The Quantum Universe:

From creation ex nihilo to the omega point, we're on a roller coaster we can't stop

By DIETRICK E. THOMSEN

Cosmology is the science of beginnings and endings. Cosmologists tend to concentrate on the first three milliseconds, or the first three seconds, or at most the first three years of history; and on the last few eons as well. It was not always this way. In olden days scientists tended to believe in a static universe. But 60 years ago the world learned that the universe is not static, and then the questions "Where did we come from?" and "Where are we going?" became scientific questions. When these questions are mixed with modern theories of general relativity and quantum mechanics — as seemed appropriate at the recent Third Loyola Conference on Quantum Theory and Gravitation, held at Loyola University in New Orleans — some interesting ideas result.

Alexander Vilenkin of Tufts University in Medford, Mass., proposes to demonstrate that the universe was created from nothing. As he points out, "the idea is very old in the context of theology." It is also more than a decade old scientifically, going back to a 1973 suggestion by Edward P. Tryon of Hunter College of the City University of New York.

What Tryon noticed was that over the whole universe many of the conserved quantities of physics add up to zero. Conservation laws — which state that the total amount of some quantity in a system undisturbed from outside does not change — are fundamental to physical analysis. Quantities such as energy and momentum are conserved. On the subatomic level many of the qualities, collectively known as quantum numbers, that differentiate one kind of particle from another are conserved. As it happens, many of those that have positive and negative aspects, like electric charge, add up to zero over the whole universe. By choosing appropriate boundary conditions, Vilenkin points out, cosmologists can make others come to zero also.

All this means that the universe could be a "quantum mechanical fluctuation." In quantum mechanics zero does not always remain zero. In a balanced situation, as this kind of thinking postulates for the universe, the positives and negatives can separate enough for some physical processes to occur for a fleeting time. Quantum mechanical fluctuations generally last for so short a time that measuring instruments cannot be sure they existed at all. If the universe is one, and we are living in the middle of it, it is a very interesting and paradoxical place to be. The fluctuation may last eons for us who are inside it, but hardly any time at all from an outside point of view, about which we know nothing.

Vilenkin points out that until recently the standard Big Bang theory of the universe's development conflicted with such ideas of a zero-point beginning. Big Bang theorists were never precisely clear on how large the universe was when it started to expand, but it seems that it had to be larger than a fluctuation could be to reach its present size with a steady rate of expansion. Now, however, cosmologists have inflationary growth scenarios, such as those championed by Alan H. Guth of Massachusetts Institute of Technology (who has also remarked on the possibility of creation *ex nihilo*). These theories postulate a period of very rapid expansion early in history, and so can accommodate the beginning that Vilenkin wants.

That beginning involves another paradox of quantum mechanics: tunneling. "The universe arises by quantum tunneling from nothing, a state with no classical space-time." To borrow something Gertrude Stein said about Oakland, Calif., there's no there there. There's also no then then.

Tunneling is a phenomenon frequently encountered in electronic circuitry — in Josephson junctions, for example. If there is an insulating gap in an electric circuit that represents an energy barrier greater than the energy possessed by moving electrons, current will not flow — according to the classical theory of electric circuits. Regarding the system quantum mechanically, however, requires representing the electrons with wave equations that, among other things, give physicists the ability to calculate the probability for electrons to be in one place or another. It turns out that the wave equations give a certain probability for electrons to be on the opposite side of the barrier, and in practice they turn out to be there: A certain current flows, nevertheless.

To go from the spaceless, timeless state

A Zero-Point Fluctuation?

of nothingness to a state of somethingness in which space and time exist and in which matter can exist requires the passage of a similar barrier. Vilenkin can write down a wave equation for the whole universe and "calculate the tunneling probability — whatever it means." The meaning of the probability is not all that clear, because in this instance Vilenkin is dealing not with the statistics of millions and billions of electrons in a circuit, but solely with the one and only universe we know about. The philosophical foundations of quantum mechanics can get a bit self-contradictory when dealing with "one and only" situations.

Whatever probability may mean in the case of the one and only universe, Vilenkin can calculate from the equation that the universe began as if it had come through such a tunnel, nucleating as a tiny bubble in which space and time exist and matter can be generated. He can even give a formula for the size of the bubble; it depends on the density of the universe and the time since it came out of the tunnel. The bubble expands from there. This universe, says Vilenkin, is homogeneous and isotropic — two characteristics we observe, or think we observe, in the universe today. It is also a closed universe: If it *is* a quantum mechanical fluctuation, it eventually has to relax back to the state of zero-based nothingness that it started from.

