Cosmology

Cosmology is the study of the structure and evolution of the universe. Since gravity cannot be canceled, it is the force that dominates at large distances for large objects. Thus general relativity, the geometrical theory of gravity, is used to describe the universe in cosmology.

One of the central problems in cosmology is to determine the metric for the universe as a whole. For this discussion, I will use a simple form for illustration. Although there are deviations from a flat geometry caused by the uneven distribution of matter, when those are averaged out and the universe is considered on a large scale, it is very close to flat. In fact, some popular models called "inflationary" make it exactly flat on the large scale. However, the overall scale increases with time to account for the expansion of the universe suggested by the Hubble relation $v=H_0d$. the metric then has a simple form

$$ds^2 = dt^2 - R(t)^2\left[dx^2 + dy^2 + dz^2\right] .$$

The function R(t) gives the scale of the universe. It is increasing with time now. The coordinates used are called comoving coordinates. Objects like galaxies that ride with the overall expansion of the universe have fixed spatial coordinate, and the increasing physical distance between them is accounted for by R(t).

The actual form of R as a function of t is determined by solving Einstein's equations (the same equations that were solved to get the Schwarzschild black hole metric). At early times, R was small, and the universe was very hot and dense and all particles were highly relativistic. That is called the radiation dominated era. In that era, R was proportional to $t^{1/2}$. After about 100,000 years, the universe had expanded and cooled to the point that the main contribution to the energy was from slow massive particles, as it still is today. The time dependence of this matter dominated era is $t^{2/3}$.

After even longer times, the effects of gravity and curvature become most important. Then there are two possibilities. If there is not enough matter to pull it back, the universe will keep expanding forever. If the matter density is greater than a certain value, the expansion will eventually stop and the universe will fall back in on itself in the big crunch. At the moment, the observational data are not quite accurate enough to determine which is the case. We are close to the critical density that separates the two behaviors. However, it is likely that this question will be settled within a few years. Current betting is that it will expand forever.

When the universe was very hot and dense, atoms had not yet formed. There was a plasma of electrons, protons, and photons. The photons interacted strongly with the charged particles. At around 300,000 years, the universe had cooled enough so that the electrons combined with protons to make neutral hydrogen atoms. At that point, the photons stopped interacting with the neutral matter. These photons are still around to be observed. They have cooled further as the universe has expanded and now have a temperature of about 2.7K and a wavelength in the microwave region. This is called the *cosmic microwave background radiation* . It can be detected in a receiver tuned to microwaves. It is the most tangible evidence that the universe really began in a big bang around 10-20 billion years ago. A remarkable property of this radiation is that it is very uniform. No matter which way you point your receiver, you get almost the same signal. The deviations are at the level of a part in 10^5. In receiving these photons, we are looking back to the time of about 300,000 years after the big bang when they were emitted. We conclude that at that time, the universe was very smooth so that the radiation is very uniform now.

There are some serious problems with this picture that are associated with light cones and causality. The path of a light ray is given by ds=0 so that

$$dt = R(t)\,dr \quad \text{or} \quad dr = \frac{dt}{R(t)} \quad .$$

With R(t) given, this equation determines the greatest distance from which a signal could have arrived at the origin if it were emitted at the beginning of the universe. Since the physical distance a photon travels is proportional to t, but the early universe is expanding much faster: like $t^{1/2}$ or $t^{2/3}$ at small t, the expansion is running ahead of the propagation of light. Specifically, for $t^{1/2}$ the greatest coordinate distance from which a photon could arrive is finite and proportional to $t^{1/2}$. This result follows from integrating the above equation. Try it. Thus at t=300,000 years, the regions of the universe that could have exchanged a light signal and become causally related are finite in spatial size.

Now to the problem. At 300,000 years the causally related regions had a size that appears to us now to be a difference of about 1° in direction on the sky. But we have already noted that the cosmic microwave radiation looks almost the same in all directions. How can that be if the regions had never communicated?

The currently popular resolution to this is to hypothesize that at very early times there was a period of *inflation* in which the universe grew exponentially fast

$$R \quad e^{Ht} \quad .$$

This can solve the causality problem. At some very early time there was a small causally connected volume with uniform properties. During inflation, this expanded by a huge factor. Then inflation ended, and the evolution of the universe grew more slowly as $t^{1/2}$. All of the presently observable universe came from the small volume that was causally connected before inflation. This explains the uniformity of the cosmic microwave background radiation, and can also solve some other problems like why the universe is so flat.

It is a very attractive idea but is by no means established. However, by very accurate measurements of the small nonuniformities in the cosmic microwave radiation, it is possible to tell if this picture is correct. In a few more years there will be new satellites flown to do the experiment. It's going to be a very exciting time.

There is another problem with our understanding of cosmology. Although the universe is near the boundary between expanding forever or heading back to a big crunch, it is very hard to find the matter that could be accounting for this. This is called the *dark matter problem* . There is some gravitating matter out there, but it is not emitting radiation that we can see. What could it be? There are lots of exotic ideas. The most mundane is that it is neutrinos with a small mass. Out on the more radical fringe is the suggestion that it is black holes left over from the big bang. Particle physics, and in particular, supersymmetry can offer several suggestions. There is no shortage of ideas. What we need are more data to whittle down the list.