Topics: Observing the acceleration, concordance model (flatness evidence), early universe and big bang nucleosynthesis

Reading:

- Read *From Slow Down to Speed Up* by Riess and Turner (Scientific American, 2004) – see link on website
- *Optional*: You can read – or skim – the original research paper that shows the acceleration – Riess et al., "Type Ia Supernova Discoveries at $z > 1$ from HST: Evidence for Past Deceleration and Constraints on Dark Energy Evolution," *Astrophysical Journal*, 607, 665, 2004 – see link on website, but also note that you can find research papers on the Astrophysical Data System: http://adsabs.harvard.edu/abstract_service.html. And note Figure 8.
- *Optional*: You can read *The Cosmic Symphony*, another Scientific American article, this one about the cosmic microwave background anisotropies (observations of which show that the universe's geometry is flat). But also see Fig. 2 here in this document.
- Read section 3 of Ch. 24 (pp. 564-68) of Ryden and Peterson.

Summary of work to submit:

- Nothing to hand in for Tuesday's class.

Overview:

To solidify your understanding of the evidence for and effect of the acceleration, challenge yourself to map the (qualitative) trends in the scale factor shown in Fig. 24.3 – which demonstrates how the expansion changes with time – to the evolution of the Hubble parameter, shown in most detail in Fig. 24.6 (b) – which also demonstrates how the expansion changes with time. Specifically, note how the expansion decelerates for a while, then starts accelerating (quite recently on the logarithmic x-axis of Fig. 24.3). And how Fig. 24.6 shows galaxies at $z \sim 0.5$ from an era when the expansion was slower (that's the acceleration that started just a few billion years ago – not too far back along the x-axis in Fig. 24.3), while at even higher redshifts in Fig. 24.6 you see galaxies from a time so far back that the universe was decelerating due to matter dominating over Λ. (...since the universe was decelerating then, the expansion is faster as you look to higher redshifts in a Hubble diagram.) To explain this zig-zagging behavior of the expansion (see the figure in this document, below, showing the different $a(t)$), a universe with $\Omega_{\mathrm{m,o}} = 0.3$ and $\Omega_{\Lambda,\mathrm{o}} = 0.7$ does a good job. It is the universe in which we appear to live! Its age is about 14 billion years (so older than the flat, all matter universe and older than the oldest known stars), and it will expand forever (unless the dark energy is something quite different than the cosmological constant), and it is flat (as the Omegas imply, since they sum to one). But there's also independent evidence for the universe being flat – the CMB anisotropies are consistent with the Euclidean angle-size-distance relationship. And the mass density reconstructed from gravitational lensing (and other methods of measuring gravity-producing mass – so baryonic and dark matter, both) is consistent with $\Omega_{\mathrm{m,o}} = 0.3$. All three observations agree. So...what other observations can confirm this scenario? Well, if the early universe was very hot, then atomic nuclei formed as it cooled, and then they joined together to form heavier nuclei (helium, primarily, from hydrogen) as the early universe expanded and cooled (still very hot, though!). Eventually (a few minutes after the big bang) the universe was cool enough that no more reactions could occur. And we ended up with a certain amount of hydrogen, deuterium, helium, and lithium. For a given history, $a(t)$, we can predict the relative amounts of each element produced...and our observations are in good agreement with this prediction (basically, that 25 percent of the baryonic matter is helium and most of the rest is hydrogen). Furthermore, they show that only a small fraction of the matter in the universe is baryonic (see Fig. 3 in this document).

Commentary on the reading, viewing, and other preparation:

The scene-setting in the overview, above, is primarily covered in section 2 of Ch. 24, but it also is covered in the Riess and Turner *Scientific American* article. As you read that article, compare the well-annotated figure on p. 67 to Fig. 24.6b of Ryden and Peterson. Also think about the too-dim vs. too-bright supernovae holding the key and re-read the discussion on p. 561 (and remember that higher magnitudes represent lower fluxes – dimmer sources).

The somewhat complicated first-decelerating-then-accelerating universe we live in seems kind of weird. The scale factor in this/our universe can be visualized:

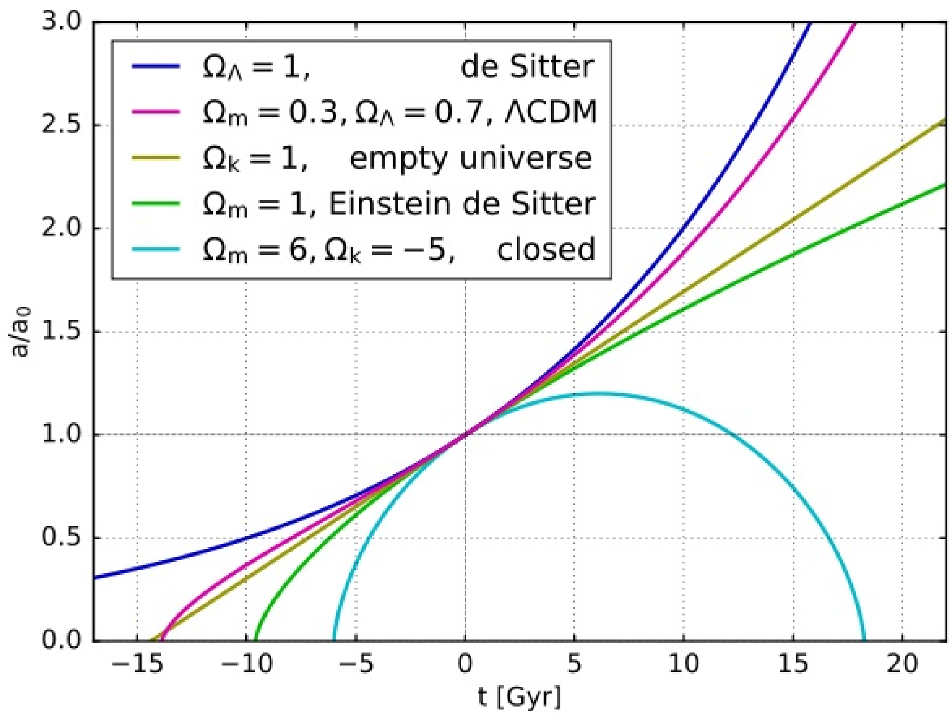

Fig. 1 Our universe is the pink one. The current time, $t_o = 0$ on this scale. In each universe, the big bang happened at a different time. Note that the green universe (flat, all matter) is one we've been computing. And the empty universe is also shown. One weird coincidence is that the age of our zig-zag universe (first decelerating then accelerating) is almost exactly equal to the Hubble time (the age of a constant expansion universe).

How do we know the universe is flat? The CMB has hot and cold spots, reflecting low- and high-density regions in the last-scattering surface of the CMB at a redshift of 1100, when the universe was about 400,000 years old. We know (remarkably) how big these spots should be (linearly; in meters or megaparsecs) – see the Hu and White article if you want details. Has to do with sound waves traveling across the early universe. The point is, since we know how big they are (or should be) and we know how far away they are (CMB temperature tells us their redshift, and our model of the scale factor tells us redshift vs. time), so we know what angular size they should have. If the geometry of space is flat...or hyperbolic or spherical. And the observed angle-size-distance relationship is consistent with flat – with $\theta = \ell/d$.

