Matter, matter, everywhere . . .

The grand unified particle theories offer the first natural explanation of why the universe prefers matter over antimatter

In the past few years, cosmologists concerned with the early universe have embraced the grand unified theories of particle interaction almost as enthusiastically as have the physicists who invented them.

Here is a class of theories, differing from each other only in detail, which describe the strong, weak, and electromagnetic forces in a single mathematical framework; the betting is heavy that one of them is the correct theory of nature. They were developed with no reference whatsoever to cosmology; yet they allow cosmologists to model the evolution of the universe as early as 10^{-35} second after the Big Bang. In particular, it now seems that they offer a natural and philosophically satisfying explanation for one of the great cosmological puzzles: the universal preference for matter over antimatter.

"I think this is the most exciting thing in cosmology in the last 10 years," says Los Alamos National Laboratory astrophysicist Edward Kolb, who has worked extensively on computer models of particle dynamics in the early universe. In the 1960's astrophysicists worked out how helium and other light elements were created from hydrogen by nucleosynthesis just after the Big Bang, he says. "Now we're on the verge of understanding where the baryons themselves come from."

In this context the word "baryons" refers simply to the protons and neutrons of ordinary matter. Until the advent of the grand unified theories, it seemed that the number of baryons minus the number of antibaryons was always a conserved quantity in particle reactions. So if the universe today has a preponderance of matter over antimatter—if its baryon number density is positive—then it always did.

Since the preponderance is clearly there, cosmologists seeking to understand it were faced with some unpalatable choices. Either they could say that there is no antimatter in the universe, in which case they had to accept the asymmetry as some kind of initial condition of the Big Bang, or they could say that antimatter is just as abundant as matter—only it's somewhere else.

Most observers found the first alternative distinctly unaesthetic. Why should the universe prefer one kind of substance over the other? To say it was an initial condition seems too arbitrary; if nature plays favorites, there ought to be some reason. The very existence of antimatter—the principle that for every kind of particle in nature there is an antiparticle of equal and opposite charge and identical mass—arises from fundamental symmetries within relativity and quantum theory. P. A. M. Dirac first predicted the positron on this basis in 1928. Accelerator physicists now verify the concept every day; particle-antiparticle pairs are produced copiously every time a beam interacts with its target.

True, there is one particle-antiparticle asymmetry in the field equations, the so-called CP violations observed in the decay of K mesons; James W. Cronin of the University of Chicago and Val L. Fitch of Princeton University jointly won the 1980 Nobel prize in physics for their detection of this phenomenon in 1964. CP violation allows one type of K meson to decay in a slightly different way than its antiparticle. Unfortunately, it does nothing to explain the asymmetry in the world at large. K meson decays are rare and the discrepancy is tiny.

$$X \longrightarrow \bar{Q}\,\bar{Q} \qquad \begin{array}{l}\text{Baryon}\\ \text{number} = -2/3\\ \text{rate} = R\end{array}$$

$$\bar{X} \longrightarrow Q\,Q \qquad \begin{array}{l}\text{Baryon}\\ \text{number} = +2/3\\ \text{rate} = \bar{R}\end{array}$$

$$\Delta B \propto (-2/3)R + (2/3)\bar{R} = 2/3(\bar{R} - R)$$

A recipe for baryons

According to models based on the grand unified theories, the generation of baryon number began about 10^{-35} second after the Big Bang, with the decay of X and anti-X bosons. Shown here is one of several decay modes: an X boson decays into a pair of antiquarks (baryon) number $-2/3$ at a rate R; its antiparticle decays into a pair of quarks (baryon number $+2/3$) at a slightly faster rate $\bar{R}$. The net baryon number after all the bosons are gone is just proportional to the difference in the rates. A similar result holds for the other decay modes; a universe starting out with equal numbers of X and anti-X bosons can thus end up with more quarks than antiquarks.

Most important, the decays still preserve baryon number; there is no way they could generate a baryon excess that was not there to begin with.

But the idea of a symmetric universe, with matter separated from antimatter, runs into severe problems of its own. The two kinds of matter have to be very separated indeed; with a few minor exceptions, such as cosmic-ray antiprotons that are probably produced by high energy collisions in the interstellar medium, the observable universe appears utterly devoid of antimatter.

"From satellite gamma-ray observations it's established beyond a shadow of a doubt that our own galaxy is matter," says Gary Steigman of the Bartol Research Institute in Newark, Delaware, who has studied the subject extensively. The observational key is antimatter's famous habit of annihilating matter on contact, converting mass into energy with a sudden flash of gamma rays.

