Lec 26: 04/27/2010

Acoustic Peaks and Baryon vs Dark Matter Density:

As we discussed, the perturbations in the coupled fluid of baryons and photons obey the same equation as a harmonic oscillator. For modes with $\lambda > \lambda_J$, we have an inverted harmonic oscillator, and hence perturbations grow. Once $\lambda < \lambda_J$, we have an ordinary oscillator, thus oscillations. In the presence of dark matter, we have a forced (driven) harmonic oscillator, where dark matter perturbations provide the external force.

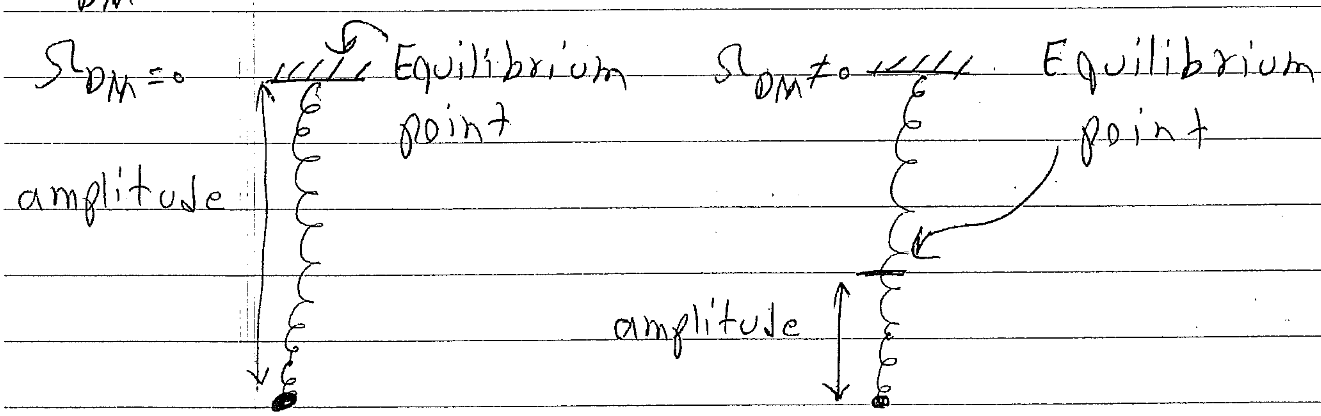
Now let us discuss some of the qualitative features of the CMB power spectrum that are related to this physical picture:

(1) First acoustic peak. The stretche oscillators starts oscillating about its equilibrium point once $\lambda < \lambda_J$.

The maximum stretch corresponds to maximum compression of baryon/photon fluid. Because of the baryon and photon coupling, compression (overdensity) of baryons results in overdensity of photons through $\delta n_\gamma \propto \delta n_B$. This leads to temperature fluctuation $\frac{\delta T}{T} \sim \frac{1}{3}\frac{\delta n_\gamma}{n_\gamma}$ (recall that $n_\gamma \propto T^3$).

These temperature fluctuations are what we observe in the CMB power spectrum.

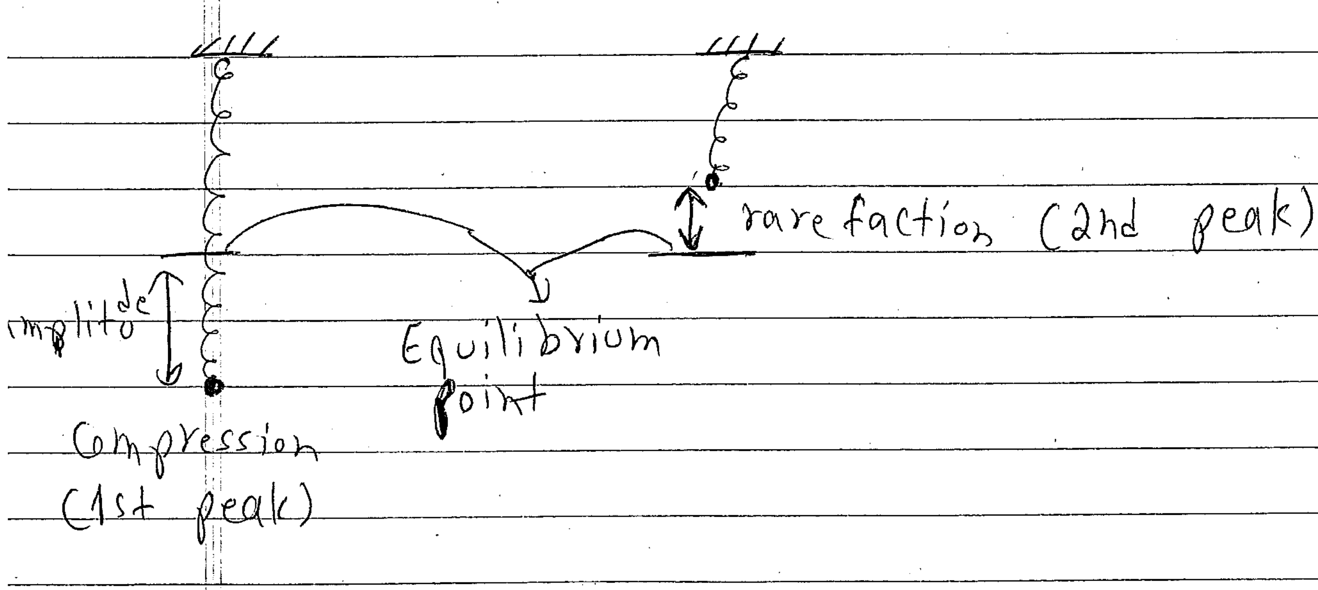
Assuming $\Omega_B + \Omega_{DM}$ is constant, we see how the ratio of $\frac{\Omega_B}{\Omega_{DM}}$ can affect the first peak:



The height of the first peak is given by the amplitude of oscillations. Dark matter lowers the equilibrium point, hence a smaller amplitude. Therefore a larger baryon fraction leads to a higher first peak:

$$\boxed{\Omega_B \uparrow \Rightarrow \text{higher 1st peak}}$$

2) Second acoustic peak. A given mode keeps oscillating once $\lambda < \lambda_J$. Half a period later than the maximum compression, the fluid reaches maximum rarefaction:



Note that these are oscillations in the presence of an external force coming from dark matter perturbations:

$$\ddot{\delta}_B + \frac{4}{3t}\dot{\delta}_B + \left(\frac{k^2}{3t^{4/3}} - \frac{2\omega_B}{3t^2}\right)\delta_B = \frac{2\omega_{DM}}{3t^2}\delta_{DM} \qquad (*)$$

Where:

$$\ddot{\delta}_{DM} + \frac{4}{3t}\dot{\delta}_{DM} = \frac{2}{3t^2}(\omega_{DM}\delta_{DM} + \omega_B\delta_B) \quad (**)$$

We see that evolution of δ_{DM} also depends on δ_B, which is not surprising because dark matter feels gravity only (hence total energy density).

This results in an additional positive term on the right-hand side of (*), which depends on δ_B. In the harmonic oscillator language, baryons give rise to a positive force (through their self gravity).

As long as the oscillator is stretched this contribution opposes the restoring force (which is negative in this case). Once the oscillator passes the equilibrium point, this contribution adds to the restoring force. In consequence, the oscillator stops earlier than it would if this term did not exist.

This effect suppresses the 2nd peak relative to the 1st peak, and is more pronounced for larger Ω_B.

Note that the effect reverses as the oscillator goes through another half period, which for the fluid is from maximum rarefaction (2nd peak) to another maximum compression (3rd peak).

Thus the overall effect of Ω_B is to suppress even peaks relative to odd peaks:

$\boxed{\Omega_B \uparrow \Rightarrow \text{even peaks suppressed}}$

A rather small 2nd peak detected by BOOMERANG and MAXIMA experiments (back in 2000) led to thinking of a large Ω_B as a possible explanation. This, however, was not consistent with the value inferred from BBN, and resulted in some confusion. A small 2nd peak has gone now (with WMAP data) and belongs to the past.

(3) <u>Third acoustic peak.</u> Perturbation modes that started to oscillate early, can reach a second maximum compression (3rd peak). Therefore higher acoustic peaks are observed for modes that start oscillating well before the photon decoupling, and even before matter-radiation equality. Those modes that start oscillating in the radiation-dominated era are ramped up because dark matter perturbations do not grow in that era (as we discussed earlier). This has the effect of moving the equilibrium point of the oscillator higher, and hence a larger oscillation amplitude. The rise in the CMB power spectrum happens because of this and is an indicator of the dark matter density. Therefore the height of the 3rd peak is a measure of Ω_{DM}:

$\Omega_{DM} \uparrow \Rightarrow$ higher 3rd peak

As we will see later, the spectrum does not keep rising because of suppression at small scales due to Silk damping.

We see from this discussion that acoustic peaks and their (relative) heights can be used to infer the values of Ω_B and Ω_{DM} from the CMB. With the latest WMAP data (7 year) the first three acoustic peaks are clearly seen. There are other experiments that see higher peaks. For example, ACBAR and QUaD see up to 6 peaks. There is a point of causion here. There are degeneracies in the cosmological parameters so long as CMB is concerned. For example, cosmological constant vs curvature. One needs other observations in order to break these degeneracies and determine the cosmological parameters.

Sachs-Wolfe Effect:

It is important to note that photons that arrive from over dense (odd peaks) and under dense (even peak) regions experience gravitational redshift. Over density results in a potential well, and hence photons will be redshifted while climbing out of the well. Similarly, photons falling from a mountain formed by an underdensity will be blueshifted. This is the so-called Sachs-Wolfe effect.

It turns out that the redshift/blue shift is dominant over temperature fluctation. A cold region (rarefied, $\delta T<0$) is also under dense ($\delta\rho<0$), and the blueshift will eventually make the photon energy larger.

A hot region (compressed, $\delta T>0$) is also over dense ($\delta\rho>0$).

and the redshift will eventually make the photon energy smaller.

As a result, the blue spots in the CMB maps actually correspond to cold regions, while the red spots correspond to hot regions.

A final comment is in order. So far we have discussed the evolution of perturbations with a given wavelength. As time goes by it will go through various processes (growth, oscillations, first compression, first rarefaction, etc). However, CMB provides a snapshot of all the modes at a given time, i.e. photon decoupling epoch. Modes with a shorter wavelength, corresponding to higher multipoles "ℓ", have had a longer time to evolve. These are the modes that exhibit higher acoustic peaks, and this is why we see higher peaks at larger values of "ℓ".