Leading Scientists Explore the Origin, Mysteries, and Future of the Cosmos

The Universe

EDGE.ORG PRESENTS

Brian Greene, Alan Guth, Andrei Linde, Frank Wilczek, Benoit Mandelbrot, Lisa Randall, *and more*

EDITED BY

John Brockman

EDITOR OF *THIS WILL MAKE YOU SMARTER*

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Dedication

I wish to thank Peter Hubbard of HarperCollins for his encouragement. I am also indebted to my agent, Max Brockman, for his continued support of this project.

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Introduction

In this, the fourth volume of The Best of *Edge* series, following *Mind, Culture*, and *Thinking*, we focu on ideas about the universe. We are pleased to present twenty-one pieces, original works from th online pages of *Edge.org*, which consist of interviews, commissioned essays, and transcribed talk many of them accompanied online with streaming video.

Edge, at its core, consists of the scientists, artists, philosophers, technologists, and entrepreneurs the center of today's intellectual, technological, and scientific landscape. Through its lectures, mast classes, and annual dinners in California, London, Paris, and New York, *Edge* gathers together th "third-culture" scientific intellectuals and technology pioneers exploring the themes of the pos industrial age. These are the people who are rewriting our global culture.

And its website, *Edge.org*, is a conversation. The online *Edge.org* salon is a living document millions of words that charts the conversation over the past eighteen years. It is available, gratis, the general public.

Edge.org was launched in 1996 as the online version of the Reality Club, an informal gathering intellectuals that met from 1981 to 1996 in Chinese restaurants, artists' lofts, the boardrooms Rockefeller University and the New York Academy of Sciences, investment banking firms, ballroom museums, living rooms, and elsewhere. Though the venue is now in cyberspace, the spirit of th Reality Club lives on, in the lively back-and-forth conversations on hot-button ideas driving th discussion today. In the words of novelist Ian McEwan, a sometime contributor, *Edge.org* is "ope minded, free ranging, intellectually playful . . . an unadorned pleasure in curiosity, a collectiv expression of wonder at the living and inanimate world . . . an ongoing and thrilling colloquium."

This is science set out in the largely informal style of a conversation among peers—nontechnica equationless, and colloquial, in the true spirit of the third culture, which I have described as consistin of "those scientists and other thinkers in the empirical world who, through their work and exposito writing, are taking the place of the traditional intellectual in rendering visible the deeper meanings our lives, redefining who and what we are."

For this volume—coming as it does in the wake of the recent stunning discovery of gravitation waves by the BICEP2 radio telescope at the South Pole, an apparent confirmation of the prin cosmological theory of inflation—we've assembled online contributions from some of *Edge's* be minds, most of them pioneering theoretical physicists and cosmologists. They provide a picture cosmology as it has developed over the past three decades—a "golden age," in the words of MIT Alan Guth, one of its leading practitioners.

This Golden Age of Cosmology has reached a high point—not just with the recent revelations the South Pole but with the 2012 discovery, by the Large Hadron Collider at CERN, of the long-soug Higgs boson, whose field is thought to give mass to the elementary particles making up the universe.

We lead off, appropriately enough, with a 2001 talk by Guth, the father of inflationary theor Then, at an *Edge* gathering at Eastover Farm in Connecticut a year later, Guth goes head to head wi Paul Steinhardt, who presents his rival theory of a cyclic universe—a theory that the new data gravitational waves may put paid to. Stay tuned.

Andrei Linde, the father of "eternal chaotic inflation," emphasizes the concepts of the multiver and the anthropic principle that arose from it ("... different exponentially large parts of the univer may ~~be very different from each other, and we live only in those parts where life as we know~~ it possible").

Lisa Randall and Neil Turok elaborate on the theory of branes, two-dimensional structures arisi from string theory—and whose existence is central to the cyclic universe.

Sean Carroll ponders the mystery of "why our observable universe started out in a state of su pristine regularity and order."

