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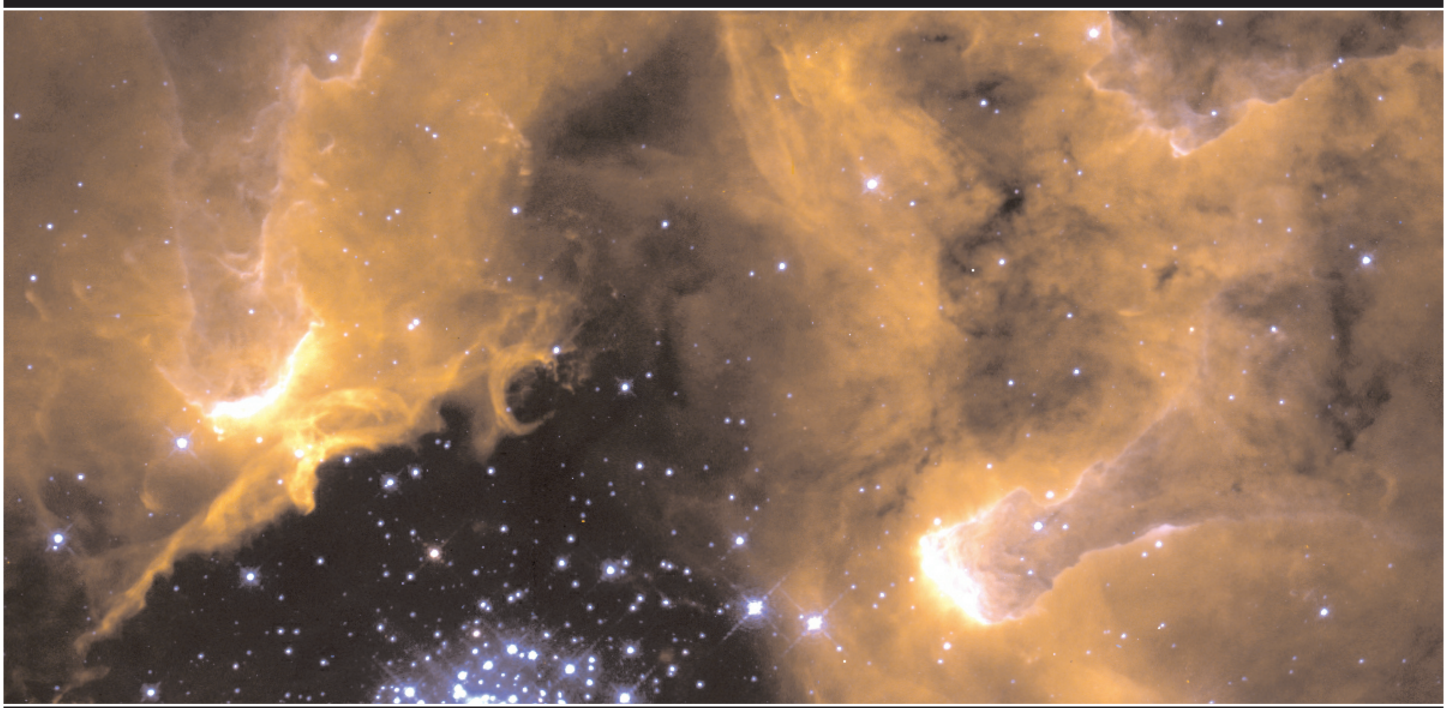
Mysteries of the Universe

Dennis Overbye, a science reporter for The Times, explores the mysteries of the universe – from black holes to quantum mechanics – in this collection of articles, selected by Mr. Overbye.



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Mysteries of the Universe

COSMOLOGICAL CONSTANT

A Famous Einstein 'Fudge' Returns to Haunt Cosmology

By DENNIS OVERBYE

There are few scientists of whom it can be said that their mistakes are more interesting than their colleagues' successes, but Albert Einstein was one. Few "blunders" have had a longer and more eventful life than the cosmological constant, sometimes described as the most famous fudge factor in the history of science, that Einstein added to his theory of general relativity in 1917. Its role was to provide a repulsive force in order to keep the universe from theoretically collapsing under its own weight. Einstein abandoned the cosmological constant when the universe turned out to be expanding, but in succeeding years, the cosmological constant, like Rasputin, has stubbornly refused to die, dragging itself to the fore, whispering of deep enigmas and mysterious new forces in nature, whenever cosmologists have run into trouble reconciling their observations of the universe with their theories.

This year the cosmological constant has been propelled back into the news as an explanation for the widely reported discovery, based on observations of distant exploding stars, that some kind of "funny energy" is apparently accelerating the expansion of the universe. "If the cosmological constant was good enough for Einstein," the cosmologist Michael Turner of the University of Chicago remarked at a meeting in April, "it should be good enough for us."

Einstein has been dead for 43 years. How did he and his 80-year-old fudge factor come to be at the center of a revolution in modern cosmology?

The story begins in Vienna with a mystical concept that Einstein called Mach's principle. Vienna was the intellectual redoubt of Ernst Mach (1838-1916), a physicist and philosopher who bestrode European science like a Colossus. The scale by which supersonic speeds are measured is named for him. His biggest legacy was philosophical; he maintained that all knowledge came from the senses, and campaigned relentlessly against the introduction of what he considered metaphysical concepts in science, atoms for example.

Another was the notion of absolute space, which formed the framework of Newton's universe. Mach argued that we do not see "space," only the players in it. All our knowledge of motion, he pointed out, was only relative to the "fixed stars." In his books and papers, he wondered if inertia, the tendency of an object to remain at rest or in motion until acted upon by an outside force, was similarly relative and derived somehow from an interaction with everything else in the universe.

"What would become of the law of inertia if the whole of the heavens began to move and stars swarmed in confusion?" he wrote in 1911. "Only in the case of a shattering of the universe do we learn that all bodies, each with its share, are of importance in the law of inertia."

Mach never ventured a guess as to how this mysterious interaction would work, but Einstein, who admired Mach's incorrigible skepticism, was enamored of what he sometimes called Mach's principle and sometimes called the relativity of inertia. He hoped to incorporate the concept in his new theory of general relativity, which he completed in 1915. That theory describes how matter and energy distort or "curve" the geometry of space and time, producing the phenomenon called gravity.

In the language of general relativity, Mach's principle required that the space-time curvature should be determined solely by other matter or energy in the universe, and not any initial conditions or outside influences -- what physicists call boundary conditions. Among other things, Einstein took this to mean that it should be impossible to solve his equations for the case of a solitary object -- an atom or a star alone in the universe -- since there would be nothing to compare it to or interact with.

So Einstein was surprised a few months after announcing his new theory, when Karl Schwarzschild, a German astrophysicist serving at the front in World War I, sent him just such a solution, which described the gravitational field around a solitary star. "I would not have believed that the strict treatment of the point mass problem was so simple," Einstein said.

Perhaps spurred in part by Schwarzschild's results, Einstein turned his energies in the fall of 1916 to inventing a universe with boundaries that would prevent a star from escaping its neighbors and drifting away into infinite un-Machian loneliness. He worked out his ideas in a correspondence with a Dutch astronomer, Willem de Sitter, which are to be published this summer by the Princeton University Press in Volume 8 of "The Collected Papers of Albert Einstein." Like most of his colleagues at the time, Einstein considered the universe to consist of a cloud of stars, namely the Milky Way, surrounded by vast space. One of his ideas envisioned "distant masses" ringing the outskirts of the Milky Way like a fence. These masses would somehow curl up space and close it off.

His sparring partner de Sitter scoffed at that, arguing these "supernatural" masses would not be part of the visible universe. As such, they were no more palatable than Newton's old idea of absolute space, which was equally invisible and arbitrary.

In desperation and laid up with gall bladder trouble in February of 1917, Einstein hit on the idea of a universe without boundaries, in which space had been bent around to meet itself, like the surface of a sphere, by the matter within. "I have committed another suggestion with respect to gravitation which exposes me to the danger of being confined to the nut house," he confided to a friend.

This got rid of the need for boundaries -- the surface of a sphere has no boundary. Such a bubble universe would be defined solely by its matter and energy content, as Machian principles dictated. But there was a new problem; this universe was unstable, the bubble had to be either expanding or contracting. The Milky Way appeared to be neither expanding nor contracting; its stars did not seem to be going anywhere in particular.

Here was where the cosmological constant came in. Einstein made a little mathematical fix to his equations, adding "a cosmological term" that stabilized them and the universe. Physically, this new term, denoted by the Greek letter lambda, represented some kind of long range repulsive force, presumably that kept the cosmos from collapsing under its own weight.

Admittedly, Einstein acknowledged in his paper, the cosmological constant was "not justified by our actual knowledge of gravitation," but it did not contradict relativity, either. The happy result was a static universe of the type nearly everybody believed they lived in and in which geometry was strictly determined by matter. "This is the core of the requirement of the relativity of inertia," Einstein explained to de Sitter. "To me, as long as this requirement had not been fulfilled, the goal of general relativity was not yet completely achieved. This only came about with the lambda term."

The joke, of course, is that Einstein did not need a static universe to have a Machian one. Michel Janssen, a Boston University physicist and Einstein scholar, pointed out, "Einstein needed the constant not because of his philosophical predilections but because of his prejudice that the universe is static."

Moreover, in seeking to save the universe for Mach, Einstein had destroyed Mach's principle. "The cosmological term is radically anti-Machian, in the sense that it ascribes intrinsic properties (energy and pressure-density) to pure space, in the absence of matter," said Frank Wilczek, a theorist at the Institute for Advanced Study in Princeton.

In any event, Einstein's new universe soon fell apart. In another 10 years the astronomer Edwin Hubble in California was showing that mysterious spiral nebulae were galaxies far far away and getting farther -- in short that the universe might be expanding.

De Sitter further confounded Einstein by coming up with his own solution to Einstein's equations that described a universe that had no matter in it at all.

"It would be unsatisfactory, in my opinion," Einstein grumbled, "if a world without matter were possible."

De Sitter's empty universe was also supposed to be static, but that too proved to be an illusion. Calculations showed that when test particles were inserted into it, they flew away from each other. That was the last straw for Einstein. "If there is no quasi-static world," he said in 1922, "then away with the cosmological term."

In 1931, after a trip to the Mount Wilson observatory in Pasadena, Calif., to meet Hubble, Einstein turned his back on the cosmological constant for good, calling it "theoretically unsatisfactory anyway."

He never mentioned it again.

In the meantime, the equations for an expanding universe had been independently discovered by Aleksandr Friedmann, a young Russian theorist, and by the Abbe Georges Lemaitre, a Belgian cleric and physicist. A year after his visit with Hubble, Einstein threw his weight, along with de Sitter, behind an expanding universe without a cosmological constant.

But the cosmological constant lived on in the imagination of Lemaitre, who found that by judicious application of lambda he could construct universes that started out expanding slowly and then sped up, universes that started out fast and then slowed down, or one that even began expanding, paused, and then resumed again.

This last model beckoned briefly to some astronomers in the early 1950's, when measurements of the cosmic expansion embarrassingly suggested that the universe was only two billion years old -- younger Earth. A group of astronomers visited Einstein in Princeton and suggested that resuscitating the cosmological constant could resolve the age discrepancy. Einstein turned them down, saying that the introduction of the cosmological constant had been the biggest blunder of his life. George Gamow, one of the astronomers, reported the remark in his autobiography, "My World Line," and it became part of the Einstein legend.

Einstein died three years later. In the years after his death, quantum mechanics, the strange set of rules that describe nature on the subatomic level (and Einstein's bete noire) transformed the cosmological constant and showed just how prescient Einstein had been in inventing it. The famous (and mystical in its own right) uncertainty principle decreed that there is no such thing as nothing, and even empty space can be thought of as foaming with energy.

The effects of this vacuum energy on atoms had been detected in the laboratory, as early as 1948, but no one thought to investigate its influence on the universe as a whole until 1967, when a new crisis, an apparent proliferation of too-many quasars when the universe was about one-third its present size, led to renewed muttering about the cosmological constant. Jakob Zeldovich, a legendary Russian theorist who was a genius at marrying microphysics to the universe, realized that this quantum vacuum energy would enter into Einstein's equations exactly the same as the old cosmological constant.

The problem was that a naive straightforward calculation of these quantum fluctuations suggested that the vacuum energy in the universe should be about 118 orders of magnitude (10 followed by 117 zeros) denser than the matter. In which case the cosmological constant would either have crumpled the universe into a black hole in the first instant of its existence or immediately blown the cosmos so far apart that not even atoms would ever have formed. The fact that the universe had been sedately and happily expanding for 10 billion years or so, however, meant that any cosmological constant, if it existed at all, was modest.

Even making the most optimistic assumptions, Dr. Zeldovich still could not make the predicted cosmological constant to come out to be less than a billion times the observed limit.

Ever since then, many particle theorists have simply assumed that for some as-yet-unknown reason the cosmological constant is zero. In the era of superstrings and ambitious theories of everything tracing history back to the first micro-micro second of unrecorded time, the cosmological constant has been a trapdoor in the basement of physics, suggesting that at some fundamental level something is being missed about the world. In an article in Reviews of Modern Physics in 1989, Steven Weinberg of the University of Texas referred to the cosmological constant as "a veritable crisis," whose solution would have a wide impact on physics and astronomy.

Things got even more interesting in the 1970's with the advent of the current crop of particle physics theories, which feature a shadowy entity known as the Higgs field, which permeates space and gives elementary particles their properties. Physicists presume that the energy density of the Higgs field today is zero, but in the past, when the universe was hotter, the Higgs energy could have been enormous and dominated the dynamics of the universe. In fact, speculation that such an episode occurred a fraction of a second after the Big Bang, inflating the wrinkles out of the primeval chaos -- what Dr. Turner calls vacuum energy put to a good use -- has dominated cosmology in the last 15 years.

"We want to explain why the effective cosmological constant is small now, not why it was always small," Dr. Weinberg wrote in his review. In their efforts to provide an explanation, theorists have been driven recently to talk about multiple universes connected by space-time tunnels called wormholes, among other things.

The flavor of the crisis was best expressed, some years ago at an astrophysics conference by Dr. Wilczek. Summing up the discussions at the end of the meeting, he came at last to the cosmological constant. "Whereof one cannot speak, thereof one must be silent," he said, quoting from Ludwig Wittgenstein's "Tractatus Logico-Philosophicus."

Now it seems that the astronomers have broken that silence.

Quantum Theory Tugged, and All of Physics Unraveled

By DENNIS OVERBYE

They tried to talk Max Planck out of becoming a physicist, on the grounds that here was nothing left to discover. The young Planck didn't mind. A conservative youth from the south of Germany, a descendant of church rectors and professors, he was happy to add to the perfection of what was already known.

Instead, he destroyed it, by discovering what was in effect a loose thread that when tugged would eventually unravel the entire fabric of what had passed for reality.

As a new professor at the University of Berlin, Planck embarked in the fall of 1900 on a mundane sounding calculation of the spectral characteristics of the glow from a heated object. Physicists had good reason to think the answer would elucidate the relationship between light and matter as well as give German industry a leg up in the electric light business. But the calculation had been plagued with difficulties.

Planck succeeded in finding the right formula, but at a cost, as he reported to the German Physical Society on Dec. 14. In what he called "an act of desperation," he had to assume that atoms could only emit energy in discrete amounts that he later called quanta (from the Latin quantus for "how much") rather than in the continuous waves prescribed by electromagnetic theory. Nature seemed to be acting like a fussy bank teller who would not make change, and would not accept it either.

That was the first shot in a revolution. Within a quarter of a century, the common sense laws of science had been overthrown. In their place was a bizarre set of rules known as quantum mechanics, in which causes were not guaranteed to be linked to effects; a subatomic particle like an electron could be in two places at once, everywhere or nowhere until someone measured it; and light could be a wave or a particle.

Niels Bohr, a Danish physicist and leader of this revolution, once said that a person who was not shocked by quantum theory did not understand it.

This week, some 700 physicists and historians are gathering in Berlin, where Planck started it all 100 years ago, to celebrate a theory whose meaning they still do not understand but that is the foundation of modern science. Quantum effects are now invoked to explain everything from the periodic table of the elements to the existence of the universe itself.

