Frontiers in Cosmology

This, to put it mildly, is a *big* topic! Indeed, the tremendous diversity of cosmology means that if you interviewed several cosmologists you'd undoubtedly find rather distinct points of view about the most important realms, let alone specific topics. With that in mind, take the following list as just a taste of the many possibilities for research that exist in the future. I'll try here to include abstruse theoretical problems as well as more down to Earth (sort of!) observational issues.

What was before the Big Bang?

This is either an important question, or a non-question, depending on who you ask. Some people argue that time came into existence at the Big Bang, so that asking what happened before is like asking what is north of the North Pole. In such a point of view, we shouldn't think of the cosmos hanging around doing nothing for an infinite time, then popping a universe into existence.

However, there are plenty of people who are investigating other possibilities. They are also motivated by allergies to singularities. That is, in general relativity, if we project backwards in time we get to a point of actually infinite density and temperature. Mind you, this statement is not obvious. It may seem so at first glance, because if you reverse the expansion you get contraction, duh! However, think about what you would expect if you saw a collection of particles collapsing on a static background. As we discussed earlier in the class, you'd find that any small amount of angular momentum would cause the collapse to stop at some finite radius, and even if you didn't have any angular momentum you would get violent relaxation. Thus a singularity may seem avoidable. It isn't, though, at least in general relativity, because in the 1960s and 1970s Penrose and Hawking proved a series of theorems that show that the universe would indeed collapse completely.

This is similar to what is thought to exist at the center of a black hole (in density, at least). However, an infinite answer probably means that we are extrapolating our theory beyond its domain of applicability. At some point, then, it is thought that a new theory, quantum gravity, enters, and somehow rescues us from the infinities.

To estimate when that happens, it is often felt that when the density approaches the "Planck density"

$$\rho_{\rm Pl} = \frac{c^5}{G^2\hbar} \approx 5\times 10^{89}\ {\rm kg\ m^{-3}} \tag{1}$$

quantum gravitational effects should enter. That's a rather high density, and means that we aren't likely to be able to test this directly any time soon. One could, however, imagine indirect tests in which a theory of quantum gravity that predicted measurable quantities would imply some specific effect at the Planck density. We would then be motivated to accept that implication.

For example, in the so-called "ekpyrotic universe" of Paul Steinhardt and colleagues, what is really happening is that we exist on the "surface" of a higher-dimensional "brane" (short for membrane). Other branes exist, and tend to come together and then bounce apart without intersecting. A bounce is what we see as the Big Bang. In this model, no singularity is reached; this does not violate the theorems of Hawking and Penrose, because they assumed the correctness of general relativity at all densities.

Another possibility is that the universe itself is a vacuum fluctuation. In this picture, we can imagine the cosmos hanging around, and every now and then a universe is spawned off. Pretty weird stuff!

Fascinating though this may be, it would be nice if there were some way of testing it. So far, things aren't all that promising for direct tests, and it's not so satisfying to continuously appeal to the argument that if an all-encompassing theory predicts something, we accept it. One possibility involves gravitational waves. Inflationary theory predicts that there will be primordial gravitational radiation, but ekpyrotic theory suggests that the level will be tens of orders of magnitude below what inflationary theory predicts. Sounds good: just detect the background, and ekpyrotic theory is out the window. The problem, though is that (1) the predicted level from inflation is already orders of magnitude below what could be detected, at least in the next several decades, and (2) do you really think that detection of such a background would cause the ekpyrosts to give up the ghost? We'll see.

Why are there more particles than antiparticles?

When people learn about antimatter, a common question is whether there is much of it out there in the universe. There is some: very high energy processes can produce positrons, for example, and we can see the resulting annihilation when they meet up with electrons. More intriguing, though, is whether there could be antimatter galaxies, or clusters, or large scale structure. Antimatter atoms have the same energy states as normal atoms, so the spectra would look the same. How could we tell?

The way we would know is that since our galaxy is almost all matter, if the matter outside our galaxy were antimatter then at the boundary there would be copious annihilation, from which we would see gamma rays. The same is true if the region outside the local group, or the local supercluster, were antimatter: basically, lots of 511 keV radiation from electron-positron annihilation would be evident. It isn't. Therefore, the universe is almost all matter. An even stronger argument could be made by thinking about the universe when it was significantly hotter and denser. Interaction rates scale as the density squared, so at the time before decoupling any spare antimatter would have been gobbled up quickly.

But why is this the case? At a fundamental level, particles and antiparticles are the same... almost. For there to be more of one than the other requires some breaking of the symmetry. Various such mechanisms have been suggested and might be tested in laboratories, but at this point I believe that there is nothing definite. It is also worth keeping in mind that the asymmetry isn't much: the reason that we have $\sim 10^9$ photons per baryon (or per electron) is that almost every particle met up with an antiparticle at some point to convert into photons.

What is dark energy?

We discussed this a fair amount earlier. I suspect that most people would consider this to be the most important question in cosmology. A search of the literature reveals many suggestions, from the idea that there is no dark energy, just normal expansion, to proposals of what it might be. Nothing seems particularly compelling or predictive to me. You might be interested in checking out http://www.arxiv.org/pdf/0705.2533 for a recent discussion.

