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Is our Universe likely to decay within 20 billion years?

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Observations that we are highly unlikely to be vacuum fluctuations suggest that our universe is decaying at a rate faster than the asymptotic volume growth rate, in order that there not be too many observers produced by vacuum fluctuations to make our observations highly atypical. An asymptotic linear e-folding time of roughly 16 Gyr (deduced from current measurements of cosmic acceleration) would then imply that our universe is more likely than not to decay within a time that is less than 19 Gyr in the future.

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Einstein is quoted as saying that the most incomprehensible thing about the world is that it is comprehensible. This mystery has both a philosophical level[1] and a scientific level. The scientific level of the mystery is the question of how observers within the universe have ordered observations and thoughts about the universe.

It seems obvious that our observations and thoughts would be very unlikely to have the order we experience if we were vacuum fluctuations, since presumably there are far more quantum states of disordered observations than of ordered ones. Therefore, I shall assume that our observational evidence or order implies that we are not vacuum fluctuations.

If we reject solipsism as not the simplest explanation of our observations, our universe seems to have produced a large number of varied observers and observations. Therefore, we cannot expect any good theory of the universe to predict a unique observer or observation. We should instead expect a good theory to predict an ensemble of observers and observations such that ours is not too unusual or atypical. (See [1,2] for ways to define typicality.) In particular, we should expect a good theory to predict that ordered observations are not too atypical. This would not be the case if the theory predicts that almost all observations arise from vacuum fluctuations, because only a very tiny fraction of them would be expected to be ordered (have comprehension).

If we have a theory for a finite-sized universe that has ordinary observers of finite size for only a finite period of time (e.g., during the lifetime of stars and nearby planets where the ordinary observers evolve), each of which makes only a finite number of observations (perhaps mostly ordered), then the universe would have only a finite number of ordinary observers with their largely ordered observations. On the other hand, if such a theory predicts that the universe lasts for an infinite amount of time, then one would expect from vacuum fluctuations an infinite number of observers (mostly very short-lived, with very little ordered memory) and observations (mostly with very little order). Such a theory would violate the requirement that a good theory predict our ordered observations as not too unusual or atypical. (This argument is a variant of the doomsday argument [3–7].)

Therefore, a good theory for a finite-sized universe should also predict that it have a finite lifetime. (For example, this was a property of the $k = +1$ Friedmann-Robertson-Walker (FRW) model universes with nonnegative pressure.)

For an infinite universe (infinite spatial volume), the argument is not so clear, since one could get an infinite number of both ordinary observations and disordered observations, and then there may be different ways of taking the ratio to say whether either type is too unusual. However, here I shall assume that it is appropriate to take the number of both types of observations per comoving spatial volume of the universe, which would give the right answer for any finite universe, no matter how large. Then we can conclude that any model universe should not last forever if it has only a finite time period where ordinary observers dominate [8].

The next question is what limits on the lifetime can be deduced from this argument. In [8] it was implicitly assumed that the universe lasted for some definite time t and then ended. Then the requirement was that the number of vacuum fluctuation observations per comoving volume during that time not greatly exceed the number of ordered observations during the finite time that ordinary observers exist. For any power-law expansion with exponent of order unity, I predicted [8] that the universe would not last past $t \sim e^{10^{50}}$ years, and for an universe that continues to grow exponentially with a doubling time of the order of 10 Gyr, I predicted that the universe would not last past about 10^{60} years.

However, the main point of the present paper is that the expected lifetime should be much shorter if the universe is

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[1]A theistic explanation is that the universe was created by an omniscient God, so then at least God comprehends it. If God made humans in His own image, this might help explain why humans can also comprehend part of it, though of course we would like a scientific explanation of the details of how this was accomplished.

expanding exponentially and just has a certain decay rate for tunneling into oblivion. Then the decay rate should be sufficient to prevent the expectation value of the surviving 4-volume, per comoving 3-volume, from diverging and leading to an infinite expectation value of vacuum fluctuation observations per comoving 3-volume.

