Is the Universe a Vacuum Fluctuation?

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The author proposes a big bang model in which our Universe is a fluctuation of the vacuum, in the sense of quantum field theory. The model predicts a Universe which is homogeneous, isotropic and closed, and consists equally of matter and anti-matter. All these predictions are supported by, or consistent with, present observations.

RECENT observations confirm that the 2.7 K background radiation does indeed have a blackbody spectrum (see refs 1 and 2), which establishes beyond reasonable doubt that some version of the big bang theory is correct. Here I propose a specific big bang model which I believe to be the simplest and most appealing imaginable—namely, that our Universe is a fluctuation of the vacuum, where 'vacuum fluctuation' is to be understood in the sense of quantum field theory.

Creation

In any big bang model, one must deal with the problem of 'creation'. This problem has two aspects. One is that the conservation laws of physics forbid the creation of something from nothing. The other is that even if the conservation laws were inapplicable at the moment of creation, there is no apparent reason for such an event to occur.

The prevailing attitude towards creation is that our Universe is probably undergoing merely one in an infinite sequence of expansions (with intervening contractions). According to this view the Universe has always existed, so its origin lies in the infinite past where it is hopefully not a problem for science.

The preceding viewpoint may indeed be correct, but it leaves unanswered two important questions. First, by what mechanism does the Universe 'bounce back' from each contraction? No satisfactory mechanism has ever been proposed. Second, why does the Universe have its particular values for energy, electric charge, baryon and lepton number and so on?

In my model, I assume that our Universe did indeed appear from nowhere about 10^{10} yr ago. Contrary to widespread belief, such an event need not have violated any of the conventional laws of physics. The laws of physics merely imply that a Universe which appears from nowhere must have certain specific properties. In particular, such a Universe must have a zero net value for all conserved quantities.

Conservation

The conserved quantities of physics fall into two categories—discrete and continuous. The discrete quantities are those which characterise elementary particles: electric charge, baryon and lepton number, strangeness and so on. All these quantities have equal magnitude but opposite sign for particles and anti-particles. Hence the discrete conservation laws simply imply that a universe which appears from nowhere must consist equally of matter and anti-matter. Such a possibility is consistent with the properties which have so far been established for our own Universe. (The possibility that our Universe consists equally of matter and anti-matter has been studied by many authors; for a recent review see ref. 3.)

Of the remaining conservation laws, the most important for cosmology is that concerning energy: although matter and energy can be converted into each other, the net energy remains constant if an intrinsic energy of mc^2 is assigned to each piece of matter.

The Universe has an enormous amount of mass energy, and this might be thought to preclude a creation of the cosmos from nothing. There is, however, another form of energy which is important for cosmology, namely gravitational potential energy. The gravitational energy of a mass m due to its interaction with the rest of the Universe is given roughly by

$$E_g \approx -GmM/R$$

where G is the gravitational constant and M denotes the net mass of the Universe contained within the Hubble radius $R=c/H$, where H is Hubble's constant.

The density of matter which has so far been observed is somewhat less than the critical value ρ_c required for the Universe to be closed:

$$\rho_c = 3H^2/8\pi G$$

Sandage's recent determination[4] of the cosmic deceleration parameter indicates, however, that our Universe probably is closed, in which case the true ρ exceeds ρ_c. If I assume the critical density in my estimate of E_g, I obtain

$$E_g \approx -mc^2/2$$

Hence within a factor of order unity, the negative gravitational energy of any piece of matter is sufficient to cancel the positive mass energy of mc^2. This naive argument indicates that the net energy of our Universe may indeed be zero.

P. Bergmann has presented a more sophisticated argument which indicates that any closed universe has zero energy. In its simplest form, the argument proceeds as follows (J. M. Cohen, private communication).

Suppose the Universe were closed. Then it would be topologically impossible for any gravitational flux lines to escape. If the Universe were viewed from the outside, by a viewer in some larger space in which the Universe were imbedded, the absence of gravitational flux would imply that the system had zero energy. Hence any closed universe has zero energy.

The preceding remarks indicate that our Universe may have zero net values for all conserved quantities. If this be the case, then our Universe could have appeared from nowhere without violating any conservation laws.

Quantum Field Theory

To indicate how such a creation might have come about, I refer to quantum field theory, in which every phenomenon that could happen in principle actually does happen occasionally in practice, on a statistically random basis. For example, quantum electrodynamics reveals that an electron, positron and photon occasionally emerge spontaneously from a perfect vacuum. When this happens, the three particles exist for a brief time, and then annihilate each other, leaving no trace behind. (Energy conservation is violated, but only for the brief particle lifetime Δt permitted by the uncertainty relation $\Delta E \Delta t \sim h$, where ΔE is the net energy of the particles and h is Planck's constant.) The spontaneous, temporary emergence of particles from a vacuum is called a vacuum fluctuation, and is utterly commonplace in quantum field theory.