What is dark matter?

This we also discussed. Here I think there are more promising avenues than for dark energy. The reason is that, although definitive predictions are still hard to find, in the supersymmetric particle sector there are some promising candidates for dark matter. There are even occasional claims for a significant detection, but not at such a level that everyone agrees. There is hope that the Large Hadron Collider will be able to throw more light on this because of its high energies, but if it doesn't then there is still plenty of phase space available. Another interesting test for the next several decades could involve modified gravity. The acceleration scale implied in such theories is roughly $a_0 = 10^{-10}$ m s^{-2}, but much better accuracies than that are needed to test deviations from normal Newtonian gravity. For example, one fitting function is that the true acceleration is given by $a_{\rm true} = \sqrt{a^2_{\rm Newt} + a^2_0}$, meaning that relative accuracies of 10^{-20} or so are necessary. This isn't entirely insane, but it is 3-5 orders of magnitude better than current experiments. In addition, there has for a few years been a claim that the Pioneer spacecraft are experiencing an anomalous acceleration at something like this value. A number of analyses have suggested various mundane possibilities (e.g., outgassing or solar acceleration), but the team continues to insist that there is something else going on.

What reionized the universe?

After decoupling, the universe rapidly became almost neutral, other than a certain amount of residual nonequilibrium ionization. Now, however, the universe is almost completely ionized. What started this process? The reason for interest is that whatever did this was also representative of the first structure. For example, it could be that light from the first stars was the dominant ionizer. If so, then one pictures the early universe as mainly neutral, with a few highly ionized and sharply defined bubbles. The reason that there would be a sharp distinction between ionized and neutral regions is that the ionizing radiation is in the UV, just beyond the hydrogen ionization energy. The cross section is quite large at those energies, meaning that such photons travel until they get to their first neutral atom, then ionize and stop. When the neutral fraction creeps decently above zero, the photons can't travel too far. Therefore, the bubbles would be well defined.

In contrast, suppose that the dominant ionizing radiation came from accretion onto black holes. This radiation is primarily in the X-rays, at energies many times the ionization threshold, where the cross section is relatively low. In addition, ionization produces secondary high-energy electrons that themselves go on to ionize further atoms. This picture would then be one of more diffuse ionized regions. The literature seems to go back and forth about which of these sources is more important.

How did the first stars, black holes, and galaxies form?

The general answer appears to be that dark matter concentrations (halos) came together until their escape speeds were high enough to retain gas. The gas then cooled and sank in the potential wells of the halos, eventually forming stars.

The details, however, are far from clear although progress is being made. For example, the very first stars (Population III stars) formed with essentially nothing heavier than helium. It has been suggested that this would produce very massive stars, perhaps hundreds of solar masses. In turn, this means that the Pop III stars would be extraordinarily luminous, and would therefore prevent the formation of stars anywhere near them. Their UV radiation also has complicated effects on the production of the H_2 molecule, a prime coolant in the early universe. How does this interact to form the first dwarf galaxies and globular clusters? Are there Pop III remnants we could observe now? For these purposes, we need to be able to observe the $z > 10$ universe directly. This is the main goal of the James Webb Space Telescope, which will focus on IR because of the high redshifts. It is also conceivable that a future radio array (e.g., the Square Kilometer Array) would be able to detect redshifted 21 cm emission lines from hot ionized bubbles. Stay tuned…

Detection of a gravitational wave background

We mentioned this earlier in the context of an inflationary era background. There are other suggestions as well, of which the most commonly discussed is a gravitational wave background from a phase transition such as the one went from free quarks to hadrons. Such phase transitions tend to be bubbly, meaning that some regions change their nature, then this propagates out. If the transition is first-order (meaning that quantities such as density or temperature change), then collisions between bubbles can in principle produce gravitational radiation. There is, of course, a lot of uncertainty in all this, but detection with any of the existing or planned gravitational wave detectors would be big news.

Characterization of the microwave background to $l \sim 2000$

This, for me, was one of the most important things I learned in preparing for this class. WMAP has done a great job, but there are still degeneracies in some of the cosmological parameters used to fit the power spectrum. With Planck, it will be possible to deal with those very nicely because much higher multipoles will be seen. This will also allow many tests of the underlying model, e.g., that the fluctuation spectrum is Gaussian; with cosmic variance limited accuracy to $l \sim 2000$, each l will have $2l + 1$ different modes to examine.

X-ray observations of galaxy clusters

Finally, let's not overlook galaxy clusters. These, recall, are the largest virialized structures in the universe. Therefore, observing them tells us a lot about structure formation. In addition, the Sunyaev-Zeldovich effect from clusters will give us independent information about the Hubble parameter and the structure of the universe. The basis behind this method is that background microwave radiation is upscattered by the hot gas in the clusters, and the resulting change in the spectrum depends on the gas density, temperature, and cluster size in a way that can be decoupled using X-ray and radio observations. This is a prime example of a secondary anisotropy in the CMB, and will be probed nicely by dedicated arrays on the ground in the next several years.

Intuition Builder

What single problem in cosmology do you find most intriguing?