

# The Cyclic Universe: An Informal Introduction

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The Cyclic Model is a radical, new cosmological scenario which proposes that the Universe undergoes an endless sequence of epochs which begin with a ‘big bang’ and end in a ‘big crunch.’ When the Universe bounces from contraction to re-expansion, the temperature and density remain finite. The model does not include a period of rapid inflation, yet it reproduces all of the successful predictions of standard big bang and inflationary cosmology. We point out numerous novel elements that have not been used previously which may open the door to further alternative cosmologies. Although the model is motivated by M-theory, branes and extra-dimensions, here we show that the scenario can be described almost entirely in terms of conventional 4d field theory and 4d cosmology.

## 1. Introduction

Through a combination of inspired theoretical insights and ingenious experiments and observations, cosmologists have emerged with a consensus model of the Universe, a mixture of the big bang picture and inflationary cosmology[1,2], that is able to explain a whole host of observations in exquisite detail. The results raise our confidence that we are converging on the right story of the evolution of the Universe.[3] But maybe we’re not!

The purpose of this paper is to introduce a new type of cosmological model – not a variant of an older model, but, a genuinely new cosmological framework. This new paradigm turns cosmic history topsy-turvy. And yet, as you will see, it is able to reproduce all of the successful predictions of the consensus model with the same exquisite detail. Perhaps you will even conclude that the cyclic Universe accomplishes the feat more economically.

The key difference between the consensus paradigm and the new paradigm can be simply stated. The consensus model relies on the idea that space and time had a beginning when the Universe had nearly infinite temperature and density. It has been expanding every since, going

from hot to cold, from dense to nearly vacuous. The new model predicts that the Universe is infinite in both space and time. It is cyclic in time, undergoing endless cycles of evolution and renewal, cooling and heating - in which the density and temperature remain finite throughout. All of the differences between the two paradigms harken back to the disparate assumptions about whether there is a “beginning” or not.

The cyclic model of the Universe[4,5] draws heavily on ideas we developed earlier in collaboration with Justin Khoury (Princeton), Burt Ovrut (Penn) and Nathan Seiberg (IAS) in a precursor theory known as the ‘ekpyrotic Universe.’[6–8]

Both cyclic and ekpyrotic scenarios were very much inspired by string theory, M-theory and the notion of brane-worlds. The introductory papers are expressed in this language. However, as is often the case, the notions that inspire an idea are not necessarily required. The idea may be more general. So it is, we think, for the cyclic Universe. To make that point most forcefully, we will present this paper with hardly any mention of string theory until the very end. Instead, we will use the more prosaic and generic language of 4d field theory, scalar fields, and potentials. Only at the end will we mention string theory to show how it provides a natural setting and simple

geometric interpretation of these ideas.

## 2. The Consensus Model

To appreciate the cyclic model, it is useful to review the key features and assumptions that underly the consensus big bang/inflationary picture.

**Big Bang:** The consensus model is based on the notion that the big bang is a beginning of space and time with nearly infinite temperature and density. What is important is that the Universe starts out expanding, and there are patches over which the inflaton field has high potential energy density. Regions of higher potential energy would expand faster, and come to dominate. Hence one can argue that most of the Universe would be taken up by such high potential energy regions, which would then inflate for a long time. This is the idea underlying chaotic inflation, for example.[9] However, if the big bang were not a beginning, but, rather, a transition from a pre-existing contracting phase, then the inflationary mechanism would fail (or require major amendments). During a contracting phase, scalar field potential energy drives exponentially rapid collapse so regions of high potential energy would shrink away faster than regions of low energy density (just the time reversed behavior), so regions of high potential energy would not survive into the expanding phase to drive inflation.

The assumptions are all physically plausible and reasonable. However, we raise these points to emphasize that they are *unproven assumptions* that should not be taken for granted. The theory is incomplete until they are proven. The issue is important because, as we shall see, the cyclic model makes different plausible and reasonable assumptions about the nature of the bang.

