The early universe and high-energy physics

David N. Schramm

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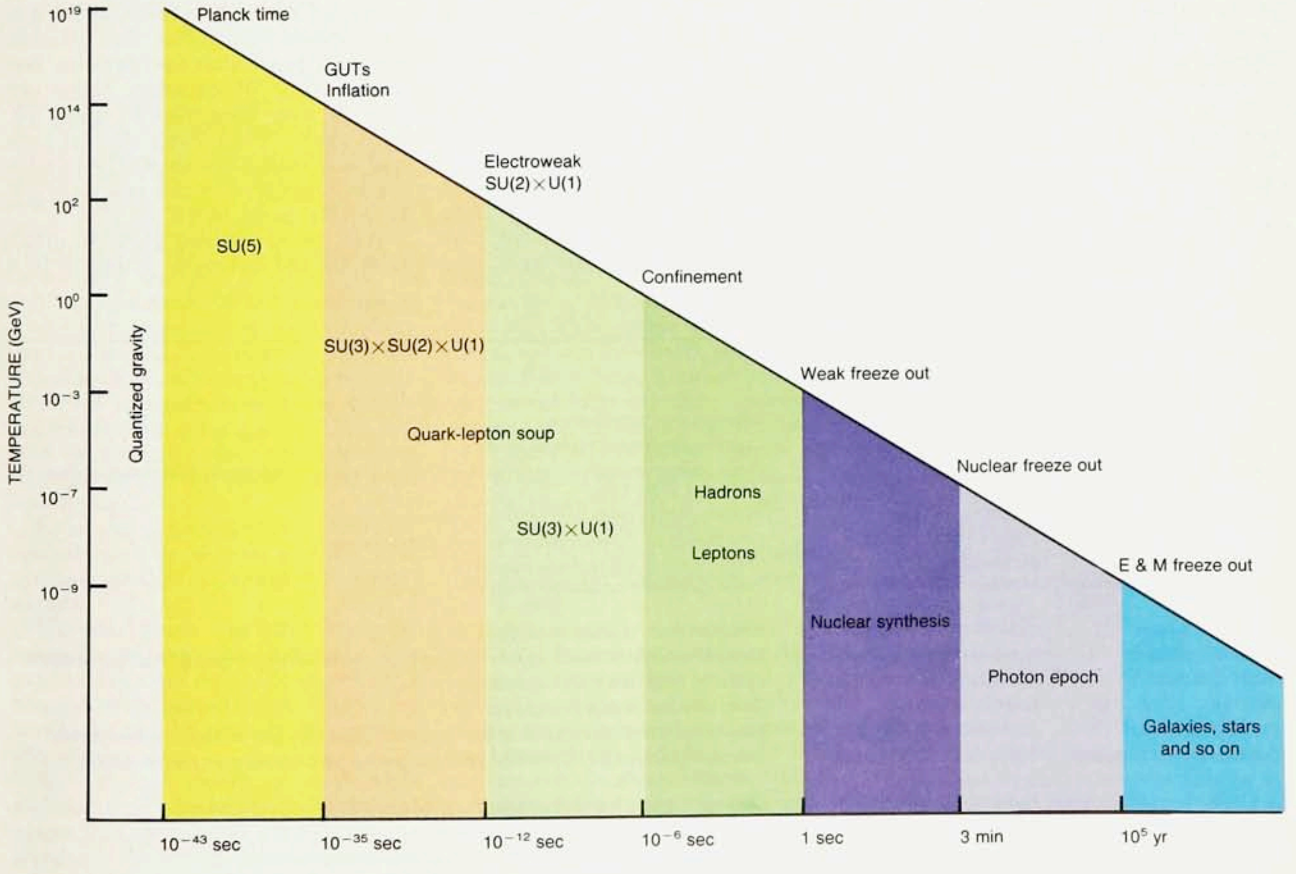
The early universe and high-energy physics

Many properties of the new particle field theories can only be tested by comparing their predictions about the physical conditions immediately after the Big Bang with what we can reconstruct about this event from astronomical data.

David N. Schramm

15 billion years ago, an experiment was carried out that related to the interaction between cosmology and particle physics and the unification of physics in general. This is the experiment that we call the Big Bang. It resulted in about 10^{90} bits of data spread out over 10^{28} cm^3. We know the original apparatus had about 10^{19} GeV (see figure 1), but, unfortunately, the graduate student who designed this equipment is no longer around, and, as a result, she can't tell us exactly what she did. So we have to try to piece together the data on our own to see if we can understand what happened in this experiment. From some of the data that we've been able to assemble—for example, from observing the 3-K background radiation—we know the early universe was hot and dense. We also know that about one-quarter of the



Early history of the Universe as predicted by the standard Big Bang model and conventional quantum field theory. Confirming data are expected from experiments using high-energy accelerators to duplicate the extreme conditons of energy and matter at times in the life of the Universe earlier than 10^5 years, when the Universe finally became transparent. Figure 1

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mass of the Universe is in the single isotope helium-4. This figure is really rather amazing. The sum total of all the other heavier elements (carbon, oxygen, iron and so on) makes up less than 2 percent of the mass of the Universe. Stars make these other heavy elements, but they make them in total abundances of the order of a fraction of a percent. Yet the Universe is 25% helium-4—and this is exactly the figure the standard theoretical model of the Big Bang predicts!

