unimpeded. 

Approximately 150 million years later the first stars began to form to lighten up the Universe. In particular the recent results of the EDGES experiment tell us that when the Universe was about 200 million years old, it was full of radiation provided by the first stars. This epoch between recombination and the formation of the first stars is commonly known as the Dark Ages.

In this work we investigate whether it is actually true that the Universe turned completely dark right after the decoupling of photons. To this end we “place” a hypothetical human observer into the early Universe where no human being existed (actually, no structure more complicated than atoms of Hydrogen, Helium and a few other light elements existed) and analyze how much light her eye would actually register. We find that even without any additional optical devices, the observer would register enough photons of visual wavelengths long after photon decoupling to perceive the Universe as “bright”.

An approach of presenting physical events through the prism of a “human observer” is of course not a new one. It is used not only in the context of popular science, but also in solid scientific works. For example, in general relativity one may discuss the following purely academic question: what would an observer see while falling into a black hole? (see for example Refs. ). When discussing the future of our Universe and illustrating how a continuing accelerated expansion would look like, one again appeals to “future cosmology” in both research and popular science articles.

A lot of research and popular literature has been devoted to the subject of habitable planets, where one often “depicts” how life would look like with different kinds of suns including “life in the early Universe”. Other papers about “physics via human eyes” can be found e.g. here in part motivated by the recent movie Interstellar.

This paper takes a new step in the before-mentioned direction. It tries to bridge a gap between an “artistic impression” of the history of the Universe and an actual physical picture behind it. It is therefore, relevant to the scientific and broader audience, interested in the subject of the early Universe.

A. The Human Eye

The property of the human eye is to transform light into visual pictures in the brain. Light, emitted or re-
The visual part of the electromagnetic spectrum is known as the photopic vision (CIE 1978 V(λ)) for the high exposures and a scotopic luminosity function (CIE 1951 V′(λ)) for the low exposures.31

390 nm ≤ λ ≤ 720 nm, (1)

Planck’s law of black body radiation and brightness estimates

Next, we identify what one might call “see the light”. We know that too much light will blind us while the opposite makes our world dark. We therefore choose two reference objects – the Sun as seen from the Earth as an upper limit, making us blind in a short amount of time,33 and a candle as the lower limit, placed at a distance, making it possible for the human eye only to glimpse it. We assume that between those two regimes, it will therefore be possible for the human eye to detect something and at the same time not be blinded by the light.

We assume throughout these calculations that all the light is in the form of the black body radiation of relic photons (that would later become the Cosmic Microwave Background). The spectral energy distribution is given by Planck’s law:34

\[ B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_BT}} - 1} \] (2)

Here h is Planck’s constant, c is the speed of light, λ is the wavelength, T is the black body temperature, and \( k_B \) is the Boltzmann constant.

Furthermore we assume that only visual light has any influence on the human vision, and therefore we neglect any potential damage that high-energy radiation can do to the vision/the observer. We thus integrate Planck’s law between the wavelengths covering the visual part of the electromagnetic spectrum, to obtain the radiance, \( L_e \),

\[ L_e = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} d\lambda B_\lambda(\lambda, T) \] (3)

where \( \lambda_{\text{max}} \) and \( \lambda_{\text{min}} \) are specified in Eq. (1). We can also define the fraction of radiance in the visual part of the spectrum as a function of the temperature. This is naturally given as:

\[ f(T) = \frac{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} d\lambda B_\lambda(\lambda, T)}{\int_0^{\infty} d\lambda B_\lambda(\lambda, T)} , \] (4)

where the denominator is just \( \sigma T^4/\pi \) with \( \sigma \) being the Stefan-Boltzmann constant. Fig. 2 shows \( f(T) \) for different regimes of human vision.