**Inflation:** The consensus model assumes that, shortly after the big bang, the Universe underwent a brief period of rapid, superluminal expansion: inflation. To have inflation, new ingredients have to be added to the simple big bang picture. In typical models of inflation, the ingredients consist of a scalar field (the inflaton) and a scalar potential with the property that, over some range of values, the field rolls so slowly down the potential

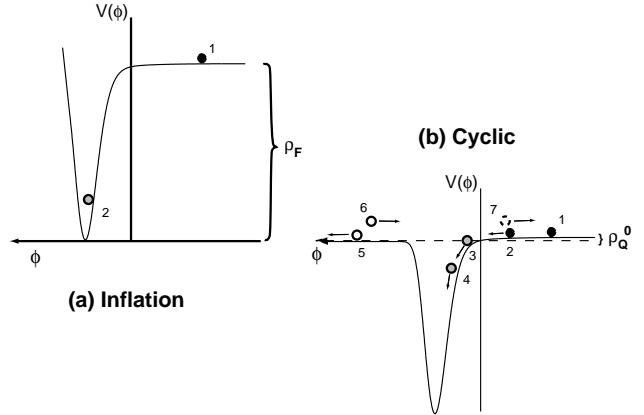


Figure 1. Schematic plot of the potential  $V(\phi)$  as a function of the field  $\phi$  for (a) inflationary cosmology and (b) cyclic models. The numbered sequence of stages is described in the article.

that its kinetic energy is much less than its potential energy. Figure 1(a) is a schematic illustration. In this case, the slow-roll evolution occurs on the plateau (stage 1 in Figure 1(a)). When the potential energy dominates, the pressure of the scalar field (the difference between kinetic and potential energy density) is negative, causing the Universe to undergo a period of cosmic acceleration. The height of the plateau is chosen so that the acceleration is extraordinarily rapid, causing the Universe to double in size every  $10^{-35}$  seconds (a fiducial number, assuming GUT-scale inflation).

It is essential that the slow-roll comes to an end in order to stop inflation. In the schematic example, the end of inflation occurs where the scalar reaches the end of the plateau and falls into the potential well (stage 2). The field oscillates around the minimum and decays into ordinary matter and radiation.

Despite the period of inflation which causes the Universe to become homogeneous and flat, quantum fluctuations cause different regions to reach the end of the plateau and to reheat and cool at different times, leading to fluctuations in

the temperature and density. The result of a careful analysis is that the spectrum of fluctuations is nearly scale-invariant, gaussian and adiabatic,[10] in excellent accord with what is observed in measurements of the cosmic microwave background anisotropy and large-scale structure. All this must be accomplished before the Universe is a second old in order to recover the successful predictions of primordial nucleosynthesis.

**Radiation and Matter Domination:** When the Universe reheats after inflation, the temperature is higher than the characteristic scales of cosmic nucleosynthesis and structure formation, so the subsequent expansion and cooling precisely mimics the original big bang picture and all of the associated successful predictions are re-accrued. Nucleosynthesis occurs during the radiation epoch. The Universe becomes transparent and structure forms in the matter-dominated epoch.

**Dark energy??:** Recently, the consensus model has had to incorporate a major amendment, the addition of dark energy. The observations of the cosmic microwave background, large-scale structure and distant supernovae all suggest that most of the energy density of the universe is some form of dark energy component with negative pressure which causes the expansion of the Universe to accelerate.[11,3]

*The discovery of dark energy is a complete surprise from the point-of-view of big bang and inflationary cosmology.* It serves no known role. It may consist of a vacuum energy (or cosmological constant) or quintessence. Although dark energy was not predicted, it can be accommodated by stipulating that the inflaton decayed into some combination of matter, radiation and dark energy. However, the added conditions are *ad hoc*, and extreme tuning is required to explain the ratio of dark energy to matter energy.

**The future???:** Because dark energy comes as a surprise and its nature is not predicted, the long-term future of the Universe is uncertain. If the dark energy is a cosmological constant, the accelerated expansion will continue forever, and the Universe will become increasingly empty. If the dark energy is quintessence, many alternatives are

possible. For example, quintessence can decay and cause the acceleration to end.

### 3. The Cyclic Model

Cosmic evolution in the cyclic model differs remarkably from the consensus picture:

**The “bang”:** Each cycle can be said to begin with a bang. Unlike the traditional concept of the big bang, the density and temperature of the Universe do not diverge, and, in the M-theory picture, space does not disappear. Instead, the bang is a transition or bounce from a pre-existing contracting phase to an expanding phase during which matter and radiation are created at a large but finite temperature.

**Radiation and Matter Domination:** The bang is followed by an immediate entry into the radiation-dominated epoch. There is no inflation and no need for the scalar field or potential required by inflation. Other mechanisms, to be discussed below, are responsible for making the Universe homogeneous and flat and for making density fluctuations. The radiation and matter-dominated epoch are essentially identical to the consensus model.