Fortunes have been made on quantum weirdness, as it is sometimes called. Transistors and computer chips and lasers run on it. So do CAT scans and PET scans and M.R.I. machines. Some computer scientists call it the future of computing, while some physicists say that computing is the future of quantum theory.

"If everything we understand about the atom stopped working," said Leon Lederman, former director of the Fermi National Accelerator Laboratory, "the G.N.P. would go to zero."

The revolution had an inauspicious start. Planck first regarded the quantum as a bookkeeping device with no physical meaning. In 1905, Albert Einstein, then a patent clerk in Switzerland, took it more seriously. He pointed out that light itself behaved in some respects as if it were composed of little energy bundles he called lichtquanten. (A few months later Einstein invented relativity.)

He spent the next decade wondering how to reconcile these quanta with the traditional electromagnetic wave theory of light. "On quantum theory I use up more brain grease than on relativity," he told a friend.

The next great quantum step was taken by Bohr. In 1913, he set forth a model of the atom as a miniature solar system in which the electrons were limited to specific orbits around the nucleus. The model explained why atoms did not just collapse -- the lowest orbit was still some slight distance from the nucleus. It also explained why different elements emitted light at characteristic wavelengths -- the orbits were like rungs on a ladder and those wavelengths corresponded to the energy released or absorbed by an electron when it jumped between rungs.

But it did not explain why only some orbits were permitted, or where the electron was when it jumped between orbits. Einstein praised Bohr's theory as "musicality in the sphere of thought," but told him later, "If all this is true, then it means the end of physics."

While Bohr's theory worked for hydrogen, the simplest atom, it bogged down when theorists tried to calculate the spectrum of bigger atoms. "The whole system of concepts of physics must be reconstructed from the ground up," Max Born, a physicist at Gottingen University, wrote in 1923. He termed the as-yet-unborn new physics "quantum mechanics."

Boy's Mechanics

The new physics was born in a paroxysm of debate and discovery from 1925 to 1928 that has been called the second scientific revolution. Wolfgang Pauli, one of its ringleaders, called it "boy's mechanics," because many of the physicists, including himself, then 25, Werner Heisenberg, 24, Paul Dirac, 23, Enrico Fermi, 23, and Pascual Jordan, 23, were so young when it began.

Bohr, who turned 40 in 1925, was their father-confessor and philosopher king. His new institute for theoretical physics in Copenhagen became the center of European science.

The decisive moment came in the fall of 1925 when Heisenberg, who had just returned to Gottingen University after a year in Copenhagen, suggested that physicists stop trying to visualize the inside of the atom and instead base physics exclusively on what can be seen and measured. In his "matrix mechanics," various properties of subatomic particles could be computed -- but, disturbingly, the answers depended on the order of the calculations.

In fact, according to the uncertainty principle, which Heisenberg enunciated two years later, it was impossible to know both the position and velocity of a particle at once. The act of measuring one necessarily disturbed the other.

Physicists uncomfortable with Heisenberg's abstract mathematics took up with a friendlier version of quantum mechanics based on the familiar mathematics of waves. In 1923, the Frenchman Louis de Broglie had asked in his doctoral thesis, if light could be a particle, then why couldn't particles be waves?

Inspired by de Broglie's ideas, the Austrian Erwin Schrodinger, then at the University of Zurich and, at 38, himself older than the wunderkind, sequestered himself in the Swiss resort of Arosa over the 1925 Christmas holidays with a mysterious woman friend and came back with an equation that would become the yin to Heisenberg's yang.

In Schrodinger's equation, the electron was not a point or a table, but a mathematical entity called a wave function, which extended throughout space. According to Born, this wave represented the probability of finding the electron at some particular place. When it was measured, the particle was usually in the most likely place, but not guaranteed to be, even though the wave function itself could be calculated exactly.

Born's interpretation was rapidly adopted by the quantum gang. It was a pivotal moment because it enshrined chance as an integral part of physics and of nature.

"The motion of particles follows probability laws, but the probability itself propagates according to the law of causality," he explained.

That was not good enough for Einstein. "The theory produces a good deal but hardly brings us closer to the secret of the Old One," Einstein wrote in late 1926. "I am at all events convinced that he does not play dice."

Heisenberg called Schrodinger's theory "disgusting" -- but both versions of quantum mechanics were soon found to be mathematically equivalent.

Uncertainty, which added to the metaphysical unease surrounding quantum physics, was followed in turn in 1927 by Bohr's complementarity principle. Ask not whether light was a particle or a wave, said Bohr, asserting that both concepts were necessary to describe nature, but that since they were contradictory, an experimenter could choose to measure one aspect or the other but not both. This was not a paradox, he maintained, because physics was not about things but about the results of experiments.

Complementarity became the cornerstone of the Copenhagen interpretation of quantum mechanics -- or as Einstein called it, "the Heisenberg-Bohr tranquilizing philosophy."

A year later, Dirac married quantum mechanics to Einstein's special relativity, in the process predicting the existence of antimatter. (The positron, the antiparticle to the electron, was discovered four years later by Carl Anderson.)

Dirac's version, known as quantum field theory, has been the basis of particle physics ever since, and signifies, in physics histories, the end of the quantum revolution. But the fight over the meaning of the revolution had just barely begun, and it has continued to this day.

Quantum Wars

The first and greatest counterrevolutionary was Einstein, who hoped some deeper theory would rescue God from playing dice. In the fall of 1927 at a meeting in Brussels, Einstein challenged Bohr with a series of gedanken, or thought experiments, designed to show that quantum mechanics was inconsistent. Bohr, stumped in the morning, always had an answer by dinner.

Einstein never gave up. A 1935 paper written with Boris Podolsky and Nathan Rosen described the ultimate quantum gedanken, in which measuring a particle in one place could instantly affect measurements of the other particle, even if it was millions of miles away. Was this any way to run a universe?

Einstein called it "spooky action at a distance."

Modern physicists who have managed to create this strange situation in the laboratory call it "entanglement."

Einstein's defection from the quantum revolution was a blow to his more conservative colleagues, but he was not alone. Planck also found himself at odds with the direction of the revolution and Schrodinger, another of "the conservative old gentlemen," as Pauli once described them, advanced his cat gedanken experiment to illustrate how silly physics had become.

According to the Copenhagen view, it was the act of observation that "collapsed" the wave function of some particle, freezing it into one particular state, a location or velocity.

Until then, all the possible states of the particle coexisted, like overlapping waves, in a condition known as quantum superposition.

Schrodinger imagined a cat in a sealed container in which the radioactive decay of an atom would trigger the release of cyanide, killing the cat. By the rules of quantum mechanics the atom was both decayed and not decayed until somebody looked inside, which meant that Schrodinger's poor cat was both alive and dead.

This seemed to be giving an awful lot of power to the "observer." It was definitely no way to run a universe.

Over the years physicists have proposed alternatives to the Copenhagen view.

Starting in 1952, when he was at Princeton, the physicist David Bohm, who died in 1992, argued for a version of quantum mechanics in which there was a deeper level, a so-called quantum potential or "implicate order," guiding the apparent unruliness of quantum events.

Another variant is the many-worlds hypothesis developed by Hugh Everett III and John Wheeler, at Princeton in 1957. In this version the wave function does not collapse when a physicist observes an electron or a cat; instead it splits into parallel universes, one for every possible outcome of an experiment or a measurement.

Shut Up and Compute

Most physicists simply ignored the debate about the meaning of quantum theory in favor of using it to probe the world, an attitude known as "shut up and compute."

Pauli's discovery that no two electrons could share the same orbit in an atom led to a new understanding of atoms, the elements and modern chemistry.

Quantum mechanics split the atom and placed humanity on the verge of plausible catastrophe. Engineers learned how to "pump" electrons into the upper energy rungs in large numbers of atoms and then make them all dump their energy all at once, giving rise to the laser. And as Dr. Lederman said in an interview, "The history of transistors is the history of solving Schrodinger's equation in various materials."

Quantum effects were not confined to the small. The uncertainty principle dictates that the energy in a field or in empty space is not constant, but can fluctuate more and more wildly the smaller the period of time that one looks at it. Such quantum fluctuations during the big bang are now thought to be the origin of galaxies.

In some theories, the universe itself is a quantum effect, the result of a fluctuation in some sort of preuniversal nothingness. "So we take a quantum leap from eternity into time," as the Harvard physicist Sidney Coleman once put it.

Where the Weirdness Goes

Bohr ignored Schrodinger's cat, on the basis that a cat was too big to be a quantum object, but the cat cannot be ignored anymore. In the last three decades, the gedanken experiments envisioned by Einstein and his friends have become "ungedankened," bringing the issues of their meaning back to the fore.

Last summer, two teams of physicists managed to make currents go in two directions at once around tiny superconducting loops of wire -- a feat they compared to Schrodinger's cat. Such feats, said Wojciech Zurek, a theorist at Los Alamos National Laboratory, raise the question of why we live in a classical world at all, rather than in a quantum blur.

Bohr postulated a border between the quantum and classical worlds, but theorists prefer that there be only one world that can somehow supply its own solidity. That is the idea behind a new concept called decoherence, in which the interaction of wave functions with the environment upsets the delicate balance of quantum states and makes a cat alive or dead but not in between.

"We don't need an observer, just some 'thing' watching," Dr. Zurek explained. When we look at something, he said, we take advantage of photons, the carriers of light, which contain information that has been extracted from the object. It is this loss of information into the environment that is enough to crash the wave function, Dr. Zurek says.

Decoherence, as Dr. Zurek notes, takes the observer off a pedestal and relieves quantum theory of some of its mysticism, but there is plenty of weirdness left. Take the quantum computer, which Dr. Lederman refers to as "a kinder, gentler interpretation of quantum spookiness."

Ordinary computers store data and perform computations as a series of "bits," switches that are either on or off, but in a quantum computer, due to the principle of superposition, so-called qubits can be on and off at the same time, enabling them to calculate and store myriads of numbers at a time.

In principle, according to David Deutsch, an Oxford University researcher who is one of quantum computing's more outspoken pioneers, a vast number of computations, "potentially more than there are atoms in the universe," could be superposed inside a quantum computer to solve problems that would take a classical computer longer than the age of the universe.

In the minds of many experts, this kind of computing illuminates the nature of reality itself.

Dr. Deutsch claims that the very theory of a quantum computer forces physicists to take seriously the many-worlds interpretation of quantum theory. The amount of information being processed in these parallel computations, he explains, is more than the universe can hold. Therefore, they must be happening in other parallel universes out in the "multiverse," as it is sometimes called.

"There is no other theory of what is happening," he said. The world is much bigger than it looks, a realization that he thinks will have a psychological impact equivalent to the first photographs of atoms. Indeed, for Dr. Deutsch there seems to be a deep connection between physics and computation. The structure of the quantum computer, he says, consists of many things going on at once, lots or parallel computations. "Any physical process in quantum mechanics," he said. "consists of classical computations going on in parallel."

"The quantum theory of computation is quantum theory," he said.

The Roots of Weirdness

Quantum mechanics is the language in which physicists describe all the phenomena of nature save one, namely gravity, which is explained by Einstein's general theory of relativity. The two theories -- one describing a discontinuous "quantized" reality and the other a smoothly curving space-time continuum -- are mathematically incompatible, but physicists look to their eventual marriage, a so-called quantum gravity.

"There are different views as to whether quantum theory will encompass gravity or whether both quantum theory and general relativity will have to be modified," said Lee Smolin, a theorist at Penn State.

Some groundwork was laid as far back as the 1960's by Dr. Wheeler, 89, who has argued quantum theory with both Einstein and Bohr. Even space and time, Dr. Wheeler has pointed out, must ultimately pay their dues to the uncertainty principle and become discontinuous, breaking down at very small distances or in the compressed throes of the big bang into a space-time "foam."

Most physicists today put their hope for such a theory in superstrings, an ongoing and mathematically dense effort to understand nature as consisting of tiny strings vibrating in 10-dimensional space.

In a sort of missive from the front, Edward Witten of the Institute for Advanced Study in Princeton, N.J., said recently that so far quantum mechanics appeared to hold up in string land exactly as it was described in textbooks. But, he said in an e-mail message, "Quantum mechanics is somehow integrated with geometry in a way that we don't really understand yet."

The quantum is mysterious, he went on, because it goes against intuition. "I am one of those who believes that the quantum will remain mysterious in the sense that if the future brings any changes in the basic formulation of quantum mechanics, I suspect our ordinary intuition will be left even farther behind."

Intuition notwithstanding, some thinkers wonder whether or not quantum weirdness might, in fact, be the simplest way to make a universe. After all, without the uncertainty principle to fuzz the locations of its buzzing inhabitants, the atom would collapse in an electromagnetic heap. Without quantum fluctuations to roil the unholy smoothness of the big bang, there would be no galaxies, stars or friendly warm planets. Without the uncertainty principle to forbid nothingness, there might not even be a universe.

"We will first recognize how simple the universe is," Dr. Wheeler has often said, "when we recognize how strange it is." Einstein often said that the question that really consumed him was whether God had any choice in creating the world. It may be in the end that we find out that for God, the only game in town was a dice game.

In the New Physics, No Quark Is an Island

By DENNIS OVERBYE

"The universe," the poet Muriel Rukeyser once wrote, "is made of stories, not atoms." This being the science section, you might be tempted to regard that statement as a predictable humanistic rant against cold scientific reality. For the last 300 years, after all, the story that physicists have been telling us is that the shifting shape of the world is made exactly of atoms, irreducible and indestructible nuggets of existence, bouncing around according to Newton's and a few other simple laws.

The job of the physicist was simply to elucidate the identity and properties of the elementary particles engaged in this dance. Democritus, who invented the idea of atoms, endowed them simply with mass, shape and motion; today's elementary particles -- quarks and electrons -- have mass, charge, spin, strangeness and charm, among other properties, but the basic picture remains the same.

Or does it? Nowadays physicists -- those coldblooded reductionists -- are telling a more poetic but no less mathematically rigorous tale. It is a story not of a clockwork world but an entangled interactive world whose constituents derive their identities and properties from one another in endless negotiation -- a city, in one physicist's words, of querulous social inhabitants. In other words, they are telling a tale about relationships.

Take, for example, a recent calculation in which mass -- surely one of the fundamental properties of an elementary particle -- seems to conjure itself out of thin mathematical air in a phenomenon that Frank Wilczek, a physicist at M.I.T., calls "mass without mass."

Dr. Wilczek found that when he used a simplified version of the equations of quantum chromodynamics, which describes the behavior of quarks, to compute the masses of the proton and the neutron, he got the right answer even if the quarks inside them had no mass at all.

Where did the mass come from? It turns out that the quarks zipping around inside the proton, say, have a lot of kinetic energy, and that energy is equivalent to mass, according to Einstein's relativity.

In a talk in San Francisco last month, Dr. Wilczek referred to his calculation as an example of "it from bit," a phrase coined by the Princeton theorist John Wheeler to describe the dream of a theory of the universe based entirely on logic without any adjustable parameters -- a universe with no knobs to twiddle. In this case, the theory of quantum chromodynamics seems to leave God with no choice about the mass of the proton. The mass comes entirely from the arrangement of the quarks and not at all from the quarks themselves.

Particle physics, Dr. Wilczek and his colleagues like to point out, is not really about particles anymore, but about their mathematical relationships -- in particular symmetries -- aspects of nature that remain invariant under different circumstances and viewpoints. One example of this snowflake approach to science is the dictate that the laws of physics be the same at any speed, which forms the basis of Einstein's theory of relativity.

Another was the so-called eightfold way, a pattern that Murray Gell-Mann and Yuval Ne'emann discerned in 1961 in the properties of what was then a burgeoning list of elementary particles, allowing them to predict the existence of a previously unsuspected particle. The work contributed to Dr. Gell-Mann's 1969 Nobel Prize. Today physicists hoping for a toehold on a theory that would unite all the forces of nature into a single mathematical expression are straining for a glimpse of something called supersymmetry.

