Is cosmic microwave background relic radiation of Big Bang or thermal radiation of cosmic dust?

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**video:** [https://youtu.be/DVejwsJGOK8](https://youtu.be/DVejwsJGOK8)
Cosmic microwave background (CMB) – history

Theoretical predictions and observations

- **Ralph Alpher & Robert Herman** (1948) – the existence of ‘relic radiation’ as radiation remaining from the hot Big Bang, the blackbody temperature estimated to 5 K
- **George Gamov** (1952, 1956) – temperature estimates 7 and 6 K
- **Yakov Zel’dovich and Robert Dicke** in the early 1960s – rediscoveries and re-estimates of the CMB temperature
- **Arno Penzias & Robert Wilson** (1965) – discovery of strong microwave radiation from all directions, the blackbody temperature of ∼3 K, Nobel prize in 1978
- **Robert Dicke** et al. (1965) – proposed to interpret the CMB as blackbody radiation originated in the hot Big Bang
- **CMB experiments**: COBE, BOOMERANG, DASI, WMAP, Planck
Origin of observed light: stars, galactic dust, intergalactic dust, Big Bang

![Graph showing light coming from the Universe with bands: optical, far-infrared, micro-wave. Extragalactic background light (EBL), cosmic microwave background (CMB).]
Temperature of galactic dust in the Milky Way

- Dust temperature $T$ varies between 15 K and 30 K
- $T$ depends on the dust density and light emitted from nearby stars

All-sky thermal dust emission

Planck 2013 Results

$<T> = 19.6$ K
The CMB temperature is quite stable and uniform $T = 2.72548 \pm 0.00057$ K. Still, it displays some fluctuations called the temperature anisotropies.

![CMB temperature map](https://map.gsfc.nasa.gov/media/)
The CMB is linearly polarized with two types of polarization (E-modes, B-modes). Polarization anomalies correlate with the temperature anisotropies.
CMB as relic radiation of Big Bang
Commonly accepted origin of the CMB

CMB as relic radiation:
• Radiation produced at very high redshifts ($z \sim 1100$, last scattering surface)
• Radiation is cooling due to adiabatic expansion of the Universe
• Temperature anisotropies: reflect density and velocity fluctuations at $z \sim 1100$
• Polarization anisotropies: Thomson scattering in a heterogeneous plasma

Difficulties and open questions:
• Unexpected features at large angular scales
  • non-Gaussianity of the CMB anisotropies (Vielva et al., 2004)
  • violation of statistical isotropy and scale invariance (Planck 2014)
• Light from the very early Universe should be distorted in later epochs (Vavryčuk, 2017)
  • due to absorption by galactic dust
  • due to absorption by intergalactic dust
The total CMB intensity should be declined. The distortion is at least 1 nWm\(^{-2}\) sr\(^{-1}\), well above the sensitivity of the COBE/FIRAS, WMAP or Planck.

**Model A**: constant proper dust density with redshift

**Model B**: proper dust density is related to the global stellar mass density

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**Graph:**

- \(\Delta I\) (nW m\(^{-2}\) sr\(^{-1}\)) vs Redshift \(z\)

- \(G\) – distortion by dust in galaxies

- \(IG\) – distortion by intergalactic dust

CMB as thermal radiation of intergalactic dust
Alternative origin of the CMB: dust in the Universe

CMB as thermal radiation of dust:

• Dust is thermalized by absorbing light of stars and emits thermal radiation
• Galactic dust produces thermal radiation at FIR wavelengths (EBL)
• Intergalactic dust is colder than galactic dust and emits CMB

Difficulties and open questions:

• Why the CMB radiation is so uniform and isotropic, although dust distribution is very likely quite heterogeneous?
• Why the CMB is not affected by a variety of redshifts of radiating dust grains? We should observe a mix of differently redshifted spectra.
• What is the origin of the CMB polarization anisotropies?
• Why the CMB temperature and polarization fluctuations are correlated?

abandoned
Dust theory – revisited
Alternative origin of the CMB: dust in the Universe

- Universe is not transparent but partially opaque due to light absorption by dust
- Dust grains are warming up and emit thermal radiation:
  - galactic dust produces the EBL at FIR wavelengths (T \sim 15 - 40\text{K})
  - intergalactic dust produces the CMB (T \sim 3\text{K})

Precollapse Black Cloud B68, ESO

example of reddening
Origin, size, composition and properties of dust

- **Size and shape**
  typically ~ 1 µm, needle-shaped or elongated dust grains, complex fluffy aggregates

- **Origin**
  supernovae collapses – outflow of material into the space

- **Composition**
  graphite, silicates, metals

- **Properties**
  - electrical conductivity
  - wavelength-dependent light absorption

Extinction curve

\[ \lambda^b \text{ extinction law} \]
\[ b \sim 1.4 - 2.0 \]

Jessberger et al. (2001)

Mathis (1990), Draine (2011)
Galactic and intergalactic opacities

**Galactic opacity & type of a galaxy**
(Calzetti 2001, Holwerda et al, 2005)

- elliptical galaxies: 0.04-0.08 mag
- Sa-Sab: 0.5-0.75 mag
- Sb-Scd: 0.65-0.95 mag
- irregular galaxies: 0.3-0.4 mag