The galaxy is a well-mixed thing, says Steigman. Clouds collide, stars form, and supernovas inject material back into space. If any antimatter were present it would be in constant contact with matter, and thus would constantly be producing annihilation gamma rays—which are not observed.

The same argument applies on a larger scale. For example, no one can tell just by looking at it whether the Andromeda galaxy is made of matter or antimatter. But the local group of galaxies is known to be embedded in hydrogen gas. The Milky Way isn't annihilating the hydrogen, and Andromeda isn't annihilating it, so both must be made of the same kind of stuff. Likewise, the galaxies of the giant Virgo cluster orbit through an intracluster haze of hot, x-ray–emitting gas. The gamma-ray observations limit Virgo's antimatter content to less than 1 part per million.

So if large quantities of antimatter are present in the universe they would have to be separated from matter at least on the scale of clusters, Steigman concludes. This means that anyone who believes that the universe as a whole is symmetric must also explain how the universe managed to sort out chunks of material weighing at least 10^{15} solar

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masses—without annihilating them first. People have tried very hard to come up with plausible mechanisms. None of the proposals have been convincing, in Steigman's opinion, and most researchers have given up the effort.

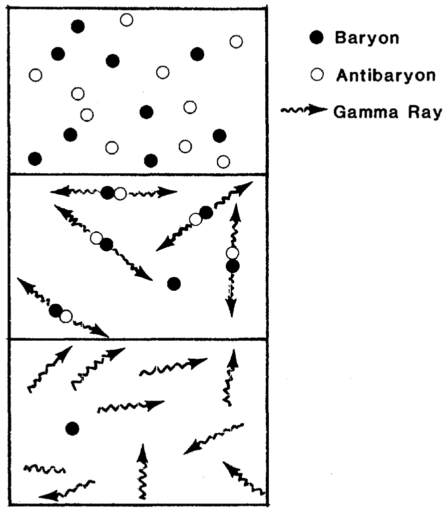
It is into this gap that the grand unified theories have come. They do essentially two things: they predict certain processes that violate the conservation of baryons, and they allow for a kind of arrow, a CP symmetry violation that guides the baryon-nonconserving processes into the creation of matter rather than antimatter. And, a very important contribution from the observational point of view, each theory makes a specific prediction for how big the discrepancy will be.

Paradoxically, despite the vast quantities of matter in the universe and the virtual absence of antimatter, that discrepancy is quite tiny. Its empirical value is about 10^{-10}.

To see how astrophysicists arrive at this number, it is helpful first to understand what it means in terms of the early universe. According to the "standard model" of the Big Bang, the universe during its first microseconds was hot enough for particles, antiparticles, and photons to be in thermal equilibrium; no sooner would baryon annihilate antibaryon than an identical pair would be regenerated in another reaction. But things were not quite in balance; somehow, for every 10 billion antibaryons, there were 10 billion and one baryons.

Then, as the temperature fell below 10^{12} K some 10^{-4} second after the Big Bang, the rate of pair production began to fall behind the rate of annihilation. Baryon and antibaryon started consuming one another; very quickly, all that remained was a hurricane of gamma rays—and that one leftover baryon out of 10 billion. It was this tenuous remnant that one day would give rise to the earth and all the planets, stars, and galaxies. And it is this thin sliver of asymmetry that cosmologists have sought so long to explain.

Today, after 10 to 20 billion years of cosmic expansion, the average density of this leftover matter has fallen to about 5×10^{-8} baryon per cubic centimeter. To estimate the total density of baryons and antibaryons before annihilation, cosmologists start from the fact that in those early instants of thermal equilibrium, such particles were very nearly as abundant as photons. Moreover, to a first approximation, the number of photons in the universe has remained constant ever since. Their density has simply fallen with cosmic expansion by the same factor as has the density of matter; we see them now as the 3 K microwave background radiation. So counting 3 K photons now is nearly the same thing as counting baryons and antibaryons then. The average matter density, divided by the 3 K photon density—about 500 per cubic centimeter—is a constant, independent of time or rate of expansion. The numerical value of that ratio, 10^{-10} (it is uncertain by an order of magnitude), represents the fractional discrepancy between matter and antimatter just after the Big Bang . (To be technically accurate one should speak not of photon density but of entropy density; in the modern universe, however, the entropy is dominated by 3 K photons.)



