Bubbles upon the River of Time

A Princeton astrophysicist models the cosmos as an infinity of bubbles, each a separate universe; he thereby offers an explanation of the origin of matter and energy

Many and strange are the universes that drift like bubbles in the foam upon the River of Time.—ARTHUR C. CLARKE, "The Wall of Darkness"

Arthur C. Clarke wrote of a universe twisted on itself like a Moebius strip. J. Richard Gott's cosmology is not that strange, but his river of time is equally as bountiful.

Gott, an astrophysicist at Princeton University, proposes* that our universe is only one of perhaps an infinite number that formed like bubbles in a very hot, dense space called de Sitter space. Each of these universes is itself "open," or infinite in extent, and each will continue to expand forever. According to the general theory of relativity (Einstein's theory of gravity), says Gott, the interior of any given bubble behaves almost exactly as in the standard Big Bang model.

The latter model holds that the universe began in a singularity of infinite density and temperature. That singularity has always worried scientists. It seems to imply the breakdown of all physical law. Gott's model does away with it, however, by allowing the initial bubble to form smoothly out of the surrounding de Sitter space. In addition, his model explains a number of things that are mysteries in the standard picture. Among them are the ultimate origin of matter and energy, and the remarkable large-scale uniformity of the universe.

Gott's work stands in the mainstream of recent efforts to understand the interplay between gravitation and particle physics, and particularly between the grand unified theories and cosmology (*Science*, 20 February 1981, p. 803; 3 July 1981, p. 121). The inspiration for this work came in 1974, when Cambridge physicist Stephen Hawking proved that a black hole does more than swallow things up; it also emits radiation as if it were hot. Later, Hawking and others proved that this is just a special case of a more profound theorem, that thermal radiation is emitted anywhere there is an "event horizon"—loosely speaking, the boundary of a region from which light cannot escape. "One of the most famous properties of de Sitter space," Gott told *Science*, "is that it is just full of event horizons and Hawking radiation."

This particular kind of space is named after Willem de Sitter, who first studied its properties in 1917. It is a solution to Einstein's gravitational field equations with the addition of a cosmological constant, a kind of universal repulsive force. It describes an infinite, curved universe that is expanding, in the sense that individual particles tend to move apart at an exponentially increasing rate.

It is the exponential expansion that creates the event horizons, explains Gott; if two points are sufficiently far apart, they separate so rapidly that a light beam starting out from one will never reach the other. The Hawking radiation associated with these event horizons has been calculated by Hawking and G. W. Gibbons; in the first half of his model Gott takes their result, which expresses the energy density of the radiation in terms of the de Sitter expansion rate, and imposes a consistency requirement.

The cosmological constant, explains Gott, is mathematically equivalent to filling de Sitter space with a fluid whose density is constant and positive, and whose pressure is constant and *negative*—a kind of universal suction. Bizarre as this sounds, he says, recent calculations in quantum field theory indicate that Hawking radiation might behave in exactly this way under certain conditions. This result allows Gott to join all these pieces into a full circle: the cosmological constant, or fluid, causes the exponential expansion of the de Sitter space; the expansion creates event horizons; the horizons generate Hawking radiation; and the radiation becomes the fluid that caused the expansion in the first place. He finds that this is only possible if the radiation is fiercely hot (5×10^{31} K) and exceedingly dense (3×10^{93} grams per cubic centimeter). It is probably no coincidence, he notes, that these are also the conditions under which gravity itself begins to act like a quantum field.

In the second half of his model, Gott assumes that somewhere in the midst of this cauldron there occurs a kind of phase tradition, a subtle change in the nature of matter. He is deliberately vague about the details of the transition, since the overall picture is independent of those details. (Particle physicists have

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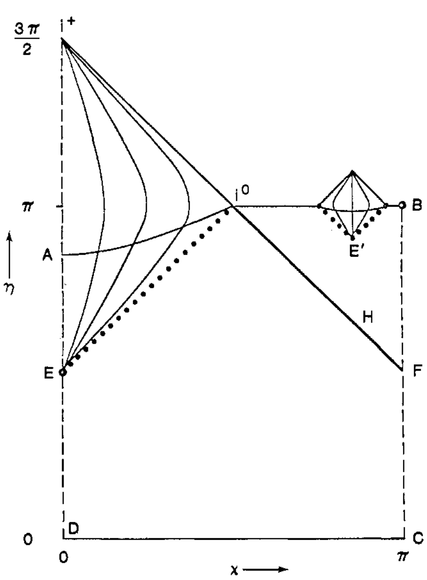

