Lecture Notes 1: Was There a Beginning of Time? (Part 1)

1 Hubble's Law and the Big Bang

People have long speculated about the origin of the Universe, but it wasn't until the 1920s that cosmology — the study of the Universe as a whole — started to become a true scientific endeavor. Our basic picture of the history of the Universe began to emerge in 1929, when the American astronomer Edwin Hubble discovered that most of the galaxies we observe in the night sky are moving away from us.[1] A few are moving towards us, but the overwhelming majority of them are moving away. I won't get into the details of how he was able to *deduce* this — he used something called "redshift" — but for now I'll ask you to take my word on this.

Noticing that most of the galaxies in the Universe are moving away from you is an interesting thing to notice. So, if you were Hubble, and you had *any* curiosity at all, you'd probably be wondering, "Hey, why are all these galaxies moving away from me?" As far as I can see, there are at least two simple hypotheses that you can immediately guess to explain to explain Hubble's observation.

The first is what I'll call the Geocentric Pop hypothesis. To form the hypothesis, first notice that, since all the galaxies are moving away from us, they were of course closer to us yesterday than they are today. And the day before they were even closer, and so on, and so forth. So you might guess that at one point we were all *very* close — that at some time in the distant

[1] He actually discovered something more precise (and more profound): *The speed that a given galaxy moves away from us is proportional to how far it is located from us.* So, a galaxy located 200 million light years from us will move away from us twice as fast as a galaxy located 100 million light years from us. (A light year is simply how far light travels in a year.) This more precise statement of Hubble's observation is known as *Hubble's law.*

past everything in the Universe was located exactly we *we* are today. In other words, you can hypothesize that *we* are the center of the Universe, and that all the galaxies in the world are moving away from us (for some reason).

This hypothesis would be perfectly consistent with what we observe — all the galaxies *are* moving away from us — but it seems to single us out as somehow "special," and there's no fundamental principle of science that actually says that we are. *Maybe* we are, but there's definitely nothing in the known laws of physics that says that.

There's another hypothesis you can guess, which can also legitimately explain why most galaxies are moving away from us, which isn't as egoist as the Geocentric Pop hypothesis, but which is slightly more complicated. It's known as the Big Bang hypothesis. To understand this hypothesis, first imagine that you're an inch worm living on the surface of a balloon. Being an inch worm with limited observational and mental capabilities, the whole world seems 2-dimensional to you: you can walk forwards and backwards, left and right, and any combination of the two, but that's all. You have no concept of *depth* or *elevation*. Of course, we *humans* can just look at the balloon and see all 3 dimensions, but imagine for now that you're several steps down in the evolutionary tree.

Now let's say that on the balloon there's a bunch of dots that someone has marked with a magic marker. You, the inch worm, can see these dots, you can measure the distances between them, and so on. Now let's say that you measure the distance between you and some dot and get a number, like 3 inches. What would happen to this distance if I were to blow up the balloon? Well, the balloon inflates, so obviously you and the dot will move away from each other, and the distance will increase. Notice that the same thing would happen if you were someplace else on the balloon; inflating the balloon would cause the dot to move away from you there as well. So we notice that, *regardless of where you are*, inflating the balloon will cause the dots on the balloon to move away from you. There's no special point on the balloon such that this is true; it happens *everywhere*.

Now let's pretend that these dots are *galaxies*. If the balloon is inflating, then you'll observe all of the galaxies to be moving away from you. You can probably see where I'm going; I hereby redeem human status unto the reader. In this second hypothesis to explain why most galaxies are moving away from us, we are like the inch worm living on the balloon. The balloon inflating corresponds to our Universe "expanding," and the dots moving away from the worm on the balloon corresponds to the galaxies moving away from us in the real Universe. As I said in the balloon analogy, no point on the balloon is special. This means that every observer in the Universe would also observe all the galaxies to be moving away, whether you're here on Earth or living in some galaxies trillions of miles away.

Of course, *our* world is *3*-dimensional, rather than 2-dimensional, so the kind of balloon we'd have to be sitting on the real world would have to be some kind of *hyper*-balloon living in 4 dimensions. Now, I'll be the first to admit that I personally have a hard time imagining a 4th dimension. The good news is that this 4th dimension in extending our balloon analogy is fictional; it's just an artifact of the analogy that has no real meaning. According to this hypothesis, the Universe does expand in a very real sense, but not in the kind of way that a balloon expands or inflates. To say that the Universe is "expanding" is simply to say that the distance between points in the Universe is increasing. The Universe isn't expanding *into* anything. The Universe just *is*, and the space between the points in the Universe is increasing.[2] It's just easier to understand this fact about the Universe when we have an analogy in mind, like a balloon inflating.

The two hypotheses — Geocentric Pop and Big Bang — are similar in that they both hold that, in the past, everything in the Universe was closer than it is today. In fact, if you go back far enough, both hypotheses predict that the Universe exists in a state of "singularity," where all the matter and energy in the Universe is actually concentrated at a *single* point. This singularity is then interpreted as being the "beginning of time," and any question asked of what happened *before* this singularity becomes meaningless. (Amazingly, the amount of time that has passed since the Beginning — *i.e.*, the age of the Universe — can actually be calculated from astronomical observations. It turns out to be about 13.7 billion years.)