Quantum mechanics, which are the house rules of particle physics, enforce their own powerful version of relatedness. According to them, it is possible to create "entangled" particles which remain connected even if they are light-years apart, so that measuring one instantaneously affects the outcome of measuring the other. Einstein, who did not like quantum mechanics, labeled this effect "spooky action at a distance," but it is real enough to have a future in cryptography and quantum computers.

Einstein did try to embrace another, even spookier, kind of action at a distance in his general theory of relativity, which describes gravity as a warp in the geometry of space. This was a suggestion by Ernst Mach, a 19th-century physicist, philosopher and scourge of absolutist thinking, that since all motion was relative, the inertia of any given object in the universe was somehow determined by its relation to all the other masses in the universe. According to Mach's principle, it makes no sense to think of a single particle alone in the universe. Scholars seem to agree that Einstein's theory did not achieve this goal, but the idea continues to haunt the work of theorists working to marry Einstein's gravity to quantum mechanics.

"It can no longer be maintained that the properties of any one thing in the universe are independent of the existence or nonexistence of everything else," the quantum gravity theorist Lee Smolin wrote in his 1997 book, "The Life of the Cosmos." No electron is an island.

Dr. Smolin argues in his book that society (and for that matter science) has yet to come to grips with the lessons of relativity and quantum mechanics. Cosmologists, for example, persist in speaking as if they can observe the whole universe, which they cannot do because they must remain part of it, messing it up by their activities.

According to relativity, each place in the universe is unique and thus yields a unique viewpoint. As a result, he suggests, we have to abandon the idea that any single observer can compile a complete description of the universe. It may be that cosmological knowledge is a community effort, with each individual only able to attain a piece of the truth. "I accept that I cannot know everything," Dr. Smolin has written. "But perhaps, at least in principle, we can know everything."

To the extent that the stories we tell about nature seem to be connected to the stories we tell about ourselves, such thoughts could augur a shift that might yet reverberate through the metaphysical foundations of society. Scholars have noted what sometimes seems like a parallel between human social and political arrangements and our perception of the nature of the physical world. Metaphors from one arena of life seem to be able to infect others.

"There are periods when a particular idea holds sway in many different fields," said Gerald Holton, a historian and physicist at Harvard. "The great question is why?"

One such episode, Dr. Holton points out, happened early in the 20th century, when the notions of discontinuity and non-Euclidean geometry began to predominate in both art and science. Among those influenced by these ideas was the Russian abstract artist Wassily Kandinsky, who said that he was inspired in his quest to transgress the boundaries of traditional painting by experiments in 1912 showing that the previously inviolable atom in fact had an internal structure, namely a nucleus. "The collapse of the atom model," he wrote in his memoir, "Rückblick," "was equivalent in my soul to the collapse of the whole world." After that, anything was possible.

It has been speculated that watching the movements of the stars gave humans their first hints of order in the universe. Is it a coincidence that life was dominated by hierarchies of kings and medieval court societies while the heavens were thought to consist of concentric spheres centered on the earth? Or that modern democracy with its view of autonomous citizens with inalienable rights arose at about the same time as Newtonian physics with its atoms with their fixed properties bouncing in absolute space?

"In the beginning, when the King's will began to take effect, He engraved signs into the heavenly sphere," it says in the Zohar, a book of Kabbalistic writings from the first century. What signs do we see on the heavenly spheres today?

Newtonian atoms seem like a prescription for alienation. If the word got out that all particles were entangled, would we accept that our lives too were entangled? Dr. Wilczek, whose own book (with Betsy Devine) was called "Longing for the Harmonies," said that the connection between physics and society was "subtle," but he also agreed enthusiastically that the potential for influence was enormous. "If you have the idea that everything is connected and related, it might make you take everything more seriously," Dr. Wilczek said. "Many conflicts and concerns might seem very petty."

It would be pretty to think that physicists could remake society, but the metaphors probably flow the other way, according to some historians of science. "After all," says Lynn K. Nyhart, who studies the history of biology at the University of Wisconsin, "science is surrounded by society," pointing out that the phrase "natural selection" was first used in economic circles before Darwin appropriated it to describe biological evolution. (Although the economists seem to have borrowed the word "nature" first.) Dr. Nyhart said she thought that utopian language in quantum physics books sounded like a reaction against the atomization of society. "We are so atomized by the markets and people are trying to find ways to reassert their connections."

In short we want a new story to tell ourselves.

From Light to Darkness: Astronomy's New Universe

By DENNIS OVERBYE

BALTIMORE, April 5 -- A gasp went through the auditorium of the Space Telescope Science Institute on Wednesday when Dr. Adam Riess, a young astronomer from the institute, put the last mark on his so-called Hubble diagram, a plot of the brightness and speed of distant objects that astronomers use to divine the history of the universe.

The Darth Vaders of astronomy had gathered here to take stock of their expanding and increasingly dark realm. Once upon a time astronomy was about what could be seen in the sky, about jewel-like lights that moved in eternally recurring patterns and the soft glow of galaxies and comets.

Now it is about what cannot be seen. In the last few decades astronomers have had to confront the possibility that stars and galaxies -- not to mention the creatures that inhabit them -- are barely more than flecks of froth on a stormy sea of dark matter.

Now Dr. Riess was presenting his colleagues with evidence, based on observations of a star that exploded 11 billion years ago, that the universe -- dark matter and all -- was being blown apart under the influence of a mysterious antigravitational force known only as "dark energy."

"We are doing astronomy of the invisible," admitted Dr. Mario Livio, a theorist at the Space Telescope institute, who had organized the meeting, called "The Dark Universe: Matter, Energy, and Gravity" last fall.

As it turned out, the meeting coincided with a NASA news conference announcing the breakthrough discovery by Dr. Riess and his colleagues and thus was dominated by discussions of new telescopes in space and new dimensions in the universe as astronomers grappled with the meaning of dark energy and how to take its measure.

Now physicists, some of whom have been reluctant to take acceleration of the universe seriously, will have to explain what this dark energy is. "Those numbers are alarming, and apparently true," said Dr. Michael Dine, a theoretical physicist from the University of California at Santa Cruz. He described his colleagues as now working "frantically" to find an explanation.

On one level, the universe, with all of its dark baggage, seems to make sense. The total amount of matter and energy seems to be just enough to guarantee that the large-scale geometry of space-time is "flat," or Euclidean, a result that cosmologists have long considered to be the most desirable and aesthetic. On the other hand, the detailed breakdown of the constituents of the cosmos is, as Dr. Livio says, "ugly" -- 65 percent dark matter, 30 percent dark matter of unknown nature and only 5 percent stars, gas and dust.

"We live in a preposterous universe," said Dr. Michael Turner, an astrophysicist at the University of Chicago. "Dark energy. Who ordered that?"

Of course, it was Einstein who originally ordered dark energy when he inserted a fudge factor called the cosmological constant into his gravitational equations describing the universe. Lambda, as it is known, after the Greek letter, represented a sort of cosmic repulsion associated with space itself that kept the cosmos from collapsing of its own weight. Einstein abandoned the cosmological constant when it was discovered that the universe was expanding, and resisted efforts to bring it back, once referring to it as his biggest blunder.

But he couldn't keep it out forever. In 1998 two competing teams of astronomers trying to measure how the expansion of the universe was slowing down because of cosmic gravity, found that the universe was actually speeding up, as if the galaxies were being pushed apart by a force -- dubbed, in the spirit of the times, "dark energy."

"This was a very strange result," recalled Dr. Riess, who was a member of one of the teams. "It was the opposite of what we thought we were doing." Was this Einstein's old cosmological constant, something even weirder or a mistake?

The effect had showed up as an unexpected dimness on the part of certain exploding stars known as supernovae that the astronomers were using as so-called standard candles, objects whose distance could be gauged from their apparent brightness. The astronomers deduced that these stars were farther away than they should have been in an evenly expanding universe, and that therefore the expansion was actually accelerating.

But dust or chemical changes over the eons in the stars could also have dimmed the supernovae. The cleanest test of dark energy and the acceleration hypothesis, Dr. Riess explained, would be to find supernovae even farther out and back into the past, halfway or more back to the Big Bang itself. Because it is space itself that provides the repulsive push, according to Einstein's equations, that push should start out small when the universe is small and grow as the universe expands. Cosmic acceleration would only kick in when lambda's push got big enough to dominate the gravity of ordinary matter and energy in the universe, about five or six billion years ago. Before then the universe would have been slowing down, like a Mark McGwire blast that has not yet reached the top of its trajectory, and a supernova glimpsed at that great distance would appear relatively brighter than it should. If dust or chemical evolution were responsible, such distant stars should appear relatively even dimmer.

By chance the Hubble Space Telescope had observed a supernova in late 1997 and early 1998 that proved to be 11 billion light-years away -- the most distant yet seen. On Dr. Riess's Hubble diagram it appeared twice as bright as it should.

"Extraordinary claims require extraordinary evidence -- I hope the I.R.S. doesn't say that to you," Dr. Riess told his audience, but, he concluded, "the cosmological constant looks good for this supernova."

Dr. Livio said, "A year ago probably a large fraction of the people in this room would not have believed it."

But there were more complicated explanations, forms of dark energy other than the cosmological constant on physicists' drawing boards, as well as the possibility that astronomers were still being fooled. To explicate the nature of the dark energy, astronomers need to observe more supernovae as far back as 11 billion years ago, to cover the time when the universe began to accelerate.

"How fast did it go from deceleration to acceleration?" asked Dr. Riess. Answering such questions could help astronomers determine how hard the dark energy is pushing on the universe compared with the predictions for the cosmological constant. A fast turnaround, he said, "begins to tell you there is a lot of oomph for a given amount of 'it.' "

"The cosmological constant is the benchmark oomph," he said.

To find those supernovae so far out cosmologists will have to go to space, said Dr. Saul Perlmutter, a physicist at the University of California's Lawrence Berkeley National Laboratory and a veteran dark energy hunter.

On the ground, the supernova researchers have to employ a wide network of people and telescopes to detect the explosions, diagnose their type and then to watch them fade. Dr. Perlmutter described an orbiting telescope that would perform all three functions. The Supernova/Acceleration Probe, or SNAP, would combine an 80-inch diameter mirror (only about 16 percent smaller than the Hubble), a giant electronic camera with a billion pixels and a special spectroscope.

If all goes well, Dr. Perlmutter said, the telescope could be launched in 2008. In three years of operation, he estimated, SNAP could harvest about 2,000 supernovae. To distinguish the different ideas about dark energy, observations would have to be refined to the level of 1 or 2 percent uncertainty .

"We're all excited," he said.

So are the physicists. Their list of suspects begins with Einstein's cosmological constant, but therein lies a problem. About the time that Einstein was abandoning it, quantum mechanics -- the set of rules that govern the subatomic realm -- was establishing a theoretical foundation for the cosmological constant. According to quantum theory, empty space should be foaming with temporary particles and their cumulative energy would outweigh the matter in the universe, including dark matter, by 120 orders of magnitude -- that is, a factor of 10 followed by 119 zeros. At that level, the force of the vacuum would either have crumpled the universe or blown it apart before even an atom had the chance to form.

The fact that the universe is in fact puttering along rather gently suggests that there is something fundamental about physics and the universe that physicists still don't know. Dr. Steven Weinberg, the Nobel Prize-winning particle theorist at the University of Texas, has called the cosmological constant "the bone in our throat." If the dark energy really is Einstein's cosmological constant, then physicists have to answer questions like why it is so small -- roughly comparable, in fact, to the density of matter in our own epoch.

Lacking an answer so far, even from string theory, the mathematically daunting candidate theory of everything, some theorists have resorted to a controversial and somewhat philosophical notion called the anthropic principle, which, in effect, says that physicists need to factor in their own existence when they think about the universe. Out of all the possible universes that can be imagined, this line of thinking goes, the only ones in which humans can find themselves is one that is conducive to human life.

That means, Dr. Weinberg has pointed out, that the cosmological constant has to be small enough to allow time for galaxies and stars to condense from the primordial fog before it takes over and starts blowing the universe apart.

Dr. Alex Vilenkin of Tufts University in Massachusetts pointed out to the Dark Universe audience that the universe was at its peak in making stars about five billion or six billion years ago, just about the time that dark energy and the matter density would have been equal. Our own sun, some 4.5 billion years old, was on the tale end of that wave, and now here we are. "Observers are where the galaxies are," said Dr. Vilenkin. "A typical observer will see a small cosmological constant."

Many physicists are uncomfortable with this line of reasoning, and they are seeking the answer in different class of theories known as quintessence, after the Greek word for the fifth element. Modern physics, noted Dr. Paul Steinhardt, a theorist at Princeton, is replete with mysterious energy fields that would exhibit negative gravity. The trick, Dr. Steinhardt explained, is finding a field that would act like the dark energy without a lot of fudging on the part of theorists.

"The observations are forcing us to do this," he said. "Dark energy is an interesting problem. Any solution is quite interesting."

One theory that captured the fancy of the astronomers in Baltimore was a modification of gravity recently proposed by three string theorists at New York University: Dr. Gia Dvali, Dr. Gregory Gabadadze and Dr. Massimo Porrati. In string theory -- so named because it describes elementary particles as tiny vibrating strings -- the ordinary world is often envisioned as a three-dimensional island (a membrane, or "brane" in string jargon) floating in a 10- or 11-dimensional space. Ordinary particles like electrons and quarks and forces like electromagnetism are confined to three dimensions, to the brane, but gravity is not.

As a result, Dr. Dvali suggested that gravity could only travel so far through conventional space before it leaked off into the extra dimensions, thereby weakening itself. To an observer in the traditional three dimensions it looks as if the universe is accelerating. The cosmological constant, in effect, he said, is a kind of gravitational brane drain. "Gravity fools itself," he said. "It sees itself as a cosmological constant."

Dr. Dvali's theory was welcomed by the astronomers as a sign that string theory was beginning to come down from its ivory tower of abstraction and make useful, testable predictions about the real world. (In another string contribution, Dr. Steinhardt introduced a new theory of the early universe, in which the Big Bang is set off by a pair of branes clashing together like cymbals.)

Afterward Dr. Riess and Dr. Perlmutter pressed Dr. Dvali on what they would see when they looked out past the crossover point where gravity began falling out of the world; would the transition between a decelerating universe and an accelerating one happen more abruptly than in the case of the cosmological constant? Dr. Dvali said he hadn't done any calculations, but he said it was his "naïve guess" that the crossover would happen more smoothly than in a lambda world.

"I'd love to see this guy do some Hubble diagrams," Dr. Riess said.

Even if Dr. Dvali could be coaxed into providing a prediction, however, success in identifying the dark energy was not guaranteed to the astronomers. Calling himself a spokesman for the "cranky point of view," Dr. Steinhardt pointed out that the oft-proclaimed era of "precision cosmology" was bound to have its limits. Other cosmological parameters, particularly the cosmic density of matter in the universe, were not likely to be known well enough for even SNAP to untangle the models in which the quintessence varied over time. Worried that the overselling of SNAP could sap astronomers' will to come up with new ideas, he said, "We should try to make as few pronouncements as possible."

Dr. Turner refused to be swayed from his "irrational exuberance." Appealing to the astronomers' pride, he urged them to be ambitious. "We have a chance to do fundamental physics here," he said. "Let's see if we can crack this nut. Maybe we'll fall on our faces. Maybe cranky Paul is right.

"I still have a lot of youthful juices in my body."

Before the Big Bang, There Was . . . What?

By DENNIS OVERBYE

What was God doing before he created the world? The philosopher and writer (and later saint) Augustine posed the question in his "Confessions" in the fourth century, and then came up with a strikingly modern answer: before God created the world there was no time and thus no "before." To paraphrase Gertrude Stein, there was no "then" then.

Until recently no one could attend a lecture on astronomy and ask the modern version of Augustine's question -- what happened before the Big Bang? -- without receiving the same frustrating answer, courtesy of Albert Einstein's general theory of relativity, which describes how matter and energy bend space and time.

If we imagine the universe shrinking backward, like a film in reverse, the density of matter and energy rises toward infinity as we approach the moment of origin. Smoke pours from the computer, and space and time themselves dissolve into a quantum "foam." "Our rulers and our clocks break," explained Dr. Andrei Linde, a cosmologist at Stanford University. "To ask what is before this moment is a self-contradiction."

