Inflation and the Mysteries of the Cosmos

Modern particle theory and the inflationary scenario may explain how the universe was filled with matter and energy

For cosmologists, the beautiful thing about the grand unified theories (GUT's) of the strong, electromagnetic, and weak interactions of elementary particles is that they predict how matter behaves at exceedingly high temperatures—those that prevailed some 10^{-35} second after the Big Bang, for example.

That particular instant seems to have been a crucial moment in the history of the universe. Theorists have recently realized that GUT mechanisms operating at 10^{-35} second give a satisfactory explanation of one of the deep cosmic mysteries: the baryon asymmetry, the virtual absence of antimatter in the universe (*Science*, 20 February, p. 803).

Now, early universe researchers are applying GUT's to two other cosmological mysteries, known as the horizon problem and the flatness problem. If their theories are valid, GUT mechanisms acting at about 10^{-35} second were responsible for the production of essentially all the matter and energy in the universe.

Nothing has done more to focus attention on this possibility than the "inflationary scenario" proposed in 1980 by Alan H. Guth, a particle theorist at the Massachusetts Institute of Technology. "It's a great idea for solving some of the outstanding problems in cosmology," says Gary Steigman of the University of Delaware, chairman of a recent early universe workshop at the Institute for Theoretical Physics in Santa Barbara, California. "Some of the details have not yet worked out satisfactorily," he adds—something Guth himself is the first to admit. But the inflationary scenario is a good illustration of the kind of thinking now going on, and, as Edward C. Kolb of Los Alamos recently told *Science*, it contains some appealing features that may well survive in any final theory.

The horizon problem, explains Guth, is basically the problem of understanding the homogeneity of the universe. Galaxies are scattered more or less at random throughout the cosmos, and the 3 K background radiation is uniform to a few parts per thousand. Yet, as intuitive and as natural as this homogeneity may seem, it is, in fact, a very unnatural condition. The photons of the background radiation were emitted from the cooling cosmic plasma only 100,000 years after the Big Bang. But photons that are now arriving from opposite sides of the sky were emitted from regions that were much more than 100,000 light years apart. Since no physical interaction can propagate faster than light, there is no way those regions could have come into thermal equilibrium with each other. Each lay beyond the other's "horizon." Thus, Guth notes, the homogeneity of the universe cannot be regarded as something that evolved naturally. It has to be assumed as an initial condition—and a very special initial condition. There are many more ways for disconnected regions to be different than for them to be the same.

The flatness problem is the question of understanding the mass density of the universe. In conventional models of the universe, if the density is greater than a certain critical value, then the equations of general relativity—Einstein's theory of gravity—predict that the universe must be a closed space of finite volume. Moreover, its expansion will one day come to a halt and it will collapse back into a point. If the density is less than critical, then the universe must be infinite and it will expand forever. If the density is precisely critical, the universe will be infinite but "flat" in a certain geometric sense.

Today the density of matter lies (conservatively) between 0.02 and 10 times the critical density, says Guth. That may not seem remarkable, but in fact it requires an exquisite precision of initial conditions in the early universe. For the mass density to be this close to critical now, some 10 billion to 20 billion years after the Big Bang, it must have differed from criticality at 10^{-35} second by less than one part in 10^{49}.

That's like balancing a pencil on its point so accurately that it's still upright tens of billions of years later, says Guth. An initial condition that precise cries out for an explanation—especially since the known laws of physics are perfectly consistent with any value of the initial density whatsoever.

More often than not, attempts at an explanation have involved some vague hand-waving about unknown laws of physics: "quantum gravity" effects that somehow set the initial conditions at times even earlier than 10^{-35} second. Unfortunately, no one has the slightest idea how to write down a quantum theory of gravity, so such explanations tend to resemble the "Here there be dragons" school of ancient cartography.

But with the advent of the GUT's, Guth and many of his colleagues believe, there arises the possibility of a more definitive solution to the horizon and flatness problems, involving phase transitions in the early universe.

