PHY 475/375
Lecture 11
(April 30, 2012)

The Benchmark Model

As noted in a previous lecture, the Benchmark model is the best fit to the currently available observational data. While we will look at some of these observational data in future lectures, let us write down the major aspects of the Benchmark model for now. Note that what Ryden calls the Benchmark Model is part of what is more commonly called the *Concordance Model*.

- According to the Benchmark model, the Universe is spatially flat.
- The Hubble constant is $H_0 = 70$ km s^{-1} Mpc^{-1}.
- The Universe contains radiation, matter, and a cosmological constant (recall a previous note that a more updated text might replace this with "dark energy, which might be in the form of a cosmological constant").
- The radiation component of the Benchmark model consists of photons and neutrinos. The photons are assumed to be provided solely by a Cosmic Microwave Background (CMB) with current temperature $T_0 = 2.725$ K, and density parameter $\Omega_{\gamma,0} = 5.0 \times 10^{-5}$. The energy density of the neutrino background is theoretically calculated to be 68% of that of the CMB, as long as neutrinos are relativistic.
- The matter content in the Benchmark model of the Universe consists partly of baryonic matter (i.e., matter composed of protons and neutrons, with associated electrons), and partly of nonbaryonic dark matter. In future lectures, we will look at evidence that most of the matter in the universe is nonbaryonic dark matter. The baryonic matter has a density parameter $\Omega_{\text{bary, 0}} \approx 0.04$ today, whereas the density parameter of the nonbaryonic dark matter is about $\Omega_{\text{dm, 0}} \approx 0.26$.
- The bulk of the energy density in the Benchmark model is provided not by radiation or matter, but by a "dark energy" which might be in the form of a cosmological constant, with $\Omega_{\Lambda,0} = 1 - \Omega_{m,0} - \Omega_{r,0} \approx 0.70$.
- The Benchmark model was radiation-dominated in the earliest stages of the Universe, then was matter-dominated, and is now entering into its Λ-dominated phase. As calculated previously, radiation gave way to matter at a scale factor $a_{\text{rm}} \approx 2.8 \times 10^{-4}$, corresponding to a time $t_{\text{rm}} = 47,000$ yr. Matter, in turn, gave way to the cosmological constant at $a_{m\Lambda} = 0.75$, corresponding to $t_{m\Lambda} = 9.8$ Gyr. The current age of the Universe is $t_0 = 13.5$ Gyr.

With $\Omega_{r,0}, \Omega_{m,0}$, and $\Omega_{\Lambda,0}$ known, the scale factor $a(t)$ can be computed numerically using the Friedmann equation (6.6); the result is shown in Figure 6.5 of your text.

Once $a(t)$ is known, other properties can be computed using the Benchmark model. For example, the upper panel in Figure 6.6 in your text shows the current proper distance to a galaxy with redshift z; from that figure, we see that in the limit $z \to \infty$, the proper distance $d_p(t_0)$ approaches a limiting value of $3.24\, c/H_0$ for the Benchmark model. Thus, the Benchmark model has a finite horizon distance

$$d_{\rm hor}(t_0) = 3.24\, \frac{c}{H_0} = 14,000 \text{ Mpc} \tag{6.42}$$

This means that if the Benchmark model is a good description of our Universe, then we can't see objects more than 14 Gpc away, because light from them has not yet reached us.

When we observe a distant galaxy, we may ask the related, but not identical questions, "How far away is the observed galaxy?" and "How long has the light from the observed galaxy been traveling?"

- We can answer the question "How far away is the observed galaxy?" by computing the proper distance $d_p(t_0)$.
- We can answer the question "How long has the light from the observed galaxy been traveling?" by computing the *lookback time*. If light emitted by the galaxy at time t_e is observed at t_0, then the lookback time is simply $(t_0 - t_e)$.

In the limit of very small redshifts, the lookback time is $t_0 - t_e \approx z/H_0$.

At larger redshifts, however, the relationship between lookback time and redshift becomes nonlinear, and depends strongly on the cosmological model used, as shown in Figure 6.7 in your text. For example, consider a galaxy at redshift $z = 2$.

- In the Benchmark model, the lookback time to that galaxy is 10.5 Gyr, that is, we are seeing a redshifted image of that galaxy as it was 10.5 billion years ago.
- In a flat, Λ-only universe with $H_0^{-1} = 14$ Gyr, the lookback time to a $z = 2$ galaxy is 15.4 Gyr.
- In a flat, matter-dominated universe with $H_0^{-1} = 14$ Gyr, the lookback time to a $z = 2$ galaxy is only 7.5 Gyr.

That is why it is so important to measure quantities like $\Omega_{m,0}$ and $\Omega_{\Lambda,0}$.

The posted notes for this class are shorter because about 50% of the time was spent on a review for the Midterm. We did start discussing the section on the efforts to measure cosmological parameters, but the notes will be posted in the next lecture for continuity.