Lecture Notes 2: Was There a Beginning of Time? (Part 2)

1 The Friedmann Universe

Although from an observational point of view, the Big Bang theory is easy enough to understand, one might still be unsatisfied. For example, what is this expansion, and why did it happen?

To really understand this expansion, the appropriate physical theory we need is Einstein's general theory of relativity. I'll have a lot more to say about general relativity when I talk about time travel in an upcoming lecture, but for now the important thing to know is that it's a theory linking space, time, and gravity. (It's actually a more accurate theory of gravity than Newton's theory, which you may have heard about, with the apple and all.)

Einstein published his theory of general relativity back in 1916, and since then it has become one of the two most successful physical theories ever proposed (the other being quantum theory). Shortly after Einstein published his theory, people began to wonder what sorts of consequences the theory has. In particular, they wondered what the theory would imply for the Universe itself.

In 1922, a Russian mathematician named Alexander Friedmann worked on this question and came up with an answer. Now, making a prediction about the Universe itself may seem like a daunting task — and it is! After all, just look around you — the Universe is *messy*! How could possibly be able to model all of this stuff? Not only that …the Universe is also pretty big! You've got to have a lot of confidence to think that you could actually model the Universe and make predictions about it. (I can't even come up with a theory for how girls work!) When I discussed the Big Bang model, I mostly talked about things that we've inferred from observations. But actually *explaining* these observations at a rigorous level is something completely different. (In fact, Friedmann worked on this problem before Hubble made his famous discovery, so he didn't even know what the answer would be.)

The good news is that physicists have a trick in solving hard problems:

When faced with a hard problem, just solve a simpler one.

And this is precisely what Friedmann did. Instead of trying to model the Universe in super-precise details, he made some approximations. The first approximation he made is that it is homogeneous, which simply means that the Universe is more or less uniform; it doesn't change much as you move from one place to another. The density of matter and energy in the Universe doesn't change much as you travel about.

At this point, you might think to yourself, "Aha! Friedmann's plan is doomed to fail! The Universe obviously *isn't* homogeneous! I mean, just look around you! There's a person there, a chair there, a schoolbus there .... And you mean to tell me that the Universe is *homogeneous*? Come on! I know that physicists like to BS the public, but this is going too far."

The problem with this objection is that it's biased towards observations that we humans casually make about things on the small scale. Over small scales — *i.e.*, over large distances — the Universe certainly isn't homogeneous. But, as I said before, the Universe is *pretty big*. And it turns out that if you were to look at the Universe over *large* scales, then you'd see that the Universe *is* approximately homogeneous. This is an observational fact that astronomers have discovered. So, in a sense, the Universe is rather boring over large scales. Once you traveled around, you'd see a galaxy here, a galaxy there, a galaxy there, and so on. Not incredibly interesting.

The second assumption Friedmann made is that the Universe is isotropic, which just means that the Universe looks the same, regardless of which direction you look. As with the homogeneity assumption, this assumption seems to be *obviously wrong* — just look around you! But it also turns out that, over large scales, the assumption of isotropy is a pretty good approximation. The observation that the Universe is both homogeneous and isotropic, over large scales, is known as the "cosmological principle."

Note that it's possible for the Universe to be homogeneous and not isotropic, and it's also possible for it to be isotropic and not homogeneous. Of course, it's also possible for the Universe to be neither! Here's one way for it to be homogeneous and not isotropic:

[add in figure later]

And here's a way for it to be isotropic and not homogeneous.

[add in figure later]

With these two assumptions of homogeneity and isotropy, we can simply crank through the equations of general relativity — which, of course, I'm not going to do for you in these notes. But when you *do* go through the equations, as Friedmann did, you discover that this is actually a doable problem, and the answer is very interesting.

What Friedmann found is that there are *three* possible solutions for the Universe. That is, what he found is that our Universe must be one of three possible ways that the equations of general relativity allow it to be. In each of these solutions, the Universe has a beginning of time — a "Big Bang." So, according to general relativity, a Universe that is homogeneous and isotropic *must* have had a beginning. However, how the Universe changes after the beginning, and what the shape, size, and ultimate fate of the Universe is, actually depends on the (average) *density* of the Universe.