Gott's model illustrated in a conformal diagram, in which light rays always travel at 45°. Material particles, less rapid than light, always travel along more vertical paths. If there were no bubbles, both the timelike coordinate η and the spacelike coordinate χ would run from 0 to π, and the region ABCD *would be a perfect square enclosing all of de Sitter space. The line* DC *would lie in the infinite past (η = 0), the line* AB *in the infinite future ($\eta = \pi$). However, a bubble appears at* E *and its wall (dotted line) expands outward at the speed of light, until in the infinite future it reaches spatial infinity (i°). Within the bubble, meanwhile, the time coordinate is drastically altered. Individual particles of Hawking radiation (solid lines) move apart along with the expanding bubble. About 10^{-42} second after* E *(line* Ai°*) the phase transition inside the bubble is complete, and the bubble continues to expand as in the standard Big Bang model. In the infinite future (i+) all particles have receded to infinity. (The curvature of the lines is an artifact of the conformal diagram). The line* H *marks the event horizon of this bubble; no light can reach it from the upper right-hand corner. At* E *another bubble universe forms, forever out of reach of the first.*

explored a number of possibilities within the context of the grand unified theories. Massless quarks might suddenly acquire a mass through a process known as spontaneous symmetry breaking, for example.) In any case, a low-density bubble forms and expands at virtually the speed of light. Hawking radiation enters from the surrounding de Sitter space and, during the next 10^{-42} second or so, converts to ordinary matter with a positive pressure. Human astronomers, denizens of the bubble some 10 billion or 20 billion years later, look back on it all and call it the Big Bang.

Where did all the matter and energy in the universe come from? It was Hawking radiation, says Gott. The 3 K cosmic microwave background radiation is a modern remnant. Why are the microwave background and the universe as a whole so well blended and uniform? Because in de Sitter space, says Gott, the Hawking radiation is naturally uniform.

Gott's bubbles form just like bubbles in a glass of beer—randomly. De Sitter space could easily hold an infinity of them. But alas, there is no way to communicate with our neighbors. Light would never make it from one bubble universe to the next. So how does Gott propose to test his model?

"We need to do more detailed quantum mechanical calculations of how bubbles behave in de Sitter space," he says. "If it becomes a nice, self-consistent theoretical framework, that would stand it in good stead.

"The most important observational test is the large-scale structure of the universe," he adds. "Galaxies and clusters never would have formed in a completely homogeneous universe. So there must have been some *in*homogeneities. But no one has ever been able to figure out where they came from. This theory might allow us to calculate the initial spectrum of random fluctuations, and see if those fluctuations could grow up into the large-scale structure we see today."—M. MITCHELL WALDROP

Leprosy Vaccine Trials to Begin Soon

Microorganisms isolated from armadillos are the basis of vaccine; investigators finally establish the disease in primates

Leprosy is a disease marked by myth and misinformation. The disease is commonly associated with the Bible, for example, but the mentions of leprosy in the Book of Leviticus and the Gospels may be mistranslations of the Hebrew and Greek terms for less serious forms of skin disease. It is widely believed that leprosy is highly infectious—and the term "leper" has come to mean an individual who is shunned by society—but in fact the disease is only mildly contagious and as much as 90 percent of the world's population may be immune. Individuals whose disease is controlled by drugs are completely noninfectious.

It is also believed that leprosy has been largely controlled. This may be true in the United States, where there are at most some 5000 cases, but it is not true in the rest of the world. There are about 12 million cases worldwide—3.5 million in India alone—and the prevalence in some small communities may be as high as 7 percent. Moreover, the problem is getting worse rather than better: the infective agent has begun to develop resistance to the most commonly used and most effective drug, dapsone.

But there is also a bright side. During the last decade, investigators have succeeded in infecting armadillos with leprosy, making significant quantities of the infective microorganism available for the first time. They are now using these microorganisms to produce a vaccine that is expected to undergo safety trials sometime this year. Some preliminary results from Venezuela suggest that this vaccine might even help people who already have the disease. Recently, furthermore, investigators have succeeded for the first time in infecting primates with leprosy, hoping to provide an animal model that more closely resembles the human disease. And finally, investigators are beginning clinical trials with combinations of drugs (see box) that promise to overcome drug resistance and that might even provide a cure.

Production of the vaccine requires an extraordinary amount of cooperation among several research groups.

Leprosy is primarily a disease of the skin and peripheral nerves. It is characterized by a spectrum of severities ranging between two polar forms, tuberculoid and lepromatous. About 20 percent of leprosy victims develop the lepromatous form, which is characterized by skin lesions that appear over most of the body. The skin on the forehead and face thickens, with natural lines becoming exaggerated, and loss of facial hair can occur. Lepromatous patients are unable to produce a cell-mediated immune response to the microorganism for reasons that are not yet understood.

In the more common and less severe tuberculoid form, single skin lesions and loss of feeling in the involved areas are frequent early symptoms. Nerve involvement can also lead to damage to muscles and bones, and patients often inadvertently mutilate hands and feet because of the anaesthesia. These patients produce a partially effective cell-mediated immune response, but this weak response may also damage tissues. As many as 30 percent of all leprosy victims develop deformities.

Leprosy today is primarily a disease of the tropics; in the United States, it is restricted primarily to California, Texas, and Hawaii. The incidence in this country has more than tripled since 1965; many of the more than 225 new cases each year are discovered among immigrants from endemic areas. Investigators speculate that the higher incidence in developing countries may reflect poor sanitation. The disease is believed to be spread through nasal secretions.

The causative agent, *Mycobacterium leprae*, is related to the mycobacterium that causes tuberculosis. One of its most unusual characteristics is an exceptional-

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