Physics restricts itself to material causes and material effects. However, the Loyola discussion dealt with what could be the very first material cause and the very last material effects, and the participants had something of a difficult time keeping God out of it. "Why is the universe so large?" asked Don N. Page of the Institute for Advanced Study in Princeton, N.J. "To say that God created it is outside of physics." In the next breath Page went on to quote the Bible about the initial condition of the universe: "without form, and void."

The usual way to answer the question Page poses is to make a mathematical model of the development of the universe and solve it accordingly. Page described work to that end that he has been doing in partnership with Stephen Hawking of Cambridge University in England. As Page points out, such a model is built of three parts: the physical quantities that vary; dynamical equations that describe the variations of the physical quantities and their relations to each other; and the boundary conditions, the special qualities and beginning and end values that apply to the particular case.

'Why is the universe so large? To say God created it is outside of physics.'

In the case of the whole universe, the relevant physical variables are the geometry of three-dimensional space and the matter field, the nature and constitution of matter in any given space. The geometry may be positively curved (parallel lines eventually meet) by one or another amount, negatively curved (parallel lines eventually diverge) by one or another amount, or flat (parallel lines remain equidistant to infinity). Each combination of geometry and matter field characterizes a different universe. We can imagine an infinity of such combinations, and all these universes could exist parallel to one another.

To sort out this multiplicity, John Wheeler of the University of Texas at Austin introduced, about two decades ago, the notion of a superspace, a hypothetical space in which each possible combination of geometry and matter field is represented by one point. Page and Hawking do much of their mathematical operation in this Wheeler superspace.

The dynamical equations are two workhorses of theoretical physics, Hamilton's and Schroedinger's. But the equations alone will not explain the state of the actual universe we are in, the only one we are certain exists. It is a unique universe with a very special set of boundary conditions that theorists must consider. Our universe is homogeneous on the large scale, isotropic, apparently flat or very nearly so, and it has, Page says "a very strong arrow of time." The last point means that neither we nor any macroscopic procedures we know of can go backward in time. Page estimates that the chances of "the creator sticking in a pin" and pulling out just this combination of qualities that make such a unique universe are way beyond astronomical, 1 in $(10,000,000,000)^{124}$.

A final boundary condition is whether the universe has a geometric boundary: If we go far enough, will we fall off the edge? Hawking suggests not: "What could be more special than that the universe has no boundary?"

Robert Bourdeaux

The appearance of Schroedinger's equation indicates that Page's and Hawking's work also involves a wave equation for the whole universe—in other words, a quantization of the entire universe. Deriving a wave equation for something so macroscopic as the whole universe leads to some questions about the meaning of quantum mechanics. Page got into a pointed discussion of these problems with Eugene Wigner of Louisiana State University in Baton Rouge and Arthur Komar of Yeshiva University in New York City.

A quantum mechanical wave equation can be interpreted as a predictor of probabilities. Very often such an equation represents what physicists call "a superposition of states." That is, it involves two or more states of being for a given system, say A and B. In dealing with a large number of similar microscopic objects — millions or billions of electrons, for instance — the physicist can say that such and such a percentage of them are in state A and such and such a percentage in state B. If only one electron is concerned, one can imagine that it is somehow alternately in each of the states. As it is impossible in principle to measure the state or follow the action of a single microscopic object, the physicist can get away with the apparent self-contradiction: Nobody can know exactly what is going on. With macroscopic objects, which *can* be exactly measured, and whose actions *can* be followed individually, the contradiction pinches.

One of the founders of quantum mechanics, Erwin Schroedinger, illustrated it with a famous cat. The wave equation for this cat is a superposition of two states: alive and dead. This is absurd. The cat is either alive or dead; it cannot be both. Nor can it be alive one instant, dead the next and alive again still later.

A closely related question, raised by Wigner, whose own contribution to the conference was a paper questioning the philosophical bases of quantum mechanics, is "What happens when you make a measurement?" Komar seconded Wigner, saying: "I have 100 percent probability [after making a measurement]; what is my wave function?" and "When you make a measurement the wave function collapses." That is, if you know something for certain (that the cat is alive, perhaps), the wave function becomes meaningless.