A little touch of asymmetry in the night

Until about 10^{-4} second after the Big Bang (top), baryons and antibaryons were in thermal equilibrium, their densities nearly equal. As the universe continued to expand, however, the rate of baryon-antibaryon annihilation exceeded the rate of regeneration (middle). In the end, after all the antibaryons had been consumed, one odd baryon out of ten billion was left over (bottom). It was this tiny remnant that gave rise to all the planets, stars, and galaxies.

Since the asymmetry already existed at 10^{-4} second, its source must clearly be sought at much earlier times. The grand unified theories, the first of which were proposed in 1974 by Harvard physicists Sheldon Glashow and Howard Georgi, and independently by Abdus Salam of Imperial College, London, and Jogesh Pati of the University of Maryland, give cosmologists the theoretical tools to do just that. The Georgi-Glashow-type theories in particular purport to describe the behavior of matter at energies of 10^{14} billion electron volts and beyond; they allow cosmologists to extend their models as far back as 10^{-35} second. Temperatures then ranged to 10^{27} K. The density of matter far exceeded that of an atomic nucleus. Fragile constructs such as baryons or antibaryons were impossible; thermal buffeting would have ripped them apart. The universe, in fact, was a jungle of quarks, antiquarks, electrons, positrons, neutrinos, and all the other entities that physicists are currently calling fundamental.

Among the denizens of this particular zoo were the most massive particles that physicists have ever seriously proposed: the X bosons, weighing in at 10^{14} billion electron volts, 100 trillion times the mass of the proton. The grand unified theories achieve their unification of the fundamental forces in part by putting quarks, antiquarks, and leptons (electrons, neutrinos, and their cousins) on the same mathematical footing; the X bosons are the physical manifestation of this. For example, in the familiar world of strong, weak, and electromagnetic forces, a quark, no matter how much it may be knocked around otherwise, always remains a quark; let it interact with an X boson, however, and it becomes an antiquark, or even a lepton.

According to conventional ideas of particle physics, such behavior is heretical. With X bosons on the loose, baryon number is no longer conserved; the number of baryons minus the number of antibaryons—or more generally, the number of quarks minus the number of antiquarks—need no longer stay constant in particle interactions. Yet this is just the breakdown of baryon conservation that is needed in the early universe to generate a baryon excess.

Baryon nonconservation is also responsible for the most famous prediction of the grand unified theories: the instability of the proton (*Science*, 21 November 1980, p. 851). The predicted lifetime of the proton is on the order of 10^{32} years, which happens to be roughly Avogadro's number times the age of the universe. While this is a ludicrously large number in practical terms, the detection of proton decay and precise measurement of the proton's lifetime would be an important test of the ideas of the grand unified theories. Such data would also indicate which of the various theories has a chance of being true. Several experiments are now under way; results are expected within a year or two.

The idea that the matter-antimatter asymmetry somehow arose from baryon nonconservation in the early universe is a fairly old one. The general features of such a process were sketched in 1967 by the Soviet physicist Andrei Sakharov. In 1978, a number of particle theorists began exploring the idea in the context of the grand unified theories.

One popular model begins with the observation that the processes that violate baryon conservation, as in proton decay, were enormously accelerated at the temperatures and pressures of the Big Bang. Even if the universe had started out with some kind of quark-antiquark imbalance, the X bosons would quickly have brought things into symmetry. Before 10^{-35} second, in fact, the universe was in thermal equilibrium; the density of X bosons equaled the density of anti-X bosons, quark density equaled antiquark density, lepton density equaled antilepton density, and so forth. The net baryon number of the universe was zero.

As the universal expansion proceeded, however, temperatures and densities fell. When things reached the state where X and anti-X bosons were decaying faster than they were regenerating, thermal equilibrium was no longer possible. Intuitively, things should have stayed symmetric even so: for every X boson that decayed into a pair of antiquarks (and thereby violated baryon number conservation), for example, its antiparticle should have been balancing things out with a pair of quarks.

Which is exactly what happened—almost. The balance was not quite perfect. Very general theorems in relativistic field theory demand that a particle and its antiparticle decay at the same rate. But (most of) the grand unified theories allow X and anti-X bosons to decay in slightly different patterns; the discrepancy is analogous to the CP violation observed long ago in K meson decay (except, of course, that here it does not preserve baryon number).