Grand unified theories predict that matter will undergo one or perhaps several of these transitions at temperatures around 10^{27} K, Guth explains. The theories contain too many undetermined parameters to allow a precise prediction of the nature of the transitions, so it is possible that they occur quickly, in which case the cosmological consequences would be unimportant. But it is also possible that they happen slowly, with the expanding universe supercooling many orders of magnitude below the transition temperature. This possibility, he notes, leads to the inflationary scenario.

According to GUT's, matter above the transition temperature was in a very symmetric state. Quarks, the constituents of protons and neutrons, and leptons, including electrons, neutrinos and the like, all behaved identically. Below the transition point, however, the differences were made manifest through a process called spontaneous symmetry breaking. An oft-used analogy is that of the ferromagnet: above the Curie point the atomic spins are oriented at random, and all directions are equivalent; below the Curie point, however, all the spins line up in parallel, and one direction becomes different from all the others.

If the universe did indeed supercool as it expanded, says Guth, it would have passed below the transition temperature into a metastable state known as the false vacuum, which has been studied extensively by Sidney Coleman at Harvard University. The false vacuum not only retained symmetry among disparate

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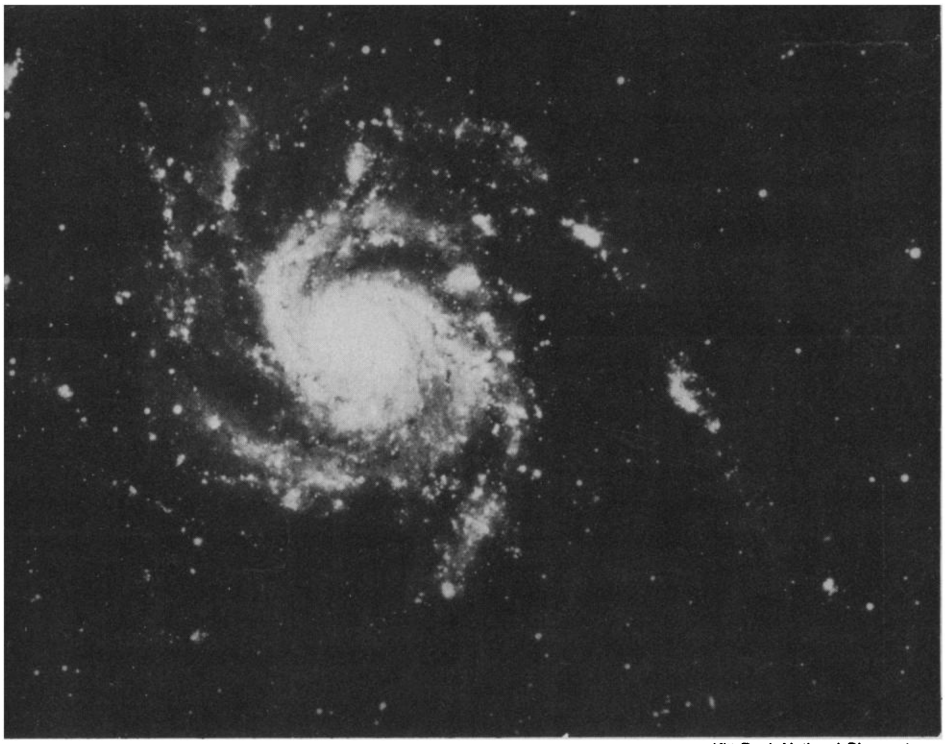

Kitt Peak National Observatory

The galaxy M101 in Ursa Major

The stars, the planets, and human beings—did they all come from the false vaccuum?

particles far below the transition temperature, it produced a large energy density in otherwise empty space. Moreover, the energy density had the peculiar property of remaining constant as the universe expanded. There were other oddities, such as a negative pressure, but the upshot, says Guth, is that a constant energy density, combined with the relativistic equations that describe the expansion of the universe, predicts a universe that expanded exponentially with time. (In the standard model it expands only as the square root of time.)