The obtained quantity \( L_e \) from Eq. (3) is related to the radiant flux, \( \phi_e \), by the following expression:35

\[ \phi_e = \Omega L_e A \cos \theta. \] (5)

The subscript e denotes ‘energetic’ which is a reference to radiometric quantities. Radiometric quantities are measures of the absolute quantities of light in terms of the
The angular extent of the Sun is approximately $\theta_{\text{Sun}} \approx 16\arcmin$, where the prime denotes arcminutes. Converting this value into radians, we obtain: $\Omega_{\text{Sun}} \approx 6.8 \times 10^{-5}\text{sr}$. Using the surface temperature of the Sun, $T_{\text{Sun}} = 5780\text{K}$, we integrate the Sun’s black body distribution from Eq. (2) and hereafter use Eq. (5) to calculate the radiant flux as received from the Sun (neglecting the atmosphere). In this way we obtain the following radiant flux from the Sun:

$$\phi_{\text{Sun},e} = 1.7 \times 10^{-3}\text{W}. \quad (7)$$

The resulting answer is very close to the Solar constant $F_\odot = 1365\text{W/m}^2$ multiplied by the area of the pupil and corrected by the fraction of solar energy delivered in the visible part of the spectrum (atmospheric transmittance in the visible part of the spectrum is known to be close to 100%, therefore we neglect the corresponding corrections). We will choose the value (7) as an upper threshold, indicating the limit between human vision and a blindly bright flux of light.

**B. Lower Limit: distant stars and distant candle**

What is the dimmest object a human observer can possibly see? Many works have tried to estimate or measure this limit. The lowest possible limits are obtained when detecting glimpsing light, as described in e.g. Refs. These estimates are not directly applicable to our case, as the Universe darkens “slowly” and we need to identify the dim object discernible for the human eye over longer time intervals. One of the ways this flux can be estimated is based on humans’ ability to see dim stars. The limiting magnitude of a star is a statistical concept that depends upon a series of factors such as the capability to use averted vision, the individual eye sensitivity, the length of time the field has been observed etc, see the discussion in Refs. In Ref. the limiting magnitude is found to be 6.8 while it is meanwhile discussed that this might be excessive to the true value. As we only need a rough estimate for the calculation carried out in this paper, we choose the naked eye limiting magnitude to be 6. The flux of an object corresponding to a specific magnitude is defined as

$$\frac{F_1}{F_{\odot}} = 100^{m_\odot - m_1} \quad (8)$$

where $F_{\odot}$ is the solar constant, $m_\odot = -26.76$ is the apparent magnitude of the Sun and $F_1$ and $m_1$ are equivalent quantities for an arbitrary star. Using the limiting magnitude $m_1 = 6.0$, $F_1$ is easily calculated to be $F_1 = 1.074 \times 10^{-10}\text{W/m}^2$. The corresponding power is obtained from

$$P_1 = 2f(T_\odot)F_1\pi r^2, \quad (9)$$

where $r = 4\text{mm}$ is the radius of a wide-open pupil, $f(T_\odot) = 0.3988$, and the constant 2 accounts for the
area of both eyes. In this way \( P_1 = 4.4 \times 10^{-15} \text{ W} \). To put this in perspective this light is comparable to a candle flame located at a distance of about 2.6 km from an observer.\textsuperscript{48} Indeed, the flame of a regular candle can be assumed to have a \textit{prolate ellipsoidal shape} with two principal axes: \( 2a = 2b \sim 5 \text{ mm} \) and another principal axis: \( 2c \sim 20 \text{ mm}. \textsuperscript{49,50} \) The volume of this ellipsoidal flame is \( V = \frac{4}{3}\pi abc = 2.6 \times 10^{-7} \text{ m}^3 \). At a distance of 2.6 km, the solid angle subtended by this flame is calculated from Eq. (6) to be \( \Omega_{\text{candle}} = 7.3 \times 10^{-12} \text{ sr} \). By estimating the temperature of the candle to be \( T_{\text{candle}} = 1400 \text{ K}, \textsuperscript{48} \) we calculate its radiance by integrating Eq. (2). In the same way as the calculations done for the Sun, we apply Eq. (5) to find the received radiant flux from the candle to get:

\[
\phi_{\text{candle},e} = 1.8 \times 10^{-14} \text{ W}.
\]  

This result is about 11 orders of magnitude lower than our upper threshold (7).