But lately, emboldened by progress in new theories that seek to unite Einstein's lordly realm with the unruly quantum rules that govern subatomic physics -- so-called quantum gravity -- Dr. Linde and his colleagues have begun to edge their speculations closer and closer to the ultimate moment and, in some cases, beyond it.

Some theorists suggest that the Big Bang was not so much a birth as a transition, a "quantum leap" from some formless era of imaginary time, or from nothing at all. Still others are exploring models in which cosmic history begins with a collision with a universe from another dimension.

All this theorizing has received a further boost of sorts from recent reports of ripples in a diffuse radio glow in the sky, thought to be the remains of the Big Bang fireball itself. These ripples are consistent with a popular theory, known as inflation, that the universe briefly speeded its expansion under the influence of a violent antigravitational force, when it was only a fraction of a fraction of a nanosecond old. Those ripples thus provide a useful check on theorists' imaginations. Any theory of cosmic origins that does not explain this phenomenon, cosmologists agree, stands little chance of being right.

Fortunately or unfortunately, that still leaves room for a lot of possibilities.

"If inflation is the dynamite behind the Big Bang, we're still looking for the match," said Dr. Michael Turner, a cosmologist at the University of Chicago. The only thing that all the experts agree on is that no idea works -- yet. Dr. Turner likened cosmologists to jazz musicians collecting themes that sound good for a work in progress: "You hear something and you say, oh yeah, we want that in the final piece."

One answer to the question of what happened before the Big Bang is that it does not matter because it does not affect the state of our universe today. According to a theory known as eternal inflation, put forward by Dr. Linde in 1986, what we know as the Big Bang was only one out of many in a chain reaction of big bangs by which the universe endlessly reproduces and reinvents itself. "Any particular part of the universe may die, and probably will die," Dr. Linde said, "but the universe as a whole is immortal."

Dr. Linde's theory is a modification of the inflation theory that was proposed in 1980 by Dr. Alan Guth, a physicist. He considered what would happen if, as the universe was cooling during its first violently hot moments, an energy field known as the Higgs field, which interacts with particles to give them their masses, was somehow, briefly, unable to release its energy.

Space, he concluded, would be suffused with a sort of latent energy that would violently push the universe apart. In an eyeblink the universe would double some 60 times over, until the Higgs field released its energy and filled the outrushing universe with hot particles. Cosmic history would then ensue.

Cosmologists like inflation because such a huge outrush would have smoothed any gross irregularities from the primordial cosmos, leaving it homogeneous and geometrically flat. Moreover, it allows the whole cosmos to grow from next to nothing, which caused Dr. Guth to dub the universe "the ultimate free lunch."

Subsequent calculations ruled out the Higgs field as the inflating agent, but there are other inflation candidates that would have the same effect. More important, from the pre-Big-Bang perspective, Dr. Linde concluded, one inflationary bubble would sprout another, which in turn would sprout even more. In effect each bubble would be a new big bang, a new universe with different characteristics and perhaps even different dimensions. Our universe would merely be one of them.

"If it starts, this process can keep happening forever," Dr. Linde explained. "It can happen now, in some part of the universe."

The greater universe envisioned by eternal inflation is so unimaginably large, chaotic and diverse that the question of a beginning to the whole shebang becomes almost irrelevant. For cosmologists like Dr. Guth and Dr. Linde, that is in fact the theory's lure.

"Chaotic inflation allows us to explain our world without making such assumptions as the simultaneous creation of the whole universe from nothing," Dr. Linde said in an e-mail message.

Questions for Eternity: Trying to Imagine The Nothingness

Nevertheless, most cosmologists, including Dr. Guth and Dr. Linde, agree that the universe ultimately must come from somewhere, and that nothing is the leading candidate.

As a result, another tune that cosmologists like to hum is quantum theory. According to Heisenberg's uncertainty principle, one of the pillars of this paradoxical world, empty space can never be considered really empty; subatomic particles can flit in and out of existence on energy borrowed from energy fields. Crazy as it sounds, the effects of these quantum fluctuations have been observed in atoms, and similar fluctuations during the inflation are thought to have produced the seeds around which today's galaxies were formed.

Could the whole universe likewise be the result of a quantum fluctuation in some sort of primordial or eternal nothingness? Perhaps, as Dr. Turner put it, "Nothing is unstable."

The philosophical problems that plague ordinary quantum mechanics are amplified in so-called quantum cosmology. For example, as Dr. Linde points out, there is a chicken-and-egg problem. Which came first: the universe, or the law governing it? Or, as he asks, "If there was no law, how did the universe appear?"

One of the earliest attempts to imagine the nothingness that is the source of everything came in 1965 when Dr. John Wheeler and Dr. Bryce DeWitt, now at the University of Texas, wrote down an equation that combined general relativity and quantum theory. Physicists have been arguing about it ever since.

The Wheeler-DeWitt equation seems to live in what physicists have dubbed "superspace," a sort of mathematical ensemble of all possible universes, ones that live only five minutes before collapsing into black holes and ones full of red stars that live forever, ones full of life and ones that are empty deserts, ones in which the constants of nature and perhaps even the number of dimensions are different from our own.

In ordinary quantum mechanics, an electron can be thought of as spread out over all of space until it is measured and observed to be at some specific location. Likewise, our own universe is similarly spread out over all of superspace until it is somehow observed to have a particular set of qualities and laws. That raises another of the big questions. Since nobody can step outside the universe, who is doing the observing?

Dr. Wheeler has suggested that one answer to that question may be simply us, acting through quantum-mechanical acts of observation, a process he calls "genesis by observership."

"The past is theory," he once wrote. "It has no existence except in the records of the present. We are participators, at the microscopic level, in making that past, as well as the present and the future." In effect, Dr. Wheeler's answer to Augustine is that we are collectively God and that we are always creating the universe.

Another option, favored by many cosmologists, is the so-called many worlds interpretation, which says that all of these possible universes actually do exist. We just happen to inhabit one whose attributes are friendly to our existence.

The End of Time: Just Another Card In the Big Deck

Yet another puzzle about the Wheeler-DeWitt equation is that it makes no mention of time. In superspace everything happens at once and forever, leading some physicists to question the role of time in the fundamental laws of nature. In his book "The End of Time," published to coincide with the millennium, Dr. Julian Barbour, an independent physicist and Einstein scholar in England, argues that the universe consists of a stack of moments, like the cards in a deck, that can be shuffled and reshuffled arbitrarily to give the illusion of time and history.

The Big Bang is just another card in this deck, along with every other moment, forever part of the universe. "Immortality is here," he writes in his book. "Our task is to recognize it."

Dr. Carlo Rovelli, a quantum gravity theorist at the University of Pittsburgh, pointed out that the Wheeler-DeWitt equation doesn't mention space either, suggesting that both space and time might turn out to be artifacts of something deeper. "If we take general relativity seriously," he said, "we have to learn to do physics without time, without space, in the fundamental theory."

While admitting that they cannot answer these philosophical questions, some theorists have committed pen to paper in attempts to imagine quantum creation mathematical rigor.

Dr. Alexander Vilenkin, a physicist at Tufts University in Somerville, Mass., has likened the universe to a bubble in a pot of boiling water. As in water, only bubbles of a certain size will survive and expand, smaller ones collapse. So, in being created, the universe must leap from no size at all -- zero radius, "no space and no time" -- to a radius large enough for inflation to take over without passing through the in-between sizes, a quantum-mechanical process called "tunneling."

Dr. Stephen Hawking, the Cambridge University cosmologist and best-selling author, would eliminate this quantum leap altogether. For the last 20 years he and a series of collaborators have been working on what he calls a "no boundary proposal." The boundary of the universe is that it has no boundary, Dr. Hawking likes to say.

One of the keys to Dr. Hawking's approach is to replace time in his equations with a mathematical conceit called imaginary time; this technique is commonly used in calculations regarding black holes and in certain fields of particle physics, but its application to cosmology is controversial.

The universe, up to and including its origin, is then represented by a single conical-shaped mathematical object, known as an instanton, that has four spatial dimensions (shaped roughly like a squashed sphere) at the Big Bang end and then shifts into real time and proceeds to inflate. "Actually it sort of bursts and makes an infinite universe," said Dr. Neil Turok, also from Cambridge University. "Everything for all future time is determined, everything is implicit in the instanton."

Unfortunately the physical meaning of imaginary time is not clear. Beyond that, the approach produces a universe that is far less dense than the real one.

The Faith of Strings: Theorists Bring On The 'Brane' Worlds

But any real progress in discerning the details of the leap from eternity into time, cosmologists say, must wait for the formulation of a unified theory of quantum gravity that succeeds in marrying Einstein's general relativity to quantum mechanics -- two views of the world, one describing a continuous curved space-time, the other a discontinuous random one -- that have been philosophically and mathematically at war for almost a century. Such a theory would be able to deal with the universe during the cauldron of the Big Bang itself, when even space and time, theorists say, have to pay their dues to the uncertainty principle and become fuzzy and discontinuous.

In the last few years, many physicists have pinned their hopes for quantum gravity on string theory, an ongoing mathematically labyrinthean effort to portray nature as comprising tiny wiggly strings or membranes vibrating in 10 or 11 dimensions.

In principle, string theory can explain all the known (and unknown) forces of nature. In practice, string theorists admit that even their equations are still only approximations, and physicists outside the fold complain that the effects of "stringy physics" happen at such high energies that there is no hope of testing them in today's particle accelerators. So theorists have been venturing into cosmology, partly in the hopes of discovering some effect that can be observed.

The Big Bang is an obvious target. A world made of little loops has a minimum size. It cannot shrink beyond the size of the string loops themselves, Dr. Robert Brandenberger, now at Brown, and Dr. Cumrun Vafa, now at Harvard, deduced in 1989. When they used their string equations to imagine space shrinking smaller than a certain size, Dr. Brandenberger said, the universe acted instead as if it were getting larger. "It looks like it is bouncing from a collapsing phase."

In this view, the Big Bang is more like a transformation, like the melting of ice to become water, than a birth, explained Dr. Linde, calling it "an interesting idea that should be pursued." Perhaps, he mused, there could be a different form of space and time before the Big Bang. "Maybe the universe is immortal," he said. "Maybe it just changes phase. Is it nothing? Is it a phase transition? These are very close to religious questions."

Work by Dr. Brandenberger and Dr. Vafa also explains how it is that we only see 3 of the 9 or 10 spatial dimensions the theory calls for. Early in time the strings, they showed, could wrap around space and strangle most of the spatial dimensions, keeping them from growing.

In the last few years, however, string theorists have been galvanized by the discovery that their theory allows for membranes of various dimensions ("branes" in string jargon) as well as strings. Moreover they have begun to explore the possibility that at least one of the extra dimensions could be as large as a millimeter, which is gigantic in string physics. In this new cosmology, our world is a three-dimensional island, or brane floating in a five-dimensional space, like a leaf in a fish tank. Other branes might be floating nearby. Particles like quarks and electrons and forces like electromagnetism are stuck to the brane, but gravity is not, and thus the brane worlds can exert gravitational pulls on each other.

"A fraction of a millimeter from you is another universe," said Dr. Linde. "It might be there. It might be the determining factor of the universe in which you live."

Worlds in Collision: A New Possibility Is Introduced

That other universe could bring about creation itself, according to several recent theories. One of them, called branefall, was developed in 1998 by Dr. Georgi Dvali of New York University and Dr. Henry Tye, from Cornell. In it the universe emerges from its state of quantum formlessness as a tangle of strings and cold empty membranes stuck together. If, however, there is a gap between the branes at some point, the physicists said, they will begin to fall together.

Each brane, Dr. Dvali said, will experience the looming gravitational field of the other as an energy field in its own three-dimensional space and will begin to inflate rapidly, doubling its size more than a thousand times in the period it takes for the branes to fall together. "If there is at least one region where the branes are parallel, those regions will start an enormous expansion while other regions will collapse and shrink," Dr. Dvali said.

When the branes finally collide, their energy is released and the universe heats up, filling with matter and heat, as in the standard Big Bang.

This spring four physicists proposed a different kind of brane clash that they say could do away with inflation, the polestar of Big Bang theorizing for 20 years, altogether. Dr. Paul Steinhardt, one of the fathers of inflation, and his student Justin Khoury, both of Princeton, Dr. Burt Ovrut of University of Pennsylvania and Dr. Turok call it the ekpyrotic universe, after the Greek word "ekpyrosis," which denotes the fiery death and rebirth of the world in Stoic philosophy.

The ekpyrotic process begins far in the indefinite past with a pair of flat empty branes sitting parallel to each other in a warped five-dimensional space -- a situation they say that represents the simplest solution of Einstein's equations in an advanced version of string theory. The authors count it as a point in their favor that they have not assumed any extra effects that do not already exist in that theory. "Hence we are proposing a potentially realistic model of cosmology," they wrote in their paper.

The two branes, which form the walls of the fifth dimension, could have popped out of nothingness as a quantum fluctuation in the even more distant past and then drifted apart.

At some point, perhaps when the branes had reached a critical distance apart, the story goes, a third brane could have peeled off the other brane and begun falling toward ours. During its long journey, quantum fluctuations would ripple the drifting brane's surface, and those would imprint the seeds of future galaxies all across our own brane at the moment of collision. Dr. Steinhardt offered the theory at an astronomical conference in Baltimore in April.

In the subsequent weeks the ekpyrotic universe has been much discussed. Some cosmologists, particularly Dr. Linde, have argued that in requiring perfectly flat and parallel branes the ekpyrotic universe required too much fine-tuning.

In a critique Dr. Linde and his co-authors suggested a modification they called the "pyrotechnic universe."

Dr. Steinhardt admitted that the ekpyrotic model started from a very specific condition, but that it was a logical one. The point, he said, was to see if the universe could begin in a long-lived quasi-stable state "starkly different from inflation." The answer was yes. His co-author, Dr. Turok, pointed out, moreover, that inflation also requires fine-tuning to produce the modern universe, and physicists still don't know what field actually produces it.

"Until we have solved quantum gravity and connected string theory to particle physics none of us can claim victory," Dr. Turok said.

In the meantime, Augustine sleeps peacefully.

Theorists of Inner Space Look to Observers of Outer Space

By DENNIS OVERBYE

The Big Bang, David Schramm, the University of Chicago cosmologist, liked to say, is the poor man's particle accelerator: in its detritus, which after all includes the whole universe, are the effects of energies and processes unattainable on Earth. If astronomers looked closely enough at the sky, he maintained, they could test theories and phenomena that were beyond the power and the budgets of physicists to recreate in their laboratories.

That's a notion that seems to have caught fire lately among the practitioners of string theory, the daunting "theory of everything" that describes nature as comprising tiny strings and membranes vibrating in 10 or 11 dimensions.

Since its inception, string theory has been criticized for producing ideas that seem as experimentally untestable as they are mathematically elegant. But in the last couple of years string theorists have began turning out new models of the universe designed to show that so-called stringy physics "can have an observable effect on precision cosmological measurements," as one recent paper put it. In some of these, for example, cosmic history begins with a pair of island universes slapping together in the fifth dimension like wet leaves. If the string theorists are right, they say, tangible support for such notions may come from detailed measurements of faint radio waves from the Big Bang or from studies of so-called gravitational waves crisscrossing space-time, making it expand and contract like an accordion.

Emboldened by the prospect of their newfound empiricism, the theorists have even ventured out to cosmological conferences -- to the delight of astronomers eager for some new observing challenge.

During a recent meeting in Baltimore, for example, Dr. Gia Dvali, a physicist at New York University, was besieged by astronomers eager for more details and precise astronomical predictions after he offered a string-based explanation of the so-called dark energy that seems to be accelerating the expansion of the universe.

In romancing the cosmologists, string theorists are following a well trodden path. In the last half century -- as astronomers have found quasars, pulsars and a faint radio hiss alleged to be the primordial fireball itself -- physicists looking for fresh fields to conquer have migrated in waves into cosmology.