In the example just cited, the anti-X bosons might produce a few more quarks than the X bosons produce antiquarks. Other decay modes would display similar differences. So in the end, when all the X's had disappeared, quarks would outnumber antiquarks by some small margin; when these particles had all coalesced into baryons and antibaryons a few instants later, the baryons would be the more numerous by just that same margin. Thus it was this one difference, this one tiny asymmetry in the decay patterns of the X bosons, that would ultimately give rise to one leftover baryon out of 10 billion and thence to all the matter in the observable universe.

Even the most enthusiastic astrophysicist will admit that, in a sense, this scenario does not actually explain anything; in place of an arbitrary initial condition on baryon number, it postulates an equally arbitrary CP violation within the theory. In another sense, however, it represents a profound advance. Any given grand unified theory allows one to calculate the baryon/photon ratio in terms of the parameters of the theory. These parameters could, in principle, be measured in the laboratory. So instead of two cosmic mysteries—matter-antimatter asymmetry and elementary particle dynamics—there is now only one.

Kitt Peak National Observatory

The Virgo cluster

No antimatter to be found.

Rigorous calculation of the asymmetry is enormously difficult, however. A given theory may contain hundreds of baryon-number violating reactions, all of which must be followed as the universe expands. "It's quite complicated," says Kolb. "The sign of the baryon anomaly will go one way, then another reaction will take over and it will swing back."

The only way to handle all the variables is by computer. Two groups have devoted themselves to the task. One consists of University of Chicago astrophysicists James Fry, Keith Olive, and Michael Turner; the other of Kolb and California Institute of Technology researchers Jeffrey Harvey, David Reiss, and Steven Wolfram. Both groups have obtained essentially identical results.

The Caltech scientists, for example, looked at five different grand unified theories: three in which the symmetry group relating quarks, antiquarks, and leptons is SU(5), and two in which it is SO(10). The original SU(5) theory of Georgi and Glashow is the simplest and most popular, says Kolb. It only talks about the quarks and leptons that are already known, and postulates the absolute minimum number of supermassive X bosons required to make the theory mathematically consistent. The simplicity of this "minimal SU(5)" theory has led many people to believe that it is most likely the correct one.

Unfortunately, says Kolb, it has proved impossible for this theory to produce an asymmetry as large as 10^{-10}; there is simply no way to generate enough CP violation. One way out, first suggested by the Chicago group, is to complicate the theory with additional leptons and quarks, presumably too heavy to be observed. In such an expanded theory it is indeed possible to produce enough asymmetry, Kolb says, but just barely, and only for a very narrow range of parameters.

The other way out is to postulate a larger collection of very massive particles (the so-called Higgs bosons). This works much better, according to Kolb. Such theories can produce asymmetries as large as 10^{-3}.

In all fairness, it must be said that, despite the undeniable elegance and naturalness of the X-boson decay model, it has in no way been "proved"; at most, the calculations show that the scenario is plausible. Indeed, it is hard to see how such a theory could be proved, although a measurement of proton decay would go a long way toward establishing the basic idea of grand unification.

It should also be said that not everyone agrees with the emerging consensus. Floyd Stecker of Goddard Space Flight Center in Greenbelt, Maryland, has long been an advocate of symmetric cosmologies. He points out that certain types of grand unified theories allow for a CP violation that varies from place to place.

If this is, in fact, the way nature works, then it is possible—Stecker says inevitable—that the matter-antimatter asymmetry will itself depend on position. There would then be places where matter is even more predominant than it is locally, places that are empty because baryon had canceled antibaryon almost completely during the Big Bang, and, of course, places where antimatter is now dominant.

These regions would obviously have to be separated by vast distances if this scenario is to agree with the gamma-ray observations quoted by Steigman; critics wonder if this is possible even if the theory itself is true. They also contend—although Stecker disagrees—that the scenario predicts distortions in the 3 K microwave background much larger than are observed.

Still, Stecker claims that the diffuse gamma radiation seen in satellite data has a spectral distribution consistent with annihilation at very distant matter-antimatter boundaries. Moreover, the universe seems to have a lacy, cellular structure, with the vast superclusters separated by equally vast spaces that seem utterly empty. So it may just be that the local supercluster is matter, he says, but the next one over is antimatter.—M. MITCHELL WALDROP