**Dark energy:** The Universe subsequently enters the dark energy dominated epoch and cosmic acceleration commences. Recall that dark energy was unanticipated in the consensus model and has no purpose. Here, dark energy plays a pivotal, and absolutely crucial role. The field that comprises the dark energy is the engine that drives the whole cyclic scenario.

The dark energy is due to a scalar field rolling down a potential, similar to the inflaton of the consensus model. However, here the scalar field governs the whole of the evolution of the Universe, not just the beginning. In inflation, the scalar field causes acceleration and reheating. Here, the scalar field acts as dark energy, causes a period of slow acceleration, converts the acceleration into deceleration and contraction, triggers the bounce, reheats the Universe and begins the cycle anew. Furthermore, the scalar field has a natural geometric interpretation in string theory, as described in Section 7.

Compared to inflation, the potential is shifted downwards in energy, as illustrated in Figure 1(b). The plateau corresponds to a tiny potential energy density equal to the current dark energy density. The scalar field acts as a form of quintessence, and so we have labeled the height of the potential as  $\rho_Q^0$ . During the radiation and matter dominated phases, the scalar field is effectively frozen in place by the Hubble red shift of its kinetic energy (stage 1 in Fig. 1(b)). However, as the Universe cools and expands, the potential energy ultimately comes to dominate that energy density. Also, the field begins to roll downhill (stage 2).

The period in which the potential energy dominates is important for several reasons. It provides the source for the presently observed dark energy and cosmic acceleration. It makes the Universe flat and homogeneous, replacing inflation. Although both dark energy and inflation entail cosmic acceleration, the acceleration due to dark energy is 100 orders of magnitude smaller, causing the Universe to double in size every 15 billion years or so, compared to every  $10^{-35}$  seconds for inflation. The very slow acceleration is, nevertheless, sufficient to empty the Universe of its matter and radiation. After trillions of years, there is less than one particle per horizon. Locally, the Universe has been restored to nearly pristine vacuum.

The emptying of the Universe is crucial to a cyclic model. Historically, oscillatory models have been plagued by the fact that the entropy density rises from cycle to cycle, as shown by Richard Tolman in the 1930s.[12] The lengths of cycles increase steadily. Consequently, extrapolating backwards in time, the lengths of cycles decrease steadily, so that the sum converges at a finite time – a beginning of the Universe that one was trying to avoid. In our cyclic model, the dark energy dilutes the entropy density to negligible levels at the end of each cycle, preparing the way for a new cycle of identical duration.

Note that the second law of thermodynamics is respected. The total entropy of the Universe rises from cycle to cycle. The number of black holes rises as well. (Equivalently, the entropy and black holes per unit comoving volume increase.) However, the physical entropy density – the entropy

per proper volume – is expanded away in each cycle. Since it is the physical entropy density which determines the expansion rate, the expansion and contraction history in each cycle is the same from one cycle to the next. (A key feature is that entropy density decreases in the expansion phase but, as we shall see, does not grow significantly during the contraction phase due to the effects of the scalar field, countering the effects of contraction.)

It may seem peculiar that the entropy density remains finite at the crunch. That is, even if the entropy density is made exponentially small during the dark energy dominated phase, why doesn't it diverge? The answer will be that the crunch is modified by the interaction between matter-radiation and the scalar field.

**Contraction:** As the field rolls off the plateau and heads downhill, the potential energy crosses zero (stage 3). The Universe is dominated by the kinetic energy of the scalar field, which causes the expansion to decelerate once again. As the field rolls to values where the potential energy is increasingly negative, the expansion stops altogether (stage 4) and reverses to contraction.

The contraction is extremely slow at first, taking billions of years. During this very slow evolution phase, quantum fluctuations have time to cause spatial variations in the rate of contraction. At first, these variations are only on large length scales, but, as time proceeds, they occur on smaller and smaller length scales. The big surprise, as first demonstrated by Khoury *et al.* in the context of the ekpyrotic model,[6,8] is that the resulting spectrum is scale-invariant if the potential flattens exponentially at large  $\phi$ . (Small deviations from exponential behavior result in small deviations from scale-invariance.)

Differences in the contraction rate result in differences in when different regions bounce, reheat to high temperature and expand. Consequently, the scale-invariant spectrum generated in the contraction phase evolves to become a spectrum of temperature and density perturbations after the bang. (The detailed computation of perturbations in the ekpyrotic and cyclic models led to fierce debate in the literature over the

precise matching conditions. Matching conditions according to which the scale-invariant spectrum generated in the contraction phase propagate across the singularity have been proposed, and whilst these have not yet been fully justified at a fundamental level, progress has been made [19–21].)