Page responds that you can't test the absolute probability of anything, and he quotes Hawking: "When I hear of Schroedinger's cat, I reach for my gun." Somewhat less categorically, Page insists on relative probabilities: If you measure something to be A, you put that in your memory bank and go on to ask the wave equation, given A, what is the relative probability of B? He feels this is a meaningful way to proceed, although it didn't appear that he had convinced the questioners.

Proceeding that way, nevertheless, Page derives a model that gives the universe the proper expansion, including the inflationary period at the very beginning that is necessary to get the universe to the correct present size, and does it without the fine tuning of conditions required by some other inflationary models. Page's model doesn't seem to explain the specific boundary conditions of our universe, but nevertheless, he says, "A number of things have been done with this. This proposal does agree with some observations."

Cosmologists talk a lot about the beginning and the middle; they seem less inclined to consider the end. Perhaps this is because they don't know which end it will be. There is general agreement that the universe started small and expanded. The end depends on whether the universe is open or closed. The universe as we have it seems to be very nearly flat (which for the discussion that follows is a special case of open). However, if there is a slight curvature, it could be in the direction of closed. Frank Tipler of Tulane University in New Orleans presented a scenario for each case:

Both scenarios leave little hope for the long-term survival of humans made of flesh and blood.

An open universe will expand forever, and things will gradually run down like a clock that nobody winds. A closed universe will reach some maximum size and then eventually collapse, coming to what Tipler calls "a crunch singularity," a state in which temperature and density become infinite and the radius of the cosmos is zero. Both scenarios leave little hope for the long-term survival of humans made of flesh and blood, but Tipler nevertheless holds out a hope for the survival of some kind of being capable of storing and processing information.

Tipler's open and flat universe scenario begins with the sun leaving the main sequence of stellar evolution in about a billion years and becoming unreliable as a steady source of energy. In a trillion years stars will cease to form. Stars then begin to cool off until, after 10^{15} years, we will have dead planets detached from dead stars.

The dead stars evaporate as the protons in them decay during the period from 10^{31} to 10^{34} years. Then black holes of about the sun's mass decay by giving off radiation in a manner that Hawking proposed some years ago. This is over by 10^{54} years. By 10^{71} years most of the electrons and positions left over from the decays form positronium, a quasiatom in which an electron and a positron are bound together and orbit around each other. By 10^{102} years even the most massive black holes, those with masses as large as superclusters of galaxies, have evaporated into Hawking radiation.

In the last eons the fates of open and flat universes differ slightly. In a flat universe, the positronium will decay as electrons and positrons meet each other and annihilate each other into photons or particles of light. By 10^{116} years only photons and a few residual protons are left. The universe is now so spread out that these protons are the equivalent of black holes, and they decay by Hawking radiation. By 10^{128} years there remains only silence, cold and some incredibly dim and spread-out light.

In the open universe, some of the positronium would be left. The average distance between electron and positron in these relict quasiatoms would be 100 times the present size of the universe, and their orbital speed a micron per century.

In the closed universe, the cosmos must first reach its maximum size—we know it is still expanding now—and then start to collapse. Therefore, the time scale is uncertain. When the universe gets down to $^1/_{100}$ of its present size and a temperature of 100 kelvins (compared to the present 3 K), galaxies merge. At $^1/_{1,000}$ of present size, the sky becomes as bright as the sun and the temperature is 3,000 K. At a millionth of present size and 3 million K, the sky is as hot as the cores of stars. At a billionth of present size (which equals about 10 light-years for the diameter of the universe) and 30 million K, atomic nuclei are dissociated into neutrons and protons. Finally, at a ten-billionth of present size (or about a hundredth of a light-year) and 30 trillion K, neutrons and protons disintegrate into quarks.

"It looks bad for mankind," says Tipler. "We're getting clobbered." But such a gloomy assessment, he says, is based "only on the idea that intelligence can be coded only in *Homo sapiens.*"

Suppose some intelligent machine existed that could withstand the physical conditions of far future. It would have to find the energy to process information and have a mechanism for storing the information. Tipler finds such conditions in the closed universe, and he says, "If life [defined as information processing and storage] exists forever, the universe must be closed." Borrowing an idea from Jesuit paleontologist and philosopher Pierre Teilhard de Chardin, Tipler predicts that "the universe must have one point singularity [a point toward which everything converges] in the customary cosmology. Call it an omega point." ☐