Lectures 14-15 – The CMB – Prof. Wilkinson

Slides will be available on the web.

Need to know:
- Main observational facts
- Basic observational techniques & problems to be overcome
- Basic physics behind the observed structure
- What new observations can tell us about cosmology

Powerpoint presentation on its own will not be enough for a good pass grade.

Basic facts about the CMBR
(Some things to look up)
1. Surface of last scattering
2. Horizon problem
    - How can the CMBR be so isotropic (Inflation?)
3. Spectrum
    - Black body, with $T = 2.725k$
    - Peak is spectrum (from Wien's law $T\lambda_{\max} = 2.9\times10^{-3}\,m\,k$; $c = f\lambda$ gives frequency [few 100GHz])
4. Energy density
    - ~400 photons per cc → $400\times10^{6}m^{-3}$. (from black body physics) ~0.2 baryons m^{-3} (from counting galaxies & from early nucleosynthesis calculations)
    - Energy density in photons from $\varepsilon = aT^{4}$ (Stefan's law) with $a = 7.57\times10^{-16}Wm^{-3}k^{-4}$ and $T = 2.725k$ → $\varepsilon_{photons} \approx 4\times10^{-14}Jm^{-3}$
      cf. baryons $\sim 10^{9}eV$ each (mass of photon or neutron) →
      $0.2\times10^{9}eVm^{-3} = 3.2\times10^{-11}Jm^{-3}$
      CMBR is $\approx 500 \rightarrow 1000$ less energy density than in baryons (and they only have 5% of total)
      Not energetically dominant.
5. Isotropy
    - Isotropic to ~1%
6. Breakdown of isotropy
    - Due to Earth's motion
        - Dipole $\sim 10^{-1}\%$
        - Simple Doppler effect (<u>through</u> space)
        - Non-relativistic → $\frac{v}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\Delta f}{f} \rightarrow \frac{\Delta E}{E} \rightarrow \frac{\Delta T}{T}$

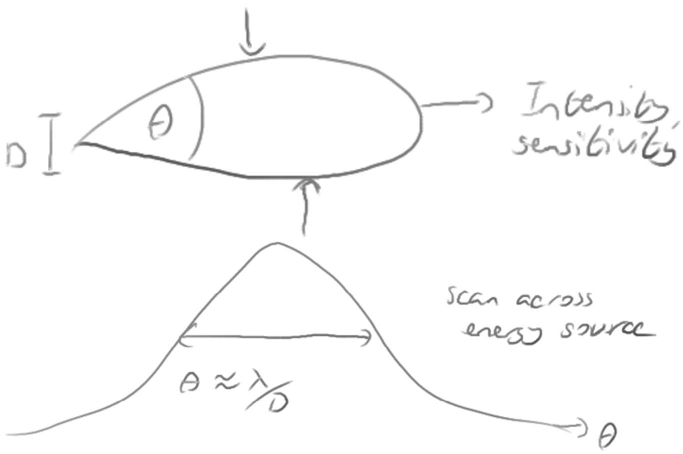
      $\frac{\Delta T}{T} \sim 10^{-3}$ → $v_{Earth} \sim 10^{-3}c$ or $100's\,km\,s^{-1}$
    - * Due to intrinsic structure *
        - $< 10^{-3}\%\ \left(1:10^{-5} \rightarrow 10^{-6}\right)$
7. The confusing effect of our galaxy
    - + external galaxies & clusters on the CMBR.

Observing the CMBR

Radio Telescopes

Very basic. Dish / horn focuses radiation into (horn +) receiver.
Physical optics: radiation reception pattern.

$\theta \simeq \frac{\lambda}{D}$ radians



Typical resolution we need for CMBR: $1° \to 0.1°$
So if we know $\lambda \to D$ size of aperture of telescope.
Typical λ for CMBR study ~ mm wavelength
→ apertures can be quite small $\leq 1 metre$
($D = 1m$; $\lambda = 2mm$ → 500λ across
$\theta \to \frac{1}{500^{th}}$ of a radian $\sim 0.1°$)

BUT: how many square degrees in the sky (sphere)? [$360^2 = 129,600$]
A $0.1°$ resolution telescope covers $0.1 \times 0.1 = 10^{-2}$ square degrees in its beam. How many of these in the sky? A lot.
One "trick" is to have many "beams", i.e. many receivers at the focus of the telescope capture radiation from different directions.

Problems:

1. Atmosphere
   - water vapour absorbs and emits at microwave wavelengths. H_2O vapour is poorly mixed – varies from place to place.
   - Scale height of problem $\sim 2km$ (e^{-1} of the total water vapour is below 2km).
   - Use switched beams – have two overlapping beams, and compare them. H_2O vapour is pretty similar in each, or at least partly so – take $A - B$ [differencing] and the problem cancels out in part the atmosphere signal.
   - Even better: interferometers (see separate powerpoint presentation on how arrays work).
     Responses from the horns overlap to a great extent – but still atmosphere can be a problem.
2. Stray radiation from the ground

Balloons fly to 10's of km altitude. $e^{-10's/2}$ of the water vapour is left. Fly dishes + focal arrays of receivers.

Experiments to look up:

- Ground based: Cosmic Background Image (CBI) – Caltech
    - Typical of the type
- Balloon based: BOOMERanG (several versions)
- Satellite: WMAP

Two good sites to look at:
Wayne Hu's website on CMB theory
Max Tegmark's website on CMB generally. Also contains info on observations.