Astro 596/496 PC

Lecture 37

April 23, 2010

Announcements:

- PS6 out, due in class *Wednesday* next week

  Updated version posted April 22!

  Mistakes were made. Q2b, Q3b now corrected/clarified.

  Management regrets the error.
- **ICES** available online staring *today* – please do it!

  written comments most helpful to future generations

Last time: CMB anisotropies

Q: what quantity is plotted to show CMB "wiggles"?

Q: what is the physical origin of CMB "wiggles"?

CMB Anisotropies and Cosmological Parameters

Small angular scales: peaks at density extrema
can measure peak scales (ℓ positions), amplitudes

Peak Positions

recall: all oscillations begin together (in phase)
then scale k has phase $\omega\eta = c_s k\eta$
observe: density at recomb, when phase is $c_s k d_{\rm rec}$
peaks at extrema
1st peak: scale at 1st compression, 2nd peak: 1st rarefaction ...

$$\lambda = 2c_s d_{\rm rec,com}\left(1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \cdots\right) \tag{1}$$

harmonics, first peak scale $\sim 2d_{\rm s,hor} \sim d_{\rm hor,com}$

angular diameter measurement! standard ruler=comoving horizon

sensitive to geometry $\rightarrow$ curvature

$\Rightarrow$ peak positions: Ω_0

why? in flat matter-dominated U: physical particle horizon is

$$d_{\mathrm{hor,phys}}(z) = (1+z) d_{\mathrm{hor,com}}(z) = (1_z) \int_0 dt/a 2\Omega_{\mathrm{m}}^{-1/2} d_{\mathrm{H},0} (1+z)^{1/2} \tag{2}$$

angular diameter distance is

$$d_{\mathrm{A}}(z) = \frac{r(z)}{1+z} = 2\Omega_{\mathrm{m}}^{-1/2} d_{\mathrm{H},0} (1+z) \tag{3}$$

and so expect *sound horizon* angular diameter

$$\vartheta_{\mathrm{hor,s}} = \frac{c_s}{c} \vartheta_{\mathrm{hor}} = \frac{c_s}{c} \frac{d_{\mathrm{hor,phys}}(z_{\mathrm{rec}})}{d_{\mathrm{A}}(z_{\mathrm{rec}})} \simeq \frac{1}{\sqrt{3}} \frac{1}{\sqrt{1+z_{\mathrm{rec}}}} \sim 1^\circ \tag{4}$$

WMAP: first peak at $\ell_{\mathrm{peak}} \sim 200 \rightarrow \vartheta_{\mathrm{peak,obs}} \sim 1^\circ \rightarrow$ $\Omega_0 = 1$

Q: what about amplitudes? 1st peak? 2nd peak?

Acoustic Peak Amplitudes

Amplitude measures degree of compression/rarefaction
$\longrightarrow$ strength of driving force $\longrightarrow$ matter density
mostly DM density, but baryons too

Effect of baryons: alter the gravitational potential well
▷ during compression: baryons make well deeper
▷ during rarefaction: baryons make well shallower
Net effect: higher Ω_{baryon} $\longrightarrow$ bigger odd peaks (compression)
smaller even (rarefaction) peaks

If measure one of each, e.g., 1st + 2nd peaks $\rightarrow$ get Ω_B!
⋆ CMB is cosmic baryometer!
⋆ independent of BBN (also more precise)
As we saw: decent CMB-BBN concordance
...but Li problem remains

CMB Polarization

Recall: pre-recombination, photons coupled to baryons
via Thompson scattering with electrons
Key fact: Thompson scattering is anisotropic and polarized
intensity and polarization of scattered radiation scales as

$$\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon}_{\rm in} \cdot \hat{\epsilon}_{\rm sc}|^2 = \cos^2\theta \tag{5}$$

max scattered intensity & pol'n in plane normal to initial pol'n
zero scattered intensity in direction of initial pol'n

classical picture: e^- as dipole antenna
incident polarized wave accelerates e^-
$\rightarrow$ azimuthally symmetric radiation, peaks in $\theta = 0$ plane

note: since $\cos^2\theta \propto \cos 2\theta$, scattered rad has 180^0 periodicity
$\rightarrow$ a "pole" every 90^0: quadrupole

Polarization and Inhomogeneity

Pre-recomb: repeated Thompson scattering
randomizes polarization → CMB unpolarized

But at recomb, last scattering evens "uncompensated"
- if plasma homogeneous: still no net polarization
- but inhomogeneities → net linear polarization in CMB

How? consider point at 90° corner of hot region
- *Q: is there polarization? if so, orientation?*

Now consider "checkerboard vertex" (local quadrupole in T)
→ net linear polarization towards us, aligned w/ "cold" axis

`www: cool Wayne Hu movie`

Now consider point at hot/cold "wall"

locally sees dipole T anisotropy

net polarization towards us: zero! *Q: why?*

Q: what about edge of circular hot spot? cold spot?

polarization tangential (ring) around hot spots
radial (spokes) around cold spots
(superpose to “+” = zero net polarization–check!)

`www: WMAP polarization observations of hot and cold spots`

Note: polarization & T anisotropies *linked*
$\rightarrow$ consistency test for CMB theory and hence hot big bang

Polarization Observed

First detection: pre-WMAP!
⋆ DASI (2002) ground-based interferometer
at level predicted based on T anisotropies! Woo hoo!

WMAP (2003): first polarization-T correlation function

WMAP (2006):
- better statistics
- also polarization autocorrelation

⋆ used T-pol'n links to get model-independent
3-D density power spectrum: consistent with scale invariant!

CMB Summary and Outlook

What has the CMB done for us

- confirmed hot, dense, smooth early universe
- measured primordial power spectrum, consistent w/ inflation
- seen acoustic peaks
- measured a wealth of cosmological parameters
- seen polarization: confirms underlying physics model

What will the CMB do for us

- better polarization $\rightarrow$ gravity wave signal from inflation!
- CMB as background illumination for structure formation
  SZ effect, 21-cm, ...
- stay tuned!