Dr. Saul Perlmutter, a physicist at Lawrence Berkeley National Laboratory who led one of two teams of astronomers that discovered that the expansion of the universe is apparently speeding up, admitted that he sidled into astronomy in part to avoid being a cog in a giant particle accelerator experiment.

"Astronomers ought to be able to ask fundamental questions without accelerators," Dr. Perlmutter said.

But the marriage of inner space and outer space has not always gone smoothly. Astronomers are traditionally solitary, sometimes spending years following a single star. Physicists are sociable and like to tackle problems in gangs. Each group is capable of defending its turf.

Physicists were amused when Dr. Schramm, a burly and self-confident crusader who died in an airplane crash in 1997, claimed in the 1970's that measurements of the abundance of helium produced in the Big Bang could be used to conclude that there were only three or four kinds of neutrinos, mysterious lightweight elementary particles, in the universe. Experiments at CERN -- the leading European particle physics laboratory -- and at Stanford in 1989 proved him and his colleagues right.

More than a few physicists have recalled being taken aback at the apparent simplicity of the standard models of the Big Bang, in which only three parameters, or numbers, control the history and destiny of the universe.

Einstein was a cagey and early exploiter of the connection between inner space and outer space. Even before he was finished formulating his general theory of relativity, which explains gravity as the warping of space-time by matter and energy, he began to lobby astronomers to measure the effect of light bending during a total solar eclipse, when light rays from a distant star would graze the sun's disk and -- he predicted -- bend enough to cause the star to appear to be displaced outward. In 1919, three years after the theory was published, the English astronomer Arthur Eddington announced with great fanfare that he had confirmed the effect (although some historians have criticized his handling of the data), anointing Einstein the new Copernicus.

In the meantime Einstein had fudged his equations so that they would not lead inexorably to the conclusion that the universe was expanding, having been convinced by common astronomical lore that it was static. He unfudged them in 1931 after the astronomer Edwin Hubble discovered that the cosmos was indeed expanding.

Nevertheless, despite its obvious relevance to the universe at large and its mathematical elegance, general relativity soon became a kind of backwater in physics, regarded as a beautiful theory that didn't seem to have much to do with the real world. Lacking a way to test some of the more bizarre consequences of the theory, such as the notion that stars collapsing under their own weight could wrap space around them like a cloak and literally disappear into what were later dubbed "black holes," not even Einstein knew what ideas to take seriously.

All this changed in the 1960's when astronomers discovered quasars, distant starlike objects that seemed to radiate baffling amounts of energy. Black holes --- although the name had not yet been invented -- were the best way to explain them. Suddenly it seemed that "the relativists with their sophisticated work were not only magnificent cultural ornaments but might actually be useful to science," as the British astrophysicist Thomas Gold put it during a meeting in 1963. "What a shame it would be," he added, "if we had to go and dismiss all the relativists again."

The string theorists, who would lay claim to Einstein's mantle, have not had their light-bending moment yet. The question is whether they ever will. The standard form of the theory holds that the energies at which the forces are supposed to be unified and the effects of string physics show up are thousands of trillions of times the expected capacity of the largest particle accelerator now envisioned, CERN's Large Hadron Collider, which will shoot protons around an electromagnetic racetrack 18 miles around in Geneva and collide them at energies of 14 trillion electron volts. (In a string theory variant proposed a few years ago, interference from a neighboring universe could produce effects at the low energies in earthly accelerators.)

Fortunately, however, as Dr. Schramm would have pointed out, nature has already done the experiment using the poor man's particle accelerator. And the results may be written on the sky -- in ripples inscribed on the primordial fireball, astronomers say, when it was only a billionth of a trillionth of a trillionth of a second old, or in gravitational waves fluttering the fabric of space.

The job of reading those cosmic ripples, with delicate radio telescopes lofted on balloons and satellites, has just begun and is expected to take the rest of the decade. Likewise the quest to unravel the history of the strange acceleration of the universe. The serious study of gravitational waves -- which have not been directly detected yet -- is even further in the future.

String theorists must hope that in the ranks of the astronomers carrying out those investigations there dwells their own Eddington.

Cracking the Cosmic Code With a Little Help From Dr. Hawking

By DENNIS OVERBYE

Like some quantum particle popping into existence out of nowhere, "The Universe in a Nutshell," by the University of Cambridge physicist Stephen W. Hawking, was published and immediately popped onto the best-seller lists a few weeks ago.

Physicists say such magical seeming appearances, called quantum fluctuations, are more likely when there is a large energy field to draw from, and this book draws from one of the largest energy fields in the history of publishing, namely Dr. Hawking's 1988 book, "A Brief History of Time: From the Big Bang to Black Holes."

As a result, many thousands of Americans could spend the holidays confronting statements like: "We have come to realize that this standing still of real and imaginary time (either both stand still or neither does) means that space-time has a temperature, as I discovered for black holes," as Dr. Hawking writes on Page 63.

Dr. Hawking's first book for a wide audience, "A Brief History of Time," took readers on a tour through black holes, the gravitational traps from which not even light can emerge, and imaginary time as he described the quest for the vaunted "theory of everything" that would enable us to "know the mind of God." It lived on the best-seller lists for two years, selling 10 million copies.

The question that still haunts publishers, critics and others, incredulous that there could be as big an audience for a serious discussion of the origin of the universe as for the life of a movie star, is why?

According to popular and publishing lore, it was also one of the great unread classics of our time -- with James Joyce's "Finnegan's Wake" or David Foster Wallace's "Infinite Jest" as coffee-table monuments honored mostly in the breach. So a lot of people, suspicious that the earlier book was bought for Dr. Hawking's celebrity or its egghead aura -- are already wondering if the same thing will happen to the new book.

To colleagues, Dr. Hawking is a stubbornly intuitive theorist whose work on black holes has helped light the way to an eventual union of relativity and quantum theory -- a union that neither Einstein nor anybody else has yet been able to broker. To the world, he is the personification of courage and brilliance, St. George in a wheelchair tilting with galaxies and the unknown, who as been accorded some of the ultimate accolades in pop culture -- appearing as Einstein's poker buddy on "Star Trek: The Next Generation," and as a guest star on "The Simpsons."

While a graduate student, in 1963, he learned he had amyotrophic lateral sclerosis and was given a few years to live. He has moved about in a wheelchair for more than 25 years and now speaks only through a voice synthesizer. Dr. Hawking, for whom the word "puckish" seems to have been invented, has often said his disability is an advantage because it frees him to sit and think. Next month his colleagues will celebrate his 60th birthday with a weeklong all-star symposium in Cambridge.

In the new book's introduction, Dr. Hawking admits that "A Brief History of Time" was "not easy going" and laments that some readers got stuck and did not finish it. He has tried, he says, to make this one easier. Slightly longer than the earlier book, "Nutshell," at 216 pages, is embellished with colorful illustrations that give it a coffee-table-book look.

So far the critics are in qualified agreement; one, Bryan Appleyard in the The New Statesman of London, called it "difficult, though not absolutely so." The Times of London, did an informal poll, asking seven reporters and a math student to read it and report on its accessibility. The verdict was mixed. "It all made beautiful sense as I read it, though it tended to vanish like a dream when I put the book down," one wrote.

Albert Einstein once said that scientific theories should be able to be described so simply that a child could understand them. Complaints that modern physics fails this standard abysmally are as old, well, as modern physics, and are not confined to the childlike public.

The story goes that when the astronomer Arthur Eddington, whose observations of light bending during a solar eclipse in 1919 confirmed Einstein's general theory of relativity, was congratulated by a colleague on being one of the three people in the world who understood the abstruse theory, Eddington fell uncharacteristically silent. Chided for exhibiting a false modesty, Eddington replied, on the contrary, that he had been trying to imagine who the third person could be.

This newspaper's early accounts of Einstein's and Eddington's 1919 breakthroughs focused on the theory's incomprehensibility. "Efforts made to put in words intelligible to the nonscientific public the Einstein theory of light proved by the eclipse expedition so far have not been very successful," began a article on Nov. 10, 1919.

Niels Bohr, one of the founders of quantum mechanics, once said that anyone who was not outraged on hearing about the theory -- with its waves acting as particles, particles acting like waves, and the microscopic randomness and uncertainty it ascribed to nature -- had not really understood it.

Recent advances have made it even harder to explain the universe. The latest version of the putative theory of everything posits a universe with 10 or 11 dimensions, instead of the 3 of space and 1 of time of everyday experience, inhabited by wriggling strings or membranes. Nevertheless, scientists go on gamely trying to tell us what they are up to, in a book-writing tradition that includes Darwin's "Origin of Species," and Einstein's, "Relativity: The Special and the General Theory," written in 1916 and never out of print.

Part of the lure of these books is the chance to reclaim one's citizenship in a troubled and baffling cosmos by hearing the word from the horse's mouth, from someone who has touched the cosmic mystery personally. But another part is surely being treated like an adult, of entering a rough-hewn colleagueship by being trusted to put work into deciphering statements like the one at the beginning of this essay, or to deal with straight talk of the nature of science and the universe.

Here, for example, is Dr. Hawking about those troublesome extra dimensions required by string theory but apparently unavailable for parking cars. "I must say that personally, I have been reluctant to believe in extra dimensions," he writes on Page 54 of the new book. "But as I am a positivist, the question 'Do extra dimensions really exist?' has no meaning. All one can ask is whether mathematical models with extra dimensions provide a good description of the universe."

In other words, if the experiments come out right, it doesn't matter. This could be considered jarring if you cling to the notion that science is the search for a reality that is deeper than the measurements on a laboratory table. But, quantum theory and relativity have taught us, science is about what can be observed and measured or it is about nothing at all. In science, as in democracy, there is no hidden secret knowledge, all that counts is on the table, observable and falsifiable. All else is metaphysics.

When it comes to putting the goods on the table without condescending, Dr. Hawking is a genius. While many authors of science books plough through chapters full of fundamentals before getting to the new stuff, Dr. Hawking, with perhaps a heightened appreciation of time, breezes speedily to the frontier without apologies.

For those who cannot keep up, Dr. Hawking has also provided a legacy. The success of his earlier book and that of Carl Sagan's "Cosmos" are widely credited with having given a commercial lift to the science-book genre, helping pave the way for efforts like "The Elegant Universe," by Dr. Brian Greene, a Columbia University string theorist; "The Inflationary Universe," by Dr. Alan Guth, cosmologist at the Massachusetts Institute of Technology; and "The Quark and the Jaguar," by the Nobel laureate Murray Gell-Mann.

To the extent that Dr. Hawking's earlier success has spawned imitators and widened the circle of readers and their sophistication, he has engineered a kind of positive feedback, and he has increased the odds that the readers will follow him and get to the end of the book this time.

The End of Everything

By DENNIS OVERBYE

In the decades that astronomers have debated the fate of the expanding universe -- whether it will all end one day in a big crunch, or whether the galaxies will sail apart forever -- aficionados of eternal expansion have always been braced by its seemingly endless possibilities for development and evolution. As the Yale cosmologist Dr. Beatrice Tinsley once wrote, "I think I am tied to the idea of expanding forever."

Life and intelligence could sustain themselves indefinitely in such a universe, even as the stars winked out and the galaxies were all swallowed by black holes, Dr. Freeman Dyson, a physicist at the Institute for Advanced Study, argued in a landmark paper in 1979. "If my view of the future is correct," he wrote, "it means that the world of physics and astronomy is also inexhaustible; no matter how far we go into the future, there will always be new things happening, new information coming in, new worlds to explore, a constantly expanding domain of life, consciousness, and memory."

Now, however, even Dr. Dyson admits that all bets are off. If recent astronomical observations are correct, the future of life and the universe will be far bleaker.

In the last four years astronomers have reported evidence that the expansion of the universe is not just continuing but is speeding up, under the influence of a mysterious "dark energy," an antigravity that seems to be embedded in space itself. If that is true and the universe goes on accelerating, astronomers say, rather than coasting gently into the night, distant galaxies will eventually be moving apart so quickly that they cannot communicate with one another. In effect, it would be like living in the middle of a black hole that kept getting emptier and colder.

In such a universe, some physicists say, the usual methods of formulating physics may not all apply. Instead of new worlds coming into view, old ones would constantly be disappearing over the horizon, lost from view forever.

Cosmological knowledge would be fragmented, with different observers doomed to seeing different pieces of the puzzle and no single observer able to know the fate of the whole universe or arrive at a theory of physics that was more than approximate.

"There would be a lot of things about the universe that we simply couldn't predict," said Dr. Thomas Banks, a physicist at the University of California at Santa Cruz.

And perhaps most important, starved finally of the energy even to complete a thought or a computation, the domain of life and intelligence would not expand, but constrict and eventually vanish like a dwindling echo into the silence of eternity. "I find the fate of a universe that is accelerating forever not very appealing," said Dr. Edward Witten, a theorist at the Institute for Advanced Study.

That is an understatement, in the view of Dr. Lawrence M. Krauss, an astrophysicist at Case Western Reserve University in Cleveland, who along with his colleague Dr. Glenn D. Starkman has recently tried to limn the possibilities of the far future. An accelerating universe "would be the worst possible universe, both for the quality and quantity of life," Dr. Krauss said, adding: "All our knowledge, civilization and culture are destined to be forgotten. There's no long-term future."

Einstein's Last Laugh

Until about four years ago, an overwhelming preponderance of astronomers subscribed to the view that the cosmic expansion was probably slowing down because of the collective gravity of the galaxies and everything else in the universe, the way a handful of stones tossed in the air gradually slow their ascent. The only question was whether the universe had enough gravitational oomph to stop expanding and bring itself back together in a "big crunch," or whether the galaxies would sail ever more slowly outward forever.

It was to measure that rate of slowing of this outward flight, and thus find the long-sought and elusive answer to the cosmic question, that two teams of astronomers started competing projects in the 1990's using distant exploding stars, supernovas, as cosmic beacons.

In 1998 the two teams announced that instead of the expected slowing, the galaxies actually seem to have speeded up over the last five or six billion years, as if some "dark energy" was pushing them outward.

"It's definitely the strangest experimental finding since I've been in physics," Dr. Witten said. "People find it difficult to accept. I've stopped expecting that the finding will be proved wrong, but it's an extremely uncomfortable result."

To astronomers this dark energy bears a haunting resemblance to an idea that Albert Einstein had back in 1917 and then abandoned, later calling it his biggest blunder. In that year he inserted a mathematical fudge factor that came to be known as the cosmological constant into his equations of general relativity in order to stabilize the universe against collapse; Einstein's constant acted as a kind of cosmic repulsion to balance the gravitational pull of the galaxies on one another.

Einstein gave up the cosmological constant after the American astronomer Edwin Hubble discovered that the universe was expanding and thus did not need stabilizing. But his fudge factor refused to die. It gained a new identity with the advent of quantum mechanics, the bizarre-sounding rules that govern the subatomic realm. According to those rules, empty space is not empty, but rather foaming with energy. Inserted into Einstein's equations, this energy would act like a cosmological constant, and try to blow the universe apart.

According to astronomers the recently discovered dark energy now accounts for about two-thirds of the mass of the universe. But is this Einstein's old fudge factor, the cosmological constant, come home to roost -- in which case the universe will accelerate eternally? Or is the presumed acceleration only temporary, driven by one of the many mysterious force fields, dubbed quintessence, allowed by various theories of high energy physics?

Or is the acceleration even real?

"It's important to find out if the cosmological constant is really constant," said Dr. Witten.

Because the repulsive force resides in space itself, as the universe grows, the push from dark energy grows as well. "If dark energy is the cosmological constant then it is a property of the vacuum that will always be with us, getting more powerful as the universe gets bigger and the universe will expand forever," explained Dr. Adam Riess of the Space Telescope Science Institute in Baltimore. But if the dark energy is some form of quintessence, "then there may be more such fields which arise in the future, possibly of the opposite sign, and then all bets are off for the future of the universe."

Dr. Krauss said, "The good news is that we can't prove that this is the worst of all possible universes."

The Long Goodbye

It might seem strange or presumptuous for astronomers to try to describe events all the way to the end of time when physicists are still groping for a "theory of everything." But to Dr. Krauss, this is testimony to the power of ordinary physics. "We can still put ultimate limits on things without even knowing the ultimate theory," he said. "We can put limits on things based on ordinary physics."