Martin Rees, the U.K.'s Astronomer Royal, speculates on whether we are living in a simulatio produced by a superintelligent hypercomputer.

Lee Smolin discusses the nature of time. Then he and Leonard Susskind (string theory's fathe engage in a gentlemanly donnybrook over Smolin's theory of cosmological natural selection and th efficacy of the anthropic principle.

Brian Greene, Paul Steinhardt, and Einstein biographer Walter Isaacson speculate on how Einste might view the theoretical physics of the 21st century, and Steinhardt and Greene come gentlemanly blows over string theory.

In a calmer vein:

Science historian Peter Galison muses on the similarity, and fundamental dissimiliarity, betwee two contemporaries and giants of early 20th-century physics, Einstein and Poincaré; Arizona Sta University cosmologist Lawrence Krauss throws up his hands at the conundrum of dark energy; Car Rovelli (*Professeur de classe exceptionelle, Université de la Méditerranée*) recommends a willingne to return to basics; and Nobelist Frank Wilczek relishes a future devoted to "following up ideas physics that I've had in the past that are reaching fruition."

Berkeley's Raphael Bousso, too, is an optimist. ("I think we're ready for Oprah, almost . . [W]e're going to learn something about the really deep questions, about what the universe is like o the largest scales, how quantum gravity works in cosmology.")

Seth Lloyd, a quantum mechanical engineer, explains how the universe can, in a sense, progra itself; Steven Strogatz sees cosmic implications in the synchronous flashing of crowds of fireflies; a Oxford physicist David Deutsch predicts that his "constructor theory" will eventually "provide a ne mode of description of physical systems and laws of physics. It will also have new laws of its ow which will be deeper than the deepest existing theories such as quantum theory and relativity."

And finally, as a kind of envoi, the late Benoit Mandelbrot, nearing eighty, looks back on a lo career devoted to fractal geometry and newly invigorated: "A recent, important turn in my li occurred when I realized that something I have long been stating in footnotes should be put on t marquee. . . . I'm particularly long-lived and continue to evolve even today. Above a multitude specialized considerations, I see the bulk of my work as having been directed toward a sing overarching goal: to develop a rigorous analysis for roughness. At long last, this theme has give powerful cohesion to my life."

A Golden Age of Cosmology it may be, but you will find plenty of roughness—of doubt a disagreement—here. In spite of its transcendent title, this collection is hardly the last word. In t months (and the years) ahead, as the Large Hadron Collider pours out more data about the microwor and powerful telescopes and satellites continue to confirm—or, who knows, cast fresh doubt on—o leading theories of the macroworld, the arguments will surely continue.

May the conversation flourish!

John Brockman

Editor and Publisher
Edge.org

1 A Golden Age of Cosmology

Alan Guth

Father of the inflationary theory of the Universe and Victor F. Weisskopf Professor of Physics a MIT; inaugural winner, Milner Foundation Fundamental Physics Prize; author, *The Inflationa Universe: The Quest for a New Theory of Cosmic Origins*

It's often said—and I believe this saying was started by the late David Schramm—that today we are a golden age of cosmology. That's really true. Cosmology at this present time is undergoing transition from being a bunch of speculations to being a genuine branch of hard science, whe theories can be developed and tested against precise observations. One of the most interesting areas this is the prediction of the fluctuations, the nonuniformities, in the cosmic background radiation, area I've been heavily involved in. We think of this radiation as being the afterglow of the heat of th Big Bang. One of the remarkable features of the radiation is that it's uniform in all directions, to accuracy of about 1 part in 100,000, after you subtract the term that's related to the motion of th Earth through the background radiation.

I've been heavily involved in a theory called the inflationary universe, which seems to be our be explanation for this uniformity. The uniformity is hard to understand. You might think initially tha maybe the uniformity could be explained by the same principles of physics that cause a hot slice pizza to get cold when you take it out of the oven; things tend to come to a uniform temperature. B once the equations of cosmology were worked out so that one could calculate how fast the univer was expanding at any given time, physicists were able to calculate how much time there was for th uniformity to set in.