In the first possibility, the density of the Universe is higher than a certain "critical density" (equal to about 10 hydrogen atoms per cubic meter). In this case, the Universe initially expands right after the Big Bang, but eventually starts to contract on account of its overpowering gravity. This contraction ultimately ends in some kind of a "Big Crunch," marking the end of time (and space). Furthermore, in this possibility, the Universe is actually *finite* in size. The *kind* of finite is the same kind of finite that the surface of a balloon is: there's no *boundary* that marks the "edge" of the Universe. You're not going to eventually reach a sign that says "End of the Universe. Dead End." However, if you were to travel in one direction for a long enough time, then you'd eventually reach your starting point, in exactly the same way that an ant living on a balloon would eventually reach his starting place if he kept crawling in the same direction long enough. For this reason, such a universe is called "closed."

In the second possibility, the density of the Universe is smaller than the critical density. In this case, the Universe expands forever; there's not enough gravity to eventually halt the expansion. There was a beginning of time, but there will be no end. Furthermore, the Universe is *infinite*; if you traveled in a single direction, you'd never reach your starting point again. Such a universe is called an "open" universe.

Finally, there is the possibility that the density of the Universe is *equal* to the critical density. In this case, the Universe also expands forever and is also infinite, but the velocity of separations between galaxies eventually reaches zero, whereas in the open case it eventually reaches some nonzero number. Such a universe is called a "flat" universe.

Thus, if our Universe is homogeneous and isotropic — which astronomical observations certainly indicate it is — and if general relativity is true — which every experiment and observation ever done to date has confirmed — then one of these three solutions must describe our Universe. So, the big question is: What kind of universe do we live in?

This was an open question until just 10 years ago, when it was discovered that the expansion of the Universe is in fact accelerating. (Note that Hubble merely discovered that the Universe was expanding.) The way it was discovered was by observation certain explosions of stars known as "supernovas." It turns out that the brightness of these explosions changes very little depending on the supernova, so these systems are often referred to as "standard candles." (It's as though you can simply go to the store and buy one; they'd all be the same.) By measuring how fast these supernovas are moving away from us, as well as their distance from us, physicists were able to compare the expansion rate of the Universe now and the expansion rate in the past. What they found is that the expansion rate is increasing, *i.e.*, that the expansion of the Universe is accelerating.

The discovery that our Universe is expanding at an accelerating rate rules out the possibility that we live in a closed universe. More recently, by measuring the "anisotropy" of the cosmic microwave background radiation — these microwaves are almost isotropic, but slightly *an*isotropic — physicists were actually able to conclude that the Universe is flat, or, at least, very close to being flat. We've really begun to zero down on the density of the Universe, and every indication seems to be that the Universe is *at* the critical density or extremely close to it.

So here we are. What I've described is the conventional picture of the Universe, as of 2008. According to this conventional picture, there *was* a beginning of time — which we call the Big Bang — and, ever since, the Universe has been expanding, and it will continue to expand forever. There will not be an end of time.

Well, you might be wondering now, "Hmm, OK, so the Universe lives forever. I guess that's good for the *Universe* ... but what about me? Or my children? What's going to happen to the future of humanity? And what about the future of the solar system, the stars, the galaxies, ...?"

Unfortunately, the answers to these questions are a bit gloomier than the answer to the question of the ultimate fate of the Universe. Let's start with the Sun. The Sun shines because of a powerful nuclear energy source at its center. But, as each day passes, this fuel source gradually decreases in supply. And, one day, it will eventually completely run out. Not only would that be bad news for the Sun — it would be terrible news for us! We depend on the Sun for a heckuva lot! The good news is that this won't happen for billions of years, so you can sleep tight tonight.

What about everything else in the Universe? Well, it looks as though every interesting object in the Universe will eventually decay, leading to an eternal Dark Universe. See http://en.wikipedia.org/wiki/Future_of_an_expanding_universe for a good summary.

Now, you might object to some of these predictions, simply based on the fact that they don't take into account the existence of intelligent life, much less the future state of currently existing intelligent life (*e.g.*, human beings). After all, supposing that humanity doesn't blow itself up in the near future, and supposing that other existential disasters don't occur, we have an enormous amount of potential as a species. How much potential *do* we have? That's anybody's guess, but historically humans have failed to surprise themselves in technological achievement. So, if you're an optimist, then you should agree that *maybe* we'll be able to fix the Sun some day, *maybe* we'll be able to prevent all matter from decaying into black holes, and *maybe* we'll even be able to alter the (effective) laws of physics. This is all pure speculation, but I think the role of intelligent life in regard to the fate of the Universe (and its contents) is an interesting question, and I personally would like to see such questions explored more than they are today.