I suppose, when Hubble first published his results, you could have believed either of these two hypotheses; both were consistent with his observations. For a scientist who wishes to be objective about the way she studies the Universe, however, the Big Bang hypothesis is far more elegant and is therefore preferable. For this reason (and also because the kind of expansion that occurs in the Big Bang hypothesis is the kind of expansion that general relativity predicts would occur; general relativity does *not* predict the kind

[2] I hope this all sounds very weird to you, because it is! The physical theory which describes precisely how this expansion of space works goes by the name of "general relativity" and will be part of the subject of the next two lectures.

of expansion that occurs in the Geocentric Pop hypothesis), we won't have much occasion to refer to the Geocentric Pop hypothesis any more. Nonetheless, the Big Bang hypothesis did not yet receive universal support, because there was, in fact, a *third* view which you could've taken — which some people did take for a while — and that was to believe in what was known as the "steady-state model."

In this view, there was *no* beginning of time; the Universe is eternal. However, matter and energy are created spontaneously throughout the Universe as the Universe expands. This model — which has the aesthetic appeal of possessing the "perfect cosmological principle" (to be discussed later) — can explain Hubble's observation, but it cannot explain the existence of the cosmic microwave background radiation (to be discussed in the next section), so it was eventually discarded by nearly all cosmologists.

2 The Cosmic Microwave Background

As we've noted several times in these notes, the Big Bang hypothesis "predicts" that, in the past, everything in the Universe was closer, and so the Universe was denser than it is today. It must therefore have had different properties than it has today. One important question we can ask is, "As we rewind time, what happens to the temperature of the Universe?"

To get a handle on this question, let's first look at the related question of squeezing a container of gas (to make it denser), which contains, of course, gas molecules. Let's focus on a single molecule in this container. It's moving about in pretty random, unpredictable directions. Let's assume for simplicity that it only moves in zig-zags, zigging and zagging only when it collides with something, either another gas molecule or the wall of the container. Now remember that the wall of the container is closing in on all the molecules. So, when our molecule hits the wall that's moving towards it, the molecule is going to bounce back with a greater speed than what it had when it hit it. This effect (due to a law of physics known as the "conservation of momentum") is just what happens in baseball when the batter swings at a fast-moving ball; the ball goes farther when someone throws it at the swinging bat than if the bat just swings at a ball at rest in front of it. So, compressing the container will cause all the molecules to move, on the average, faster. Now, the whole idea of "temperature" is simply a measure of the average kinetic energy (energy of motion, *i.e.*, energy due to speed) that the molecules in a gas have. Therefore, as you compress a gas, its temperature goes up.

Similarly, as you rewind the history of the Universe, the temperature of the stuff in the Universe goes up. So, if you go back far enough in time, the temperature of the Universe was *really* high — much higher than the center of the Sun! In fact, if you go back far enough, you'll reach a point where the temperature is so high that all the atoms in the Universe are moving *so* fast, and the collisions of atoms is *so* frequent, that all of the electrons in the atoms get kicked out by these super-energetic collisions! Therefore, the Universe will consist of mostly *ions* plus electrons, rather than atoms. Actually, there will also be photons (particles of light), neutrinos (very light neutral particles), and some others, but it's the presence of the plasma and the photons that concerns us. (An ionized gas is known as a "plasma.")

Now, it turns out that plasmas are very "opaque" to photons — the photons present at this time get repeatedly absorbed and scattered by the electrons, so a given photon simply can't travel any appreciable distance before it interacts with another electron. However, eventually the plasma will cool down to a sufficiently low temperature that the nuclei and electrons will combine to form atoms, in a process (somewhat confusingly) called "recombination." When this bonding happens, photons are released, and these photons no longer interact to a significant extent with the matter present in the Universe. Thus, after recombination, the photons are able to roam free. We therefore expect that, today, these photons released during recombination should still exist. So the Big Bang hypothesis predicts that there should be some kind of a Big Bang *afterglow* in the night sky.

This is a definite prediction of the Big Bang hypothesis, and we can get a definite answer by going out an *observing* the night sky. Well, people did this the first time in the 1960s, looking for the specific signature of this afterglow (which one can calculate, but which I, of course, won't get into). And, lo and behold, they observed exactly what the Big Bang hypothesis predicts! We observe precisely the photons predicted by the Big Bang, although we observe them in the form of microwaves, electromagnetic waves less energetic than visible light. (They were about 1,000 times more energetic when they were released, but because of the expansion of the Universe since then, the wavelength of these waves has been stretched out, resulting in less energetic waves.)

We call these microwaves the "cosmic microwave background radiation," or the CMB for short. The discovery of the CMB was striking evidence that the Big Bang really happened, and since its discovery, increasingly precise measurements of the CMB (like the fact that it has the distribution of what's called "blackbody radiation") have lent even more support for the Big Bang. Coupled with other lines of evidence — examples include the abundance of light elements produced very early in the Universe, as well as the evolution and distribution of galaxies — there are now very few people in the scientific community that dispute the Big Bang model. It is the best theory of the evolution of the Universe that has ever been proposed, and it has passed all tests ever put forth towards it.

Yet despite all these successes, there are very good reasons to believe that the Big Bang model is incomplete. Nobody doubts the essential processes predicted by the Big Bang, but one question in particular seems conspicuously left unaddressed by the model. As wondered by Alan Guth: Just what banged, why did it bang, and what happened before it banged?

The Big Questions
Summer 2008