Inflationary cosmology

Problems with standard cosmology

Now we have some idea about the present and perhaps the future of the universe, it is time to face up to the difficult questions about the origin of the expanding universe. We have identified a number of outstanding questions:

(1) **The expansion problem** What set the universe expanding?

(2) **The Horizon problem** How did the initial expansion manage to be uniform, given that regions of space separated by $> ct$ could not communicate at early times?

(3) **The structure problem** How does the universe nevertheless manage to be sufficiently non-uniform to generate structures like galaxies?

(4) **The antimatter problem** Why was there a small initial excess of matter over antimatter?

One possibility is that the answers to all these questions lurk in the times before 10^{-43} seconds, where quantum gravity is required. However, many recent ideas in cosmology try to solve the problems by using exotic physics operating at lower energies.

Unification in particle physics

We need to summarize a few key ideas from particle physics, which is the theory of how matter is constructed on the smallest scales.

(1) **Quarks and leptons** The quarks are particles that make up protons and neutrons; Examples of leptons are electrons and neutrinos. There are **three families** of these particles: three pairs of quarks, the electron + neutrino pair, plus two further pairs containing more massive versions of the electron (the **muon** and the **tau**).

(2) **The interactions** The matter particles interact by the exchange of **gauge bosons**, such as the photon. There are three types of interaction (excluding gravity): electromagnetic, weak and strong. The weak force causes processes like neutron decay; the strong force binds the quarks together to make nucleons.

(3) **Broken symmetry** Why does nature re-use the same pattern, having three families and three different interactions? A common assumption is that these particles and interactions are in fact all the same, but that this symmetry is **spontaneously broken**. This is a bit like pressing down on a ruler – it bends to left or right, even though both directions are equally probable. In particle physics, this phenomenon is associated with the production of a new particle, the **Higgs boson**. The search for the Higgs is one of the key preoccupations of particle physics.

The interest of all this for cosmology is that the breaking of the symmetry may be undone at high energies and temperatures, so new phenomena will operate at early times in the expanding universe. Some of the expected effects are already measured in particle accelerators. For example, at energies about about 300 GeV, the weak and electromagnetic interactions become aspects of a single interaction. What happens at these energies is that typical particles have enough energy to 'knock' the particle-physics universe from one state to another, just as the bent ruler can be flipped from one side to the other. The energy scale at which this happens marks out the expected mass-energy of the associated Higgs boson.

Although the strong interaction is still very much the strongest interaction at all laboratory energies, it does decline very slightly with energy. By extrapolating, we can guess the point at which **grand unification** occurs. It appears that this will happen at the colossal energy of 10^{15} GeV. This is 10,000 times lower in energy than the Planck energy, so gravity can still be treated classically. Can the strange initial conditions of the big bang be understood in terms of grand-unified processes?

The inflationary universe

The most interesting aspect of symmetry breaking in particle physics is that it involves a change in the energy density of the vacuum. The analogue of the bending ruler in particle physics is a **Higgs field**. The field is a concept of key importance in science; an example is the gravitational field, where a point mass defines a force at every point in space, pointing towards the mass. Similarly, the Higgs field defines a number at each point in space. Unlike gravity, fields can also change with time, as is the case with the oscillating **electromagnetic fields** that make up light. The dynamics of the Higgs field are identical to those of a ball rolling in a trough, and this gives a way of visualizing symmetry breaking. Imagine a ball placed in the centre of a trough shaped like a wine bottle: the ball will roll down to the circular locus where its height is minimized. In so doing, it minimizes its gravitational potential energy and breaks the symmetry of the situation.

In particle physics, the Higgs field is driven to break the symmetry by the chance to lower the energy density of the vacuum. At high temperature, the 'ball' is kicked up to the symmetric point, but at low temperature it will prefer to fall. We can easily see by how much the vacuum energy density changes, as follows. If the symmetry is restored above temperature T, then the thermal energy density at that time must be overcoming the vacuum energy density. We therefore need the energy density of black-body radiation at 10^{15} GeV. Remember that 1 eV is equivalent to about 10^4 K, so we have $T \simeq 10^{28}$ K. The energy density of black-body radiation is aT^4, where $a = 7.6 \times 10^{-16}\ \mathrm{J\,m^{-3}\,K^{-1}}$. Expressed as a mass density, this is

$$\boxed{\rho_{\rm vac} = \frac{aT^4}{c^2} = 10^{80}\,\mathrm{kg\,m^{-3}}.}$$

In other words, above the grand-unification temperature, the vacuum was incredibly dense.