Dr. Dyson said his venture into eschatology was inspired partly by a 1977 paper on the future of an ever expanding universe by Dr. J. N. Islam, now at the University of Chittagong in Bangladesh, in The Quarterly Journal of the Royal Astronomical Society. Dr. Dyson was also motivated, he wrote in his paper, to provide a counterpoint to a famously dour statement by Dr. Steven Weinberg, who wrote in his book "The First Three Minutes," "The more the universe seems comprehensible, the more it also seems pointless."

Dr. Dyson wrote, "If Weinberg is speaking for the 20th century, I prefer the 18th."

If the present trend of acceleration continues this is the forecast:

In about two billion years Earth will become uninhabitable as a gradually warming Sun produces a runaway greenhouse effect. In five billion years the Sun will swell up and die, burning the Earth to a crisp in the process. At about the same time the Milky Way will collide with its twin the Andromeda galaxy, now about two million light-years away and closing fast, spewing stars, gas and planets across intergalactic space.

Any civilization that managed to survive these events would face a future of increasing ignorance and darkness as the accelerating cosmic expansion rushes most of the universe away from us. "Our ability to know about the universe will decrease with time," said Dr. Krauss. "The longer you wait, the less you see, the opposite of what we always thought."

As he explains it, the disappearance of the universe is a gradual process. The faster a galaxy flies away from us, the dimmer and dimmer it will appear, as its light is "redshifted" to lower frequencies and energies, the way a police siren sounds lower when it is receding. When it reaches the speed of light, the galaxy will appear to "freeze," like a dancer caught in midair in a photograph, in accordance to Einstein's theory of relativity, and we will never see it get older, said Dr. Abraham Loeb, an astronomer at Harvard. Rather it will simply seem dimmer. The farther away an object is in the sky, he said, the younger it will appear as it fades out of sight. "There is a finite amount of information we can collect from the universe," Dr. Loeb said. About 150 billion years from now almost all of the galaxies in the universe will be receding fast enough to be invisible from the Milky Way. The exceptions will be galaxies that are gravitationally bound to the cloud of galaxies, known as the Local Group, to which the Milky Way belongs. Within this cloud, life would look much the same at first. There would be galaxies in the sky. "When you look at the night the stars will still be there," said Dr. Krauss. "To the astronomer who wants to see beyond, the sky will be sadly empty. Lovers won't be disturbed -- scientists will be."

But about 100 trillion years from now, when the interstellar gas and dust from which new stars condense is finally used up, new stars will cease to be born. From that time on, the sky will grow darker and darker. The galaxies themselves, astronomers say, will collapse in black holes within about 1030 years.

But even a black hole is not forever, as Dr. Stephen Hawking, the Cambridge University physicist and best-selling author, showed in path-breaking calculations back in 1973. Applying the principles of quantum mechanics to these dread-sounding objects, Dr. Hawking discovered that a black hole's surface, its so-called event horizon, would fluctuate and exude energy in the form of random bursts of particles and radiation, growing hotter and hotter until the black hole eventually exploded and vanished.

Black holes the mass of the sun would take 1064 years to explode. For black holes the mass of a galaxy those fireworks would light up space-time 1098 years from now.

Against the Fall of Night

Will there be anything or anyone around to see these quantum fireworks?

Dr. Dyson argued in his 1979 paper that life and intelligence could survive the desert of darkness and cold in a universe that was expanding infinitely but ever more slowly by adopting ever slower and cooler forms of existence. Intelligence, could reside, for example, in the pattern of electrically charged dust grains in an interstellar cloud, a situation described in the 1957 science fiction novel "The Black Cloud," by the British astronomer Sir Fred Hoyle, who died in August.

As an organism like the black cloud cooled, he argued, it would think more slowly, but it would always metabolize energy even more slowly, so its appetite would always be less than its output. In fact, Dr. Dyson concluded, by making the amount of energy expended per thought smaller and smaller the cloud could have an infinite number of thoughts while consuming only a finite amount of energy.

But there was a hitch. Even just thinking requires energy and generates heat, which is why computers have fans. Dr. Dyson suggested that creatures would have to stop thinking and hibernate periodically to radiate away their heat.

In an accelerating universe, however, there is an additional source of heat that cannot be gotten rid of. The same calculations that predict black holes should explode also predict that in an accelerating universe space should be filled with so-called Hawking radiation. In effect, the horizon -- the farthest distance we can see -- looks mathematically like the surface of a black hole. The amount of this radiation is expected to be incredibly small -- corresponding to a fraction of a billionth of a billionth of a billionth of a degree above absolute zero, but that is enough to doom sentient life.

"The Hawking radiation kills us because it gives a minimum temperature below which you cannot cool anything," said Dr. Krauss. Once an organism cools to that temperature, he explained, it would dissipate energy at some fixed rate. "Since there is a finite total energy, this means a finite lifetime."

Infinity on Trial

Although Dr. Dyson agrees with this gloomy view of life in an accelerating universe, he and Dr. Krauss and Dr. Starkman are still arguing about whether life is also doomed in a universe that is not accelerating, but just expanding and getting slower and colder.

Quantum theory, the Case Western authors point out, limits how finely the energy for new thoughts can be shaved. The theory decrees that energy is emitted and absorbed in tiny indivisible lumps called "quanta." Any computation must spend at least this much energy out of a limited supply. Each new thought is a step down an energy ladder with a finite number of steps. "So you can only have a finite number of thoughts," said Dr. Krauss.

"If you want to stare at your navel and not think any new thoughts, you won't dissipate energy, " he explained. But that would be a boring way to spend eternity. If life is to involve more than the eternal reshuffling of the same data, he and Dr. Starkman say, it cannot be eternal.

Dr. Dyson, however, says this argument applies only to so-called digital life, in which there is a fixed number of quantum states. Creatures like the black cloud, which could grow along with the universe, he said, would have an increasing number of quantum states, and so there would always be more rungs of the ladder to step down. So the bottom need never be reached and life and thought could go on indefinitely.

But nobody knows whether such a life form can exist, said Dr. Krauss.

Compared with the sight of the World Trade Center towers collapsing or the plight of a sick child, this future extinction may seem a remote concern. Dr. Allan Sandage, an astronomer at Carnegie Observatories in Pasadena, Calif., who has spent his life investigating the expansion and fate of the universe, said: "Life on this earth is going to vanish in 4.5 billion years. I wouldn't get hung up on the fact that the lights are all going out in 30 billion years."

Dr. Dyson said he was still an optimist. It is too soon to start panicking, he counseled in an e-mail message. The observations could be wrong.

"At present all possibilities are open," he wrote. "The recent observations are important, not because they answer the big questions about the history of the universe, but because they give us new tools with which to explore the history."

Even in an accelerating universe, Dr. Dyson said, humans or their descendants might one day be able to rearrange the galaxies and save more of them from disappearing. Another glimmer of hope comes from the deadly and chilling Hawking radiation itself, said Dr. Raphael Bousso, from the Institute of Theoretical Physics at the University of California at Santa Barbara. Since that radiation is produced by unpredictable quantum fluctuations, he pointed out, if you wait long enough anything can appear in it, even a new universe. "Sooner or later one of those quantum fluctuations will look like a Big Bang," he said.

In that case there is the possibility of a future, if not for us, at least for something or somebody. In the fullness of time, after all, physics teaches that the improbable and even the seemingly impossible can become the inevitable. Nature is not done with us yet, nor, as Dr. Dyson indicates, are we necessarily done with nature.

We all die, and it is up to us to decide who and what to love, but, as Dr. Weinberg pointed out in a recent article in The New York Review of Books, there is a certain nobility in that prospect.

"Though aware that there is nothing in the universe that suggests any purpose for humanity," he wrote, "one way that we can find a purpose is to study the universe by the methods of science, without consoling ourselves with fairy tales about its future, or about our own."

Dark Matter, Still Elusive, Gains Visibility

By DENNIS OVERBYE

Sometimes, defying its wont, science makes the cosmos look a little simpler. Recently it seems as if astronomers have been sprung from a long cosmological nightmare. Last month a consortium of astronomers announced that an analysis of some 130,000 galaxies showed that the universe, at least on large scales, is structured pretty much the way it looks.

That might sound unremarkable, but it didn't have to come out that way.

"It was not a mad idea that galaxies don't trace the matter," said Dr. Licia Verde, an astronomer at Rutgers and Princeton Universities, who was the lead author of a paper submitted last month to the journal Monthly Notices of Royal Astronomical Society.

The reason is something called dark matter.

For centuries people have found meaning -- or thought they did -- in the sky, in the forms of the constellations, the sudden careering of comets, the stately dance of the planets, the filigree of galaxies, spanning space as far as the telescope can see, like an old jeweled fishing net cast across the void.

But what if all this is just an illusion? Suppose the real universe is something we can't see and all the glittering chains of galaxies are no more substantial, no more reliable guides to physical reality, than greasepaint on the face of a clown?

That was the humiliating prospect that astronomers faced in the 1980's, as they grudgingly came to accept that decades of astronomical observations were telling them that most of the universe was invisible. They could deduce that dark matter was there by its gravitational effect on the things they could see. If Newton's laws of gravity held over cosmic distances, huge amounts of it were needed to provide the gravitational glue to keep clusters of galaxies from flying apart, and to keep the stars swirling around in galaxies at high speed.

Cosmologists concluded that it was in fact dark matter, slowly congealing under its own weight into vast clouds that provided the scaffolding for stars and galaxies. And it was dark matter that would determine the fate of the universe: if there was enough of it, gravity would eventually reverse the expansion of the universe and cause a "big crunch." If not, the universe would expand forever.

Most gallingly, astronomers didn't even know whether the dark matter was distributed the way stars and galaxies are. They had no clue to the whereabouts of most of the universe. Luminous matter, the story went, is like snow on mountaintops or foam on waves, but there could, in theory, be whole mountain ranges not quite high enough to be whitecapped, hiding in the darkness.

Noting that dark matter heavily outweighed the visible galaxies, four astronomers analyzed the results of an earlier galaxy mapping project, in 1980. There was no reason the ratio of dark to light matter should be the same everywhere "and there may well exist massive systems that emit essentially no light," read the report in the Astrophysical Journal, written by Marc Davis, John Huchra, David Latham and John Tonry, all then at the Harvard-Smithsonian Center for Astrophysics.

Or as Dr. Vera C. Rubin, an astronomer at the Carnegie Institute of Washington and a pioneer of dark matter research, said a year later: "We know very little about the universe. I personally don't believe it's uniform and the same everywhere. That's like saying the earth is flat."

The new results suggest that the universe, as mysterious as it essentially is, may not be entirely perverse. As Einstein once said, "The Lord God is subtle, but malicious he is not." But it was a close call.

"In principle galaxies could bear no resemblance to the underlying dark matter distribution," explained Dr. Verde, who performed the analysis with Dr. Alan F. Heavens of the University of Edinburgh.

"We were right to be worried," Dr. Heavens said.

The notion that the luminous universe might only be greasepaint was born of the quest for beauty. In the 1980's astronomical surveys showed that the galaxies were not distributed more or less uniformly around the sky, as had been thought, but were concentrated in sheets and clusters and long looping chains separated by huge, black, presumably empty spaces millions of light-years across.

But the gravitational pull from such striking disparities in the distribution of mass would tug the galaxies to and fro violently, distorting the orderly expansion of the universe, if the most fashionable cosmological theories were right.

Those theories held that the density of matter and energy in the universe was just high enough so that the gravitational attraction between the contents of the cosmos would eventually just balance the energy of their outward rush. As a result, space on the largest scales would show no geometrical warp: it would be "flat," in cosmological jargon.

Whatever wayward velocities the galaxies had, however, was relatively modest. Rather than give up the mathematically beautiful notion of a high density universe, some theorists suggested that astronomers might have to give up an equally beautiful and seemingly bedrock notion, namely that the universe is what we see when we look up at the sky.

If the voids were just an illusion, and were not empty but just dark, cosmologists reasoned, there would be no gravitational fields tugging at the galaxies, which would explain why their so-called peculiar velocities were so low. They could keep their beautiful universe.

As the primordial clouds of dark matter grow and congeal, so this theory went, ordinary matter sinks to the center and lights up. But vast stretches of dark matter outside the center would go unflagged by visible galaxies, like mountains not quite high enough to attract snow, or reefs unmarked by buoys.

Figuring out exactly why galaxies would have formed in this pattern was another matter that engaged theorists' imaginations. Dr. Martin Rees, a cosmologist at Cambridge University and the astronomer royal of England, said he could imagine that galaxy formation could be catalyzed or impeded by some environmental event. Fierce radiation from the first quasars, for example, could ionize the protogalactic gas over large swaths of space, affecting its ability to collapse and light up.

In the 1990's, though, evidence began to mount, from the COBE satellite, which studied faint radio emanations from the Big Bang itself, and from other studies, that the density of matter was less than a third of the magic critical value needed for a perfectly "flat" universe.

In that case the clusters do not have the gravitational oomph to cause trouble and the lack of high velocities is not a problem. Luckily, theorists could still have a flat beautiful universe because the gap in the matter density was made up by the so-called dark energy that astronomers have recently discovered seems to be accelerating the expansion of the universe. But it is no longer a universe in balance; if the dark energy continues to prevail, astronomers say, the cosmos will blow apart, chilling all life.

In recent years, therefore, dark matter has surrendered some of its cachet to dark energy, but the identity of the dark matter is as mysterious as it ever was. Some of it may be ordinary matter, like rocks and dead stars. But most of it must be more exotic stuff -- perhaps elementary particles left over from the Big Bang -- according to a study published last week in the journal Nature by Dr. Robert Rood of the University of Virginia, and his colleagues. They measured the abundance of a rare form of helium in the Milky Way to determine the amount of "normal" matter produced in the Big Bang.

Nevertheless, the relationship between the light and the dark, once raised, continued to haunt astronomers. "It was perfectly reasonable if galaxies didn't cluster the same way as mass," said Dr. Heavens, adding, "the genie was out of the bottle."

He and Dr. Verde set out to measure the degree, technically known as bias, to which the distributions of luminous and dark matter were mismatched, using statistical techniques she had developed for her Ph.D. dissertation under his supervision.

For a database, they turned to a catalog of the relative distances and positions on the sky of 130,000 galaxies that had been compiled by an international consortium of astronomers known as the 2-Degree Field Galaxy Redshift Survey, or 2dF for short, using the 12-foot-diameter Anglo-Australian Telescope near Coonabarabran, Australia.

By the time it is finished, the survey, which takes its name from the field of view of the telescope, should have mapped 250,000 galaxies out to a distance of around 500 million light-years.

As Dr. Verde explained, she and Dr. Heavens used statistics to analyze the shapes of the galaxy clusters in the sky. According to gravity theory and computer simulations, she said, dark matter, which only interacts gravitationally, should start out in rounded lumps and then gradually shape itself into filaments and sheets as these lumps collapse along their shortest axes first.

"The signature of gravity is filaments," Dr. Verde said. "If there is biasing you get a distribution that is not sheets and filaments -- you get a different pattern."

The results, she and Dr. Heavens said, were clearly consistent with a filamentary structure, "like a web, not round hills and mountains."

"You would have to come up with a theory quite mad to get this pattern with biasing," Dr. Verde said. "Taken together, these measurements argue powerfully that the 2dFGRS galaxies do indeed trace the mass on large scales," she and 29 co-authors concluded in the recent paper.

The mountains are where the snow is. The universe is where the light is. Dr. Rees added: "2dF shows that things hang together. It could have not been that way. There is no evidence for enormous dark somethings with no galaxies associated with them."

At least in the present universe.

"Five billion years ago we would have gotten a different answer," said Dr. Heavens, explaining that galaxies probably did form first in concentrations at the centers of dark matter clouds but gradually spread into the hinterlands over cosmic history to reflect more accurately the overall distribution of matter, the as yet unknown cosmic stuff.

On average, galaxies today trace mass, and the astronomy of the invisible is thus also the astronomy of the visible.