**“Crunch” and “bounce”:** The scalar field picks up speed as it rolls down into the potential well. One need not fear that the field will be stuck at the bottom. Contraction causes a Hubble blue-shift of the scalar field kinetic energy. The field literally accelerates out of the minimum and flies off towards negative infinity in a finite time (stage 5). At the same time, the scale factor in the effective 4d field theory rushes towards zero and the crunch ensues.

Unlike a conventional big crunch, the temperature and density remain small and finite before the crunch. This is because the scalar field is coupled to matter and radiation in a special way. The effect of contraction in increasing the density is directly compensated by the interaction with the scalar field that drains the energy density. We will illustrate how this is possible and well-motivated in M-theory.

The field reaches negative infinity in finite time, before heading back towards positive values (stage 6). The acceleration of the field at turnaround causes some conversion of scalar field kinetic energy to matter and radiation, reheating the Universe to high but finite temperature. At the same time, the scale factor reverses and the Universe begins to expand. The field rushes back towards where it started (stage 7), but its kinetic energy is now being red-shifted in the expanding phase, especially due to the presence of matter and radiation. Soon after the radiation dominates over the scalar kinetic energy density, the red-shift causes the field to grind to a halt (stage 1).

The Universe has now come full circle, returning to the expanding, radiation-dominated phase.

#### 4. Another view: Expansion-Stagnation

We have described the cycle as a sequence of expansion contraction. Technically, we call the

second stage contraction because the scale factor  $a(t)$  is shrinking and, at the crunch, is equal to zero. However, as pointed out above, the scalar field conspires in such a way as to keep the temperature and density nearly fixed at a small value. In the brane picture, the expansion corresponds to the stretching of the branes, which dilutes the matter and radiation density. The contraction, though, is the contraction of the finite extra dimension, rather than the three large dimensions.

Consequently, an ordinary observer on our brane, say, would not recognize the behavior at the end of trillions of years of expansion as a contraction since the interval between distant objects would not appear to be shrinking in brane coordinates. Rather, since the branes stop stretching, it would appear that the expansion has stalled. The contraction of the extra dimension would not be visible, but its physical consequences would be. Namely, coupling constants would change with time at a rate that increases as the bounce approaches. This would be perceived as some mysterious new form of energy. At the bounce, this energy would suddenly produce radiation and energy that fills the universe. As the branes bounce back, the couplings are returned to their initial values. The matter and radiation force a new period of expansion (brane-stretching).

In sum, if the story is retold from the ordinary observer’s point-of-view, the universe is going through cycles of expansion, stagnation, reinitiation and then the cycle begins again.

#### 5. Consensus vs. Cyclic

We have outlined the basic elements of two cosmological scenarios based on different assumptions about the nature of space and time. The consensus picture assumes that space and time have a beginning at the big bang. The cyclic model assumes that the bang is simply a transition from contraction to expansion accompanied by the release of radiation.

Figure 2 compares the two scenarios. Several points are apparent.

*Inflation and Cyclic models entail two completely different strategies for making the Universe homogeneous*

*and flat and for generating density perturbations, each strategy resting on the respective assumptions about the beginning of the Universe.*

For Inflation, there is little time before primordial nucleosynthesis to fix conditions on large scales. An ultra-rapid period of accelerated expansion is called for. The cyclic model assumes that time continues before the bang, so there is plenty of time to set the large-scale conditions of the Universe prior to the bang. Hence, it fits quite naturally to invoke long periods of ultra-slow accelerated expansion and contraction lasting trillions of years during which the homogeneity, flatness, and density perturbations are established. For comparison, inflationary fluctuations are amplified and frozen in on a timescale of  $10^{-35}$  seconds, a length scale of  $10^{-25}$  centimeters. Whereas fluctuations are generated fractions of a second before the big bang, when their length scale is thousands of kilometres.

*Inflation requires two periods of acceleration with two different energy components, whereas the cyclic model requires only one.*

For inflation, we must introduce a hypothetical period of accelerated expansion driven by an inflation field and potential with certain properties. One must add a second component to explain the observed acceleration today. Although one can imagine both accelerations being due to the same field, there seems to be nothing to recommend it: the time and energy scales are so different that there is no natural link. By contrast, the cyclic model requires only one period of accelerated expansion, the one that is actually observed. Some corollaries are:

*Dark energy is not predicted or explained by Inflation, but is a required component in the Cyclic Model.*

*The future is not predicted by Inflation, but it is predicted in the Cyclic Model.*

### Consensus Model (big bang-inflation)

big bang  
inflation  
radiation  
matter  
dark energy??  
future???



### Cyclic Model

"bang" ←  
radiation  
matter  
dark energy  
contraction  
"crunch" →

Figure 2. Comparison of the sequence of events in the consensus big bang/inflationary and cyclic pictures. The consensus model assumes that the big bang is a beginning, inflation sets the initial conditions, and then the Universe proceeds through the matter and radiation dominated phases. Dark energy is added to explain the current acceleration, but the long-term future is uncertain. The cyclic model proposes that the Universe undergoes an endless sequences of cycles which begin with a bang and end in crunch. Initial conditions for a given cycle are produced during the dark energy-dominated and contraction phases of the previous cycle. The past and future are determined.

More generally, it is obvious that Inflation is a theory of the very early Universe, without explanation of the beginning or future of the universe. By contrast, the cyclic model offers a complete history. Knowledge of the present is also knowledge of the past and future. Consequently, it is not surprising that the cyclic model is more constrained. For example, the amplitude of long-wavelength gravitational waves is constrained to be exponentially tiny in the cyclic model whereas there is freedom to adjust the amplitude in Inflation. Nevertheless, all current observational constraints are satisfied by both models.

That the cyclic model is able to accomplish more with less suggests that it is economical. However, economy is not a reliable way to judge between the two scenarios. The critical issues are both theoretical – the nature of the bang – and experimental – searching for long-wavelength gravitational waves.

## 6. Contraction and Generation of Perturbations

The cyclic model introduces several novel features into cosmology. In this introduction, we will focus on the two most important: the new mechanism for generating a scale invariant spectrum of density perturbations and the bounce from crunch to bang.

An important discovery by Khoury *et al.* in our development of the ekpyrotic model was a new mechanism for generating a scale-invariant spectrum of density perturbations using a phase of slow contraction rather than rapid inflation.[6,8] The fact that both approaches work is shocking, at first, because they seem so different. Gravity is the strong, overwhelming influence during inflation, but it is essentially irrelevant during slow contraction.

Actually, there is a simple heuristic argument to explain the result. During slow contraction, gravity can be ignored in the equation of motion for the scalar field  $\phi$ . Its integral form is simply:

$$\dot{\phi} = \sqrt{-2V}. \quad (1)$$

For Inflation, the idealized model is a perfectly flat potential. For cyclic models, the analog is a

pure, decreasing exponential potential,

$$V = -V_0 \exp(-\sqrt{3(1+w)}\phi), \quad (2)$$

where this form is taken to be an approximation to the steeply falling part of the potential after the plateau. The solution to the full equations of motion in a gravitational background for an exponential potential is well-known. There is a scaling solution in which the field energy is that of an ideal fluid with equation of state  $w$ , in units where  $8\pi G = 1$ . Note that the same potential form can be used for inflation if  $V$  is negative and  $w \approx -1$ . In cyclic models, we need  $V_0$  positive and  $w \gg 1$ .

The equation of motion can then be integrated to provide a relation between the time and the curvature of the potential:

$$-t = \sqrt{\frac{2}{-V''}}, \quad (3)$$

where the time has been defined to be negative and to approach  $t = 0$  as the contraction reaches the big crunch. The equation of motion for the  $k$ -th fluctuation mode,  $\delta\phi_k$  is, then:

$$\delta\ddot{\phi}_k + (k^2 + V'')\delta\phi_k = 0 \quad (4)$$

the last term of which can be re-expressed in terms of the time using the solution to the equation of motion:

$$\delta\ddot{\phi}_k + \left(k^2 - \frac{2}{t^2}\right)\delta\phi_k = 0. \quad (5)$$

Those familiar with inflationary perturbations will recognize the last equation as being precisely what is obtained in inflation for a flat potential. The critical factor is the numerator of the second term, which is two for a precisely scale-invariant spectrum. The factor of  $2/t^2$  for inflation comes from the gravitational expansion term, which is proportional to  $a''/a = 2/\tau^2$  where  $a$  is the scale factor and the prime represents the derivative with respect to conformal time  $\tau$ . The magical result is that scale invariance can be obtained either when gravity is strong and expansion is nearly de Sitter, or when contraction is negligible and the potential is exponentially decreasing.

However, there is an important difference. In inflation, the scale-invariant perturbations are

generated because the gravitational factor  $a''/a$  is much greater than the mass of the inflaton  $V''$ . A corollary is that the same equation applies to any field whose mass is much less than  $a''/a$ . That is, all light degrees of freedom obtain scale-invariant fluctuations. For most degrees of freedom, these fluctuations are irrelevant because they either smooth out after re-thermalization, or never dominate or never leave a measurable imprint. Notable exceptions are the two massless tensor modes. The gravitational waves produced in inflation may not dominate the density of the Universe, but they decouple immediately after reheating and maintain a distinctive signature. Although the current generation of gravitational wave detectors is not sensitive enough, future detectors may detect directly the stochastic fluctuations created by inflation. Alternatively, the tensor fluctuations leave a distinctive signature in the cosmic microwave background polarization, which also may be detectable. The discovery of long-wavelength gravitational waves would be important proof for inflation because these long-wavelength gravitational waves are not produced in the cyclic or ekpyrotic models. For cyclic models, the critical factor of  $2/t^2$  is provided by the potential, so only fields which have the exponential potential obtain scale-invariant fluctuations. The components of the metric are massless and potential-less, so, to lowest order, there are no long-wavelength gravitational waves produced. (When gravitational back-reaction is included, one finds a blue spectrum which includes long-wavelength modes, but whose amplitude is  $10^{25}$  smaller than inflation – effectively invisible.[6])

Hence, a valuable lesson has been learned. Gravitational waves provide a litmus test for determining the conditions under which the primordial perturbations were created, during fast expansion or slow contraction.

Another difference, even harder to detect, is the higher order non-gaussian contributions to the primordial spectrum. In both models, one can compute the non-gaussian corrections to the leading order gaussian fluctuations. The inflationary contribution is very small, down by more than  $10^{-5}$  relative to the leading order. Cyclic

perturbation spectra are super-gaussian: the non-gaussian contribution due to higher order terms is exponentially suppressed.[13]

## 7. Contraction, Crunch and Bounce

If the Universe is contracting when the perturbations are created, it will continue to contract until the Friedmann-Robertson-Walker scale factor,  $a(t)$ , hits zero and the Universe undergoes a crunch. The proposal is that the crunch leads to a bounce and renewed expansion.

One of the lessons learned from the study of the ekpyrotic model is that the crunch may be much milder than expected.[7] The big crunch discussed in earlier attempts at oscillatory models was one in which the density and temperature diverge, leading to divergent curvature and uncontrolled behavior. For example, the action might be:

$$S = \int d^4x a^4 \left( \frac{1}{2} \mathcal{R} + \frac{1}{2} (\partial\phi)^2 - V(\phi) + \rho_R \right) \quad (6)$$

where  $8\pi G = 1$ ,  $\mathcal{R}$  is the Ricci scalar and  $\rho_R$  is the radiation density. We have also set  $\sqrt{-g} = a^4$ , using the conformal Friedmann-Robertson-Walker metric. Solving the equation of motions, one finds  $\rho_R \propto a^{-4}$ , which is divergent at the crunch.

However, the crunch can be mollified if the scalar field  $\phi$  has appropriate couplings to matter, as in:

$$S = \int d^4x a^4 \left( \frac{1}{2} \mathcal{R} + \frac{1}{2} (\partial\phi)^2 - V(\phi) + \beta^4(\phi) \rho_R \right). \quad (7)$$

If the coupling function  $\beta(\phi)$  has the property that  $a\beta \rightarrow \text{const.}$  as  $a \rightarrow 0$ , then the radiation density approaches a constant at the crunch because the solution to the equation of motion is modified to be  $\rho_R \propto (a\beta)^{-4}$ . The increase in density due to contraction is compensated by the effect of the scalar field, which acts as a modification of gravity. By this simple mechanism, some of the serious concerns are obviated. The density and curvature can be finite, at this classical level. The spatial singularity has properties akin to time-like conical singularities which have been resolved and tamed in string theory. Our speculation is that the cosmic singularity can be tamed, also, even after the inclusion of quantum fluctua-



tions. Efforts are underway to evaluate this speculation rigorously.

Effectively, this approach argues that the effect of the contraction of the scale factor on the density curvature is compensated by the effect of the scalar field, which acts as a modification of gravity.

## 8. A New Toolkit for the Cosmologist

We have emphasized that the cyclic scenario can be understood for the most part, in terms of ordinary field theory. Many of its basic ingredients, such as scalar fields and potentials, also appear in inflationary cosmology. The cyclic model could have been proposed at the same time as inflation, in which case it would have been interesting to see which proposal would have emerged as the more appealing idea. As it is, the cyclic model has arrived twenty years late, after cosmologists have become attached to the inflationary paradigm, so there can be no fair measure.

The cyclic model was probably delayed because of the number of novel concepts that had to be incorporated. Although each idea is rather simple, having the whole collection together at once opens the door to new cosmological possibilities. They form a new toolkit of ideas that enable the cyclic model and may inspire further alternative cosmologies. For this reason, we summarize them here:

- Negative potential energy can be used to trigger a period of collapse in a flat universe. (Previous oscillatory models assumed a closed universe.)
- Negative potentials can lead to viable cosmologies.

(Many thought that the field would roll down the potential, get stuck at the bottom, and collapse into an anti-deSitter phase. Instead, the collapse causes the kinetic energy of the scalar field to blue shift and accelerate out of the potential well. This result has important implications for model-building. For example, supergravity models have been summarily rejected in the past

because the vacuum state had negative potential energy, but now we have learned that some of the models can lead to viable cosmologies.[14])

- A period of dark energy domination can simultaneously resolve the entropy problem of cyclic models, and the homogeneity and flatness problems of the standard big bang model.
- Scale-invariant spectra can be generated during a slow contraction phase in which  $w$  for the scalar field is much greater than unity, as explained in Section 4.
- Scalar field couplings to matter and radiation can be chosen so that the (classical) density and temperature remain finite at collapse.
- Density fluctuations created in a collapsing phase can result in growing mode perturbations after a bounce.[8]
- Dark energy can make the cyclic solution a dynamical attractor so that the solution that is stable under perturbations.

## 9. Strings and Branes

Thus far, the discussion of strings and branes has been avoided. However, string theory and M-theory have been an inspiration because they provide a natural setting and a particularly appealing geometric realization of the cyclic scenario. This connection is important, giving the model quantum consistency at a deep level and connecting our scenario to the leading approach to fundamental physics.

According to  $M$ -theory, the Universe consists of a four dimensional ‘bulk’ space bounded by two three-dimensional domain walls, one with positive and the other with negative tension.[15–17] The branes are free to move along the extra spatial dimension, so that they may approach and collide. (The fundamental theory is formulated in 10 spatial dimensions, but six of the dimensions are compactified on a Calabi-Yau manifold, which for our purposes can be treated as

fixed and irrelevant). Gravity acts throughout the five dimensional space-time, but particles of our visible Universe are constrained to move along one of the branes, sometimes called the ‘visible brane.’ Particles on the other brane interact only through gravity with matter on the visible brane and hence behave like dark matter.

Now we can “name names.” The scalar field  $\phi$  responsible for the cyclic scenario is, here, naturally identified with the radion field that determines the distance between branes. It is a required component of the M-theory picture. The potential  $V(\phi)$  is the inter-brane potential caused non-perturbative virtual exchange of membranes between the boundaries. The interbrane force is what causes the branes to repeatedly collide and bounce. The particular form of the interbrane force is not known, but a plausible form for the interbrane potential is:

$$V(\phi) = V_0(1 - e^{-c\phi})F(\phi) \quad (8)$$

where  $F(\phi)$  is chosen so that the potential falls to a substantially negative value and then rapidly approaches zero as  $\phi \rightarrow -\infty$ . At large separation (corresponding to large, positive  $\phi$ ), the force between the branes should become small, consistent with the flat plateau shown in Fig. 1(b). Collision corresponds to  $\phi \rightarrow -\infty$ . But the string coupling  $g_s \propto e^{\gamma\phi}$ , with  $\gamma > 0$ , so  $g_s$  approaches zero in this limit.[7] Non-perturbative effects vanish faster than any power of  $g_s$ , for example as  $e^{-1/g_s^2}$  or  $e^{-1/g_s}$ , accounting for the prefactor  $F(\phi)$ .

The coupling to matter-radiation,  $\beta(\phi)$ , that mollifies the crunch (see Section 5) also has a natural interpretation in the brane picture. Particles reside on the branes, which are embedded in an extra dimension whose size and warp are determined by  $\beta$ . The effective scale factor on the branes is  $\hat{a} = a\beta(\phi)$ , not  $a$ , and  $\hat{a}$  is finite at the big crunch/big bang. The function  $\beta(\phi)$  is, in general, different for the two branes (due to the warp factor) and for different reductions of M-theory. However, the behavior  $\beta(\phi) \sim e^{-\phi/\sqrt{6}}$  as  $\phi \rightarrow -\infty$  is universal, since at small brane separations the warp factor becomes irrelevant and one obtains the standard Kaluza-Klein result.[7,4] This universal form satisfies the desired condition that  $a\beta \rightarrow const.$  as  $a \rightarrow 0$ .

Most importantly, the brane-world provides a natural resolution of the cosmic singularity.[7] From the brane-world perspective, the singularity is far milder than in conventional cosmology. In fact, one might say the big crunch is an illusion, since the scale factors on the branes ( $\rightarrow \hat{a}$ ) are perfectly finite there. That is why the matter and radiation densities, and the Riemannian curvature on the branes, are finite. The only respect in which the big crunch is singular is that the one extra dimension separating the two branes momentarily disappears. *That is, the apparent singularity of the 4d theory,  $a \rightarrow 0$ , corresponds to the collapse of the extra dimension only. Our regular three dimensions remain infinite.*

Our scenario is built on the hypothesis[6] that the branes separate after collision, so the extra dimension immediately reappears. Consequently, the scale factor bounces and begins to expand. This process cannot be completely smooth, since the disappearance of the extra dimension is non-adiabatic and leads to particle production. Preliminary calculations of this effect are encouraging, since they indicate a finite density of particles is produced[18,20]. In this picture, the brane collision can be viewed as a simple, partially inelastic collision. Ultimately, a well-controlled string-theoretic calculation[7,20,21] should determine the efficiency of particle production from first principles.

in this picture, an observer on a brane would experience periods when the brane is expanding (during the radiation, matter, and dark energy dominated epochs), and periods when the stretching of the brane would nearly halt. instead, the branes approach one another. The observer would perceive that the separation between distance objects on the brane is no long increasing, nor is it decreasing either. This is the stagnation discussed earlier. Rather, the action is occuring in the extra dimension. Once the collision between branes takes place and the universe is dominated once again by radiation, the expansion of the universe begins again.

On length scales larger than the separation between branes, the higher dimensional brane-world description can be reduced to an effective four-dimensional field theory. This is why, for the

most part, the cyclic scenario could be described without reference to stringy physics and higher dimensions. Nevertheless, the brane-world picture proves to be a useful geometrical picture, and string theory is probably essential for determining what happens at the crunch.

## 10. In the Beginning

With the introduction of the cyclic model, the stage is set for a scientific debate comparing two distinct conceptual frameworks, one based on the supposition that space and time have a beginning and the other based on the notion that time and space continue and the bang is merely a transitional stage from one cycle to the next. Conceptually, the two models are poles apart. Observationally, both match all current observations in exquisite detail.

To decide between the two models requires advances in both theory and experiment. Theory, particularly string theory, can shed light on the nature of the singularity. As a candidate for a quantum theory of gravity, addressing the singularity is its *raison d'être*. The fact that the singularity in question is mathematically equivalent to a collision between branes with finite energy density in a non-singular region of 5d space-time strongly suggests to these authors that time does not come to a halt at the crunch. Intuitively it seems that the branes must bounce (or equivalently, pass through one another), re-opening the extra dimension, corresponding to reversal from contraction to expansion. However, establishing this is the critical challenge for string theory and must be shown rigorously. String theory can also inform us whether the brane interaction can be of the requisite form for the model.

The ultimate arbiter will be Nature. Specifically, measurements of the stochastic gravitational background is the decisive way to distinguish the two scenarios. Another generic prediction of the cyclic model regards the ratio of the pressure to the energy density of the dark energy that is causing the current cosmic acceleration. In the cyclic picture, the dark energy is due to the scalar field  $\phi$  which has been fixed during the radiation and matter era, but is beginning

to roll downhill as the Universe becomes dark energy dominated and the expansion begins to accelerate. For a static field, the ratio of pressure to energy density is -1, but this ratio increases as the field begins to roll. Hence, measurements of the ratio today and perhaps its time-variation are further consistency checks of the cyclic picture. In the interim, it appears that we now have two disparate possibilities: a Universe with a definite beginning and a Universe that is made and remade forever.

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