In the Beginning Was Quantum Gravity

By DIETRICK E. THOMSEN

The world of quantum mechanics is a jumpy one. Transitions are abrupt and discontinuous. There is a fundamental uncertainty and a shimmering fluctuation about the measurement of such basic quantities as location, momentum, time and energy. Normally we don't see these effects or face these uncertainties, because quantum mechanics is a theory of the microcosm, involving nothing larger than atoms and molecules. In contrast, our macrocosmic world seems, at least, to be a realm of smooth transitions and precise determinations.

Cosmology is the theory by which we describe the structure and history of the universe. It is a theory usually written in the continuous, smooth terms of the macroscopic world of our ordinary perceptions. But when we trace history back, we come to a time when macrocosm was microcosm, when the universe itself was extremely tiny, and there cosmology has to take account of quantum effects.

The necessity raises severe difficulties for theoreticians. As David Finkelstein of Georgia Institute of Technology in Atlanta put it at the recent Second New Orleans Conference on Quantum Theory and Gravitation, held at Loyola University there, quantum theory defies some of classical logic. This is especially true in the still unsuccessful attempts to find a quantum theory of gravity, the most important force in cosmology. Paradox and defiance of logic, and with them violations of "common sense" expectations as well as inadequacies in some common macroscopic concepts, crop up again and again.

Marek Demianski of the University of Texas at Austin asked whether there is "any hope of seeing the very early universe where quantum gravity effects influence the structure of the universe." That is, does the present state of the universe give us any evidence of what things were like back then?

Trying to imagine the universe in its earliest epoch, before the "Planck time," 10^{-43} seconds after time 0, can strain the mind. The Planck time is the moment when the differences that we now observe that distinguish gravity from the other classes of force in nature (electromagnetism and the two short-range subatomic kinds of force) first began to appear. Before the Planck time — during the Planck era — all the forces had the same strength; today the largest difference in strength is between gravity and the strong subatomic interaction. The latter is about 10^{40} times as strong as the former. Differences in maximum range, which today run from about a fermi (10^{-13} centimeter) for the strong interaction to infinity for gravitation and electromagnetism, would have been meaningless in a universe that was less than 10^{-33} cm across.

Contemplating the Planck era, Demianski wonders whether our common ideas of continuous and smoothly flowing space and time, the ordinary space-time of macroscopic physics, are applicable there. He says, "We don't know whether space-time is an adequate concept" for describing the dynamics of the epoch. Perhaps we need quantum metric fluctuations of the sort proposed by John Wheeler of the University of Texas at Austin.

The metric is the formula by which the distance between two points is measured in a given space. It describes such properties as the curvature of the space. In the macroscopic world of today, each conceivable space has its own metric describing its curvature and determining what kind of geometry can be done in it. The major question is which of the mathematically conceivable metrics best fits the actual space-time of our existence?

Before the Planck time, as Wheeler suggests and Demianski seconds, the metric would not have been so unequivocal as it should be today. It would have been subject to quantum mechanical fluctuations. That is, there are finite probabilities for it to be several different things, and we can imagine it flashing back and forth among them. Given this kind of uncertainty about its basic characteristics, Demianski asks about the adequacy of the concept of space-time itself.

Yet this state that is so hard to imagine could have been the source of some things we see today in our more definite, better behaved universe. Demianski reviewed the major difficulties cosmologists have with the standard big-bang model of the development of the universe (SN: 2/12/83, p. 108). They include problems of causality — in its early stages the universe expanded too fast for all of its parts to stay in communication with each other; of flatness — the universe is very flat now, which implies very special initial conditions ("Sombody had to tune it very precisely," Demianski says); and of homogeneity — the universe is very homogeneous on the large scale, but on the small scale, from protons to galaxy clusters, it is clumpy.

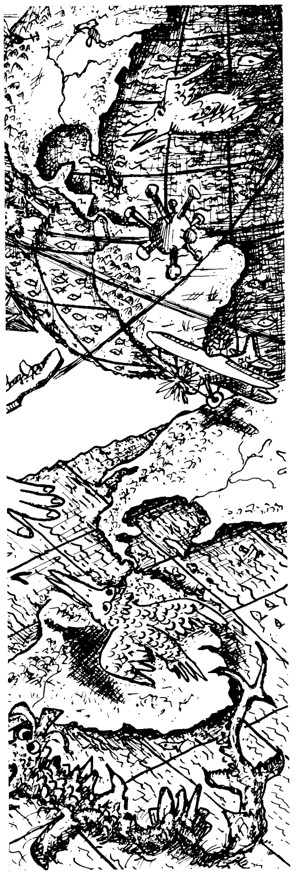
Mike Norman. From R.S. Jones, *Physics as Metaphor*, Univ. of Minn. Pr., Minneapolis. © 1982 by Univ. of Minn.