This fact was exploited by **Alan Guth**, who realized in 1979 that this huge vacuum density was just what was needed to solve the big problems of cosmology. The vacuum density doesn't change as the universe expands, whereas the radiation density scales $\propto R(t)^{-4}$. So, if the radiation and vacuum densities start out comparable, the universe need only expand by a small amount before the vacuum will dominate. We saw previously what happens in this case: the antigravity property of the vacuum will cause the expansion of the universe to accelerate at ever-increasing speed. This idea of the **inflationary universe** solves many of the problems listed earlier:

(1) **The horizon problem** is explained, because the universe can stay in the inflating state for a long time. A small patch of space can be blown up to almost any size that is desired. The difficulty with conventional decelerating cosmologies is that they expand very fast at early times, so light signals have difficulty overtaking the expansion. For an accelerating universe, the expansion is very gentle at early times, so it is easier for different parts of space to get in contact.

(2) **The expansion problem** is explained: the universe was set expanding by the vacuum antigravity. In this sense, the origin of the universe was not literally a 'big bang', but a gradual acceleration. Admittedly, we did have to assume that the universe started out with some small expansion. However, think of the alternative: contraction will quickly lead to collapse. One can therefore imagine some primordial chaos, with some parts of space expanding, and others contracting. Only the expanding parts have a chance to be inflated to large size by the vacuum energy, thus escaping contraction to a big crunch. Since life could hardly happen in the latter kind of universe, our own existence sets limits on what kind of universe must be observed. This general idea, that the universe must have certain properties before cosmology courses can be given, is called the **anthropic principle**. Just when we seemed to have extended Copernican ideas to their furthest limit, we see that perhaps we are after all privileged observers of the universe.

Ending inflation

All this leaves only one problem: how are we to get back to a normal universe with a very small vacuum density? The answer comes from symmetry breaking: the vacuum density cannot stay high forever, because the ball representing the Higgs field will want to roll to the bottom of the trough. Suppose this takes place, lowering the vacuum density to very close to zero. What happens to the energy that used to be in the vacuum? The ball in the trough will change its gravitational potential energy and will gain kinetic energy in return: i.e. it will be moving fast when it hits the bottom of the trough.

The same sort of thing happens in particle physics. As the Higgs field 'falls' past the minimum of the potential curve, it starts to oscillate. Oscillating fields look much more like normal radiation, and in fact the oscillating Higgs field will then share energy with other fields, including the electromagnetic field. What results is **reheating**: the universe emerges from the inflationary phase having exchanged its high vacuum energy for a high radiation density. We are left with a normal radiation-dominated universe, but one which inflation has prepared so that it is highly uniform.

How long does inflation have to last in order to have the right effect? According to cosmology without inflation, the time corresponding to 10^{15} GeV is about 10^{-34} s, so the horizon size is $ct \simeq 10^{-25.5}$ m. This era was at redshift $z \simeq 10^{28}$, so this patch would have expanded to be about 300 m by the present. In fact, we require the entire presently-visible universe to have been made uniform at the grand-unified era. Inflation must therefore have persisted long enough to swell 300 m up to $c/H = 4600$ Mpc, or an inflation factor of about 10^{23}. The inflationary universe is well named!

Fluctuations from inflation

Even better, inflation presents a possible solution to the **structure problem**. We need a universe that is nearly uniform, but not quite. Since the initial patch that inflated was of very much subatomic size, it is possible that quantum fluctuations were important. Just as the **uncertainty principle** told us that the vacuum could not be completely empty, so it also means that the density of the vacuum cannot be completely uniform. After reheating, we therefore expect that there will be small fluctuations in the density of the universe from place to place. The final lecture in this module will consider how these fluctuations grow into galaxies and other structures in the present-day universe.

Warning

It should be kept in mind that most of this lecture consists of ideas that are not yet tested. They therefore lack the same degree of certainty as other topics we have discussed. The experimental detection of the microwave background means that we can be confident that the basic idea of a hot big bang is correct. Inflation gives a very neat set of explanations for how such a universe may have started, but neat ideas in science often turn out to be wrong. There were many false starts in particle physics before experiments eventually led to the present set of theories. Testing inflation will be hard, because of the remoteness of the time and energy scales involved, but we will see that the task is by no means impossible.