Mean value $A_V$ over type and occurrence:

0.15-0.30 mag

**Intergalactic opacity**
(Menard et al. 2010, Xie et al. 2015)

- dust in the IGM, damped Lyman absorbers
- near galaxies and in intracluster space
- studied by quasar composite spectra which show a systematic variance with redshift
- strongly redshift dependent

Mean local value $A_V$: $\sim 0.02$ mag Gpc$^{-1}$
**Dust extinction versus hydrogen density**

**Hydrogen column densities**

Studied by the Lyman-\(\alpha\) absorption lines of damped Lyman absorbers (DLAs)

\[ N_H \text{ versus colour excess:} \]
\[ N_H / (A_B - A_V) = 5.8 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \]

\[ N_H \text{ versus extinction:} \]
\[ N_H / A_V \approx 1.87 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \text{ for } R_V = 3.1 \]

**DLA properties**

mean cross-section density \( \sim 10^{-5} \text{ Mpc}^{-1} \)

column density \( N_{\text{HI}} \sim 10^{21} \text{ cm}^{-2} \)

**Intergalactic extinction**

\[ A_V \sim 0.02 \text{ mag Gpc}^{-1} \]

(Bohlin et al., 1978, Rachford et al., 2002; Zwaan et al, 2005)

Charlton & Churchill (2000)
Light in dusty universe
How opacity affects the light in the Universe?

**EBL** – light summed from all galaxies

$$I_0^{\text{EBL}} = \frac{1}{4\pi} \int_0^{z_{\text{max}}} \frac{j(z)}{(1+z)^2} \left( e^{-\tau(z')} \right) \frac{c}{H_0} d\tau$$

- $j(z) = nL$ – luminosity density (in W m\(^{-3}\))
- $L$ – galaxy luminosity (in W)
- $n$ – galaxy number density (in m\(^{-3}\))
- $H_0$ – Hubble constant
- $E(z)$ – dimensionless Hubble parameter
- $\tau(z)$ – optical depth, decrease of amplitude

$$\tau_v(z) = \frac{c}{H_0} \int_0^z \left( \frac{\kappa_\nu}{\gamma_0} + \lambda_{\nu0} \right) (1+z')^2 \frac{d\tau'}{E(z')}$$

- $\lambda_0$ – intergalactic opacity ($\sim 0.02$ Gpc\(^{-1}\))
- $\kappa$ – mean galactic opacity ($\sim 0.22$)
- $\gamma_0$ – the galaxy mean free path ($\sim 160$ Gpc)

Vavryčuk (2017)
Universe occupied a small volume in previous epochs:
- high dust density
  (small distances between dust grains)
- high galaxy number density
- high frequencies of light due to redshift

Dust absorption strongly increases with redshift!
What is more important: galactic or intergalactic opacity?

Opacity ratio $R_\kappa$ - average ratio between attenuation caused by intergalactic dust vs galaxies

$$R_\kappa = \frac{\lambda_0 \gamma_0}{\kappa} \sim 13.5$$

$\lambda_0$ – intergalactic opacity ($\sim 0.02$ mag Gpc$^{-1}$)
$\kappa$ – mean galactic opacity ($\sim 0.22$)
$\gamma_0$ – the galaxy mean free path ($\sim 160$ Gpc)

Intergalactic opacity is higher by more than one order than galactic opacity!

$n_0$ – the galaxy number density (0.02 Mpc$^{-3}$)
$a$ – the galaxy radius (10 kpc)

$$\gamma_0 = \frac{1}{n_0 \pi a^2}$$
Galaxies produce light

Light is absorbed by dust and dust is heated up

The dust temperature *continuously* increases

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Energy balance of intergalactic dust and galaxies I

- Dust warming
- Thermal catastrophe
  (known from the Olbers’ paradox)
Energy balance of intergalactic dust and galaxies II

- Dust is heated up due to absorption of light from galaxies
- Dust emits thermal radiation, radiation is partly absorbed by galaxies
- Dust and galaxies are in energy balance → temperature is stable

Dust temperature remains low and constant!
Temperature of intergalactic dust

Energy balance between galaxies and intergalactic dust:

\[ I^D = \frac{I^D}{R_\kappa} = I^{EBL} \]

- \( I^D \) – intensity of intergalactic dust radiation (in nWm\(^{-2}\)sr\(^{-1}\))
- \( R_\kappa \) – opacity ratio (~13.5)
- \( I^{EBL} \) – intensity of the EBL radiation (~80 nWm\(^{-2}\)sr\(^{-1}\))

Predicted dust temperature

\[ T^D = \left( \frac{I^D}{\pi \sigma} \right)^{\frac{1}{4}} = 2.776 \text{ K} \]

- \( \sigma \) – Stefan-Boltzmann constant

Observed CMB temperature

\[ T^{\text{obs}} = 2.725 \text{ K} \]

\( T \) error < 2%
Relation between EBL and CMB

- The total intensities of the EBL and CMB are not independent!
- The multiplication factor is the opacity ratio $R_\kappa$