"We cannot say that flat ge geometry is false." And b may have been true at on

Like many at the meeting and elsewhere, Demianski proposes that an inflationary universe model, like the one proposed by Alan H. Guth of Massachusetts Institute of Technology in Cambridge (SN: 2/12/83, p.108), could solve most of these problems. In the usual big bang, the universe expands at a smooth rate from the beginning till today. In the inflationary model, there is a short period of extra-fast expansion that begins when the universe is about 10^{-35} seconds old or about 100 million times as old as it was at the Planck time. (We have no words for these fractions; by the time the universe was a microsecond old all of this was very ancient history.)

The inflationary universe can solve, among others, the problems of causality and flatness, but not that of the small-scale clumpiness. Cosmologists usually try to account for the clumpiness by inserting lumps — "density perturbations" — at the very beginning. Unfortunately both the standard big-bang and the inflationary model tend to smooth out most such lumps as the universe evolves. That is all very well for the large-scale homogeneity of the universe, but not for the small-scale clumps. To survive and evolve into a galaxy or a galaxy cluster an initial perturbation has to be very small indeed. Demianski spoke of looking for a proper mathematical way to make them small enough. The quantum fluctuation quality of space-time during the Planck era might help by supplying tiny quantum fluctuations of density. These might be able to evolve properly.

A variant approach to the problem of clumping plus those of the entropy of the universe and of the reason why time flows in only one direction also makes use of both the quantum quality of space-time in the earliest epoch and the inflationary model. It attributes the clumping to a quality called the entropy of the gravitational field. It is the subject of a paper in the Feb.



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When it deals with the earliest moments of the universe, cosmology becomes a quantum science

3-9 NATURE by P.C. W. Davies of the University of Newcastle upon Tyne in England. Davies was not at the New Orleans meeting, but his paper was criticized there by Don N. Page of The Pennsylvania State University at University Park.

Entropy is the measure of the disorder in a system of matter and energy. The second law of thermodynamics decrees that in a closed system, entropy should always increase. The universe, though not exactly a closed system, qualifies. Its ultimate fate should be "heat death," a state of hot thermal equilibrium, in which there is total disorder and no energy left available to impose any kind of order on anything. The paradox is that this unwound state is very like the state in which the universe is supposed to have started. As Davies puts it, "... the problem is how it was 'wound up' in the first place."

Page puts the question a little differently. "Can inflation explain the second law of thermodynamics?" he asks. Noting that the universe now has 10^{183} times the volume it had at the Planck time, he inquires, "Why was the entropy much lower? The mystery is not that low entropy goes to high, but why was the universe so highly ordered once?"

In Davies's view the universe at the Planck time was in a state of maximum entropy. Space-time, instead of having the smooth quality we observe today, had a "foamlike" character related to the quantum mechanical fluctuations it had undergone during the Planck era and which represented a state of thermal equilibrium. To get the amount of small-scale clumping we see today, Davies does not decrease the entropy. Instead he uses the inflationary period to create an "entropy gap." The onset of the inflationary period is a phase change, analogous to the freezing of some water, for example. A number of things happen suddenly or at least very quickly. The phase change injects a lot of entropy into the universe, but in Davies's view it increases the maximum amount of entropy possible even more. Thus at the end of the inflationary period the universe has an entropy gap. Even though its entropy has actually increased, it is farther from equilibrium than it was before, and it tries to catch up.

To catch up, the universe uses the entropy of its gravitational field. The usual form of entropy treated in discussions of thermodynamics is the entropy of matter and energy. The notion that the gravitational field can have an entropy is a new and highly controversial one. The question was hotly debated at the New Orleans meeting, and the discussion continues in other places.

Davies admits that physicists do not have a proper mathematical formulation for gravitational entropy, but avers that some of its qualities can be determined nevertheless. Paradoxical as it may seem, an increase in gravitational entropy means small-scale clumping. Gravity just naturally pulls things together, and in doing so it also facilitates the beginning of nucleosynthesis, which gives us atoms and later molecules and so on. In fact the highest state of gravitational entropy is a black hole. A number of cosmologists have remarked on the seeming paradox that the universe could more easily have started as a black hole, which is favored by considerations of entropy in this view, and stayed that way. Davies quotes two questions asked by Roger Penrose of Oxford University in England: "Why, when there are so many ways for the big bang to cough out black holes, did it actually disgorge smoothly distributed matter? How did the universe manage to go 'bang' in such an improbable way?"