So we can say with some confidence that the Universe we live in is some sort of hot Big Bang Universe. In fact, the Soviet physicist Jacob Zel'dovich mentioned recently at the International Astronomical Union meeting that we can regard the Big Bang model to be as well established as celestial mechanics. Within the last decade we have developed an elaborate theoretical model that agrees in detail with experiment. We are no longer discussing what the basic cosmological model should be—Big Bang or Steady State. We are concerned now with working out the details of our Big Bang model. Just as in celestial mechanics one worries about the details of perihelion shifts and so on, we are now worrying about such things as how minor perturbations can lead to the formation of galaxies.

In the past, we used telescopes to look out to larger and larger regions, to try to see more and more of the 10^{90} bits of data out there. However, now that the general model is established, we need to use a different kind of telescope to understand more about the original Big Bang experiment. In particular, we can try to duplicate parts of the initial apparatus with high-energy accelerators. We would like to use Fermilab, CERN or SLAC to duplicate some of the conditions just following the Big Bang. We are not able to observe with telescopes back to those early times, because the Universe was optically opaque at times earlier than 10^5 years after the projected singularity. So with telescopes we cannot see back to the exciting, very early times. We can only look back to times when the Universe was not that much different than it is today.

Big Bang: facts and questions

To help us use accelerators in place of the traditional astronomical tool to explore the really early times, we need to review what things we know about the original Big Bang apparatus. In particular, we believe that the Universe was hot enough to unify all the forces. Another very interesting piece of information that we know is that this early apparatus for the Big Bang could not have had within it more than four types of long-lived low-mass particles (neutrinos or other "inos"), in addition to the photons and electrons (which are low-mass particles by this definition).

This is a rather important prediction that comes out of the standard Big Bang model. We believe that we have identified at least three of these low-mass particles—the electron neutrino, the muon neutrino and the tau neutrino. If we believe the Big Bang predictions, it may be that we have found *all* of the low mass "inos" that exist. (This may be the first instance since Newton that astronomical observations have made specific predictions for fundamental physics. Normally the flow of information goes the other way.)

We know that somehow this original experimental apparatus of the Big Bang managed to get rid of monopoles—at least most of them, if not the one that was seen a few months ago in Palo Alto (PHYSICS TODAY, June 1982, page 17). Even if there was a monopole in Palo Alto, there are certainly not as many of them around as there are baryons. And yet, the standard unification theories predict as many monopoles as baryons. So we have somehow to get rid of monopoles, and we do not know yet quite how to do this. One possible way is through "inflation," a new theoretical concept we will discuss in detail later on.

We also know that the original apparatus was rather well machined. It managed to smooth everything down to parts in 10^4. That is, the temperature of the cosmic background radiation appears uniform to within parts in 10^4.

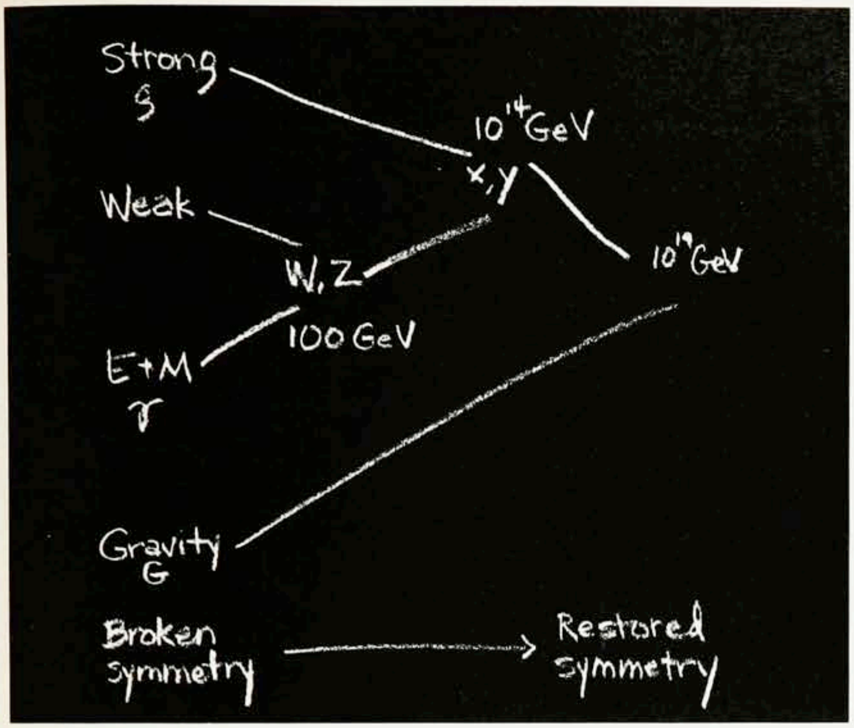
The more you think about this fact, the more amazing it seems. The 3-K radiation that we get from the horizon in opposite directions was emitted about 10^5 years after the Big Bang. But at the time of emission, these two sources were separated by about 10^7 light years. Thus they could not have had any causal connection with each other, to know to be now exactly at 3 K to within parts in 10^3 or 10^4.