If it is true that our Universe has a zero net value for all conserved quantities, then it may simply be a fluctuation of the vacuum, the vacuum of some larger space in which our Universe is imbedded. In answer to the question of why it happened, I offer the modest proposal that our Universe is simply one of those things which happen from time to time.

One might wonder how a vacuum fluctuation could occur on such a grand scale. My answer is in two parts. The first is that the laws of physics place no limit on the scale of vacuum fluctuations. The duration is of course subject to the restriction $\Delta E \Delta t \sim h$, but this merely implies that our Universe has zero energy, which has already been made plausible.

The second part of my answer lies in the principle of biological selection, which states that any Universe in which sentient beings find themselves is necessarily hospitable to sentient beings. I do not claim that universes like ours occur frequently, merely that the expected frequency is non-zero. Vacuum fluctuations on the scale of our Universe are probably quite rare. The logic of the situation dictates, however, that observers always find themselves in universes capable of generating life, and such universes are impressively large. (We could not have seen this universe if its expansion-contraction time had been less than the 10^{10} yr required for *Homo sapiens* to evolve.)

In summary, observations imply that a big bang occurred about 10^{10} yr ago. One might suppose that the Universe has always existed, undergoing periodic expansions and contractions. There is, however, no known mechanism by which the Universe might bounce back from a contraction. Furthermore, to assume the Universe is infinitely old is to evade, rather than illuminate, the issues of its origin and quantum numbers.

I assume the Universe to be undergoing its initial expansion, evidently having appeared as a fluctuation of the vacuum. The conservation laws of physics then imply that our Universe has the quantum numbers of the vacuum, including zero energy. Hence our Universe must be homogeneous, isotropic and closed, and must consist equally of matter and antimatter. All these predictions are supported by, or consistent with, present observations.

My model is admittedly speculative, and is still in an early stage of development. Quantum theory does, however, imply that the vacuum should be unstable against large scale fluctuations in the presence of a long range, negative energy, universal interaction. Gravitation is precisely such an interaction, so I am encouraged to believe that the origin and properties of our Universe may be explicable within the framework of conventional science, along the lines indicated here.

1 Muehlner, D., and Weiss, R., *Phys. Rev.*, **D7**, 326 (1973).
2 Hegyi, D. J., Traub, W. A., and Carleton, N. P., *Phys. Rev. Lett.*, **28**, 1541 (1972).
3 Omnes, R., *Phys. Rep.*, **3C** 1 (1972).
4 Sandage, A. R., *Phys. Today*, **23**, 34 (1970).

Peace Research and SIPRI

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Peace research only began in earnest twenty years ago and the Stockholm International Peace Research Institute was founded as recently as 1966.

In 1945, Einstein said that the atomic bomb "may intimidate the human race into bringing order into its international affairs, which, without the pressure of fear, it would not do". Einstein was wrong. He did not anticipate that the human race would become rapidly inured to the danger of its own destruction. Twenty years later President Kennedy, seriously alarmed by the general antipathy to the dangers inherent in the deployment of tens of thousands of nuclear weapons, warned that the greatest risk of a general nuclear war—by then capable of eliminating human life on the Earth—was not through calculated intention, but through miscalculation, madness or accident. This year, events during the fourth Middle East war dramatically demonstrated both the truth of President Kennedy's sombre statement and the degree of disorder now existing in international affairs.

Clearly, neither the United States nor the Soviet Union actually desires a nuclear confrontation. And yet the indication that Soviet troops might have been on the way to the Suez Canal led to a world-wide American military alert. The Soviet leaders' miscalculation of the possible American reaction and the American President's actual over-reaction (how much influenced by domestic political events we will probably never know) to the Soviet move brought the world to the edge of the thermonuclear abyss for the second time in a decade—the Cuban missile crisis being the first. And this nuclear confrontation occurred during a period of *détente*. Can it be reasonably doubted that in some future nuclear confrontation, one or other side will not be deterred by, or will seriously misinterpret, the other's moves? What will happen if a future crisis in a tension area occurs when both leaders of the great powers are severely stressed by domestic pressures? And how much more likely will nuclear war by miscalculation, accident or madness become when many more than the present five countries have nuclear weapons? Is it not apparent that disorder in international affairs will continue to increase unless steps are taken to reverse the trend?

Peace Research

Concern over the consequences of increasing disorder in international affairs and the consequent increase in violence, of the increasing role of military force in international relations, of the increasing probability of nuclear holocaust, of the increasing inhumanity of conventional weapons and methods of warfare, and of the increasing dangers inherent in the world's arms races are some of the objective factors which motivate scientists to work on peace research.

By far the major part of today's science and technology is funded from military expenditures. The importance attached