

Comptonization of Microwave Background

Cosmic microwave background is black body radiation emitted from entire universe at time of "recombination" (actually first combination) of protons & electrons.

Before ~379,000 years after Big Bang most matter in universe was ionized, & free electrons scattered photons, giving short path lengths. When temp. of universe fell below ~3000 K, the # of free electrons fell enough to bring $\tau \approx 1$, so photons could move freely.

Uniform CMB We see BB radiation from this time, redshifted down to 2.7 K. Essentially we see the last scattering surface. Perfect BB, & very uniform on sky.

BB spectrum of CMB Detection of clear BB spectrum considered strongest evidence that CMB caused by early hot, dense state - Big Bang theory - vs. the "steady-state" theory, which tried to explain CMB as scattered starlight.

CMB dipole CMB shows clear dipole due to motion of Earth relative to last scattering surface. This difference is $\pm 0.004 \text{ K}/2.7 \text{ K} \approx 1.5 \times 10^{-3}$, allowing calculation of Earth's relative motion. Since $\Delta T = 0.29 \text{ cm}\cdot\text{K}$, if we use $\Delta T \approx v/c$, then $\Delta T/T \approx 1.5 \times 10^{-3}$ gives $v \approx 450 \text{ km/s}$ for Earth. Combine with our known motion around Sun, galaxy to find Galactic motion.

T2

WMAP CMB
w/o dipole

Removing dipole gives clear Galactic emission. Three origins of this,

① blackbody radiation from dust.
Any significant dust emission must come from much warmer dust. If dust were at 2.7 K, it wouldn't change the radiation. If it were a little warmer, it would, but the emission per unit angle depends on S_{dust} , its solid angle. Dust is rarely optically thick on sky at these λ , so must be much hotter to dominate radiation. If much hotter, then WMAP in R-J part of spectrum.

② Bremsstrahlung from HII regions

③ Synchrotron radiation from electrons in galactic B field.

Each has different spectrum from CMB, so by imaging at different frequencies we can calculate & remove their contributions.

WMAP
multi- λ
map

WMAP CMB
map

Excising the Galactic foregrounds leaves map of CMB fluctuations.

During very early universe, quantum fluctuations produced tiny density inhomogeneities. These fluctuations were expanded to large size by rapid inflation, giving seeds of structure (galaxies, clusters) in universe.

Overdensities at epoch of reionization are slightly cooler than average, creating anisotropies in CMB.

Take 2-D Fourier transform of CMB maps to get angular power spectrum.

WMAP
CMB power spectrum

WMAP probes scales of size $> 0.2^\circ$
supplemented by small, finer-scale maps made from ground (in, e.g., Antarctic).

Calculating power spectrum, & comparing to observations gives info on curvature of universe, density of dark matter & baryons, etc. Can combine with other info (e.g. SN redshifts) to further constrain cosmology.

CMB also affected by other processes. Universe today is not neutral any more, as gas has been ionized by light from stars, AGN. Low density of universe (overall) limits effects.

But, at epoch of reionization (time of first stars?), average density of universe was larger, so Thomson scattering smeared out small anisotropies & left polarization signals.

WMAP detected these effects,

so constrained reionization to start around $\zeta \sim 11$ (400 million years after Big Bang), end at $\zeta \sim 7$ (~ 1 Gyr after Big Bang).

Today, only densest parts of universe — galaxy clusters — can strongly affect CMB.

Electrons in galaxy clusters are at high T (\sim X-ray energies), so will inverse-Compton scatter CMB photons to higher E ; Sunyaev-Zeldovich effect.

Check that E is transferred; for $10^8 K$, $\lambda \sim 1 \text{ cm}$, $4kT \sim 10^8 \text{ eV}$.

$$\text{Average boost } \frac{\Delta E}{E} \approx \frac{4kT_e}{m_e c^2} \sim 0.07 \text{ for } 10^8 K,$$

Times optical depth τ_s (typically ~ 0.005), gives

$$y = \langle \frac{\Delta E}{E} \rangle \sim 4 \times 10^{-4},$$

S-Z effect

Overall effect is BB CMB spectrum shifted to higher ν , and broadened, modified from BB.

Modified spectrum not BB any longer, as scattering doesn't produce new photons.
(Photons scattered into our line of sight replace those scattered out.)

Illustration shows $y=0.15$, ~750 times larger than typical values.

For low-freq part, scattered modified spectrum is - at a fixed freq - reduced, because photons preferentially shifted up. Microwave observations of CMB are easier below BB peak, so will detect a decrease in CMB emission, at the position of clusters. Low-energy tail maintains roughly $I_\nu \propto \nu^{-2}$ spectrum, as R-J tail. RJ spectrum is $I_\nu(\tau) = Z\nu^2 kT/c^2$.