But it seems to have done so, and since it did, gravitational entropy, for those who believe in it, can give us the small-scale clumping we see. But gravitational entropy can act only after the universe has gone through the inflationary period, according to Davies. Before that time, gravity's work was prevented by the cosmological repulsion factor. This factor is the old cosmological constant that Einstein first put into his equations and later threw out. It represents the repulsion that things feel for each other that is expressed in the expansion of the universe. In modern formulations it is, however, no longer a constant.

Davies says that the value of the repulsion factor, which is negligible now, must have been enormous in the earliest moments. Under those conditions it would have disrupted all of gravity's efforts to bring things together. The onset of the inflationary period greatly increases the repulsion factor, but as the inflation works itself out — by getting a lot of the expansion out of the system very early in its history, so to speak — it lowers the repulsion factor quite rapidly so that at the end of the inflationary period the repulsion factor is negligible. In this, now-almost-not-expanding universe, gravitational entropy can go to work.

The inflationary process is a one-way experience. It would take a highly improbable conspiracy of quantum coherence, Davies says, to reverse the phase transition. Having gone through this one-way process, the universe comes out of it with a preferred direction of time. The arrow of time is thus fixed.

Page's main criticism is that Davies takes the second law of thermodynamics for granted, as an axiom. Page would like to derive the second law from the history of the universe. Page proposes that the universe starts out in a low-entropy state, a collection of small regions uncorrelated with one another. As history proceeds, these regions interact with one another and correlate. That is, there is a growing homogenization. This produces an increase in what Page calls coarse-grained entropy. Meanwhile on the small scale there is some uncorrelated energy. This leads to the matter and radiation that we know. There is also some uncorrelated gravity, and this affects the development of space-time in such a way that no long-range force fields develop that might skew the universe or clump it on the large scale.

The provision of no long-range fields leads directly to the isotropy and large-scale homogeneity we see in the universe today. Page also says that he can derive or explain the second law of thermodynamics from this kind of a history. For the flatness of the universe, he appeals to a weak form of the anthropic principle. The anthropic principle states that the conditions of the universe were specially arranged (by Somebody or by accident) to facilitate the rise of human beings. But Page admits that his scenario does not explain the formation of galaxies.

Davies would probably object to Page's putting in the special conditions of the anthropic principle. In his paper Davies stresses that the beginning of the universe in his scheme is arbitrary, without special

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TOXICITIES OF SELECTED POISONS[a]

Substance	Minimum lethal dose (moles/kg)[d]
Botulinum toxin A	3.3×10^{-17}
Tetanus toxin	1.0×10^{-15}
Diphtheria toxin	4.2×10^{-12}
2,3,7,8-TCDD[b]	3.1×10^{-9}
Saxitoxin	2.4×10^{-8}
Tetrodotoxin	2.5×10^{-8}
Bufotoxin[c]	5.2×10^{-7}
Curare	7.2×10^{-7}
Strychnine	1.5×10^{-6}
Muscarin[c]	5.2×10^{-6}
Diisopropylfluorophosphate	1.6×10^{-5}
Sodium cyanide	2.0×10^{-4}

a—Source: Poland and Kende 1976. These data were compiled by Mosher et al., and the values indicate only relative toxicity. It should be noted that the values deal with different species, routes of administration, survival times, and in one case the mean lethal dose rather than the minimum lethal dose. Except where noted, administration was by the intraperitoneal route in mice.

b—LD$_{50}$ upon oral administration in the guinea pig.

c—Intravenous injection in the cat.

d—A mole is the gram-weight of a substance that contains 6.02×10^{23} units—molecules, atoms or ions, for example—of that substance.

Is 2,3,7,8-TCDD perhaps the most poisonous man-made chemical – as accounts on dioxin often claim? As the table at left indicates, only toxins produced in nature by certain bacteria are more potent poisons, so the statement appears to be correct. But several important caveats should be included.

First, the statement refers only to the acute LD$_{50}$ (the minimum dose that kills half of the test animals in a relatively short time period) of 2,3,7,8-TCDD in guinea pigs – the test species now known to be the most sensitive to dioxin. And, "There is great species variability in the acute toxicity of dioxin," notes Paul Stehr of the Centers for Disease Control in Atlanta.