Let us take the case in which the decay of the universe proceeds by the nucleation of a small bubble that then expands at practically the speed of light, destroying everything within the causal future of the bubble nucleation event. Suppose that the bubble nucleation rate, per 4-volume, is A (for annihilation). Consider the background spacetime of what the universe would do if it were not destroyed by such an expanding bubble. (For simplicity I shall speak as if this background spacetime had a definite classical 4-geometry, but of course one could modify the discussion to include quantum uncertainties in its geometry.) Then if one takes some event p within this background spacetime, the probability that the spacetime would have survived to that event is

$$P(p) = e^{-AV_4(p)}, \tag{1}$$

where $V_4(p)$ is the spacetime 4-volume to the past of the event p in the background spacetime.

Now the requirement that there not be an infinite expectation value of vacuum fluctuation observations within a finite comoving 3-volume (say region C) is the requirement that

$$\int_C P(p)\sqrt{-g}d^4x < \infty, \tag{2}$$

that the total 4-volume within the comoving region, weighted by the survival probability $P(p)$ for each point, be finite rather than infinite.

Let us take the case of an asymptotically de Sitter background spacetime with cosmological constant Λ (and all other matter decaying away), which asymptotically has a constant logarithmic expansion rate in all directions of

$$H_\Lambda = \sqrt{\Lambda/3}. \tag{3}$$

We assume that there is some sort of big bang or beginning of the universe in the past, so the only question is whether the integral (2) diverges in the asymptotic future part of the background spacetime. One can then readily calculate that the expectation value of the 4-volume of the surviving spacetime is finite if and only if

$$A > A_{\min} = \frac{9}{4\pi}H_\Lambda^4 = \frac{\Lambda^2}{4\pi}. \tag{4}$$

If we take $\Omega_\Lambda = 0.72 \pm 0.04$ from the third-year WMAP results of [9] and $H_0 = 72 \pm 8$ km/s/Mpc from the Hubble Space Telescope key project [10], we get

$$H_\Lambda = H_0\sqrt{\Omega_\Lambda} \approx (16 \pm 2\ \mathrm{Gyr})^{-1} \tag{5}$$

and therefore

$$A > A_{\min} \approx (18 \pm 2\ \mathrm{Gyr})^{-4}. \tag{6}$$

Let us examine the implications of taking roughly the smallest possible decay rate consistent with the assumptions and data above, which is for, say, $\Omega_\Lambda = \Omega_{\Lambda\min} = 0.68$ and $H_0 = H_{0\min} = 64$ km/s/Mpc $= 0.065\ \mathrm{Gyr}^{-1}$. This then gives

$$A > A_{\min} = \frac{9}{4\pi}\Omega_{\Lambda\min}^2 H_{0\min}^4 = 6.1\times 10^{-6}\ \mathrm{Gyr}^{-4} = (20\ \mathrm{Gyr})^{-4} = 5.2\times 10^{-245} = e^{-562.5}, \tag{7}$$

where the last two numbers are in Planck units, $\hbar = c = G = 1$.

Now let us apply this to the future of our present universe, to see how soon it might decay. Assuming that our universe is spatially flat and has its energy density dominated by the cosmological constant and by nonrelativistic matter (e.g., dark matter and baryons), then its $k = 0$ FRW metric may be written as

$$ds^2 = T^2[-d\tau^2 + (\sinh^{4/3}\tau)(dr^2 + r^2 d\Omega^2)] = a^2(-d\eta^2 + dr^2 + r^2 d\Omega^2), \tag{8}$$

where $T = 2/(3H_\Lambda) = 12.4$ Gyr (its maximal value) from the minimum values for Ω_Λ and H_0 given above (which gives the minimal value of the cosmological constant, $\Lambda = 4/(3T^2)$), where $\tau = t/T$ is a dimensionless time variable, where the scale factor is $a = T\sinh^{2/3}\tau$, and where

$$\eta = \int_0^\tau \frac{dx}{\sinh^{2/3}x} \tag{9}$$

is the conformal time. The present value of τ is $\tau_0 = \tanh^{-1}\sqrt{\Omega_\Lambda} = 1.17$, again obtaining the numerical value from using $\Omega_{\Lambda\min}$, and the present value of the conformal time is $\eta_0 = 3.10$. (If we had used the mean $\Omega_\Lambda = 0.72$, we would have obtained $\tau_0 = 1.25$ and $\eta_0 = 3.16$; if we had used the maximum $\Omega_{\Lambda\max} = 0.76$, we would have obtained $\tau_0 = 1.34$ and $\eta_0 = 3.22$.)

Given this background spacetime, the probability P that it would have survived to some dimensionless time τ or corresponding conformal time η is given by Eq. (1), where in the metric (8) the spacetime 4-volume to the past of the event p at conformal time η is

$$V_4 = \frac{4\pi}{3}\int_0^\eta d\eta' a^4(\eta')(\eta-\eta')^3. \tag{10}$$

Then in the metric (8) this gives the survival probability, as a function of the dimensionless time τ, as

$$P(\tau) = \exp\left[-\frac{16}{27}\frac{A}{A_{\min}}\int_0^\tau dx \sinh^2 x\left(\int_x^\tau \frac{dy}{\sinh^{2/3}y}\right)^3\right] \tag{11}$$

For example, for $\tau = \tau_0 = 1.17$, the minimal value for today, one gets the maximal survival probability to today (for $A = A_{\min}$) as $P(\tau_0) = 0.96$, indicating that there was at least a 4% chance that our background universe would have decayed before the present time. One can also calculate that the present decay rate has a minimal value of $-d\ln P/dt = 1.04 \times 10^{-11}\ \mathrm{yr}^{-1} = (96\ \mathrm{Gyr})^{-1}$. With the present earth population of nearly 7 billion, this would give a minimal expected death rate of about 7 persons per century. (Of course, it could not be 7 persons in one century, but all 7 billion with a probability of about one in a billion per century.)

If one instead uses the mean measured value $\Omega_\Lambda = 0.72$ and thus $\tau = \tau_0 = 1.25$, one gets the survival probability to today as $P(\tau_0) < 0.95$, and then with the mean measured value $H_0 = 72\ \mathrm{km/s/Mpc} = 0.074\ \mathrm{Gyr}^{-1}$ one would get a present decay rate of $-d\ln P/dt > 1.43 \times 10^{-11}\ \mathrm{yr}^{-1} = (70\ \mathrm{Gyr})^{-1}$. Going to the approximate maximal values $\Omega_{\Lambda\max} = 0.76$ and $H_0 = H_{0\max} = 80\ \mathrm{km/s/Mpc} = 0.082\ \mathrm{Gyr}^{-1}$ would instead give $P(\tau_0) < 0.95$ and $-d\ln P/dt > 1.95 \times 10^{-11}\ \mathrm{yr}^{-1} = (51\ \mathrm{Gyr})^{-1}$.

However, as the universe is approaching exponential expansion, the minimal logarithmic decay rate will increase, asymptotically approaching the logarithmic growth rate of the spatial volume, which has a minimum value of approximately $3H_\Lambda = 3H_{0\min}\sqrt{\Omega_{\Lambda\min}} = 16.2 \times 10^{-11}\ \mathrm{yr}^{-1} = (6.2\ \mathrm{Gyr})^{-1}$, about 15.5 times the present minimum value of the logarithmic decay rate. Therefore, one cannot simply use the present decay rate to calculate when the probability of the survival of the universe will have decreased by a factor of one-half from the present, what one might call the present half-life of our universe.

To calculate an upper limit on the present half-life of our universe, given that it has lasted until today, we calculate the value of $\tau = \tau_{1/2}$ for which the minimal rate of decay will lead to $P(\tau) = P(\tau_0)/2$. With the minimal values of Ω_Λ and H_0 from above, this gives $\tau_{1/2} = 2.71$ and a half-life (measured from the present until the survival probability is one-half what it is today) of

$$t_{1/2} < T(\tau_{1/2} - \tau_0) \approx 19.0\ \mathrm{Gyr}. \tag{12}$$

If we instead use the mean values for Ω_Λ and H_0 from above, we get $\tau_{1/2} = 2.72$ and $t_{1/2} \lesssim 15.7$ Gyr. The maximal values of Ω_Λ and H_0 from above give $\tau_{1/2} = 2.74$ and $t_{1/2} \lesssim 13.1$ Gyr.

These calculations give only lower bounds on the annihilation rate and upper bounds on the half-life of the universe. It is hard to give precise upper bounds on the annihilation rate, since even if the survival probability until today is rather low, we could simply be in the small fraction of space that does survive. However, if the logarithmic decay rate were hundreds of times higher than the minimal value above and so several inverse gigayears, it would be highly unusual for us to have evolved as late as we did in such a rapidly decaying universe, since there is no known reason why we could not have appeared on the scene a small number of billion years earlier. (One could put in the observed temporal distribution of formation times for second-generation stars to get a better estimate of how much earlier we could have appeared in our part of the universe, but I shall leave that for later publications.)

As a rather conservative upper limit on the annihilation rate, I shall here suggest that it cannot be greater than 3 orders of magnitude larger than the lower limit of Eq. (7), so

$$\begin{aligned} A_{\min} &= e^{-562.5} < A < A_{\max} \sim 1000 A_{\min} \\ &= 6.1 \times 10^{-3}\ \mathrm{Gyr}^{-4} = (3.6\ \mathrm{Gyr})^{-4} = 5.2 \times 10^{-242} \\ &= e^{-555.6}. \end{aligned}$$

This upper limit is rather extreme, since if we take the mean values for Ω_Λ and H_0 (not the minimal ones used to deduce $A_{\min}$), $A = A_{\max}$ gives a logarithmic decay rate today of 8.0 Gyr^{-1} and future half-life of 86 million years, which would make it surprising that we would live so late. Thus this value of $A_{\max}$ is indeed quite conservatively large. $A = A_{\max}$ also gives a survival probability to today of less than 4×10^{-13}. However, this absolute survival probability is less important than the logarithmic decay rate in making the time of our appearance within the universe unusual, since we would presumably need the universe to last a certain number of billions of years just to be here at all, and that should be put in as one of the necessary conditions for us to be making our observations of when we appear.

We might ask whether it is reasonable that the decay rate of the universe would be between the two limits above. In string/M theory, all that is confidently known for de Sitter spacetime [11–17] is that the decay time should be less than the quantum recurrence time, in Planck units roughly the exponential of the de Sitter entropy $\mathcal{S} = 3\pi/\Lambda$,

$$\begin{aligned} t_{\mathrm{decay}} &< e^{\mathcal{S}} = \exp\left(\frac{\pi}{H_\Lambda^2}\right) = \exp\left(\frac{\pi}{H_0^2\Omega_\Lambda}\right) \\ &\lesssim e^{3.7\times10^{122}} \sim 10^{10^{122.2}} \sim e^{e^{282.2}}. \end{aligned} \tag{14}$$

Of course, this number, which even in gigayears is enormously greater than the ten-thousand-million-million-millionth power of a googolplex, is stupendously greater than the decay times I am suggesting.

In [18], Eq. (5.20), a tunneling rate is calculated as

$$A \sim \exp(-B) = \exp\left[-\frac{\pi/4}{m_{3/2}^2}\frac{(C-1)^2}{C^2(C-1/2)^2}\right], \tag{15}$$

where $m_{3/2}$ is the gravitino mass, $C^2 > 1$ is a ratio of two supersymmetric anti-de Sitter vacua depths, and I have shifted from the normalized Planck units ($\hbar = c = 8\pi G = 1$) used in [18] to my Planck units ($\hbar = c = G = 1$).

If we define a renormalized gravitino mass to be

$$\mu_{3/2} \equiv \frac{1 - 1/(2C)}{(1 - 1/C)^2} m_{3/2} > m_{3/2}, \tag{16}$$

which for $C \gg 1$ would be the actual gravitino mass, then $-\ln A = B = \pi/(4\mu_{3/2}^2)$, so the results of Eq. (14) imply that $\mu_{3/2}$ should be within the narrow range (given in Planck units and then in GeV) of

$$0.037\,37 = 4.562 \times 10^{17}\ \mathrm{GeV} < \mu_{3/2} < 0.037\,60 = 4.590 \times 10^{17}\ \mathrm{GeV}, \tag{17}$$

of course assuming that this is the correct decay mechanism.

Looking at this result optimistically, one can say that if this is the correct decay mechanism, and if the constant C can be determined, then we would have a fairly precise prediction for the gravitino mass, with a range of only about 0.6% width. Then if the gravitino were found to have a mass within this range that could be pinned down even more precisely, we would have a refined estimate for the decay rate of the universe. Unfortunately, the predicted mass is so much larger than what is currently accessible at particle accelerators that it appears rather discouraging to be able to confirm or refute this prediction.

On the pessimistic side, the narrowness of the range for the gravitino mass in this decay scenario suggests the need for some fine-tuning that appears hard to explain anthropically (i.e., by the selection effect of observership). Within a suitable landscape or other multiverse, this selection effect can explain why the decay rate is not larger than roughly $A_{\max}$ (since in those parts of the multiverse observers would be rare), but I do not see how it can explain why the decay rate could not be smaller than $A_{\min}$, since both a finite number of ordinary observers and an infinite number of vacuum fluctuation observers per comoving volume could then exist. If $A < A_{\min}$, that would make our observations of very tiny relative measure, which I would regard as strong evidence against any theory predicting that result, but it would not be a possibility that one could rule out just from the requirement that there be observers and observations.

Furthermore, if the annihilation rate A can be within the range above for our part of the multiverse, it would still leave it unexplained why it is not less than $A_{\min}$ in some other part of the multiverse that also allows observers to be produced by vacuum fluctuations. If it were less in any such part of the multiverse, then it would seem that that part would have an infinite number of vacuum fluctuation observations (almost all of which would be expected to be much more disordered than ours and so not consistent with our observations) that is in danger of swamping the ordered observations in our part (presumably only a finite number per comoving volume).

Of course, when one tries comparing the expected number of observers and observations in different parts of a multiverse, there are severe problems with comparing the ratios if the total comoving volumes can be infinite [19–27]. It is certainly not so straightforward as comparing various numbers within the same comoving volume within a single part of the multiverse, as was done in the analysis of this paper. Therefore, one cannot be sure that the potential objection of the previous paragraph is valid, but it is a worrying note about the results of the present analysis.

Because of these potential problems with the predictions made here (that the universe seems likely to decay within 20 billion years), one might ask how the predictions could be circumvented.

One obvious idea is that the current acceleration of the universe is not due to a cosmological constant that would last forever if the universe itself did not decay away. Perhaps the current acceleration is caused by the energy density of a scalar field that is slowly rolling down a gentle slope of its potential [8,11,28–35]. However, this seems to raise its own issue of fine-tuning, since although the observership selection effect can perhaps explain the small value of the potential, it does not seem to give any obvious explanation of why the slope should also be small, unless the scalar field is actually sitting at the bottom of a potential minimum (which is basically equivalent to a cosmological constant, modulo the question of whether one would call it a cosmological constant if it could tunnel away during the quantum decay of the universe).

Another possibility is that an infinite number of observers per comoving volume simply cannot form by vacuum fluctuations, even if the universe continues to expand forever. In [8] a possible way out was given if each observer necessarily spans the entire universe, so that it cannot be formed by a local quantum fluctuation. However, this seems even more far-fetched than the possibility that the dark energy is slowly decreasing.