It is instructive to convert this power into the number of photons entering a human eye per unit time. Using the fact that scotopic vision has its peak sensitivity at \( \lambda \simeq 500 \text{ nm} \) (Fig. 1), we can approximately convert the power (10) into the number via

\[
N_{\text{photons}} = \frac{\phi_{\text{candle},e} \hbar c}{\lambda} \simeq 45 \times 10^3 \text{ photons/sec}
\]  

This estimate indeed reproduces the known result that a human eye can detect light, if an order of 10 photons enters the eye over a time period of \( \sim 10^{-3} \text{ sec}. \textsuperscript{41,51–53} \) We will adopt the value (10) as our lower threshold, beyond which the human eye cannot detect any light.

### III. TOTAL DARKNESS AND TOTAL BRIGHTNESS IN THE UNIVERSE

Having established the lower and upper limits for the radiant flux, registered by the human eye, we can now determine for which temperatures the isotropic background radiation from the Universe would produce the same radiant fluxes. For this we again use Eqs. (2) and (3) and scan over temperatures in order to determine a range when the radiant flux falls between the limits (10) and (7). By mapping this range to the age of the Universe, we will be able to determine when the “Dark Ages” really started.

Since the radiation from the Universe is isotropic, we imagine a human sitting inside a sphere, transparent to visible light. Of course the human eyes do not have a field of view of \( 360^\circ \) but instead they have an approximate field of \( 200^\circ \) horizontally and \( 135^\circ \) vertically.\textsuperscript{54} We approximate this field of view by a cone with an apex angle of \( 160^\circ \) and use Eq. (6) to find the solid angle covered by the human eye \( \Omega_{\text{eye}} \approx 5.2 \text{ sr} \). In addition to that we take into account that pupils adjust to brightness. Therefore, for radiant fluxes \( \phi_e > 10^{-6} \text{ W} \) we use the pupil radius of 1 mm while for \( \phi_e < 10^{-6} \text{ W} \) we use the pupil radius of 4 mm. A plot of these radiant fluxes can be seen in Fig. 3, where also the radiant fluxes from the Sun and the candle are plotted as references.

**Note added:** After the first version of this work appeared on arXiv.org, the preprint\textsuperscript{55} challenged our estimates arguing that rods do not cover the whole retina homogeneously and therefore the field of view of the entire eye, \( \Omega_{\text{eye}}, \) cannot be used. The arguments of Ref.\textsuperscript{55} can be roughly rephrased as follows: it is insufficient that the eye as a whole receives the necessary amount of photons. One needs to ensure that an individual rod receives no less than few photons to be activated and “register” the light.\textsuperscript{41,51} Ref.\textsuperscript{55} then argues that one needs to use \( \Omega \sim \Omega_{\text{candle}} \) instead of \( \Omega_{\text{eye}} \) for the estimates. \textit{This argument is incorrect as we explain below.}

The homogenous light of the Universe is a diffuse source. Therefore, different regions of the retina receive some amount of light. It is sufficient for any rod in any region of the retina to be activated for an observer to register the light. Let us estimate how many such regions exist in the eye based on the available experimental data. For concreteness we take an experimental setup of the experiment.\textsuperscript{41} In this experiment the source had the angular radius of 5’ and about 500 rods were affected by its image on the retina (of which only a few were actually activated).\textsuperscript{41} The solid angle is \( \Omega_5 \approx 6.6 \times 10^{-6} \) (Eq. (6)). The human eye has about 120 million rods.\textsuperscript{32} Therefore we can roughly estimate the “working” field of...
Similarly, from the comparison with the lower limit (10), we find that the Universe with temperatures higher than 1545 K would be blindingly bright to the human eye. The temperature of the Universe is related to the cosmological redshift, \( z \), via:

\[ T = T_0 (1 + z). \] (13)

Here \( T_0 \) is the present temperature of the Universe, given by \( T_0 = 2.7 \, \text{K} \). The temperature \( T = 500 \, \text{K} \) corresponds to the redshift \( z \simeq 183 \), while the temperature of \( T = 1545 \, \text{K} \) corresponds to the redshift \( z \simeq 566 \). At these redshifts, the expansion of the Universe is matter dominated with negligible contributions from radiation energy density and a cosmological constant. The periods of time that we are considering in this work are deeply within the matter-dominated epoch. Therefore, one can neglect the cosmological constant \( \Omega_{\Lambda} \) and relate the age of the Universe to its redshift via:

\[ t(z) = \frac{2}{3H_0 \Omega_{m,0}^{1/2}(1 + z)^{3/2}}. \] (14)

We also determined when the brightness of the Universe would become “tolerable” for the human eye. It turns out that this happened when the Universe cooled down to \( T \simeq 550 \, \text{K} \) – some 5.3 million years after the recombination!