How did everything get to be homogeneous and isotropic? It had to be a

Experiments of cosmological significance

Experiment	Type of experiments	Cosmological significance
Width of Z°	Accelerator/colliding beam	Checks cosmological neutrino counting
Electric dipole moment of neutron	Reactor facility	Limits baryon non-conserving CP violation, which is directly proportional to baryon-to-photon ratio produced in Big Bang
Proton decay	Underground mines	Examines GUTs predictions on baryon non-conservation
Monopole searches	Various types of detectors	Limit density of cosmological monopoles, tests inflation
Higgs Searches	Accelerators	Check nature of GUTs phase transitions
Ultra-relativistic heavy-ion collisions	Heavy-ion accelerators and cosmic rays	Probe quark–hadron phase transition
β-decay end-point	Laboratory nuclear physics	Measures mass of electron neutrino
Neutrino oscillation	Accelarators and reactors	Constrains combinations of squared mass-differences and mixing angles for massive neutrinos
"Ino" searches	Accelerators and cosmic rays	Looks for other dark matter alternatives
Flys eye	Cosmic ray	Gives ultra-high energy background
He^4, He^3, D and Li^7	Astronomical	Checks continued concordance of Big Bang nucleosynthesis and constrains baryon density
3-K background temperature	Balloon and COBE satellite	Checks agreement with blackbody curve and precise temperature gives precise number densities ($n \propto T^3$)
3-K background anisotropies	Balloons, U2 and CODE satellite	Constrains galaxy formation scenarios, gives spectrum of primordial bumps
Large-scale structure	Telescopes*	Constrains Ω and galaxy-formation scenarios,
Determintion of Hubble constant	Telescopes*	Need to remove current factor of two uncertainty in expansion rate
Nucleochronology and globular cluster ages	Nuclear and astronomical	Need to improve input parameters for non-Hubble-constant determinations of age of Universe
Neutron half-life	Nuclear	Need to reduce largest uncertainty in He^4 synthesis calculations

*Includes Space Telescope



Forces become unified at higher energies. Conventional theories predict that the electromagnetic and weak forces become identical above around 100 GeV and this force then becomes identical with the strong force above around 10^{14} GeV. Theorists are working on a SuperGUT that would unify all four forces above around 10^{19} GeV. Figure 2

very, very carefully laid out machine. Or we have to have some way to have it occur naturally, getting everything smooth naturally. We will see that in the past year there have been some rather interesting ideas on how one might do this smoothing, having to do again with the idea of inflation.

If one problem of the Universe is "why is it so smooth?", another problem is "why is it so bumpy?" On the small scale, the Universe is not smooth. It is all lumped up in these bumps called galaxies, stars, people and so on, and we need to understand how these clumps formed in this very smooth background.

So on the large scale the Universe is smooth, and on the small scale it is clumpy, neither of which we understand.

We also know that the Universe seems to be very finely tuned. The graduate student doing the experiment seemed to be exceedingly skillful at tuning things to roughly 50 decimal places.

We are not aware of any other number in physics known to 50 decimal places. In particular, the Universe seems to be tuned to at least this accuracy with regard to the parameter called Ω—the ratio of the density of the universe to the "critical density." This ratio controls how the density of the Universe evolves with expansion. In the early life of the Universe, if Ω starts out greater than 1 then it will continue to increase with a typical time scale of 10^{-43} seconds. If Ω is less than 1, it will decrease with a time scale of 10^{-43} seconds.

Now, 15 billion years after the Big Bang, Ω is still close to 1, and 15 billion years is a large multiple of 10^{-43} seconds. This means that in the Big Bang the parameter Ω was tuned to equal 1 to a large number of decimal places—at least 50. This result seems miraculous, unless again you can invent some way to bring it about naturally. Some people in the field call this the flatness problem. Others refer to it as the age problem—why is the Universe so old? (It is even a problem if you believe the Universe is only 6000 years old.)

There is another problem that we don't yet have a good answer for, but again the answer may be coming from work in particle physics. The problem is that more than 90% of the matter of the Universe seems to be in a form that we can not identify. This matter does not appear to be baryonic. What is it?

Unified field theories

At the outset I mentioned unified field theories, the theories that have been developed in particle physics in the past decade, giving us, to my mind, one of the most exciting times in physics ever.

Roughly a hundred years ago, Maxwell showed that electricity and magnetism were unified. Fifteen years ago Steven Weinberg, Abdus Salam and Sheldon Glashow showed us how the weak and electromagnetic forces are really one and the same interactions. If you get above energies of 100 GeV (the mass of the W and Z bosons that carry the weak interactions), then the weak and electromagnetic forces are identical (see figure 2). The symmetry between these forces is spontaneously broken at the energies we see in our day-to-day life, but it is restored if you get above 100 GeV. In fact, you can see this change as a phase transition. When the Universe was at higher temperatures, it had a symmetry in that the forces were unified; as the Universe cooled there was a phase transition and the symmetry was broken. Over the last decade experiments have essentially verified this theory (see, for example, the story on the discovery of the W on page 17) and thus have given theorists the courage to look for further unification.