Of course it was by following the light that astronomers were led into the darkness. Like the proverbial drunk looking under the streetlight for his keys, they never had any choice about where to look for the universe. "Thirty years ago we thought the universe was all stars. Now stars are just the tip of the iceberg," said Dr. Michael Turner, a cosmologist at the University of Chicago. "There was a worry that the light in the sky was not faithfully tracing the distribution of matter. Large surveys went out looking for clumps of matter that didn't correspond to light.

"That story is now starting to come to an end."

Now if someone would just do something about that dark energy.

Hawking's Breakthrough Is Still an Enigma

By DENNIS OVERBYE

CAMBRIDGE, England -- In the fall of 1973 Dr. Stephen W. Hawking, who has spent his entire professional career at the University of Cambridge, found himself ensnared in a horrendous and embarrassing calculation. Attempting to investigate the microscopic properties of black holes, the gravitational traps from which not even light can escape, Dr. Hawking discovered to his disbelief that they could leak energy and particles into space, and even explode in a fountain of high-energy sparks.

Dr. Hawking first held off publishing his results, fearing he was mistaken. When he reported them the next year in the journal Nature, he titled his paper simply "Black Hole Explosions?" His colleagues were dazzled and mystified.

Nearly 30 years later, they are still mystified. When they gathered in Cambridge this month to mark Dr. Hawking's 60th birthday with a weeklong workshop titled "The Future of Theoretical Physics and Cosmology," the ideas spawned by his calculation and its aftermath often took center stage.

They are ideas that touch on just about every bone-jarring abstruse concept in modern physics.

"Black holes are still fundamentally enigmatic objects," said Dr. Andrew Strominger, a Harvard physicist, who attended. "In fundamental physics, gravity and quantum mechanics are the big things we don't understand. Hawking's discovery of black hole radiation was of fundamental importance to that connection."

Black holes are the prima donnas of Einstein's general theory of relativity, which explains the force known as gravity as a warp in space-time caused by matter and energy. But even Einstein could not accept the idea that the warping could get so extreme, say in the case of a collapsing star, that space could wrap itself completely around some object like a magician's cloak, causing it to disappear as a black hole.

Dr. Hawking's celebrated breakthrough resulted partly from a fight. He was hoping to disprove the contention of Jacob Bekenstein, then a graduate student at Princeton and now a professor at the Hebrew University in Jerusalem, that the area of a black hole's boundary, the point of no return in space, was a measure of the entropy of a black hole. In thermodynamics, the study of heat and gases, entropy is a measure of wasted energy or disorder, which might seem like a funny concept to crop up in black holes. But in physics and computer science, entropy is also a measure of the information capacity of a system -- the number of bits that it would take to describe its internal state. In effect, a black hole or any other system was like a box of Scrabble letters -- the more letters in the box the more words you could make, and the more chances of gibberish.

According to the second law of thermodynamics, the entropy of a closed system always stays the same or increases, and Dr. Hawking's own work had shown that the hole's surface area always increased, a process that seemed to ape that law.

But Dr. Hawking, citing classical physics, argued that an object with entropy had to have a temperature, and anything with a temperature -- from a fevered brow to a star -- must radiate heat and light with a characteristic spectrum. If a black hole could not radiate, it could have no temperature and thus no entropy. But that was before gravity, which shapes the cosmos, met quantum theory, the paradoxical rules that describe the behavior of matter and forces within it. When Dr. Hawking added a touch of quantum uncertainty to the standard Einsteinian black hole model, particles started emerging. At first he was annoyed, but when he realized this "Hawking radiation" would have the thermal spectrum predicted by thermodynamic theory, he concluded his calculation was right.

But there was a problem. The radiation was random, Dr. Hawking's theory said. As a result, all the details about whatever had fallen into the black hole could be completely erased -- a violation of a hallowed tenet of quantum theory, which holds that it should always be possible to run the film backwards and find out the details of how something started -- whether an elephant or a Volkswagen had been tossed into the black hole, for example. If he was right, Dr. Hawking suggested, quantum theory might have to be modified. Black holes, he said in his papers and talks in the late 1970's, were ravagers of information, spewing indeterminacy and undermining law and order in the universe.

"God not only plays dice with the universe," Dr. Hawking said, inverting the phrase by which Einstein had famously rejected quantum uncertainty, "but sometimes throws them where we can't see them." Such statements aroused the attention of particle physicists. Weird as it may be, quantum theory is nonetheless the foundation on which much of the modern world is built, everything from transistors to CD's, and it is the language in which all of the fundamental laws of physics, save gravity, are expressed. "This cannot be," Dr. Leonard Susskind, a theorist at Stanford, recalled saying to himself.

It was the beginning of what Dr. Susskind calls an adversarial relationship. "Stephen Hawking is one of the most obstinate people in the world; no, he is the most infuriating person in the universe," Dr. Susskind told the birthday workshop, as Dr. Hawking grinned in the back row.

In the ensuing 20 years, opinions have split mostly along party lines. Particle physicists like Dr. Susskind and Dr. Gerard 't Hooft, a physicist at the University of Utrecht and the 1999 Nobel Prize winner, defend quantum theory and say that the information must get out somehow, perhaps subtly encoded in the radiation. Another possibility -- that the information was left behind in some new kind of elementary particle when the black hole evaporated -- seems to have fallen from favor.

Relativity experts like Dr. Hawking and his friend the Caltech physicist Dr. Kip Thorne were more likely to believe in the power of black holes to keep secrets. In 1997, Dr. Hawking and Dr. Thorne put their money where the black hole mouth was, betting Dr. John Preskill, a Caltech particle physicist, a set of encyclopedias that information was destroyed in a black hole.

To date neither side has felt obliged to pay up.

Writing on the Wall

Dr. Susskind and others have argued that nothing ever makes it into the black hole to begin with because, in accord with Einstein, everything at the boundary, where time slows, would appear to an outside observer to "freeze" and then fade, spreading out on the surface where it could produce subtle distortions in the Hawking radiation.

In principle, then, information about what had fallen onto the black hole could be read in the radiation and reconstructed; it would not have disappeared.

The confusion had arisen, Dr. Susskind explained, because physicists had been trying to imagine the situation from the viewpoint of God rather than that of a particular observer who had to be either in the black hole or outside, but not both places at once. When the accounting is done properly, he said, "No observer sees a violation of the laws of physics."

The information paradox made it important for theorists to try to go beyond thermodynamic analogies and actually calculate how black holes store information or entropy. But there was a catch. According to a well-known formula developed by the Austrian physicist Ludwig Boltzmann (and engraved on his tombstone), the entropy of a system could be determined by counting the number of ways its contents could be arranged.

In order to enumerate the possible ways of arranging the contents of a black hole, physicists needed a theory of what was inside. By the mid-1990's they had one: string theory, which portrays the forces and particles of nature, including those responsible for gravity, as tiny vibrating strings.

In this theory, a black hole is a tangled mélange of strings and multidimensional membranes known as "D-branes." In a virtuoso calculation in 1995, Dr. Strominger and Dr. Cumrun Vafa, also of Harvard, untangled the innards of an "extremal" black hole, in which electrical charge just balanced gravity.

Such a hole would stop evaporating and would thus appear static, allowing the researchers to count its quantum states. They calculated that the entropy of a black hole was its area divided by four -- just as Dr. Hawking and Dr. Bekenstein said it would be.

The result was a huge triumph for string theory. "If string theory had been wrong, that would have been deadly," Dr. Strominger said.

The success of the Harvard calculation has encouraged some particle physicists to conclude that black holes can be analyzed with the tools of quantum mechanics, and thus that the information issue has been resolved. But others say this has yet to be accomplished -- among them Dr. Strominger, who added, "It remains an unsettled issue."

Degrees of Freedom

Perhaps the most mysterious and far-reaching consequence of the exploding black hole is the idea that the universe can be compared to a hologram, in which information for a three-dimensional image can be stored on a flat surface, like an image on a bank card.

In the 1980's, extending his and Dr. Hawking's work, Dr. Bekenstein showed that the entropy and thus the information needed to describe any object were limited by its area. "Entropy is a measure of how much information you can pack into an object," he explained. "The limit on entropy is a limit on information."

This was a strange result. Normally you might think that there were as many choices -- or degrees of freedom about the inner state of an object -- as there were points inside that space. But according to the so-called Bekenstein bound, there were only as many choices as there were points on its outer surface.

The "points" in this case are regions with the dimensions of 10-33 centimeters, the so-called Planck length that physicists believe are the "grains" of space. According to the theory, each of these can be assigned a value of zero or one -- yes or no -- like the bits in a computer.

"What happens when you squeeze too much information into an object is that you pack more and more energy in," Dr. Bousso said. But if it gets too heavy for its size, it becomes a black hole, and then "the game is over," as he put it. "Like a piano with lots of keys but you can't press more than five of them at once or the piano will collapse."

The holographic principle, first suggested by Dr. 't Hooft in 1993 and elaborated by Dr. Susskind a year later, says in effect that if you can't use the other piano keys, they aren't really there. "We had a completely wrong picture of the piano," explained Dr. Bousso. The normal theories that physics uses to describe events in space-time are redundant in some surprising and as yet mysterious way. "We clearly see the world the way we see a hologram," Dr. Bousso said. "We see three dimensions. When you look at one of those chips, it looks pretty real, but in our case the illusion is perfect."

Dr. Susskind added: "We don't read the hologram. We are the hologram."

The holographic principle, these physicists say, can be applied to any space-time, but they have no idea why it works.

"It really should be mysterious," Dr. Strominger said. "If it's really true, it's a deep and beautiful property of our universe -- but not an obvious one."

The Frontiers of Beauty

That beauty, however, comes at a price, said Dr. 't Hooft, namely cause and effect. If the information about what we are doing resides on distant imaginary walls, "how does it appear to us sitting here that we are obeying the local laws of physics?" he asked the audience at the Hawking birthday workshop.

Quantum mechanics had been saved, he declared, but it still might need to be supplanted by laws that would preserve what physicists call "naïve locality."

Dr. 't Hooft acknowledged that there had been many futile attempts to eliminate quantum mechanics' seemingly nonsensical notions, like particles that can instantaneously react to one another across light-years of space. In each case, however, he said there were assumptions, or "fine print," that might not hold up in the end.

Recent observations have raised the stakes for ideas like holography and black hole information. The results suggest that the expansion of the universe is accelerating. If it goes on, astronomers say, distant galaxies will eventually be moving away so fast that we will not be able to see them anymore.

Living in such a universe is like being surrounded by a horizon, glowing just like a black hole horizon, over which information is forever disappearing. And since this horizon has a finite size, physicists say, there is a limit to the amount of complexity and information the universe can hold, ultimately dooming life.

Physicists admit that they do not know how to practice physics or string theory in such a space, called a de Sitter space after the Dutch astronomer Willem de Sitter, who first solved Einstein's equations to find such a space. "De Sitter space is a new frontier," said Dr. Strominger, who hopes that the techniques and attention that were devoted to black holes in the last decade will enable physicists to make headway in understanding a universe that may actually represent the human condition.

Dr. Bousso noted that it was only in the last few years, with the discovery of D-branes, that it had been possible to solve black holes. What other surprises await in string theory? "We have no idea how small or large a piece of the theory we haven't seen yet," he said.

In the meantime, perhaps in imitation of Boltzmann, Dr. Hawking declared at the end of the meeting that he wanted the formula for black hole entropy engraved on his own tombstone.

It's All in the Mathematics

When Stephen Hawking startled cosmologists by asserting that energy and matter could leak out of black holes, his calculations did not say how particles escaped from the black hole, only that they could. The only truth is in the mathematics, he says.

According to Heisenberg's uncertainty principle, a pillar of quantum theory, the so-called vacuum of space is not empty but rather foaming with virtual particles that flash into existence in particle-antiparticle pairs on borrowed energy and then meet and annihilate each other in a flash of energy that repays the debt of their existence.

But if only one member of a pair fell into a black hole, its mate would be free to wander away. To a distant observer it would appear to be coming out of the black hole, and, since the energy for its creation had been borrowed from the black hole's gravitational field and then not been paid back, the black hole would accordingly appear to shrink.

As the black hole shrank it would get hotter and radiate faster, according to Dr. Hawking's calculations, until it finally exploded.

The mortality of a black hole was of little practical concern. A typical black hole would last 1064 years, trillions of times the age of the universe.

Peering Through the Gates of Time

By DENNIS OVERBYE

PRINCETON, N.J., March 5 -- It's all come down to this.

In one corner is Dr. John Archibald Wheeler, 90, professor emeritus of physics at Princeton and the University of Texas, armed with a battery of hearing aids, fistfuls of colored chalk, unfailing courtesy, a poet's flair for metaphor, an indomitable sense of duty and the company of a ghost army of great thinkers.

In the other is a "great smoky dragon," which is how Dr. Wheeler refers sometimes to one of the supreme mysteries of nature. That is the ability, according to the quantum mechanic laws that govern subatomic affairs, of a particle like an electron to exist in a murky state of possibility -- to be anywhere, everywhere or nowhere at all -- until clicked into substantiality by a laboratory detector or an eyeball.

Dr. Wheeler suspects that this quantum uncertainty, as it is more commonly known, is the key to understanding why anything exists at all, how something, the universe with its laws, can come from nothing. Or as he likes to put it in the phrase that he has adopted as his mantra: "How come the quantum? How come existence?"

Standing by the window in his third-floor office in Princeton's Jadwin Hall recently, Dr. Wheeler pointed out at the budding trees and the green domes of the astronomy building in the distance. "We're all hypnotized into thinking there's something out there," he said.

Twice a week he takes a bus from his retirement home in nearby Hightstown to sit here under portraits of Albert Einstein and Niels Bohr, the twin poles of his scientific life, and confront the dragonlike ephemerality of the world, dictating his thoughts to his secretary, Emily Bennett.

"The time left for me on earth is limited," he wrote recently. "And the creation question is so formidable that I can hardly hope to answer it in the time left to me. But each Tuesday and Thursday I will put down the best response that I can, imagining that I am under torture."

He is under no illusions about who will win the confrontation. A heart attack last year has taken its toll, and he acknowledges that his thoughts are fragmentary, ideas for ideas, as he likes to put it, and not for his present-day colleagues but for the generations of colleagues down the line.

It's what he has been doing his whole life. Dr. Wheeler helped explain nuclear fission with Bohr, argued quantum theory with Einstein, helped build the atomic and hydrogen bombs and pioneered the study of what he later dubbed black holes. Along the way, he indulged his taste for fireworks and mischief and became the hippest poet physicist of his generation, using metaphor as effectively as calculus to capture the imaginations of his students and colleagues and to send them, minds blazing, to the barricades to confront nature.

The phrases Dr. Wheeler has coined constitute a kind of vapor trail marking the path of the aspirations of physics in the last few decades: black hole, quantum foam, law without law, to name a few.

"A major piece of him is that he is a visionary," said Dr. Kip Thorne, a physics professor at California Institute of Technology who was Dr. Wheeler's graduate student at Princeton. "He tries to see farther over the horizon than most people by way of his physical intuition."

"He brought the fun back into physics," said Dr. Max Tegmark, a cosmologist at the University of Pennsylvania who has recently collaborated with Dr. Wheeler, ticking off the reasons scientists love him. Physicists, he said, are usually reluctant to talk about Really Big Questions, like the why of existence, for fear of being branded flaky.

"He taught us not to be afraid," Dr. Tegmark said.

It is a season of celebration for Dr. Wheeler and of reaping the harvest from generations of seeds of inspiration. The Battelle Memorial Institution of Columbus, Ohio, has donated $3 million to endow a physics chair in Dr. Wheeler's name at Princeton, which celebrated his birthday with one-day symposium last July, and plans a larger event.

The Really Big Questions that Dr. Wheeler loves will be on the table when prominent scientists gather at a conference center here in his honor for a symposium on March 16 modestly titled "Science and Ultimate Reality" sponsored by the John Templeton Foundation and the Peter Gruber Foundation Cosmology Prize.