We also represent our results as timelines, describing the first 150 million years after Big Bang, in Fig. 4 and 5. The time of recombination as well as the tentative epoch of the formation of first stars is also shown, making it clear how the Dark Ages has been estimated to begin more than 5 million years later than usually stated.

V. DISCUSSION

In this paper we analyzed the (admittedly purely academic) question about the start of the cosmological epoch known as the “Dark Ages”. It is customary said that the Dark Ages began right after the hydrogen recombination was complete and photons traveled freely through the Universe. By placing a hypothetical observer in the early Universe, and using a human eye as a proxy of the “light detector”, we argued that the Universe did not become completely dark until it had cooled down to the temperature \( T \simeq 550 \, \text{K} \) – about the temperature of a burning candle.

We see from the results, visualized in Fig. 4 and 5 that the period of the Dark Ages, found in this paper, lies between photon decoupling and the formation of the first stars, which is in accordance with the general cosmological theory. We see that the Universe was still blindingly bright after the recombination and only became ‘tolerable’ to the human eyes when it was \( \sim 1 \) million years old. The Dark Ages lasted from \( \sim 6 - 150 \) million years preceded by the “visibility window” - when the human eye would be able to register just enough light to perceive the Universe as neither too bright nor too dim.

Throughout this paper, we have used a series of assumptions to determine the two limits of vision. These assumptions effected that only order-of-magnitude calculations were possible but at the same time made it feasible to actually carry out reasonable calculations. One of the main challenges behind human vision is that the perception of light is a complex process in which it is close to impossible to set clear limits for the minimum amount of light needed to see something and the amount of light that would blind the human eye. This is a process which is not only effected by the amount of photon energy received per unit time, but also a process influenced by internal processes in the eye, determining the amount of photon energy, actually converted into a visual perception.

Finally, we note that even though more refined as-
FIG. 4. A logarithmic scaled timeline of the Universe from Big Bang to the formation of the first stars. Limits of brightness and darkness as well as the span of the Dark Ages are shown.

![Radiometric vision diagram](image)

| Brightness limit | Darkness limit |
|------------------|----------------|
| Temperature | Redshift | Age of the Universe | Temperature | Redshift | Age of the Universe |
| Radiometric | 1545 K | 571 | $1.2 \times 10^6$ yr | 500 K | 184 | $6.8 \times 10^6$ yr |
| Photometric | 1614 K | 597 | $1.2 \times 10^6$ yr | 559 K | 206 | $5.7 \times 10^6$ yr |

TABLE I. Limits of total darkness and a blindingly bright Universe. Photometric units additionally take into account the sensitivity functions of the human eyes.

FIG. 5. A logarithmic scaled timeline of the Universe from Big Bang to the formation of the first stars. Limits of brightness and darkness (taking into account frequency-dependent sensitivity of the human eyes) as well as the span of the Dark Ages is shown.

assumptions might have led to more precise limits, the current ambiguity about exactly how long the Dark Ages lasted, because of the uncertainty concerning when the first stars were formed, makes more precise limits more or less irrelevant. The timeline showed in this paper states that the formation of the first stars happened around 150 million years after the beginning of the Universe. This is very approximate, as there are no direct observational evidences of that epoch and various estimates differ by several hundred million years. The placement of the be-
beginning of “Dark ages” by about 5 million years later (from about 400 000 to 5.7 million years after Big Bang) is irrelevant on the larger timescales concerning the duration of the Dark Ages but is still a major improvement in pinpointing an onset of this epoch.

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