They found that in order for the universe to have become uniform fast enough to account for th uniformity we see in the cosmic background radiation, information would have to have bee transferred at approximately a hundred times the speed of light. But according to all our theories physics, nothing can travel faster than light, so there's no way this could have happened. So th classical version of the Big Bang theory had to simply start out by assuming that the universe w homogeneous—completely uniform—from the very beginning.

The inflationary universe theory is an add-on to the standard Big Bang theory, and basically wh it adds on is a description of what drove the universe into expansion in the first place. In the class version of the Big Bang theory, that expansion was put in as part of the initial assumptions, so there no explanation for it whatsoever. The classical Big Bang theory was never really a theory of a bang; was really a theory about the aftermath of a bang. Inflation provides a possible answer to the questio of what made the universe bang, and now it looks like it's almost certainly the right answer.

Inflationary theory takes advantage of results from modern particle physics, which predicts that very high energies there should exist peculiar kinds of substances which actually turn gravity on i head and produce repulsive gravitational forces. The inflationary explanation is the idea that the ear universe contains at least a patch of this peculiar substance. It turns out that all you need is a patch; can actually be more than a billion times smaller than a proton. But once such a patch exists, its ov gravitational repulsion causes it to grow rapidly, becoming large enough to encompass the enti observed universe.

~~The inflationary theory gives a simple explanation for the uniformity of the observed univers~~ because in the inflationary model the universe starts out incredibly tiny. There was plenty of time fo such a tiny region to reach a uniform temperature and uniform density, by the same mechanism through which the air in a room reaches a uniform density throughout the room. And if you isolate room and let it sit long enough, it will reach a uniform temperature as well. For the tiny universe wi which the inflationary model begins, there's enough time in the early history of the universe for thes mechanisms to work, causing the universe to become almost perfectly uniform. Then inflation tak over and magnifies this tiny region to become large enough to encompass the entire univers maintaining this uniformity as the expansion takes place.

For a while, when the theory was first developed, we were worried that we would get too muc uniformity. One of the amazing features of the universe is how uniform it is, but it's still by no mean completely uniform. We have galaxies and stars and clusters and all kinds of complicated structure i the universe that needs to be explained. If the universe started out completely uniform, it would ju remain completely uniform, as there would be nothing to cause matter to collect here or there or an particular place.

I believe Stephen Hawking was the first person to suggest what we now think is the answer to th riddle. He pointed out—although his first calculations were inaccurate—that quantum effects cou come to our rescue. The real world is not described by classical physics, and even though this w very high-brow physics, we were in fact describing things completely classically, with determinist equations. The real world, according to what we understand about physics, is described quantu mechanically, which means, deep down, that everything has to be described in terms of probabilities.

The "classical" world we perceive, in which every object has a definite position and moves in deterministic way, is really just the average of the different possibilities the full quantum theor would predict. If you apply that notion here, it's at least qualitatively clear from the beginning that gets us in the direction we want to go. It means that the uniform density, which our classical equation were predicting, would really be just the average of the quantum mechanical densities, which wou have a range of values that could differ from one place to another. The quantum mechanic uncertainty would make the density of the early universe a little bit higher in some places, and in oth places it would be a little bit lower.

So, at the end of inflation, we expect to have ripples on top of an almost uniform density of matte It's possible to actually calculate these ripples. I should confess that we don't yet know enough abo the particle physics to actually predict the amplitude of these ripples, the intensity of the ripples, b what we can calculate is the way in which the intensity depends on the wavelength of the ripples. Th is, there are ripples of all sizes, and you can measure the intensity of ripples of different sizes. An you can discuss what we call the spectrum—we use that word exactly the way it's used to describ sound waves. When we talk about the spectrum of a sound wave, we're talking about how the intensi varies with the different wavelengths that make up that sound wave. We do exactly the same thing i the early universe, and talk about how the intensity of these ripples in the mass density of the ear universe varied with the wavelengths of the different ripples we're looking at. Today we can see thos ripples in the cosmic background radiation.