Second, it should be noted that the position of a chemical on an acute toxicity list does not necessarily correspond to its total risk (which includes its long-term health effects). For example, exposure to plutonium is a known cancer risk, but that substance would rank second to last on the table at left.

Ottawa. The source of the chemical in these cases might be herbicide contaminated with traces of dioxin or combustion processes that emit small amounts of dioxin, Ryan suggests.

A VA study also indicates a background level of 2,3,7,8-TCDD in human fat, Young says. Dioxin was detected in about half the subjects among 35 Vietnam veterans, whether or not they said they had been exposed to Agent Orange. The scientists say that until there are reliable methods of determining who has been exposed to dioxin, for example by accurately measuring dioxin content in fat, it will be difficult to determine epidemiologically whether dioxin has important health effects.

- In regulations published in the April 4 FEDERAL REGISTER, EPA proposes to allow the disposal of dioxin-contaminated wastes only in specially approved landfills. If finalized, the regulations would, for the first time ever, make it illegal under federal law to spray roads with dioxin-contaminated oil—the activity that was a significant link in the chain of events that led to the Times Beach incident. ☐

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conditions. "This is precisely what one would expect if the Universe is to be explained as a spontaneous random quantum fluctuation from nothing," he writes. The rules governing quantum mechanical fluctuations allow nothing to become something if it does it for a short enough time: Dust thou wert and to dust shalt thou return, but in the meantime things can happen. The universe has had something like 20 billion years of history (or 10 billion if you believe more conservative astronomers). To us that's a long time, but on the cosmic scale it may be just the briefest flicker.

This is the quantum mechanical universe to an extreme. For Guth it is a free lunch prepared in a sudden phase change. To Davies it's a flash in the pan. To John William Moffatt of the University of Toronto, it's the result of another kind of quantum mechanical fluctuation: tunneling.

Tunneling occurs when a particle, an electron, for example, meets a barrier that it does not have the energy to surmount. Nevertheless, the wave equations of quantum mechanics give a certain probability of finding the particle on the other side of the insurmountable barrier, and occasionally an electron satisfies the prediction by "tunneling" through. The phenomenon is exploited in electronics, in tunneling junctions and other devices. There is a large barrier between being nothing and being something, and Moffatt proposes that the universe tunneled through it.

Moffatt has been working on a theory he calls nonsymmetric gravitational theory (NGT), which differs from Einstein's general relativity, but which now seems to answer a couple of questions raised by recent observations (SN: 5/8/82, p. 313). Mathematically, Moffatt's theory has two field components, one related to a particle of spin 2, one related to a particle of spin 0. Einstein's has only the spin 2 field. Moffatt's theory makes an explicit connection to particle physics in that the number of fermions (subatomic particles with half-integral amounts of spin) in the universe affects the gravitational field. There is nothing like that in Einstein. The cosmological implications of NGT have some important differences from cosmologies based on general relativity as well as some important agreements.

One of the most striking differences is that in NGT cosmology there is no big bang. The universe comes into being by quantum mechanical tunneling from nothing. It has a minimum radius at which, if it should collapse, it will bounce. It has an early inflationary period that follows a phase transition occurring at about 10^{-34} seconds.

There is no horizon problem in NGT cosmology; different parts of the universe do not get out of touch with one another. The universe starts out chaotic and highly anisotropic but ends up looking isotropic (as it should to match observations). Moffatt can get galaxies of the right size to form by putting in primordial density perturbations of the right kind, a problem that has baffled some other theories.

Moffatt has already suggested using the oblateness of the sun that seems to appear in some observations reported by Henry A. Hill of the University of Arizona in Tucson at the New Orleans meeting and elsewhere (SN: 4/7/82, p. 260), in conjunction with motions of the planets, as a test of his theory (SN: 3/19/83, p. 182). Black holes, which can exist in NGT, might be another test. In NGT, black holes would emit very strong radiation of the type predicted by Stephen Hawking of Cambridge University in England. This would come to us as gamma rays.

Attempts to see things in the present day universe that would tell us about conditions in the first fraction of a second are also underway. Demianski's question whether we can see into that time is for the future to answer. In spite of much theoretical progress the basic questions remain open: how to mate quantum physics with gravity and cosmology and whether it can be done through Einstein's theory or needs some serious modification of it. The future, cosmologists hope, will have answers. ☐