The spectrum is shifted roughly parallel on a log-log plot. Assume each photon is boosted by $\Delta E/E = \epsilon = \Delta\nu/\nu = (\nu' - \nu)/\nu$. $\nu' = \nu(1 + \epsilon)$. With this boost, the bandwidth of a small group of photons increases from $d\nu$ to $(1 + \epsilon)d\nu = d\nu'$. As photons are conserved, the # of photons within this bandwidth is preserved:

$$N(\nu)d\nu = N(\nu')d\nu'$$

where $N(\nu)$ is the # of photons at ν . $\frac{I(\nu)}{h\nu} = N(\nu)$

$$\text{so } \frac{I(\nu)}{h\nu} d\nu = \frac{I'(\nu')}{h\nu'} d\nu'$$

$$I(\nu) = I'(\nu') \frac{d\nu'}{d\nu} \frac{h\nu}{h\nu'} = I'(\nu')$$

So we know the modified spectrum after the shift

$$I'(\nu') = \frac{Z\nu'^2 kT}{c^2} = \frac{ZkT}{c^2} \left(\frac{\nu'}{1 + \epsilon}\right)^2$$

We want to compare spectra at the same freq., ν_0 .
 For original intensity, $I(\nu_0) = \frac{2kT}{c^2} \nu_0^2$.

$$\text{Shifted spectrum, } I'(\nu \rightarrow \nu_0) = \frac{2kT}{c^2} \left(\frac{\nu_0}{1+\epsilon} \right)^2$$

$$\text{So } \frac{I' - I}{I} = \frac{\Delta I}{I} = \frac{1}{(1+\epsilon)^2} - 1 \approx -2\epsilon = -2 \frac{\Delta\nu}{\nu}$$

So the intensity decreases. Now, what's $\frac{\Delta\nu}{\nu}$?

Overall, $\langle \frac{\Delta\nu}{\nu} \rangle = \frac{4kTe\gamma}{mc^2}$ (average fractional ν shift — note the γ , needed to convert from only shifted photons to all photons.)

However, some photons are downshifted, while others (majority) are upshifted. In R-J tail, there are more photons at higher energies, so the smaller fraction of downscattered photons still has a big effect.

In the R-J tail, the average boost is

$$\langle \frac{\Delta\nu}{\nu} \rangle_{RJ} = \frac{kTe\gamma}{mc^2}$$

$$\text{So } \frac{\Delta I}{I} = -2 \frac{kTe\gamma}{mc^2}$$

Since $I \propto T$ in R-J tail,

$$\boxed{\frac{\Delta T}{T} = -2 \frac{kTe\gamma}{mc^2}}$$

$\gamma = S_T N_e dl, \sim \alpha_T N_e L$. For typical clusters

$$N_e \sim 2500 \text{ m}^{-3}, L \sim 3 \times 10^{22} \text{ m}, \Rightarrow \gamma \sim 0.005, T \sim 10^8 \text{ K.}$$

$$\frac{\Delta T}{T} \sim -2 \frac{k(10^8 \text{ K})(2500 \text{ m}^{-3})(3 \times 10^{22} \text{ m})}{mc^2} = -2 \times 10^{-4}$$

Detecting SZ effect requires accurate observations in microwave region ($\sim 30 \text{ GHz} = 1 \text{ cm}$), or, better at higher frequencies ($\sim 150 \text{ GHz} = 2 \text{ mm}$).

Observing in mm range requires extremely dry air, as H_2O vapor gives high optical depth. Often done from Chilean Andes, or from South Pole.

Vandervende
SZ clusters

Nice feature of SZ effect is that it doesn't depend on distance. Signal is spectral distortion, not emission.

Allows identification of clusters of galaxies independent of distance. This helps us study how clusters have formed over time.

X-ray
clusters

Can combine with X-ray observations, which measure bremstrahlung intensity. Bremss depends on N_e^2 , while SZ depends on N_e . X-ray spectrum also gives T_e . So with SZ decrement & X-ray Flux, T , can solve for cluster radius.

-Great - clusters can have non-symmetric shapes.
Can compare R from fluxes, with Θ (angular diameter) to independently measure cluster distances. Comparing cluster distances with redshift gives expansion history of universe.

More fundamental to cosmology is measuring how clusters form over time, which probes expansion of universe & distribution of matter.

E.g., Vandervende + 2010 SZ measurements improve two cosmology parameters by 50% over WMAP results alone.