As we go up to higher energies still, people including Howard Georgi and Glashow have predicted that there should be a unification of strong, weak and electromagnetic forces. From extrapolation of the physics at lower energies, they predict this unification should occur at energies of the order of 10^{14} GeV. The gauge bosons of this unification are the X and Y bosons (see figure 2) and it is at this energy you produce the monopoles we discussed before. The theories unifying these three forces are called Grand Unified Theories—or GUTs.

The hope is to bring in gravity as well and achieve "Supergrand" Unification, or SuperGUTs. Theorists tend to believe that SuperGUTs should become relevant (see figure 2) when the quantum effects of gravity become important at the order of 10^{19} GeV. Although there is a lot of work on SuperGUTs, it is regarded as more speculative than the strong, weak and electromagnetic unification.

Testing GUTs

Obviously, energies as high as those involved in GUTs or SuperGUTs are far beyond what we can get in terrestrial laboratories. Even when the Tevatron colliding-beam machine begins to operate at Fermilab we will only be up to a couple of TeV. If we build the

David N. Schramm is Louis Block Professor in the Physical Sciences and chairman of the department of astronomy and astrophysics at the University of Chicago, Chicago, Illinois. He is spending this year as "resident cosmologist" at Fermilab.

"Desertron," we are only up to tens of TeV. So we are still a long, long way from 10^4 GeV or 10^{19} GeV. SLAC scaled up to 10^{19} GeV would stretch from here to Alpha Centauri, which would ease vacuum leak problems but would make data analysis difficult—not to mention problems with the gross national (world) product. We have some other ways of probing these kinds of energies indirectly through processes such as proton decay and, if monopoles are around, "monopolonium" and monopole annihilation. But we have no direct ways of exploring these energies except for the one event that took place at these energies—the Big Bang. So there are strong motivations for particle theorists and cosmologists to get together now, because the early history of the Universe provides our best testing ground for the grand unifying ideas.

We hope that at the high temperatures of the early Universe, when the unification occurs, we will find that it explains away some of our problems in cosmology.

As an example, one of the very inspiring findings in the last few years has been the success of the Grand Unified Theories in explaining the baryon number of the Universe. Up until now, we have had no idea why the Universe contains about 10^{-10} baryons for each proton. Now, with GUTs, the ratio can arise naturally. As the universe cools (at about 10^{-35} sec), the interactions that violate both baryon number conservation and CP symmetry give rise to a slight excess of quarks over antiquarks. Later, these quarks form baryons, and then the baryons and antibaryons annihilate. One is left with a small net surplus of baryons—an excess of matter over antimatter—which is exactly what we observe. By adjusting the otherwise unknown parameters of the GUTs, the correct ratio of baryons to photons can be obtained. It is interesting that the GUT known as mininal SU(5) could not yield the observed cosmological baryon-to-photon ratio and this particular model has now also been found to be inconsistent with the Irvine-Michigan-Brookhaven experiment on proton decay. Thus the GUT must be more complex than minimal SU(5).

Prior to Grand Unification, we had to say "In the beginning there were 10^{-10} baryons per photon." Now we can say something esthetically more pleasing, "In the beginning there was a GUT."

Epochs of the universe

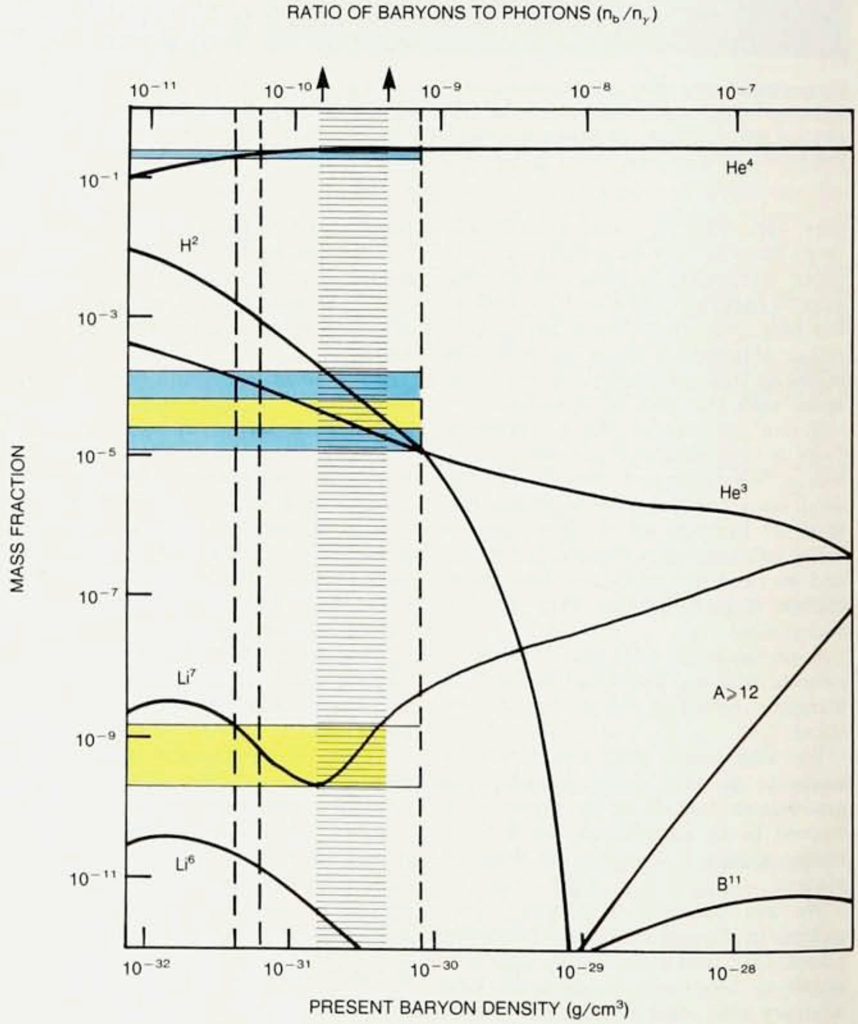
Figure 1 shows time versus temperature, as we go back to earlier and earlier times in the Universe. We always eventually hit a barrier at 10^{-43} seconds, which is the Planck time $\sqrt{(hG/c^5)}$. Because we don't have a reliable theory of quantum gravity (or SuperGUTs), we are not now able to probe into earlier times than this.

