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A research in Theorotical physics named:

THE CYCLIC THEORY OF THE UNIVERES

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Contents:

Introduction:

For us the universe is a large piece of matter that has its own rules and equations…. but there is a huge controversial about it. There still is a lot of questions that doesn't have a specific answer, like:

How old is the universe? how big is the universe? What occurred at the initial singularity? What is the ultimate fate of the universe? Does time, and the arrow of time, exist before the big bang?

Well, we all know the "**big bang theory**", which is the most famous theory that explained the creation of our universe as we know it… in this research, we will talk about another theory that addresses all of these questions and dose so without the extraordinarily rapid acceleration that characterizes inflationary models… it is "***the cyclic theory of the universe***".

“What does this theory is trying to resolve?”:

The cyclic model attempts to resolve the homogeneity, isotropy, and flatness problems and generate a nearly scale-invariant spectrum of the fluctuations during a period of slow contracting that precedes a bounce to an expanding phase. Here we describe at a contraction level the recent developments that have greatly simplified our understanding of the contraction phase and the Cyclic Model overall. The answer to many past questions and criticism are now understood. In particular, we show that the contraction phase has equation of state $w > 1$ and that contraction with $w > 1$ has a surprisingly similar properties to inflation with $w < -1$. At one stroke, this shows how the model is different from the inflation and why it may work just as well as inflation in resolving cosmological problems.

1) The importance of the theory:

Two years ago, the Cyclic Model[1] was introduced as a radical alternative to the standard big bang. Its purpose is to offer a new solution to the homogeneity, isotropy, flatness problems and a new mechanism for generating a nearly scale-invariant spectrum of fluctuations.

One might ask why we should consider an alternative when inflation has scored so many successes in explaining a wealth of new, highly precise data. There are several reasons. First, seeking an alternative is just plain good science. Science proceeds most rapidly when there are two or more competing ideas. The ideas focus attention on what are the unresolved issues theorists must address and what are the important measurements experimentalists must perform. Inflation has had no serious competition for several years, and the result has been that its flaws have been ignored. Many cosmologists are prepared to declare inflation to be established even though crucial experimental tests remain. Competition stimulates critical thinking and removes complacency.

A second reason to consider an alternative is that, even though inflationary predictions are in marvelous accord with the data thus far, the theoretical front has seen little progress. In fact, if anything, there has been retrogress.

The main questions about inflation that were cited twenty years ago remain today. What is the inflation and why are its interactions finely-tuned? How did the universe begin and why did it start to inflate?

With the advent of string theory, these issues have become severe problems. Despite heroic efforts to construct stringy inflation models with tens or hundreds of moving parts (fluxes, branes and anti-branes) and examining a complex landscape of (at least) 10^{500} vacua, even a single successful inflationary model is difficult to construct [2].

The notion that there is a landscape of 10^{500} or more string vacua has suggested to some that, if there is an acceptable vacuum

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[1] P. J. Steinhardt and N. Turok, Science 296, 1436 (2002); P. J. Steinhardt and N. Turok, Phys. Rev. D 65, 126003 (2002).

[2] S. Kachru, R. Kallosh, A. Linde, J. Maldacena, L. McAllister, S.P. Trivedi JCAP 0310 (2003) 013.

somewhere, inflation makes it possible to populate all vacua; and that the ultimate explanation for our universe is anthropic[3].

However, this cannot be the whole story since it begs the question of how the universe started in the first place. No matter where you lie in the landscape, extrapolating back in time brings you to a cosmic singularity in a finite time. The issue of the beginning remains unresolved.

Furthermore, relying on the anthropic principle is like stepping on quicksand. The power of a theory is measured by the ratio of its explanations/predictions to assumptions. A good scientific theory is observationally testable. An anthropic explanation is based upon considerations involving regions of space that are causally disconnected from us and that will, in many cases, never be observed by us. What parameters and properties can vary from region to region? What is the probability distribution? In models such as eternal inflation, the relative likelihood of our being in one region or another is ill-defined since there is no unique time slicing and, therefore, no unique way of assessing the number of regions or their volumes. Brave souls have begun to head down this path, but it seems likely to us to drag a beautiful science towards the darkest depths of metaphysics.

Another unresolved issue is trans-Planckian effects on the production of density perturbations. In inflationary cosmology, the fluctuations observed in the cosmic microwave background had wavelengths at the beginning of inflation that were smaller than the Planck scale. The standard approximation is to assume the initial distribution of sub-horizon and, hence, sub-Planckian fluctuations corresponds to quantum fluctuations on an empty, Minkowski background. However, quantum gravity effects may cause the distribution to be different on sub-Planckian wavelengths.

The unknown distortion would be inflated and produce an uncertain correction to inflationary predictions for the cosmic microwave background anisotropy.

Finally, the big bang/inflationary picture is still reeling from the recent shock that most of the universe consists of dark energy [9]. The concept had been that, once conditions are set in the early universe, the rest of cosmic evolution is simple. Dark energy has

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[3] L. Susskind, hep-th/0302219; S. Kachru, R. Kallosh, A. Linde, S.P. Trivedi, Phys.Rev. D68, 046005 (2003).

shattered that dream. Dark energy was not anticipated and plays no significant role in the theory. Observations have forced us to add dark energy ad hoc.[4]

The current approach in big bang/inflationary model-building has been to treat the key issues - the bang, the creation of homogeneity and density fluctuations, and dark energy - in a modular way. Separate solutions with separate ingredients are sought for each. Perhaps this approach will work, all the problems cited above will be resolved, and a simple picture will emerge. But, perhaps the time has come to consider a different, holistic approach.

The cyclic model has an ambitious manifesto. Its goal is to address the entire history of the universe, past and future, in an efficient, unified approach. There is one essential ingredient - branes in the higher-dimensional picture or a scalar field in the four-dimensional effective theory - that is simultaneously responsible for explaining the big bang; the solution to the homogeneity, isotropy, flatness, and monopole problems[5]; the generation of nearly scale-invariant fluctuations that seed large-scale structure [10, 11]; and, the source of dark energy [1]. Simplicity and parsimony are essential elements. The range of acceptable parameters is broad [12].

Over the past two years, the Cyclic Model has progressed remarkably. The concept has been examined by numerous groups, and many, many useful criticisms and questions have been raised [13-18]. As many scientists have tried to address these issues, the results have been interesting. First, they have discovered that the Cyclic Model already contained the answers. Not a single new ingredient has had to be added thus far. Rather, we have learned to recognize fully the physical properties of the components the model contained at the outset [19-23]. That is, they have been discovering new physical principles stemming from the original model rather than adding new ingredients and patches. Second, as they have come to understand the Cyclic Model better, the picture has become much, much simpler. If the model is going to work, it will be because of basic ideas as simple and compelling as inflation. In fact, they found that there are remarkable, unanticipated parallels between inflationary expansion and the contracting and bounce phases of the

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[4] Talk given at Dark Matter 2004, Santa Monica, CA; February 18-20, 2004.

[5] P. J. Steinhardt and N. Turok, Science 296, 1436 (2002); P. J. Steinhardt and N. Turok, Phys. Rev. D 65, 126003 (2002).

Cyclic Model[6]. There remain important open issues about the bounce itself, but, now we can confidently say that many of the issues that plagued previous attempts at contracting cosmological models have been cleared away and there are solid reasons for optimism about resolving the remaining issues.

The purpose of this essay is to present the simplified view of the Cyclic Model, focusing on the stages that are most novel and controversial: the contraction and bounce. We focus on the two key ingredients needed to understand the contracting phase: branes and the equation of state $w > 1$. As we explain, the two features lead to a series of novel physical effects that solve the homogeneity, isotropy, and flatness problems and ensure a nearly scale-invariant spectrum of density perturbations following the big bang.

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[6] J. Khoury, B. A. Ovrut, N. Seiberg, P. J. Steinhardt and N. Turok, Phys. Rev. D 65, 086007 (2002). See also M. Berkooz and B. Pioline, hep-th/0307280.

2) THE BASIC CONCEPT:

The Cyclic Model was developed based on the three intuitive notions:

1. the big bang is not a beginning of time, but rather a transition to an earlier phase of evolution;
2. the evolution of the universe is cyclic;
3. the key events that shaped the large scale structure of the universe occurred during a phase of slow contraction before the bang, rather than a period of rapid expansion (inflation) after the bang.

The last point means that, unlike previous periodic models, the cycles are tightly interlinked. The events that occurred a cycle ago shape our universe today, and the events occurring today will shape our universe a cycle from now. It is this aspect that transforms the metaphysical notion of cycles into a scientifically testable concept. We can make physical measurements today that determine whether the large scale structure of the universe was set before or after the bang.

The model is motivated by the M-theoretic notion that our universe consists of two branes separated by a microscopic gap (the \bulk")[7]. Observable particles (quarks, leptons, photons, neutrinos, etc.) lie on one brane and are constrained to move along it. Any particles lying on the other brane can interact gravitationally with particles on our brane, but not through strong or electroweak interactions. So, from our perspective, particles on the other brane are a dark form of matter that cannot be detected in laboratories looking for weakly interacting particles. (The Cyclic Model does not predict whether most of the dark matter detected cosmologically is weakly interacting particles on our brane or particles lying on the other brane. Both are logical possibilities.)

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[7] A. Lukas, B.A. Ovrut, K.S. Stelle and D. Waldram, Phys. Rev. D 59 086001 (1999).

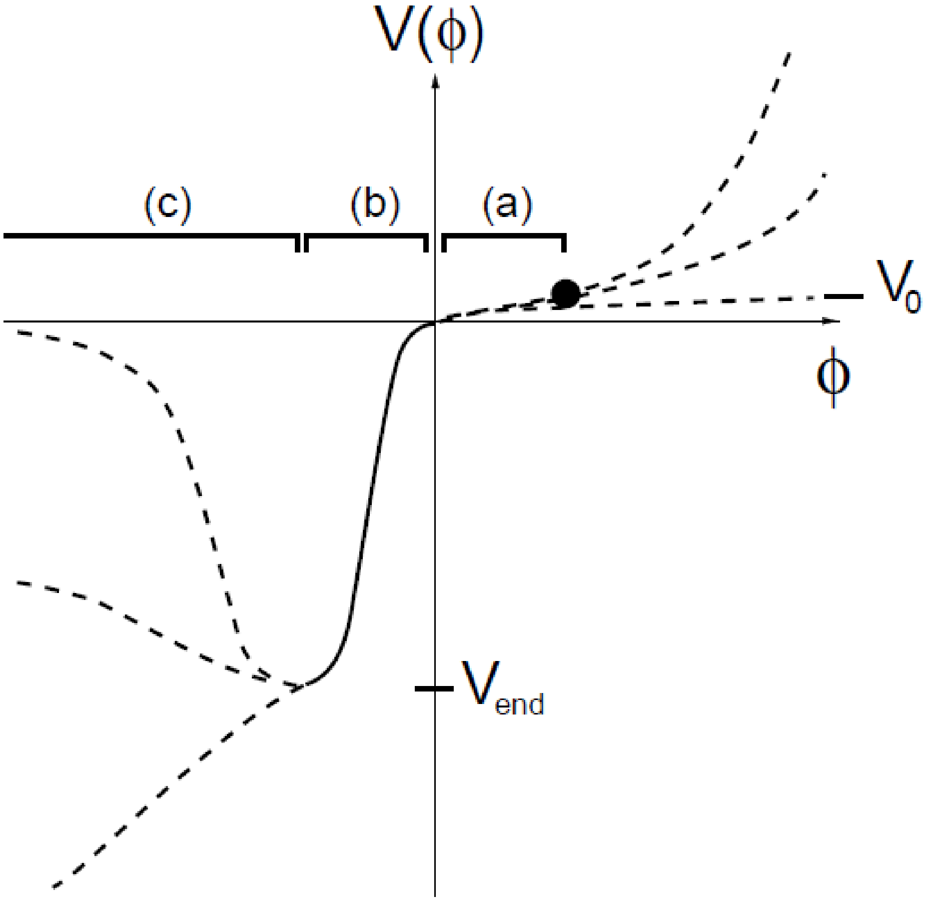

Figure 1: Scalar potentials suitable for a cyclic universe model. Running forward in cosmic time, Region (a) governs the decay of the vacuum energy, leading to the end of the slow acceleration epoch. Region (b) is the region where scale invariant perturbations are generated. In Region (c), as one approaches the big crunch ($\varphi \to -\infty$), the kinetic energy dominates.

In an exactly supersymmetric vacuum state, the branes do not interact at all. The virtual exchanges of strings and membranes cancel so that there is no force attracting or repelling them. We conjecture that, in a realistic (supersymmetry breaking) vacuum state, an attractive, spring-like force does attract them. Specifically, we imagine that the force is very weak when the branes are thousands of Planck distances apart (as they would be now), so that they are hardly moving. However, the force increases in strength as the branes draw together. Equivalently, we assume an interbrane potential of the form shown in Figure 1, where here Ø is the moduli field that determines the interbrane separation. When the branes are far apart, the potential is at and nearly positive; as the branes draw together, the potential falls steeply and becomes negative. When the branes come within a string-scale distance apart (corresponding to $V \approx Vend$ in the Figure), the potential disappears exponentially. Collision corresponds to $Ø \rightarrow -\infty$.

The scenario can be described by an effective four-dimensional theory for Ø, where Ø runs back and forth the potential from some positive value (corresponding to the present brane separation) to $-\infty$ and back.

The interbrane potential causes the branes to collide at regular intervals. The collision itself is the big bang. The bang is slightly inelastic, infusing the universe with new matter and radiation. From the four-dimensional effective theory, the kinetic energy of Ø is dominant for a brief period after the bounce, but it decreases rapidly as the universe expands. Hence, after the branes bounce apart, the branes slow down to essentially a halt, and the universe becomes radiation- and matter-dominated. The heat from the collision dominates the universe for a few billion years, but eventually it is diluted enough that the positive interbrane potential energy density dominates. This acts as a source of dark energy that causes the expansion of the branes to accelerate. The matter, radiation, and large scale structure are all diluted away exponentially over the next trillion years or so, and the branes become nearly perfect vacuua.

However, the interbrane attractive force ensures that the acceleration only lasts a finite time. Inexorably, the branes are drawn together and the potential energy decreases from positive to negative values. The acceleration stops and, once the potential decreases to the point where $V = -\frac{1}{2}Ø^2$, the total energy density is zero and the Hubble expansion rate becomes zero. The universe switches from expansion to contraction. The branes themselves do not contract or stretch significantly. Rather, the distance between them shrinks as the two branes crash together. That is, the contraction only occurs in the extra dimension between the branes. The collision is a singularity in the sense that a dimension momentarily disappears. However, the branes exist before, during and after the collision, which plays a crucial role in tracking what happens to the universe through the bounce.

During the dark energy dominated phase, the branes are stretched to the point where they are at and parallel.

During the contraction phase, the branes stop stretching and quantum fluctuations naturally cause the branes to wrinkle. Due to the wrinkles, the branes do not collide everywhere at the same time. Since the collision creates matter and radiation, this means that different regions heat and expand at different times. The result is that the universe is slightly inhomogeneous after the collision. For an exponentially steep interbrane potential, the spectrum of temperature fluctuations is nearly scale- invariant[8].

Unlike cyclic models discussed in the 1920s and 30s, the entropy density does not build up from cycle to cycle. Here is an example of where we take full advantage of the idea of branes and extra dimensions: The entropy created in one cycle is expanded and diluted to near zero density after the dark energy dominated phase, but the entropy density does not increase again in the contraction phase. The simple reason is that the branes themselves do not contract.

Only the extra dimension’s contract.

From a local observer's point of view, the entropy density undergoes precise cyclic behavior. Yet, the total entropy on the branes grows, in accord with the second law of thermodynamics. It is just that entropy is being exponentially diluted from one cycle to the next, so any given local observer cannot detect the entropy from previous cycles.

The collisions can continue indefinitely despite the fact that the brane collisions are inelastic because gravity supplies extra energy during each contraction phase. During contraction, the kinetic energy of particles or, in this case, branes, is blue shifted due to gravity. This simply means gravity is providing extra kinetic energy in addition to what the interbrane force produces. So, when the branes collide, it is with greater energy than would be obtained with the interbrane force alone. The net result is that gravity adds to the kinetic energy which converts partially to matter and radiation. A key result (shown in Ref. is that, if we consider the coupled gravity, scalar field, and radiation evolution equations, there exists a cyclic solution that is stable under small perturbations.

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[8] A. J. Tolley, N. Turok and P. J. Steinhardt, hep-th/0306109, Physical Review D, in press (2004).

3) PARSIMONY: AN EFFICIENT USE OF SPACE-TIME:

The Cyclic Model is more parsimonious than inflation in that a greater proportion of space-time looks like the universe we see. In inflationary models, most of space-time consists either of a very high energy inflating phase, or of the empty vacuum to which bubble interiors tend at late times. With exponential rarity, bubbles are formed in the high energy phase, and, within each, a hot big bang phase forms. The interior of the bubble is hot at first, but the temperature and density decrease steadily with time, and structure formation stops once dark energy dominates the universe. Hence, along any time-like world-line in the inflating universe, there is only a single brief interval (when the world-line crosses a bubble wall) in which there exist stars and galaxies. In the cyclic model, every world-line has repeated, periodically spaced intervals in which stars and galaxies form.

The description of inflation above made the conventional assumption that the interior of a bubble never undergoes further high-energy inflation. If the dark energy is due to a cosmological constant, though, this may not be the case.

Imagine a quadratic inflaton potential, say, whose minimum has a small, positive value corresponding to the currently observed dark energy density. High-energy inflation occurs when the inflaton field lies far from the minimum, high up the potential. Inflation ends in a region when the field falls to the minimum. This region is equivalent to a bubble.

However, here the minimum corresponds to a low-energy de Sitter phase. With infinitesimally small probability, de Sitter fluctuations can carry the inflaton field back up the potential high enough to begin a second period of high-energy inflation followed by a second bubble and big bang phase. In this case, a time-like world-line would have irregularly spaced intervals in which stars and galaxies form. However, even in this case, the intervals would be exponentially far apart compared to the model with periodic cycling.

By either reckoning, inflation wastes space-time. In a Bayesian comparison of the two theories, more wasted space-time translates into a reduced probability of a theory being correct. If P(A) is the probability of theory A and if P(O|A) is the probability of observation O given theory A, then

$$\frac{P(inflation)}{P(cyclic)} = \frac{P(stars|inflation)}{P(stars|cyclic)} \ll 1,$$

assuming equal priors for the two theories. (A similar analysis is sometimes used to explain why inflation is more desirable than the standard big bang model.) We make this point for amusement purposes only. At this point in time, it seems plausible to assign the models equal priors. However, we hope that future observations and developments in fundamental physics will be the decisive factors.

4) FOREVER CYCLING?:

The description in the previous section is an idealization, because there is dissipation from cycle to cycle[9]. For example, black holes formed during one cycle will survive into the next cycle, acting as defects in an otherwise nearly uniform universe. (In the vicinity of the black holes, there is no cycling due to their strong gravitational field.) Also, quantum fluctuations and thermal fluctuations will, with exponentially small rarity, create 'bad regions' which fall out of phase with the average cycling and could form giant black holes[10]. In commoving coordinates, the black holes and bad regions increase in density over time. In this sense, the commoving observer sees the universe as \winding down."

Similarly, a local observer will see the cycling as having finite duration in the sense that, at some point, after many, many cycles, he will end up inside a black hole (or bad region) and cease to cycle. Thus, we conclude that cycling conserves energy and is not perfectly efficient; it is neither perpetual motion of the first or second kind. However, because of the stretching of space, the distance between the defective regions remains larger than Hubble distance.

New cycling regions of space are being created although any one region of space cycles for a finite time. The cyclic model thereby satisfies the conventional thermodynamic laws even though the cycling continues forever.

It has been suggested that the holographic principle may place a stronger constraint on the duration of cycling. The argument is based on the fact that there is an average positive energy density per cycle. Averaging over many cycles, the cosmology can be viewed as an expanding de Sitter Universe. A de Sitter universe has a finite horizon with a maximal entropy within any observer's causal patch[11] given by the surface area of the horizon. Each bounce produces a finite entropy density or, equivalently, a finite total entropy within an observer's horizon. Hence, the maximal entropy is reached after a finite number of bounces. (Quantitatively, a total entropy of 10^{90} is

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[9] N. Turok and P.J. Steinhardt, hep-th/0403020.

[10] P.J. Steinhardt and N. Turok, Phys. Rev. D66, 101302 (2002).

[11] N. Goheer, M. Kleban, and L. Susskind, JHEP 0307, 056 (2003).

produced within an observer's horizon each cycle, and the maximum entropy within the horizon is 10^{120}, leading to a limit of
10^{30} bounces.)

Closer examination reveals a flaw in this analysis[12]. Although the overall causal structure of the four-dimensional effective theory may be de Sitter, it is punctuated by bounces in which the scale factor approaches zero.

See Figure 2. Each bounce corresponds to a spatially at caustic surface. All known entropy bounds used in the holographic principle do not apply to surfaces which cross caustics. Hence, holographic bounds can be found for

regions of space between a pair of caustics ($i., e.$ within a single cycle), but there is no surface extending across two or more bounces for which a valid entropy bound applies. If the singular bounce is replaced by a non-singular bounce at a small but finite value of the scale factor, the same conclusion holds. In order for a contracting universe to bounce at a finite value of the scale factor, the null energy condition must be violated. However, the known entropy bounds require that the null energy condition be satisfied. Once again, we conclude that the entropy bounds cannot be extended across more than one cycle. Yet another way of approaching the issue is to note that both singular and non-singular bounces have the property that light rays focusing during the contracting phase defocus after the bounce, which violates a key condition required for entropy bounds. In particular, the light-sheet construction used in covariant entropy bounds are restricted to surfaces that are uniformly contracting, whereas the extension of a contracting light-sheet across a bounce turns into a volume with expanding area. Hence, if bounces are physically possible, entropy bounds do not place any restrictions on the number of bounces.

Does this mean that the cycling has no beginning? This issue is not settled at present. We have noted that the cyclic model has the causal structure of an expanding de Sitter space with bounces occurring on at spatial slices.

For de Sitter space, the expanding phase is geodetically incomplete, so the cyclic picture cannot be the whole story.

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[12] M. Kleban, P.J. Steinhardt, N. Turok, unpublished.

The most likely story is that cycling was preceded by some singular beginning. Consider a universe that settles into cycling beginning from some at slice in the distant past many bounces ago. Any particles produced before cycling must travel through an exponentially large number of bounces, each of which is a caustic surface with a high density of matter and radiation at rest with respect to the at spatial slices. Any particle attempting this trip will be scattered or annihilated and its information will be thermalized before reaching a present-day observer. Consequently, the observer is effectively insulated from what preceded the cycling phase, and there are no measurements that can be made to determine how many cycles have taken place. Even though the space is formally geodetically incomplete, it is as if, for all practical purposes, the universe has been cycling forever. We are currently exploring if this picture can be formalized.

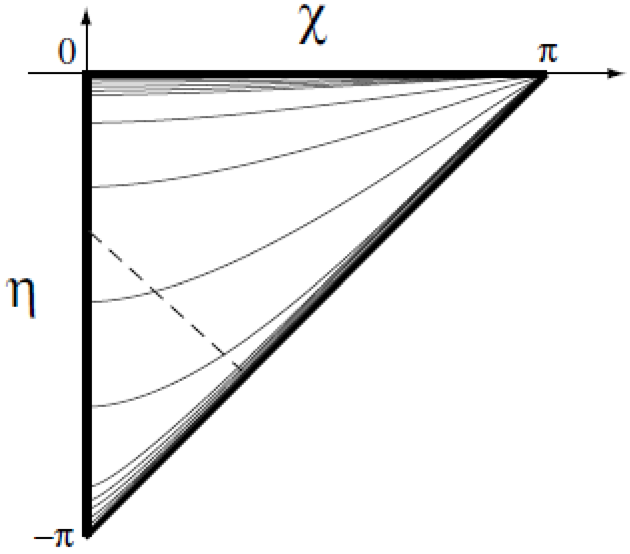

Figure 2: The cyclic model has an average positive energy density per cycle, so its conformal diagram is similar to an expanding
de Sitter space with constant density. The bounces occur along at slices (curves) that, in this diagram, pile up near the diagonal and upper boundaries. For true de Sitter space, entropy bounds limit the total entropy in the entire space-time. For the cyclic model, the bounds only limit the entropy between caustics (the bounces). Particles or light-signals emitted in an earlier cycle (or before cycling commences) are likely to be scattered or annihilated as they travel through many intervening cycles (dashed line) to reach a present-day observer. The observer is effectively insulated from what preceded the cycling phase, and there are no measurements to determine how many cycles have taken place.

5) CONTRACTION AND BOUNCE:

Major progress has been made in understanding the most controversial stages of the Cyclic Model: the contraction and bounce. Concerns about these stages are understandable. Previous attempts to construct cyclic or oscillatory models all failed due to various problems that arise during a contraction phase: the matter and radiation density diverge; the entropy density diverges; the 4-curvature diverges; the anisotropy, spatial curvature, and inhomogeneity diverge; collapse exhibits chaotic Mixmaster behavior. Hitherto, this pathological behavior has rendered it inconceivable that a nearly homogeneous, isotropic and flat universe with small-amplitude scale-invariant fluctuations could emerge from a bounce.

We now understand that the Cyclic Model can evade these problems because of two distinctive properties:

(i) Since matter and radiation are confined to branes, their background densities do not diverge at the bounce. New entropy is created but old entropy remains dilute. Unlike previous cyclic models, the entropy density does not build up from cycle to cycle. Instead, the entropy density returns to near zero towards the end of each cycle.

(ii) Because w >> 1 during the contraction phase, the universe is homogeneous, isotropic and flat with a scale-invariant spectrum of density perturbations[13].

(iii) The w >> 1 condition also ensures that anisotropies are small and first order perturbation theory remains valid until just before the bounce.

These effects due to branes and a w > 1 energy component are novel and critical to the success of a cyclic scenario.

Earlier attempts at cyclic models over the last century did not include branes because that concept came into vogue only during the last decade. However, one might naturally wonder why w > 1 was not considered previously. The probable reason is that, prior to inflation, cosmologists often assumed for simplicity that the universe is composed of “perfect fluids” for which $w = C_s^2$, where the equation of state w equals the ratio of pressure p to energy density ρ, and the

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[13] L. A. Boyle, P. J. Steinhardt and N. Turok, to appear (2004).

speed of sound C_s is defined by $C_s^2 = dp/d\rho$. If $w > 1$ and the fluid is perfect, then $C_s > 1$, which is physically disallowed for any known fluid. With the advent of inflation, cosmologists have become more sophisticated and flexible about what fluids they are willing to consider. The inflaton, for example, has $w \approx -1$, yet the speed of sound is positive and well-behaved. A rolling scalar field with canonical kinetic energy has $C_s = 1$. Similarly, it is possible to have $w > 1$ and yet $0 \leq C_s^2 \leq 1$ without violating any known laws of physics. This opens the door to a novel kind of cyclic model.

6) ONWARD TO THE NON-LINEAR REGIME:

Thus far, we have analyzed the propagation of perturbations through the bounce assuming they are linear. From this, we have learned that branes introduce a new physical element essential for propagating perturbations through the bounce. Also, we have obtained, we hope, a good estimate of the spectral amplitude. However, a full analysis including the non-linear physics close to the bounce is required to complete the picture.

Because w > 1 during the contraction phase, the universe remains nearly homogeneous, isotropic and at and the linear approximation remains valid up until the branes are about a string scale-length apart. At this point, corrections to the Einstein action become important. We cannot be sure what those corrections are. However, assuming there is a bounce, they operate for a very short time. The branes lie within a string-scale-length for roughly a string scale-time,
or about 10^{-40} seconds.

During these last instants before the bounce, the modes of interest for cosmology, e.g., wavelengths which lead to the formation of galaxies and larger scale structure, are far outside the horizon and their dynamics is frozen. Although their amplitude may become non-linear, there is not enough time during the bounce for interactions to alter the long-rang correlations. Hence, we conjecture, it is reasonable to match the linear behavior just before the bounce to the
linear behavior just after the bounce.

In fact, one approach to the matching problem may be to avoid t = 0 altogether by analytically continuing in the complex t-plane in a semicircle with radius greater than the string scale and connecting negative to positive real values of t. Then, the linear analysis described above would remain essentially uncorrected by nonlinear gravitational effects, at least on long (three-dimensional) wavelengths. Work is currently in progress to construct such a continuation in nonlinear gravity.

On the other hand, for modes with wavelength less than $10^{-30} cm$, causal dynamics can alter the dynamics in the final instants. In particular, the non-linear corrections to gravity could conceivably produce large amplitude effects that lead to the formation of many tiny primordial black holes.

The black holes are bad news for those wishing to track precisely what occurs at the bounce. String theoretic methods are probably not powerful enough to analyze precisely this kind of inhomogeneous, non-linear regime. However, from a cosmological point-of-view, it is straightforward to envisage their effect, assuming that the branes bounce.

The black holes are small and have a mass roughly of order the mass density times Hubble volume at the collision.

This scale is model-dependent, but for the wide range of parameters allowed for the cyclic model based on other constraints, the mass is sufficiently small that the black holes decay in much less than one second, well before primordial nucleosynthesis.

We conjecture that the black holes can be a boon to the scenario. (See also, who consider an alternative model that begins with a dense gas of black holes.) Their lifetime is long enough that they likely dominate the energy density before they decay. Consequently, their evaporation provides the entropy observed today. When they decay, their temperature rises near the end to values high enough to produce massive particles with baryon-number violating decays. At this point, the black holes are much hotter than the average temperature of the universe, so the decays occur when the universe is far from equilibrium. Assuming CP-violating interactions also exist, as in conventional high-temperature baryogenesis scenarios, the decay can produce the observed baryon asymmetry[14]. In addition, the decay can produce dark matter particles that can meet current observational constraints.

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[14] T. Banks and W. Fischler, hep-th/0212113, hep-th/0310288.

Conclusion:

Our study of the Cyclic Model has uncovered surprising new facts about contracting universes. Namely, a contracting

universe with w > 1 has remarkable properties analogous to an expanding phase with $w \leq -\frac{1}{3}$. The homogeneous solution to the Friedmann equation becomes spatially uniform, isotropic and at. At the perturbative level, a nearly scale-invariant spectrum of density perturbations is generated. There is a precise duality relating (linear) scalar perturbations produced in an inflating phase to those produced in a contracting (epidotic) phase. The evolution equations are also ultralocal (purely time-dependent) at least up until stringy corrections to the Einstein equation become significant when the branes are separated by less than a string scale- length.

Consequently, many of the conventional worries of the past about contracting phases are addressed, and attention is turning to what happens in the final instants before and after the collision. The goal is to determine if: (a) the bounce occurs; and, (b) perturbations on wavelengths greater than the string scale lengths (which includes the wavelengths of cosmological interest) obey the matching rule naturally inferred by analytically continuing the linear solution. Current research is focused on these exploring these issues.

The outcome has profound implications for cosmology and fundamental physics. If inflation is correct, then we are blocked from any direct knowledge of the big bang and any other pre-inflationary conditions by a period of superluminal expansion. If the Cyclic Model is correct, then our measurements of microwave background fluctuations and large-scale structure are to leading order direct probes of the big crunch and big bang, including stringy and extradimensional physics, as illustrated by Eq. Settling the cosmological issue of whether the density fluctuations were produced during a period of expansion or contraction (by searching for tensor fluctuations, non-gaussianity and non-adiabaticity) will also determine whether physical conditions near the big bang can be probed empirically or not.

This raises the stakes and enhances the importance of distinguishing the two scenarios.

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