The Philosopher King: Bohr Conversations Leave Indelible Mark

Dr. Wheeler once compared himself to Daniel Boone, who, the story goes, felt compelled to move on to new territory every time someone moved within a mile of him. It was in nuclear physics, the science of the buzzing dense cores of atoms, that he first made his mark. Born July 9, 1911, in Jacksonville, Fla., the oldest child in a family of librarians, he earned his Ph.D. in physics from Johns Hopkins at age 21.

A year later, after becoming engaged to an old acquaintance, Janette Hegner, after only three dates -- they have been married 67 years and have three children, eight grandchildren and nine great-grandchildren -- Dr. Wheeler took a boat to Copenhagen. There, Bohr was presiding over a small research institute and serving as the philosopher king of a revolution that had shaken physics and common sense to the marrow in the previous decade.

The cornerstone of that revolution was the uncertainty principle, propounded by Werner Heisenberg in 1927, which seemed to put fundamental limits on what could be known about nature, declaring, for example, that it was impossible, even in theory, to know both the velocity and position of a subatomic particle. Knowing one destroyed the ability to measure the other.

As a result, until observed, subatomic particles and events existed in a sort of cloud of possibility, a smoky dragon. In some sense no particle or other phenomenon was real, Bohr said, until it was an observed phenomenon.

The year spent in Copenhagen watching Bohr wrestle with the paradoxes of the quantum world was the beginning of a lifelong relationship that left an indelible mark.

"You can talk about people like Buddha, Jesus, Moses, Confucius, but the thing that convinced me that such people existed were the conversations with Bohr," Dr. Wheeler later said.

In January 1939 when Bohr arrived for a visit in the United States, Dr. Wheeler, a young Princeton professor, met the boat.

Within a few weeks the two had sketched out a theory of how nuclear fission, recently discovered in Germany, worked. In their model the nucleus is like a liquid drop that starts vibrating when a neutron hits it, elongating into a peanut shape that then snaps in two, shooting out energy and particles.

Dr. Wheeler was later swept up in the Manhattan Project to build an atomic bomb. But he still blames himself for a two-year delay between the time in 1939 that Einstein wrote a letter urging President Franklin D. Roosevelt to start a bomb project and when it got going. Had the war ended two years earlier, he says, millions of lives might have been saved, including that of a younger brother, Joe, who died fighting in Italy, but knew enough about what was going on in physics to have sent his older brother a card in 1944, saying simply, "Hurry up!"

Dr. Wheeler interrupted a sabbatical in Paris in 1950 to come back to the United States and help Dr. Edward Teller develop a hydrogen bomb. For his pains Dr. Wheeler was once officially reprimanded by President Dwight D. Eisenhower for losing a classified document on a train, but he was later honored by President Lyndon B. Johnson in a White House ceremony.

Gates of Time: Paradoxical Visions Of Cosmic Dead End

Back in academia, Dr. Wheeler found himself being lured away from nuclear physics by the theories of another Princeton resident, Einstein. The two occasionally talked about quantum theory, which Einstein found abhorrently random, but what intrigued Dr. Wheeler was Einstein's theory of relativity.

Gravity, according to Einstein's vision, was just the geometry of space-time, warped or "curved" in the presence of matter or energy, the way a mattress sags under a hefty sleeper.

The part that interested Dr. Wheeler most was an apocalyptic prediction contained within the equations: matter, say in a dead star, could collapse into a heap so dense that light could not even escape from it, eventually squeezing itself out of existence. At the center, space would be infinitely curved, and as Dr. Wheeler likes to say, "smoke pours out of the computer." Space, time and even the laws of physics themselves would break down at this cosmic dead end, called a singularity.

Dr. Wheeler made it his mission to alert the rest of his colleagues to the paradoxical vision of physics predicting its own demise. Dr. Wheeler made Princeton the center of research in general relativity, a field that had been moribund because of its remoteness from laboratory experiment, in the United States.

"He rejuvenated general relativity," said Dr. Freeman Dyson, a theorist at the Institute for Advanced Study, across town in Princeton.

It was not until 1967, at a conference in New York City, that Dr. Wheeler, adopting a suggestion shouted from the audience, hit upon the name "black hole" to dramatize this dire possibility for a star and for physics.

The black hole "teaches us that space can be crumpled like a piece of paper into an infinitesimal dot, that time can be extinguished like a blown-out flame, and that the laws of physics that we regard as 'sacred,' as immutable, are anything but," he later said in his 1998 autobiography, "Geons, Black Holes & Quantum Foam: A Life in Physics," written with Dr. Kenneth Ford, a former student and the retired director of the American Institute of Physics.

Moreover, Dr. Wheeler preached, the breakdown of physics could not be sealed away in a distant dead star. He pointed out that even space and time had to pay their dues to the uncertainty principle. When viewed on very small scales or in the compressed throes of the Big Bang, what looked so smooth and continuous, like an ocean from an airplane, would become discontinuous, dissolving like a dry sand castle into a mess of unconnected points and worm holes that Dr. Wheeler dubbed "quantum foam."

In a sense, black holes, or "gates of time," as he later called them, were everywhere, under our fingernails, courtesy of the uncertainty principle, and thus so was the issue of where the laws of physics came from.

By the 1970's Dr. Wheeler was ready to move on. Faced with mandatory retirement from teaching at Princeton, he moved to the University of Texas, where he turned to the very small, that is to say, the quantum, with the energy and eloquence that he had once lavished on black holes.

"Relativity is exciting but it's not surprising, it's not peculiar," he once told Dr. Ford. "Quantum theory remains a mystery; it's a greater challenge for the 21st century."

One idea that he and his Texas colleagues investigated was the notion that the universe is a giant computer and that quantum theory can somehow be derived from information theory, the logic of bits and bytes.

The work goes on, and will be one of the main items of discussion in Princeton.

It From Bit: Einstein's Words Are Set in Stone

Told that he had to slow down after bypass surgery, Dr. Wheeler moved to a retirement home near Princeton in 1986.

On his way to lunch recently Dr. Wheeler took a visitor on a detour through the old brick building once known as Fine Hall, now Jones Hall, pointing out the offices that he, Einstein and Bohr had occupied in 1939.

Across the hall was a lounge with rows of windows, leather couches and a fireplace with an inscription from Einstein on the mantelpiece. "Raffiniert ist der Herr Gott, aber Boshaft ist er nicht," Dr. Wheeler said, reading. Then he translated, roughly, "God is clever, but he's not malicious."

Asked if he agreed, Dr. Wheeler nodded, then pumped his fist in affirmation.

Back in his office Dr. Wheeler busied himself at the blackboard with a diagram that is emblematic of quantum weirdness, and of his hope for constructing the universe and its laws "higgledy-piggledy," as he likes to call it, out of nothing.

It is called double slit experiment. In it an electron or any other particle flies toward a screen with a pair of slits. Past the screen is a physicist with a choice of two experiments. One will show that the electron was a particle and passed through one or another slit; the other will show that it was a wave and passed through both slits, producing an interference pattern. The electron will turn out to be one or the other depending on the experimenter's choice.

That was weird enough, but in 1978 Dr. Wheeler pointed out that the experimenter could wait until after the electron would have passed the slits before deciding which detector to employ and thus whether it had been a particle or wave. In effect, in this "delayed choice" experiment, the physicists would be participating in creating the past.

In a 1993 paper Dr. Wheeler likened such a particle to a "great smoky dragon," whose tail was at the entrance slits of the chamber and its teeth at the detector, but in between -- before it had been "registered" in some detector as a phenomenon -- was just a cloud, smoky probability.

Perhaps the past itself is such a smoky dragon awaiting our perception.

He wonders if the delayed choice experiment is a prescription for how the universe can be built up from information, as in a cosmic game of 20 questions, a series of yes-no decisions resulting from billions upon billions of quantum observations. It's a concept that has gone by many names over the last few decades from "genesis by observership" to "participatory universe" to the current fashion, "it from bit."

Typically there is a diagram, a cartoon actually, which consists of a giant U with an eyeball on top of one stem looking back at the other. The skinny unadorned end of the U is the Big Bang, he explained, tracing his finger along the loop.

"The model of the universe starts out all skinny and then gets bigger," he said. "Finally it gives rise to life and the mind and the power to observe, and by the act of observation of those first days, we give reality to those first days."

An excerpt dated Jan. 29, 2002, from Dr. Wheeler's journal reads: "No space, no time, no gravity, no electromagnetism, no particles. Nothing. We are back where Plato, Aristotle and Parmenides struggled with the great questions: How Come the Universe, How Come Us, How Come Anything? But happily also we have around the answer to these questions. That's us."

It's a gaudy notion even for an adventurer like Dr. Wheeler.

But as Dr. Thorne pointed out, Dr. Wheeler's track record with crazy ideas is surprisingly good. One such idea had led to a Nobel Prize for Dr. Wheeler's graduate student Dr. Richard Feynman, the noted Caltech physicist. Dr. Thorne recalled Dr. Feynman's telling him once, "Some people think Wheeler's gotten crazy in his later years, but he's always been crazy."

The Most Seductive Equation in Science: Beauty Equals Truth

By DENNIS OVERBYE

In the fall of 1915, Albert Einstein, living amid bachelor clutter on coffee, tobacco and loneliness in Berlin, was close to scrawling the final touches to a new theory of gravity that he had pursued through mathematical and logical labyrinths for nearly a decade. But first he had to see what his theory had to say about the planet Mercury, whose puzzling orbit around the Sun defied the Newtonian correctness that had long ruled the cosmos and science. The result was a kind of cosmic "boing" that changed his life.

Einstein's general theory of relativity, as it was known, described gravity as warped space-time. It had no fudge factors -- no dials to twiddle. When the calculation nailed Mercury's orbit Einstein had heart palpitations. Something inside him snapped, he later reported, and whatever doubt he had harbored about his theory was transformed into what a friend called "savage certainty." He later told a student that it would have been "too bad for God," if the theory had been subsequently disproved.

The experience went a long way toward convincing Einstein that mathematics could be a telegraph line to God, and he spent most of the rest of his life in an increasingly abstract and ultimately fruitless pursuit of a unified theory of physics.

Rare indeed is the scientist who has not at one point or other been seduced by the beauty of his own equations and dumbfounded by what the physicist Dr. Eugene Wigner of Princeton once called the "unreasonable effectiveness of mathematics" in describing the world.

The endless fall of the moon, the fairy glow of a rainbow, the crush of a nuclear shock wave are all explicable by scratches on a piece of paper, that is to say, equations. Every time an airplane safely touches down on time, a computer boots up, or a cake comes out right, the miracle is recreated. "The most incomprehensible thing about the universe is that it is comprehensible," Einstein said.

Math is the language of physics, but is it the language of God?

Mathematicians often say that they feel as if their theorems and laws have an objective reality, like Plato's perfect realm of ideas, which they do not create or construct as much as simply discover. But the equating of math with reality, others say, consigns vast arenas of experience to the darkness. There are no mathematical explanations yet for life, love or consciousness.

"As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality," said Einstein.

He maintained that it should be possible to explain scientific principles in words to a child, but his followers often argue that words alone cannot convey the glories of physics, that there is a beauty apparent only to the mathematically adept.

That inhuman beauty has long been a lodestone for physicists, says Dr. Graham Farmelo, a physicist at the Science Museum in London and an editor of "It Must Be Beautiful: Great Equations of Modern Science."

"You can write it on the palm of your hand and it shapes the universe," Dr. Farmelo said of Einstein's gravitational equation, the one that produced heart palpitations. He compared the feeling of understanding such an equation to the emotions you experience "when you take possession of a great painting or a poem."

In the hopes of getting the rest of us to take possession some of our intellectual heritage, Dr. Farmelo recruited scientists, historians and science writers to write about the life and times of 11 of the most powerful or notorious equations of 20th century science.

The book is partly a meditation on mathematical beauty, possibly a difficult concept for many Americans right now as they confront their tax forms. But as Dr. Farmelo noted in an interview, even the most recalcitrant of us have had glimpses of mathematical grace when, say, our checkbooks balanced.

Imagine that your withholdings always turned out to be exactly equal to the tax you wind up owing. Or that your car's odometer turned over to all zeros every year on your birthday no matter how far you thought you had driven. Such occurrences would be evidence of patterns in your financial affairs or driving habits that might be helpful in preparing tax returns or scheduling car maintenance.

The pattern most highly prized in recent modern physics has been symmetry. Just as faces and snowflakes are prettier for their symmetrical patterns, so physical laws are considered more beautiful if they keep the same form when we change things by, for example, moving to the other side of the universe, making the clocks run backward, or spinning the lab around on a carousel.

A good equation, Dr. Farmelo said, should be an economical compression of truth without a symbol out of place. He looks for attributes like universality, simplicity, inevitability, an elemental power and "granitic logic" of the relationships portrayed by those symbols.

There is, for example, Einstein's E=mc2 , which Dr. Peter Galison, a Harvard historian and physicist, describes in the book as "a metonymic of technical knowledge writ large," adding, "Our ambitions for science, our dreams of understanding and our nightmares of destruction find themselves packed into a few scribbles of the pen."

When it comes to the quest for beauty in physics, even Einstein was a piker compared with the British theorist Paul Dirac, who once said "it is more important to have beauty in one's equations than to have them fit experiment."

An essay by Dr. Frank Wilczek, a physics professor at the Massachusetts Institute of Technology, recounts how the 25-year-old Dirac published an equation in 1928 purporting to describe the behavior of the electron, the most basic and lightest known elementary particle at the time. Dirac had arrived at his formula by "playing around" in search of "pretty mathematics," as he once put it. Dirac's equation successfully combined the precepts of Einstein's relativity with those of quantum mechanics, the radical rules that prevail on very small scales, and it has been a cornerstone of physics ever since.

But there was a problem. The equation had two solutions, one representing the electron, another representing its opposite, a particle with negative energy and positive charge, that had never been seen or suspected before.

Dirac eventually concluded that the electron (and it would turn out every other elementary particle) had a twin, an antiparticle. In Dirac's original interpretation, if the electron was a hill, a blob, in space, its antiparticle, the positron, was a hole -- together they added to zero, and they could be created or destroyed in matching pairs. Such acts of creation and annihilation are now the main business of particle accelerators and high-energy physics. His equation had given the world its first glimpse of antimatter, which makes up, at least in principle, half the universe.

The first antimatter particle to be observed, the antielectron, was found in 1932, and Dirac won the Nobel Prize the next year. His feat is always dragged forth as Exhibit A in the argument to show that mathematics really does seem to have something to do with reality.

"In modern physics, and perhaps in the whole of intellectual history, no episode better illustrates the profoundly creative nature of mathematical reasoning than the history of the Dirac equation," Dr. Wilczek wrote.

In hindsight, Dr. Wilczek writes, what Dirac was trying to do was mathematically impossible. But, like the bumblebee who doesn't know he can't fly, through a series of inconsistent assumptions, Dirac tapped into a secret of the universe.

Dirac had started out thinking of electrons and their opposites, the "holes," as fundamental entities to be explained, but the fact that they could be created and destroyed meant that they were really evanescent particles that could be switched on and off like a flashlight, explains Dr. Wilczek.

What remains as the true subject of Dirac's equation and as the main reality of particle physics, he says, are fields, in this case the electron field, which permeate space. Electrons and their opposites are only fleeting manifestations of this field, like snowflakes in a storm.

As it happens, however, this quantum field theory, as it is known, must jump through the same mathematical hoops as Dirac's electron, and so his equation survives, one of the cathedrals of science. "When an equation is as successful as Dirac's, it is never simply a mistake," Dr. Steven Weinberg, a 1979 Nobel laureate in physics from the University of Texas, writes in an afterword to Dr. Farmelo's book.

Indeed, as Dr. Weinberg has pointed out in an earlier book, the mistake is often in not placing enough faith in our equations. In the late 1940's, a group of theorists at George Washington University led by Dr. George Gamow calculated that the birth of the universe in a Big Bang would have left space full of fiery radiation, but they failed to take the result seriously enough to mount a search for the radiation. Another group later discovered it accidentally in 1965 and won a Nobel Prize.

Analyzing this lapse his 1977 book, "The First Three Minutes," Dr. Weinberg wrote: "This is often the way it is in physics. Our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world."

CITATIONS

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