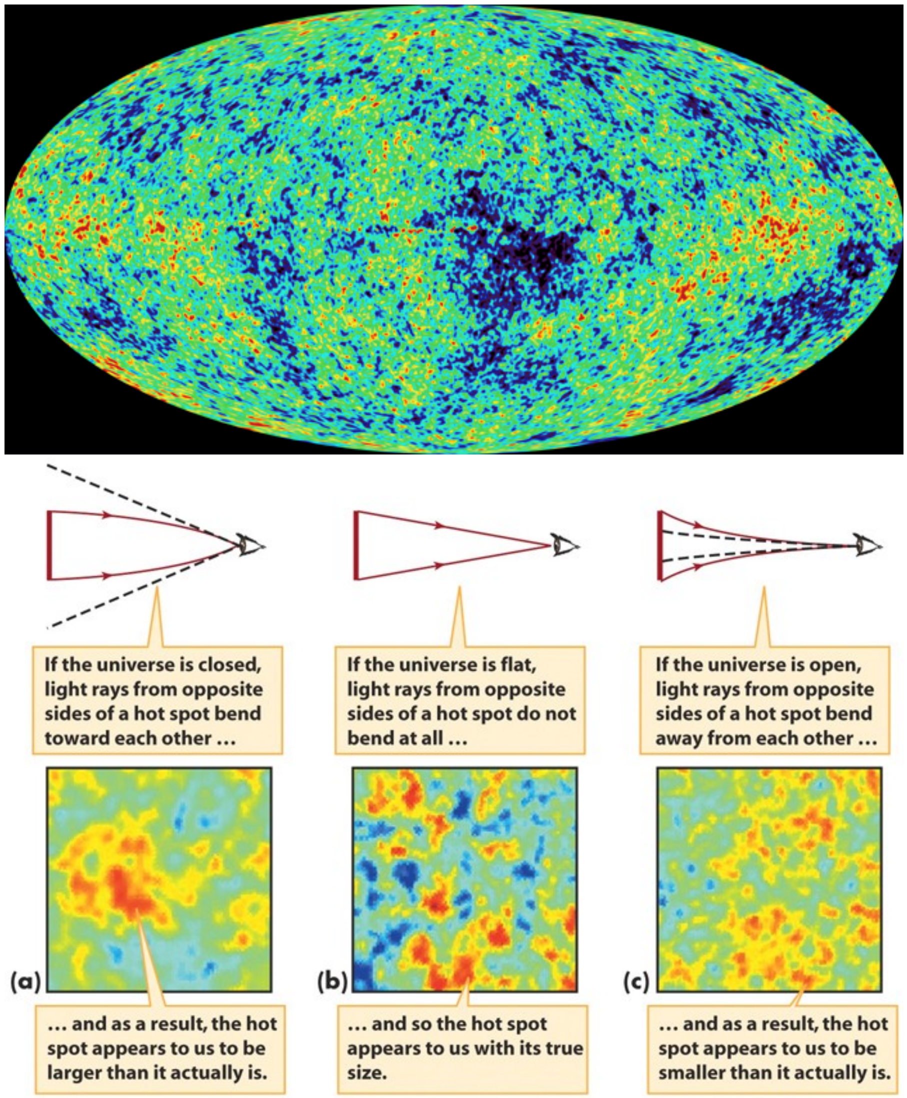

Fig. 2 The cosmic microwave background with the average signal (and all foregrounds) subtracted off (top). These variations are one part in 10^5 and represent density variations in the universe when it was about 400,000 years old. Bottom: what the size scale of the blotches (anisotropies) in the CMB would look like in the cases of different geometries of space. The middle case – flat, Euclidean geometry – is what we see.

The CMB reminds us that the universe started out hot and dense. In fact, the relationship we derived $T_{\rm CMB} \propto 1/a$ implies that the universe was infinitely hot at the big bang. The CMB photons are not from the big bang itself, because the universe was opaque when it was young and dense. At about 400,000 years it relatively suddenly became transparent.

So, all of a sudden, the photons filling the universe could just travel...in straight lines without interacting with anything. We see them today (a few of them interacted, finally, with our telescopes). The cartoon in Fig. 24.8 is simple, but good. But realize – distance from the observer corresponds to (significant) lookback time. The universe became transparent all at once everywhere, but we see the CMB from a distance, today, that's the number of light years corresponding to the age of the universe minus 400,000 years. Tomorrow, the CMB will be coming from one more light-day away from us.

In any case! Even earlier than 400,000 years after the big bang, the universe was a quite uniform, dense, hot soup of particles, combining together (in those conditions of high density – so particles frequently collide with each other – and high temperature – so those collisions are strong and can overcome the repulsion of positively charged nuclei) according to reactions on pp. 566-67.

Note the role that the decay of neutrons plays in this story (missing neutrons means hydrogen will be produced; helium has neutrons but hydrogen doesn't).

Figure 24.9 shows the results of the nuclear reactions running for a while as the density and temperature go down. Some baryonic matter density was assumed for the model, but other values can be assumed, producing more or less helium (and deuterium, lithium, etc.). Beyond just showing that the observed 25% helium is predicted, observations of primordial abundances and modeling of this so-called big bang nucleosynthesis constrain the baryon density to $\Omega_{b,o} = 0.04$, indicating that dark matter is, indeed, non-baryonic.

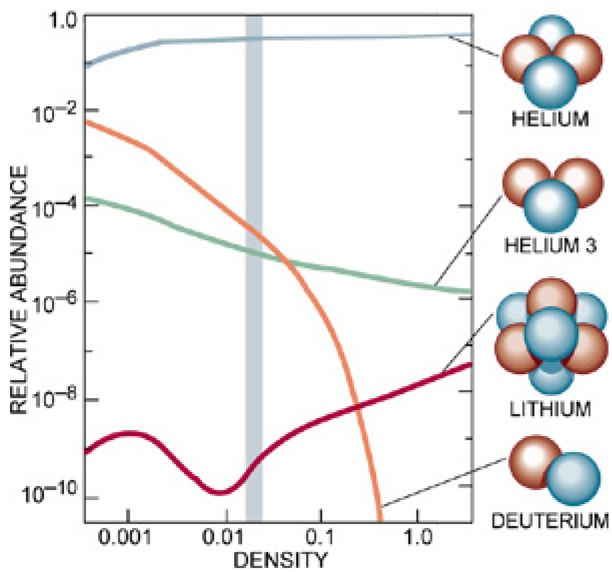

Fig. 3 Fig. 24.9 in the textbook shows the time evolution of elements in one universe (our universe). At the right hand side of that figure is a certain value of the relative abundance of various elements. Imagine you made a bunch of similar models but for different universes and plotted the final amounts of helium, deuterium, and lithium. That's this figure here. And the x-axis shows the baryonic matter density (current value scaled to the critical density) of each model. The gray vertical band shows the value range of density that gives abundances of these elements that are consistent with observations. The key point: only baryons matter for the production of these elements – dark matter doesn't interact with them. So this low value of the baryonic density shows that most of the observed $\Omega_{m,o} = 0.3$ is dark matter.