After the universe had expanded by many orders of magnitude, says Guth, the phase transition took place. The energy of the false vacuum was converted into particles of the usual types, at a temperature close to 10^{27} K. The universe thereafter expanded and cooled according to the standard model, and the baryon-antibaryon asymmetry was established in the now conventional way. Eventually these particles, born from the false vacuum, became the stuff that makes up stars, planets, and human beings.

Such an inflationary universe could easily have expanded by factors of 10^{28} or more, sufficient to solve both the horizon and flatness problems. The horizon problem disappears simply because the early universe in this scenario was much smaller than in the standard scenario; the speed of light no longer posed a barrier, and physical processes can be invoked to smooth out any inhomogeneities that may have been present initially in the Big Bang. The flatness problem is also solved because the longer the exponential expansion continued, the closer is the equality between the actual and critical mass densities. Intuitively, Guth explains, the colossal expansion led to a flatter space, just as the surface of a balloon gets flatter as the balloon expands.

The inflationary scenario may also help clear up another mystery: What happened to all the magnetic monopoles?

Monopoles are among the more bizarre prediction of GUT's. In technical terms they are "topological knots in the Higgs field expectation value." Empirically, they would be enormously heavy, stable particles—10^{16} times the mass of the proton—and each would be an isolated north or south magnetic pole. Needless to say, no one has ever seen a monopole.

John Preskill of Harvard University has pointed out that monopoles cannot be very common in the universe in any case. With such an immense mass, they would produce a far higher average density of matter in the universe than is observed. (In fact, they would have caused the universe to collapse long ago.) Current observational limits on the cosmic matter density imply that protons now outnumber monopoles by at least 10^{14} to one. However, Guth and Henry Tye of Cornell University have shown, using standard GUT models, that rapid phase transitions in the early universe would have produced monopoles copiously; they estimate a proton-to-monopole ratio closer to 1:1. For technical reasons it has proved impossible to estimate the ratio formed in a slow transition, the kind that gives rise to the inflationary scenario. But the manifest paucity of monopoles in the universe is at least another hint that the scenario is headed in the right direction, says Guth.

But alas, the scenario doesn't quite make it all the way. There seems no way to exit gracefully from the inflationary phase into normal expansion, Guth explains. The transition would occur by the process of bubble nucleation, just as it does in the laboratory with a supercooled liquid. Tiny bubbles of the new phase (quarks and leptons behaving differently) would appear randomly within the old phase (quarks and leptons behaving the same); the bubbles would then grow until—presumably—they coalesced. Unfortunately, Guth and Erick J. Weinberg of Columbia University have found that the exponentially expanding universe would be inflating more rapidly than the bubbles. As time went on the bubbles would come closer and closer to filling up all of space, but they would never fully coalesce. The resulting universe would be grossly inhomogeneous.

It may be, of course, that this problem is only apparent, that a greater insight into the physics of the transition and a more sophisticated approach to the calculations will resolve the difficulty. Another alternative, now being investigated by Guth and So Young Pi of the Stanford Linear Accelerator Center, is that the exit from exponential expansion can be made gracefully if the parameters of the particular GUT being used meet certain conditions.

In any case, phase transitions in the early universe have become a popular area of research. For example, they were the subject of a special workshop at last December's Texas Symposium on Relativistic Astrophysics. A "Grand Bang" model similar to the inflationary scenario has recently been discussed by A. D. Linde of the Lebedev Physical Institute in Moscow. At the very least, Guth's central idea, that a GUT-style phase transition could have generated most or all of the matter and energy in the universe (or, more precisely, most or all of the entropy), is an enormously appealing one that may well be an inspiration for more successful theories.

—M. Mitchell Waldrop