To assert there was a singularity 10^{-43} sec prior to this time may be totally wrong. There could be an infinite stretch of time prior to this point. The 10^{-43} figure comes from extrapolating from longer times back to infinite temperatures and zero time. We can't, in fact, really do this extrapolation because all of our physics breaks down in this region. Actually, the whole concept of time breaks down at this point. Even the term "prior" is a cheat since it implies timelike knowledge. We think of time as a continuous quantity, but at this early time in history, because gravity is quantized, according to Steven Hawking, every point in space can spontaneously become a mini black hole with a mass around 10^{19} GeV.

We also know from Hawking's work that black holes with only 10^{19} GeV mass will evaporate on time scales of 10^{-43} seconds, re-forming space again. So we are led to a picture of all space-time as a foam of mini black holes popping and off, reconnecting and forming up again. How you do physics in a situation like this, when space and time are disconnected, is *not* described in *Halliday and Resnick*.

In contrast, theorists are busy publishing what seems to be an almost infinite number of papers describing how we do physics in the region from 10^{-43} to 10^{-35} seconds. This is the Grand Unified era. As I mentioned, the baryon-to-photon ratio appears to come out of this era, and, as we will discuss a little later on, the phenomenon of "inflation" may have its origin in this era.

At 10^{-35} seconds the Universe undergoes the phase transition from GUTs to the $SU(3) \times SU(2) \times U(1)$ phase space that we are all familiar with—the strong and electroweak interactions. Eventually, we reach the phase transition mentioned earlier in which the



Isotopic abundances compared with predictions of standard Big Bang theory (black curves). Horizontal shaded areas give observed abundances for He^4, H^2, He^3 and Li^7, which all show remarkable agreement with theory for the baryon-to-photon ratio η between 3×10^{-10} and 7×10^{-10} (vertical shaded region). Figure 3

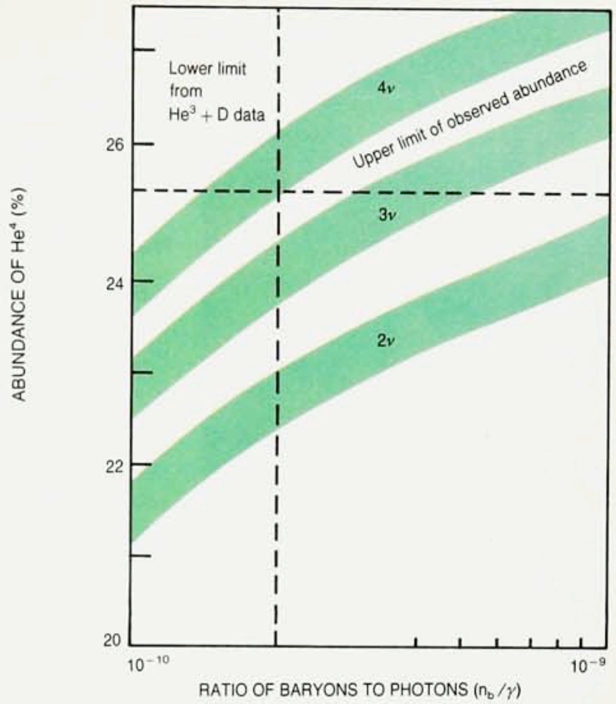
Weinberg-Salam $SU(2) \times U(1)$ symmetry is spontaneously broken to the U(1) symmetry of electromagnetism.

In this era, space is filled with a soup of quarks and leptons. Later on, at 10^{-6} seconds, there is a transition from the quark soup to "confinement"—the quarks couple together to make hadrons, the more normal kinds of particles we are used to. The Universe then cools down to where the weak interaction freezes out, the neutrinos are no longer coupled to the hadron–lepton soup. They fly away freely, and, because nothing escapes the Universe, they are still flying around today as a neutrino background, just as there is a photon background. The neutrino background would now be at a temperature of 2 K (compared to 3 K the photons). To say that it is difficult to detect 2-K neutrinos is an understatement. However, if these neutrinos happen to have a mass, we might be able to detect them through their gravitational interactions. More about this later.