![Graph showing the intensity distribution of extragalactic background light (EBL) and cosmic microwave background (CMB) across different wavelengths](image-url)

- Extragalactic background light (EBL) upper limit: 80 nW m$^{-2}$ sr$^{-1}$
- Cosmic microwave background (CMB) upper limit: 996 nW m$^{-2}$ sr$^{-1}$
Evolution of dust radiation with redshift
**Evolution of dust temperature with redshift**

- **Transparent universe**
  
  equation of radiative transfer for adiabatic expansion:

  $$\frac{d}{dt} I_\nu + 3HI_\nu = 0$$

  $H$ – Hubble parameter, $\nu$ – frequency

  $$I_{\text{relic}} = I_{0\text{relic}} (1 + z)^4$$
  $$T_{\text{relic}} = T_{0\text{relic}} (1 + z)$$

- **Opaque universe**
  
  equation of radiative transfer for adiabatic expansion:

  $$\frac{d}{dt} I_\nu + 3HI_\nu = \frac{c}{4\pi} j_\nu - c\kappa_\nu I_\nu = 0$$

  $j_\nu$ – luminosity density, $c$ – light speed, $\kappa_\nu$ – opacity

  $$I_{\text{dust}} = I_{0\text{dust}} (1 + z)^4$$
  $$T_{\text{dust}} = T_{0\text{dust}} (1 + z)$$

  balance between sources and losses

**Why the radiation is not distorted by redshift?**

Increase of $T_{\text{dust}}$ with $z$ exactly compensates change of wavelengths!
Assumption of the model:

The number of galaxies and the amount of dust are time independent!

Is such assumption physically reasonable?

No light from the early universe is evidenced by:

decline of the luminosity density with $z$

decline of the global stellar mass with $z$
Dark or opaque early universe?
Darkness vs. opacity of the early universe ($z \sim 5-20$)

Decreasing amount of observed light with increasing redshift

- **transparent universe**
  - stellar mass decreases with $z$

- **opaque universe**
  - intergalactic opacity increases with $z$

Stellar mass history

Optical depth

dust density increases as $(1+z)^3$

colors – measurements of different authors
**Luminosity density** $j$ - volume energy density of light in the Universe (Wm$^{-3}$)

- increases from $z = 0$ to $z = 3$
- decreases for $z > 3 - 4$

\[ j_A^{UV} = j_{UV}(z)(1 + z)^3 e^{-\tau(z)} \]

**Transparent universe:** $j$ reflects evolution of number of galaxies, unknown origin

**Dusty universe:** $j$ reflects expansion and dust absorption
Stellar mass density $\rho$ – number of stars per volume (in $M_{\text{sun}} \text{ Mpc}^{-3}$)

- apparent stellar mass density $\rho^A$ increases with time

\[ \rho^A(z) = \rho(z) e^{-\tau_v(z)} \]

**Transparent universe:** stellar mass density increases with time, the rate decreases

**Dusty universe:** stellar mass density is constant in time
Temperature and polarization anisotropies of CMB
CMB fluctuations are caused by the EBL fluctuations due to clusters and voids. Correlation between CMB fluctuations and voids and clusters (Kovács et al. 2017).

**Cold Spot** – related to Eridanus Supervoid (Szapudi et al, 2015)

Scale: ± 70 μK
The CMB is linearly polarized with two types of polarization (E-modes, B-modes).

Polarization anomalies correlate with the temperature anisotropies.

https://www.cfa.harvard.edu/~cbischoff/cmb/
Interaction of dust with cosmic magnetic fields:

- Needle-shaped conducting dust grains cause polarized thermal radiation
- **Galactic dust** – polarization anomalies at FIR wavelengths
- **Intergalactic dust** – polarization anomalies at the CMB wavelengths

![Planck XIX (2015, Fig. 10)](image)

Pipe Nebula  
Chamaeleon-Musca region

Tracing of magnetic field by galactic dust
Summary
Dust theory provides a consistent explanation of the CMB origin

- The CMB is thermal radiation of intergalactic dust grains.
- The temperature of the CMB is controlled by energy balance between galaxies and intergalactic dust.
- The CMB temperature is predicted with a high accuracy and it linearly increases with redshift.
- The CMB temperature anisotropies are caused by fluctuations of the EBL related to clusters and voids in the universe.
- The CMB polarization anisotropies are caused by alignment of conducting dust grains in magnetic fields in the universe.
- The CMB temperature and polarization anisotropies are correlated because they have a common origin: large scale structures in the universe.
Summary II – cosmological consequences

Dust theory is incompatible with the Big Bang

- Opacity strongly increases with redshift.
- No light from the early universe is due to its opacity rather than due to its darkness.
- Proper luminosity density corrected for the universe opacity is time independent.
- Global stellar mass corrected for the universe opacity is time independent.

Constant number of galaxies and constant amount of dust in the universe point to a cyclic cosmological model rather than to an evolution of the universe from a singularity.
A speculation repeated a thousand times becomes respected theory.
Thank you for your attention

Motto:
Be critical and distinguish between hypotheses and theories supported by observations.

References: