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Can the Universe Recycle?

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There have been speculations that, in a bounce of a closed universe, there might be a reprocessing of fundamental parameters leading to a recycling and continual recurrence of the universe. We suggest here some necessary, though by no means sufficient, conditions for a theory in which the growth of a dissipative universe is counteracted, so that recycling may be possible.

1. INTRODUCTION

When big bang cosmological models seemed to agree well with some features of our universe it was natural for scientists to ask what happened *before* the big bang? (Gamow, 1947). And, if the universe is closed and eventually contracts to a big crunch, what will happen after that crunch? Not only do our present theories give no answer to those questions, but they cannot even indicate whether or not the questions are scientifically meaningful. Singularities at the limits of solutions of the classical Einstein equations which represent expanding and contracting spaces mean that those solutions cannot be continued to epochs "before the beginning" or "after the end."

One speculation suggested by some philosophical and religious traditions is that there is an eternal recurrence of the universe (Eliade, 1954; Halpern, 1995). But even if a bounce from contraction to expansion at some minimum cosmic scale factor were possible, an effect discovered years ago by Tolman (1934) poses problems for such an idea. A bouncing closed universe in which dissipative processes occur grows, in the sense that its maximum scale factor increases from one cycle to the next. It is even possible for such a universe to reach an epoch after which it expands monotonically and never recontracts (Neugebauer and Meier, 1976).

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This is not the end of the matter, however. There may be significant departures from classical behavior when the effects of quantum gravitation become important. This should happen when mass densities approach the value $\rho_* = M_*/L_*^3 \approx 10^{95}$ g/cm^3 defined by the Planck length, time, and mass (Murphy, 1973),

$$L_* = (\hbar G/c^3)^{1/2}, \qquad T_* = L_*/c, \qquad M_* = L_* c^2/G \tag{1}$$

There have been suggestions that the modifications of classical behavior in this regime might be so profound as to lead to a "reprocessing" or "recycling" of the universe. (Misner *et al.*, 1973; Halpern, 1995, pp. 252–263). This could come about through changes in numerical parameters in the basic laws of physics, or even in the qualitative form of those laws.

If we were to imagine everything to be subject to arbitrary change, the problem would be too amorphous for us to be able to say anything at all about it. The purpose of this paper is to gain some idea of the requirements for such a recycling of the universe in as conservative a manner as possible. In particular, we will indicate what changes near the classical singularity would be required in order to counteract the growth of a dissipative universe. We shall assume that the dimensionality and signature of space-time remain unchanged in a bounce, and that the gravitational field equations are maintained. We will then be able to place some constraints on cosmological models which allow recycling.

2. CLOSED DISSIPATIVE UNIVERSES

The fact that dissipative universes grow is counterintuitive, for dissipation in classical physics generally leads to damping of oscillations. Newtonian physics is not competent to describe such cosmological models completely (Murphy, 1994). However, an increase in entropy S implies an increase in energy and thus (through a distinctively non-Newtonian relationship) an increase in active gravitational mass M ($c^2\, dM = T\, dS$). This drives oscillations to higher and higher amplitudes. The equations which describe a dissipative cosmological model with scale factor a and energy E within a sphere of radius a are

$$(da/dt)^2 = 2GE/c^4 a - 1 \qquad \text{and} \qquad dE/dt = F(a, da/dt) \tag{2}$$

with F a positive function.

If dissipation is due to bulk viscosity with coefficient ζ, then $F = 12\pi\zeta a(da/dt)^2$. Equations (2) can then be combined to give a nonlinear second-order differential equation for a. The equation cannot be solved in closed form. This presents no fundamental difficulty, for we can discern basic properties of the solution fairly easily. It is obvious from (2) that, if maxima of the scale factor occur, they must be at successively larger values of a, since E increases. A more detailed study shows that if the condition $\zeta > 1/24\pi a(da/dt)$ is satisfied at some time during an expanding phase of the model, a finite maximum will not be reached, and the model will never contract (Neugebauer and Meier, 1976).

An exact, though unrealistic, solution of (2) can be obtained by writing $F = 1/2B|da/dt|$, with B a constant. This has the necessary property that $dE/dt \geq 0$. If $B < 1$, there will be alternating expansions and contractions. In an expanding phase we will have $E = C + 1/2Ba$, and the first equation of (2) is easily integrated to give a rising portion of a cycloid, as for a closed model without dissipation. The contracting phase which follows will be described by a portion of another cycloid with a different value of the constant C. On the other hand, the model will expand forever if $B \geq 1$. We could also model the possible effects of quantum gravity in a crude way by inserting a hard-core potential in order to make a bounce occur at some nonzero minimum value a_0.

3. CONDITIONS FOR COSMIC RECYCLING

We turn now to our primary concern: How might we change the parameters of such a model in each bounce in such a way as to have recurrence? The basic requirement can be stated very simply: E must somehow be reset to its original value in each bounce.

That could be accomplished in two ways. E is a global quantity whose initial value can be chosen arbitrarily, and there could simply be a global resetting of E. However, that does not seem to be a very satisfactory procedure for a scientific theory. It amounts to a *fiat* pronouncement, "Let the energy decrease."

It would be more in accord with the usual approach of physical theories for the desired change in E to come about through changes in the basic physical parameters of space-time and matter which underlie the model. In other words, we want to produce the change by alteration of some of the fundamental physical "constants" of the universe.

It should be emphasized that while dissipative processes are most fundamentally characterized by an increase of entropy, it is only the change in the associated energy parameter which contributes to the growth of a dissipative universe. This means, among other things, that there is no direct contribution to the equations describing the expansion of the universe from the entropy associated with black holes.

Changes in the constants c, G, and $\hbar$ will not lead to recycling, for together these quantities simply establish scales for length, time, and mass through equations (1). If we write $a = \alpha L_*$, $E = \varepsilon M_* c^2$, and $t = \tau T_*$, we find that α, ε, and τ obey equations (2) with $c = G = 1$.

For recycling, some mass scale m independent of M_* is required. This would enable us to write $E = Nmc^2$, with N a dimensionless number. A resetting of m with no changes in other parameters in a bounce would then imply a resetting of E. Such a mass scale is provided, for example, by the X and Y bosons of GUTs. Their masses are related to the dimensionless coupling parameter of the theory, so that we might prefer to speak of a resetting of the coupling strength. But this would be significant for our problem only to the extent that it affected m.

It is, however, not enough simply to have such a mass m. If contraction of the model proceeds to a point where particle energies are significantly higher than their rest energies, the model will behave like one containing a photon gas, and the scale determined by the rest mass will be irrelevant. We expect the bounce in which resetting occurs to take place near the Planck scale, at which mass densities are on the order of ρ_*. In order for the value of m to make any difference at this epoch, the contribution of rest masses must contribute the major share to this density. If n is the number density of X and Y bosons (or of other particles in some future theory), a necessary condition for recycling is simply

$$nm \approx \rho_* \tag{3}$$

Now in present-day attempts to achieve a viable GUT, masses of the X and Y bosons are a couple of orders of magnitude lower than the Planck mass (Börner, 1993). If recycling in a bounce is to be possible in such a theory, condition (3) means that the number density of these particles must be very high at that epoch, so that they do not become extremely relativistic.

The situation might appear to be quite different with string theories which attempt to unify gravitation with other interactions (Polyakov, 1987). In these theories a mass scale defined by massive string modes is on the order of M_*. Thus we would apparently be able to satisfy (3) in a natural way with $m \approx M_*$ and $n \approx L_*^{-3}$.

But this appearance is illusory. If strings are truly the fundamental entities from which space-time and matter are built up, then the Planck mass is *defined* by string theory. There is not a preexisting space-time inhabited by strings. A change in the basic mass defined by string theory would amount simply to the changes in c, G, and $\hbar$ which we have already considered, and will not lead to recycling.

In order for recycling to be produced by changes in local parameters, we actually need *two* masses, the Planck mass M_* and some independent mass m (which might be on the order of M_*). This requirement, and (3), are only necessary, and by no means sufficient, conditions for recycling. In order to have a genuine theory in which recycling would be possible, we would have to conceive of a mechanism whereby the dimensionless ratio m/M_* would change in a bounce near the Planck density. Furthermore, this would have to happen in such a way that the global parameter E would decrease to the value that it had at the beginning of the cycle.

Our conclusions are very modest. But perhaps it is remarkable that we can draw any conclusions at all about what might take place in such extreme conditions. This has been possible because the requirement of an increase in the energy parameter has allowed us to pass over the detailed structure of basic theories of matter and reach some conclusions on the basis of dimensional analysis.

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