The Endless Universe:
A Brief Introduction to the Cyclic Universe

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Over the last century, cosmologists have converged on a highly successful theory of the evolution of the Universe – the big bang/inflationary picture.[1] According to this picture, space and time sprung into being 15 billion years ago in a 'big bang.' When the Universe emerged, it was filled with particles and radiation of nearly infinite temperature and density. Instants later, the Universe underwent a period of extraordinarily rapid, superluminal expansion ('inflation') which made the Universe homogeneous and flat and which created fluctuations that seeded the formation of galaxies and large-scale structure.

In the last decades, cosmological observations have supported the predictions of the big bang and inflationary theory in exquisite detail.[1,5] They have also provided one major surprise. It appears that, billions of years after the big bang, following the formation of galaxies, the Universe was overtaken by some form of dark energy that is causing the expansion rate to accelerate. Although dark energy was unanticipated and has no particular role in the big bang/inflationary picture, the general view has been that it can simply be added by fiat to the initial make-up of the Universe. There is no compelling reason for a new theoretical approach. Quite the contrary, many cosmologists regard the basic cosmic story as being settled.

In this context, a new paradigm has been recently proposed by Paul Steinhardt (Princeton) and Neil Turok (Cambridge) – the *cyclic universe* – that turns the conventional picture topsy-turvy. (Perhaps the model should be called an old paradigm since it reinvigorates ancient cosmic mythologies and philosophies, albeit using the tools of 21st century physics.) In this picture, space and time exist forever. The big bang is not the beginning of time. Rather, it is a bridge to a pre-existing contracting era. The Universe undergoes an endless sequence of cycles in which it contracts in a big crunch and re-emerges in an expanding big bang, with trillions of years of evolution in between. The temperature and density of the universe do not become infinite at any point in the cycle; indeed, they never exceed a finite bound (about a trillion trillion degrees). No inflation has taken place since the big bang. The current homogeneity and flatness were created by events that occurred before the most recent big bang. The seeds for galaxy formation were created by instabilities arising as the Universe was collapsing towards a big crunch, prior to our big bang.

The prospects for an alternative cosmology that is so different from the well-established convention would seem extremely dim. Yet, the cyclic model recoups *all* of the successful predictions

of the big bang/inflationary theory and has sufficient additional predictive power to address many questions which the big bang/inflationary model does not address at all: What occurred at the initial singularity? What is the ultimate fate of the Universe? What is the role of dark energy and the recently observed cosmic acceleration? Does time, and the arrow of time, exist before the big bang? or after the big crunch?

In the new paradigm, each cycle proceeds through a period of radiation and matter domination consistent with standard cosmology, producing the observed primordial abundance of elements, the cosmic microwave background, the expansion of galaxies, *etc.* For the next trillion years or more, the Universe undergoes a period of slow cosmic acceleration (as detected in recent observations[1]) which ultimately empties the Universe of all of the entropy and black holes produced in the preceding cycle and triggers the events that lead to contraction and a big crunch. Note that dark energy is not simply added on – it plays an essential role. The transition from big crunch to big bang automatically replenishes the Universe by creating new matter and radiation. Gravity and the transition from big crunch to big bang keep the cycles going forever. In fact, as will be discussed, the cyclic behavior is a strong attractor. That is, even if the Universe were disrupted from its periodic behavior, it would rapidly reconverge to the cyclic solution.

The linchpin to the new paradigm is the transition from big crunch to big bang. The transition was thought to be an impossible passage in which the laws of physics blow up. However, recent developments in superstring theory suggest that the cosmic singularity is otherwise, as the two authors have argued in a recent paper with Justin Khoury (Princeton), Burt Ovrut (Penn) and Nathan Seiberg (IAS). Superstring theory relies on the idea that the Universe contains nine or ten spatial dimensions, depending on the formulation, all but three of which are curled up in a compact manifold of microscopic size. In this framework, the big bang and big crunch may be an illusion. Expressed in the usual variables of general relativity, it may appear that our usual space and time are disappearing. However, viewed with the proper variables, our usual space dimensions actually remain infinite and time runs continuously. The transition from big crunch to big bang is due, instead, to the collapse, bounce and re-expansion of one of the extra dimensions. For example, in a variant known as M theory, the Universe consists of two branes (surfaces) bounding an extra dimension, and the singularity corresponds to a collision and bounce of the two branes. The temperature and density of ordinary radiation and matter remain finite at the bounce, and particles move continuously in a natural and intuitive way. By dispelling the myth that the big bang is a beginning of space and time, superstring theory opens up new possibilities for the cosmological history of the Universe. Six months ago, the "ekpyrotic model"[4] was proposed by Khoury, Ovrut, Steinhardt and Turok as one new possibility based on the idea of making a universe from a single collapse of the extra dimension. The cyclic model builds on lessons learned from the ekpyrotic example to produce a picture with remarkable predictive and explanatory power.

References

[1] For a review of the standard big bang/inflationary picture and the state of current observations, see "The Cosmic Triangle: Revealing the State of the Universe," N. Bahcall, J.P. Ostriker, S. Perlmutter and P.J. Steinhardt, *Science* **284**, 1481-1488 (1999).

[2] "A cyclic model of the universe," P.J. Steinhardt and N. Turok, hep-th/0111030 (available at xxx.lanl.gov).

[3] "From Big Crunch to Big Bang," J. Khoury, B. Ovrut, N. Seiberg, P.J. Steinhardt and N. Turok), hep-th/0108187.

[4] "The Ekpyrotic Universe: Colliding Branes and the Origin of Big Bang," J. Khoury, B. Ovrut, P.J. Steinhardt and N. Turok, hep-th/0103239.

[5] See also: feynman.princeton.edu/∼steinh