2 Beyond the Big Bang

Everything I've talked about till now has essentially been the conventional wisdom of cosmology that we've accumulated over the past century. But there are a number of questions in cosmology that nobody knows the answers to today. For example, one very important question that I've been careful to dodge is, just what was the Big Bang?

General relativity predicts that there was a beginning of time, and observations well support the hypothesis that everything in the Universe was much closer in the past as well as much hotter. Now, *theoretically*, at the Big Bang itself the density of the universe was infinite, and the temperature of the Universe was infinite. That means that the energies of all the particles in the Universe were also infinite.

Now, in physics, when we get a quantity that is theoretically infinite, this is often a clue that the theory we're using is not completely right. A very simple example is a sonic boom from a whip. If you do a calculation ignoring the friction of air, you end up calculating that something changes infinitely fast. But, once you include the friction of air, everything becomes finite again. There are many other examples.

So the question is: are the infinities at the Big Bang *real, physical* infinities, or are they just a sign that we need to work harder to get a better theory to describe things? (I'll discuss in a later lecture that, despite its successes, general relativity *cannot* be the true theory describing nature, and neither can quantum theory. Nobody knows what the true "theory of everything" is.) Some people think the infinities are real, while others think we need a better theory, and that the infinities that general relativity predicts are merely artifacts of general relativity — that, *in reality* (which the true theory of everything would perfectly describe), the density and temperature were *very high*, but not actually infinite. Discovering the theory of everything is left as an exercise to the reader.

For those of us who don't know what the theory of everything is, the fact of the matter is that we don't really know what happened all the way back to the Big Bang. We actually know what happened since about a second or so after this moment which we call the Big Bang, but before that, everything is really speculation. The reason for this is that all the particles in the Universe are just so energetic that eventually we reach a realm of the unknown in our theories of particle physics. We just don't know how particles behave at super-high energies.

People certainly have many (many would argue plausible) *theories* about how particles behave at these energies, but right now they're not more than just that, and nobody knows if they're right or not. In fact, if you go even *further* back in time, even *these* theories break down, and things become even more uncertain.

So it's entirely possible that this moment, which we call the Big Bang, wasn't the beginning of time. Most of the details of the Big Bang Model are certainly true, but as for the Bang itself, an honest physicist would tell you that we really don't know what it was.

However, there are, of course, *speculations* about what the Big Bang really was, and there are even speculations that time existed *before* the Big Bang. For example, in one version of the "inflationary" theory of the Universe, known as chaotic eternal inflation, our "universe" is just one of many universes in a vast "Multiverse," and our "big bang" was just one of many big bangs, which randomly come about due to quantum fluctuations. (I'll have more to say about inflation in Lecture Notes 3, on parallel universes.) According to inflation, time did not begin at our big bang; there was time before this. But you can still ask the question — *was* there a beginning of time according to inflation?

Unfortunately, nobody knows! According to inflation, our big bang wasn't the beginning of time, but whether there was a beginning of time in the multiverse is an unsolved question.

There are other pre-Big-Bang models. For example, there's a recently proposed model from string theory — one proposed candidate "theory of everything," which I'll discuss in a later lecture — known as the cyclic model. In string theory, there exists 3-dimensional objects called "branes" (short for "membranes") which exist in a higher-dimensional space, a bit like a 2-dimensional sheet of paper living in our perceived 3-D world. These branes occasionally collide and, when they do, the energy of these branes gets converted into the energy of many energetic particles, producing a very high-temperature situation. So, according to the cyclic model, *this* is our big bang — a collision between branes. But the cyclic model has a number of problems (most would say more than inflation does) and is rather controversial, because string theory itself is controversial, so nobody knows if the cyclic model is true.

In summary, then, according to conventional cosmology — the Big Bang model — there was a beginning of time and there will never be an end. But people have since been thinking a little harder about what the Big Bang actually was, and they've realized that we don't really know. In particular, we don't know if there was a beginning of time. It's entirely conceivable that there was a beginning, but it's also entirely conceivable that there wasn't. It *looks* as though there won't be an end, but perhaps we are even wrong about that (although most experts don't think we are). So, I apologize that I don't have a definitive answer for you as to the origin of the Universe. The truth is that nobody does. Yet.