Yet another possibility is that the normalization employed in this paper to get a finite number of ordinary observers, namely to restrict to a finite comoving volume, might not be the correct procedure if our universe really has infinite spatial volume. However, if our universe did have finite spatial volume, this procedure would seem perfectly adequate, so it is not obvious what is wrong with it for the use I am making of it. (I do agree that it is problematic for making comparisons between disconnected parts of the multiverse, since one would not necessarily know how to compare the sizes of comoving volumes in the disconnected parts. However, this problem does not arise for my comparison of ordinary observers with vacuum fluctuation observers formed to the future of the same finite comoving volume where the ordinary observers, namely we, are.)

Furthermore, there may be a tiny rate (perhaps $\sim 10^{-10^{122.2}}$) for even the comoving future of our spacetime to tunnel back to an eternal inflationary state and produce an infinite number of ordinary observers within its future [36]. Then there would be an infinite number of both ordinary observers and disordered vacuum fluctuation observers within a finite comoving volume to the future of our part of spacetime, so again it would become ambiguous as to which dominates.

My suggestion then is that one should regularize this infinity by cutting off the potentially infinite sequence of eternal inflationary periods and postinflationary periods (where stars, planets, and ordinary observers can exist) at some time very far into one of the postinflationary periods, but before there is significant probability that eternal inflation can start again. Then one would be led to the predictions of this paper. However, this is certainly an *ad hoc* proposal, so it might well be wrong.

So if the predictions made in this paper (that our universe seems likely to decay within 20 billion years) are wrong, it may be part of our general lack of understanding of the measure in the multiverse (or here, even of just different times in the same spacetime comoving volume). On the other hand, despite the fine-tuning problems mentioned above, it is not obvious to me that it really is wrong, so one might want to take it seriously unless and until some other way is found to avoid our ordered observations being swamped by disordered observations from vacuum fluctuations.

One might ask what the observable effects would be of the decay of the universe, if ordered observers like us could otherwise survive for times long in comparison with 20 billion years.

First of all, the destruction of the universe would occur by a very thin bubble wall traveling extremely close to the speed of light, so no one would be able to see it coming to dread the imminent destruction. Furthermore, the destruction of all we know (our nearly flat spacetime, as well as all of its contents of particles and fields) would happen so fast that there is not likely to be nearly enough time for any signals of pain to reach your brain. And no grieving survivors will be left behind. So in this way it would be the most humanely possible execution.

Furthermore, the whole analysis of quantum cosmology and of measures on the multiverse seems (at least to me) very difficult to do without adopting something like the Everett many-worlds version of quantum theory (perhaps a variant like my own Sensible Quantum Mechanics or Mindless Sensationalism [1,37]). Then of course if there are ‘‘worlds’’ (quantum amplitudes) that are destroyed by a particular bubble, there will always remain other worlds that survive. Therefore, in this picture of the decaying universe, it will always persist in some fraction of the Everett worlds (better, in some measure), but it is just that the fraction or measure will decrease asymptotically toward zero. This means that there is always some positive measure for observers to survive until any arbitrarily late fixed time, so one could never absolutely rule out a decaying universe by observations at any finite time.

However, as the measure decreases for our universe to survive for longer and longer times, a random sampling of observers and observations by this measure would be increasingly unlikely to pick one at increasingly late times. Although observers would still exist then, they would be increasingly rare and unusual. Of course, any particular observer who did find himself or herself there could not rule out the possibility that he or she is just a very unusual observer, but he or she would have good statistical grounds for doubting the prediction made in this paper that he or she really is quite unusual.

In any case, the decrease in the measure of the universe that I am predicting here takes such a long time that it should not cause anyone to worry about it (except perhaps to try to find a solution to the huge scientific mystery of the measure for the string landscape or other multiverse theory). However, it is interesting that the discovery of the cosmic acceleration [38,39] may not teach us that the universe will certainly last much longer than the possible finite lifetimes of $k = +1$ matter-dominated FRW models previously considered, but it may instead have the implication that our universe is actually decaying even faster than what was previously considered.

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