When the weak interaction freezes out, the ratio of neutrons to protons in the universe also freezes out. Exactly what this ratio turns out to be depends on the neutron-decay halflife, which then determines what the helium abundance is. Given the measurements of the neutron halflife, the standard Big Bang model predicts the actual helium abundance, as we mentioned before, of one quarter of the mass of the Universe in the form of helium-4. Moreover, the observed abundances of helium-3, deuterium and lithium-7 all agree perfectly with the predictions of the Big Bang theory (see figure 3). This agreement is really rather impressive. Each of these abundances evolves very differently in the galaxy, and yet each of them, even though they are obtained by competely different observational techniques, falls right in line with the Big Bang prediction. This very impressive agreement, as we noted previously, is in many ways as strong a proof for the Big Bang as the 3-K radiation. In fact, these results can be used to predict the 3-K radiation.

The last event in figure 1, about 100 000 years after the Big Bang, is the point at which the electromagnetic interaction freezes out and the photons propagate freely, just as the neutrinos did earlier. These are the photons we see today in the 3-K radiation. Shortly thereafter stars and galaxies form, and after about 10^9 years we have the dull Universe that we live in now.

We can't use photons to probe back to a time earlier than this, because the Universe was opaque to photons. To explore earlier times, we have to use other techniques. One approach is to use telescopes and so on to observe the abundances of helium, deuterium and lithium, but other phenomena, such as the neutrino background, baryon-to-photon ratio, and the phase transitions in figure 1 require exploration with particle accelerators.



Mass fraction of helium-4 made in the Big Bang is sensitive to the number of neutrino types and the ratio of the baryons to photons. For observed upper limits on helium-4 and lower limits implied from He^3 and D on n_B/n_γ, it can be argued that no more than four neutrino types exist, with a best fit of three. Figure 4

Limits on particles

One of the things that I find particularly exciting, perhaps because I was involved with it, is the prediction from the standard Big Bang model of the number of neutrino types, or any kind of "ino," such as gravitino or photino. The standard Big Bang puts limits on the number of these light, weakly or semiweakly interacting particles.

We saw the Big Bang model predicts that helium makes up approximately 25% of the mass of the Universe. There is a small variation in this number, depending on how many inos there are. In particular, if there are two kinds of neutrinos, electron and muon, say, we get the lower curve of helium abundance shown in figure 4. We get the middle curve for three neutrinos, and the upper curve for four. The uncertainty shown in the curves is due mainly to the uncertainty in the neutron halflife.

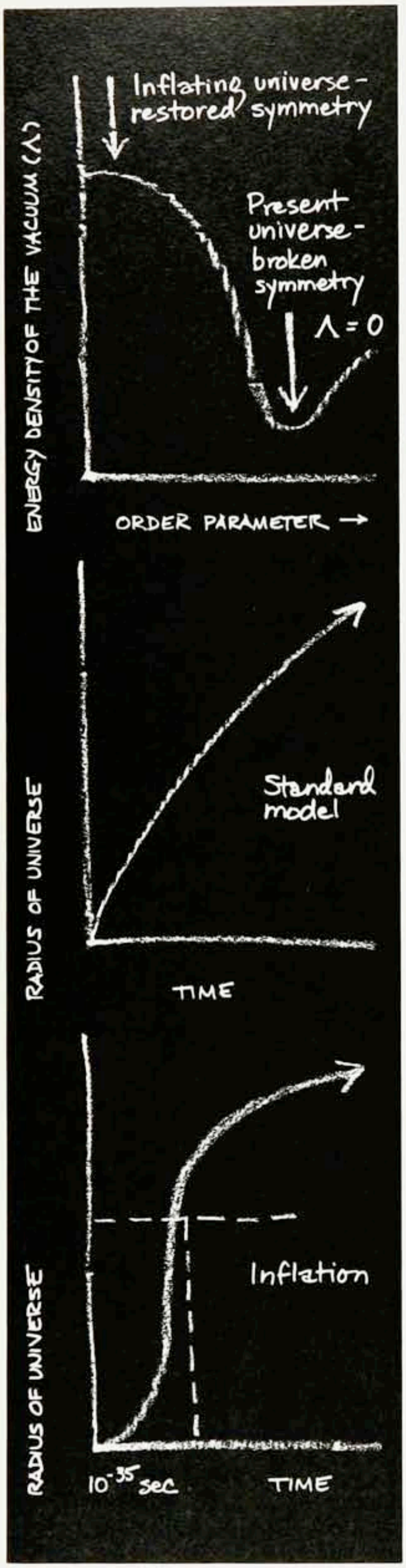
Now recall that the baryon-to-photon ratio comes out of the Grand Unified era. We can measure the actual value in a variety of ways, and we are confident we can put a lower bound on it. The consistency of Big Bang abundance for helium-3 and deuterium with the observed values gives a lower limit of 1.5×10^{-10} for the baryon-to-photon ratio.