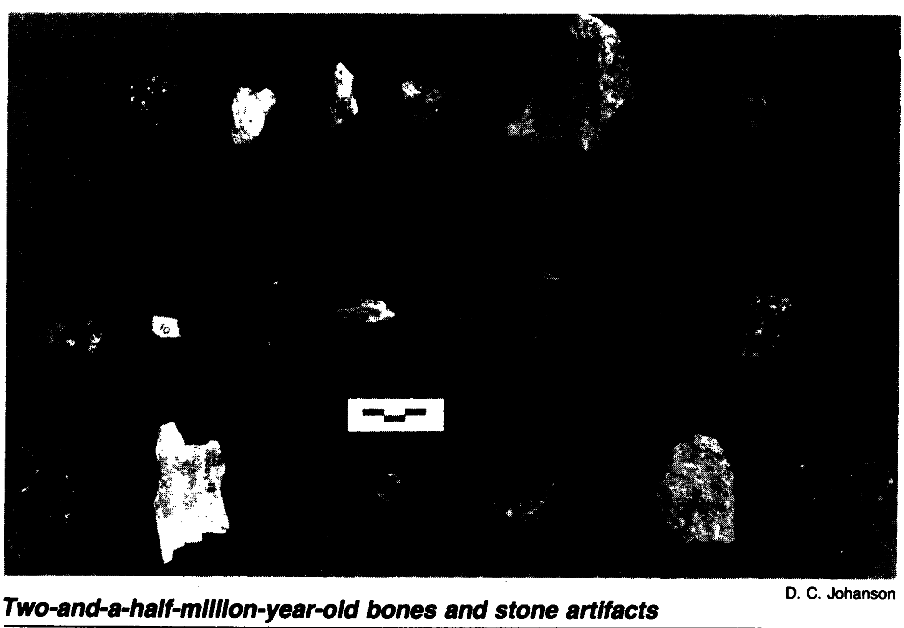
Ethiopian Stone Tools Are World's Oldest

Two-and-a-half-million-year-old artifacts pose new questions over relationship between toolmaking and brain expansion in human evolution

French archeologist Hélène Roche and New Zealander Jack Harris found putative stone tools from ancient deposits in the Hadar region of Ethiopia in 1976 and 1977. For 4 years the tools, pebble "choppers" and small stone flakes, seemed likely but unpublished candidates for being the oldest artifacts yet discovered. Recent analysis of volcanic material from the area confirms the claim, giving the tools a probable age of between 2.5 and 2.7 million years. The oldest securely dated artifacts known previously came from the Lower Omo region in southern Ethiopia: these are dated at 2.1 million years old.

"The tools come from that provocative 2 to 3 million year period," says Donald Johanson of the Cleveland Museum of Natural History and one of the leaders of the joint French-American expedition to the Hadar. "We believe that this is the time when early *Homo* first evolved from *Australopithecus afarensis* stock," he told *Science*. "It may be that the use of tools is intimately associated with that divergence between *Homo* and later species of *Australopithecus*."

The 1976–1977 field season in the Hadar was the fourth and last expedition to the area; political strife in Eritrea has so far prevented further work there. "Hélène found the first tools in November 1976," recalls Harris, "but very soon afterward she had to return to France. I went in January 1977 and stayed just 3 weeks, during which time I did some quick surface surveys of the area and one test excavation. I found 18 artifacts in situ from that excavation."



D. C. Johanson

Two-and-a-half-million-year-old bones and stone artifacts

Jack Harris recovered 18 artifacts and five fossil fragments (the white shaded objects) from a small test excavation. The artifacts are a core, flakes, and flake fragments. (Marker is 3 centimeters.)

Primitive stone artifacts can be found scattered over the ground surface of much of North and East Africa, but these are useless from an archeologist's standpoint. Unless the tools are firmly embedded in primary deposits there is no way of determining how old they are. The age of a stone tool is set by the date attributed to the deposits in which they are excavated, and this date may be established by one of several physico-chemical techniques.

"I was surveying an area west of where most of the hominid fossils have been found," Harris told *Science*, "and I came across lots of surface occurrences of artifacts. The test excavation, covering about 7 to 10 square meters, was a kilometer from where Hélène had found the first artifacts." The total haul from the site was 50 stone artifacts: three 8-centimeter cobbles from which several flakes have been struck and a collection of flakes and flake fragments. These worked cobbles are traditionally known as choppers, though archeologists are beginning to believe that they serve primarily as cores from which sharp flakes are struck. The flakes would have provided a considerable technological breakthrough, their sharp edges being more than adequate for slicing through animal hide and meat. "Only one 'chopper' and 17 flakes and flake fragments came from the excavation," says Harris, "the remainder were on the surface. The excavated artifacts were in pristine condition, with cortex clearly visible on some of the flakes."

The nature of the deposits in the area suggests that the site was on or close to a bank of a river and several kilometers

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