We can get the upper limit from figure 4. With three neutrinos (if we believe e, μ and τ exist, all with low-mass neutrinos) and a primordial helium abundance lower than 25 percent, the baryon-to-photon ratio can not be more than 6×10^{-10}. If we say that the tau neutrino does not have a low mass, then the limit would be as large as 10^{-9}. But, in any case, we get these limits on the baryon-to-photon ratio from Big Bang nuclear physics. Note also from figure 4 that four neutrinos would just barely satisfy the constraints. The better fit is with three, and so we may already have found all the neutrinos there are. At most, we could squeeze in one more.

The width in energy (that is, the reciprocal of the lifetime) of the intermediate vector boson, the Z^0, will provide a direct test of the Big Bang models, because the width is directly proportional to the number of neutrino types. When we have believable measurements of this width we will know whether the prediction of three neutrinos, which comes out of the standard Big-Bang model, is correct or not.

In many ways, the width of the Z^0 will be one of the most powerful tests of the standard Big Bang model. It will allow us to test the model at an earlier time than any other observational test to date. Thus experiments with particle accelerators will be giving us one of the best tests of cosmology.

On the other hand, cosmology is predicting a fundamental property of nature—how many fundamental particles there are. We know that each neutrino family is coupled to a quark flavor pair. The prediction of how many neutrinos there are is also a prediction of the number of quark



Theory of inflation proposes that during Grand Unified epoch the energy density of the vacuum was not zero (as in the present Universe) but was large enough during the phase transition to drive the expansion of the Universe at an exponential rate (compare rates of expansion shown in two bottom figures). Figure 5

flavor pairs. This is a surprisingly powerful statement to be coming from something that happened so long ago.

Total mass of the Universe

If we convert the upper limit on the baryon-to-photo ratio from Big Bang nucleosynthesis into Ω (the fraction of the critical density), we find that Ω is less than about 0.1. This value implies that the density of baryonic matter cannot close the Universe. So if the Universe contains only regular matter, it is an open Universe.

This certainly is a possibility. However, there are some other ways to obtain Ω by just looking at the galaxies as they exist. We can estimate the masses of the galaxies in a variety of ways. If we look at the rotation curve of a galaxy, standard Newtonian mechanics gives a mass of the order of 10^{11} solar masses for a galaxy such as ours. If we assume all galaxies have this mass, we obtain an Ω of about 0.01—a very open Universe. But this value of Ω comes from looking only at the regions where we see light being emitted.

If we apply Newtonian mechanics to a galaxy rotating around another galaxy, we calculate a mass per galaxy of 10^{12} solar masses, an order of magnitude larger then our previous estimate and an implied Ω of about 0.1. The galaxy appears to be interacting as if it has a much larger mass than the mass of the visible region. The extra mass clearly appears to be there. It is not that there is any mass missing. It is rather that the light is missing from this additional mass. We have a missing-light problem. What is this mass that is not radiating, this dark matter? We can picture a halo around each galaxy of dark matter that is not radiating.

Now, if we consider larger cluster of galaxies—in which a thousand galaxies are all whirling around each other—we can do the same physics, but in terms of a statistical ensemble of the average separation distance and the average dispersion velocity. We can calculate the fraction of the mass attributed to each of the galaxies in this large cluster, and we find that the mass per galaxy approaches the order of 10^{13} solar masses. This additional order-of-magnitude increases implies an Ω almost equal to one if all galaxies really have this much mass.

Although most galaxies are not in large clusters, a growing trend in the observational data on large scale implies that an Ω of greater than 0.1 may be appropriate. In other words, galaxies may have such large haloes around them that even the orbits of a binary do not include all of the mass.

If this is the case and Ω is actually bigger than 0.1, then we have a problem. The matter of the Universe can not be primarily baryons.

The options include massive neutrinos. Experiments are under way to check this possibility. The neutrino mass can be quite small (of the order of tens of eV). Because there are so many neutrinos (roughly as many neutrinos as there are photons or 10^{10} more neutrinos than baryons), if neutrinos only had a mass of an eV they could contribute more to the mass of the Universe than the baryons. If massive neutrinos are proven not to exist there are other "inos" that have been proposed—gravitinos or photinos might do, for instance. However, we have recently shown that other "inos" only work well if they interact like neutrinos and have masses of tens of eV. Current experiments do not as yet strongly constrain the massive neutrino option. To do the job, we require only that the massive neutrino have a mass of 20 to 30 eV. The Soviet tritium endpoint experiment claims an electron-neutrino mass in this range. However, even if this mass were shown to be less than an eV it could always be the tau neutrino which dominates the Universe. The best way to probe this mass possibility is through tau neutrino mixing with muons and electrons. But such experiments only put limits on a combination of the mass difference squared and the mixing angle. Hence a stringent limit on mass differences can always be avoided if the mixing angle is sufficiently small.

Another possibility being considered is that the extra mass could come, not from a tiny elementary particle, but from a black hole. The ordinary big (solar mass) black hole could not work. Big black holes were still baryons at the time of nucleosynthesis, so their mass is included in our nucleosynthesis account.

The suggestion, then, is to look at little black holes. However, as I mentioned, Hawking predicts black holes below a certain size will evaporate. So we have to look at black holes in the rather "narrow" mass range of 10^{15} to 10^{33} grams.

If this does not seem that narrow a range, consider the two standard ways in which black holes are created: (1) stars collapsing, which produces big black holes, or (2) a phase transition at the Planck time, which gives you Planck-mass (10^{-5} g) black holes. But we have come up with another way to make black holes with masses that fall right between these two mass ranges. At the times of Weinberg–Salam phase transition and the quark–hadron phase transition, the horizon of the Universe (the matter contained within the largest causally connected region) was around the mass of a planet. For example, at the quark–hadron transition the strong, color-gauge interaction would make black holes that measure a meter in diameter but weigh the mass of Jupiter. They would be created, not by gravitational clustering, but by the interaction involved in the phase transition. We should be able to test these ideas, as we explore quark matter and learn more about the nature of these phase transitions in sufficiently energetic heavy-ion collisions, which may be able to produce quark matter in the laboratory. Similarly we will learn about the Weinberg–Salam phase transitions from the W and Z experiments.

If the properties that we have estimated for these phase transitions turn out to be correct, these transitions should produce some planetary-mass black holes. Whether or not they can cluster in the appropriate way to be the dark matter is a question currently under study.

Inflation

Finally let us discuss inflation—an exciting new idea that appears to solve a large number of problems of the early Universe:

▶ The horizon problem—why is the Universe the same in different directions, even though they appear to be causally disconnected?

▶ The flatness problem—why is the Universe more than 10^{-43} seconds old? And how was Ω able to start out so close to 1 (within 50 decimal places) that we still don't know the answer to whether the Universe is open or closed today, after 15 billion years?

▶ The monopole problem—where did all the monopoles go?

▶ How did we get the bumps that make galaxies?

The solution, first proposed by Alan Guth, is that during the Grand Unified epoch the Universe had settled into a state called a false vacuum. In this state, the energy density of space is very large, even in the absence of any matter. If this is the case, then the false vacuum itself would drive an expansion (see figure 5). But it drives an expansion that is exponential in time rather than a normal power-law expansion. In this very, very rapid expansion, every tiny part of space, every one of those remnants of the foam of mini black holes that we talked about before, could inflate to a region that is as large as our universe is today. Since each tiny part of space was causally connected before the inflation began, the horizon problem disappears. To begin with, everything is flat across these tiny regions, so when they inflate to the size of the universe, Ω is still exactly equal to 1—and the flatness problem is solved. The inflation vastly dilutes the density of monopoles, so that after inflation there would be only about one monopole in the entire observable Universe. More might be generated later on in collisions, as Michael Turner has shown. But the original monopoles we were concerned about would be inflated away to only one. This phase transition, depending on how it occurs, could have a few bumps and wiggles, because phase transitions are never totally smooth. The bumps and wiggles that occur could become our galaxies.

So inflation is a very nice idea. Unfortunately it creates a new problem: how do you end inflation? Inflation seems to solve everything—it gives us homogeneity, flatness, gets rid of monopoles, makes bumps that can grow into galaxies and so on. But the problem is that then every part of the Universe is moving apart very fast. Now we go through the phase transition from the Grand Unified phase toward the more normal Universe that we live in [$SU(3)\times SU(2)\times U(1)$]. Normal space is a noninflating 3-dimensional space in which the vacuum has no energy. As the Universe goes through this transition, bubbles of the new phase arise in the old, expanding phase. To have a phase transition go to completion, the new bubbles need to grow and gradually coalesce and take over all the space. Unfortunately, they are inflating away from each other so fast that the walls of the bubbles are not expanding as fast as they are moving apart from each other, and so the phase transition never goes to completion.

Fortunately, there is a solution. The solution is that we live in a single bubble. Actually it is a little more complicated than this. You have to propose a special kind of phase transition to make a single bubble look like our Universe, because normally a bubble would not contain nearly as many particles as we observe in our Universe. But if we live in a single bubble, then of course we have all these other bubbles some place out there, which makes for a different philosphical idea about the Universe then we have had before. (Of course, our knowable Universe still looks the same; its only embedded in a far larger and richer minifold.)

To verify these kinds of ideas, we will really need to know the nature of the Grand Unified Theory or the Super Grand Unified Theory. We will have to probe into this regime using a variety of approaches—try to observe monopoles, proton decay, the electric dipole moment of the neutron and so on. Inflation specifically predicts that Ω is exactly unity and that the density of background cosmological monopoles should be effectively zero.

Changed philosophical view

Consider how developments in the past few years, at the boundary of particle physics and astrophysics, have really changed our whole philosophical view of things. We have known for 500 years that the Earth is not the center of the solar system. Then Harlow Shapley showed us that our Sun is not at the center of the Galaxy—it is out near the edge. Hubble and others showed us that the Galaxy is not at the center of the Universe. In fact, they went so far as to say there is no spatial center—all points are equivalent. But now, if we believe Ω is larger than 0.1, we are even further removed from being the center. We are not even made out of the dominant matter of the Universe. And then with inflation, we are not even the only bubble. I call this idea the extreme Copernican principle.

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