The fact that we can see them at all is an absolutely fantastic success of modern technology. Whe we were first making these predictions, back in 1982, at that time astronomers had just barely bee able to see the effect of the Earth's motion through the cosmic background radiation, which is a effect of about one part in a thousand. The ripples I'm talking about are only one part in 100,000—ju

1 percent of the intensity of the most subtle effect it had been possible to observe at the time we we first doing these calculations.

I never believed we would ever actually see these ripples. It just seemed too far-fetched th astronomers would get to be a hundred times better at measuring these things than they were at t time. But to my astonishment and delight, in 1992 these ripples were first detected by a satellite call COBE, the Cosmic Background Explorer, and now we have far better measurements than COB which had an angular resolution of about 7 degrees. This meant that you could see only the longe wavelength ripples. Now we have measurements that go down to a fraction of a degree, and we' getting very precise measurements now of how the intensity varies with wavelength, with marvelo success.

About a year and a half ago, there was a spectacular set of announcements from experiments call BOOMERANG and MAXIMA, both balloon-based experiments, which gave very strong evidence th the universe is geometrically flat, which is just what inflation predicts. By flat I don't mean tw dimensional; I just mean that the three-dimensional space of the universe is not curved, as it cou have been according to general relativity. You can actually see the curvature of space in the way th the pattern of ripples has been affected by the evolution of the universe. A year and a half ag however, there was an important discrepancy that people worried about, and no one was sure how b a deal to make out of it. The spectrum they were measuring was a graph that had, in principle, seve peaks. These peaks had to do with successive oscillations of the density waves in the early unive and a phenomenon called resonance that makes some wavelengths more intense than others. T measurements showed the first peak beautifully, exactly where we expected it to be, with just t shape that was expected. But we couldn't actually see the second peak.

In order to fit the data with the theories, people had to assume there were about ten times as ma protons in the universe as we actually thought, because the extra protons would lead to a friction effe that could make the second peak disappear. Of course, every experiment has some uncertainty—if experiment is performed many times, the results will not be exactly the same each time. So we cou imagine that the second peak was not seen purely because of bad luck. However, the probability th the peak could be so invisible, if the universe contained the density of protons that's indicated b other measurements, was down to about the 1-percent level. So it was a very serious-looki discrepancy between what was observed and what was expected.

All this changed dramatically for the better about three or four months ago, with the next set announcements with more precise measurements. Now the second peak is not only visible but it h exactly the height that was expected, and everything about the data now fits beautifully with t theoretical predictions. Too good, really. I'm sure it will get worse before it continues to get bette given the difficulties in making these kinds of measurements. But we have a beautiful picture no which seems to be confirming the inflationary theory of the early universe.

Our current picture of the universe has a new twist, however, which was discovered two or thre years ago. To make things fit, to match the observations, which are now getting very clear, we have assume that there's a new component of energy in the universe which we didn't know existed befo This new component is usually referred to as dark energy. As the name clearly suggests, we still don know exactly what this new component is. It's a component of energy which in fact is very much li the repulsive gravity matter I talked about earlier—the material that drives the inflation in the ear universe. It appears that, in fact, today the universe is filled with a similar kind of matter. T antigravity effect is much weaker than the effect I was talking about in the early universe, but t universe today appears very definitely to be starting to accelerate again, under the influence of this s called dark energy.

~~Although I’m trying to advertise that we’ve understood a lot, and we have, there are still~~ man uncertainties. In particular, we still don’t know what most of the universe is made out of. There’s th dark energy, which seems to comprise in fact about 60 percent of the total mass/energy of th universe. We don’t know what it is. It could in fact be the energy of the vacuum itself, but we don know that for a fact. In addition, there’s what we call dark matter, which is another 30 percent, o maybe almost 40 percent, of the total matter in the universe. We don’t know what that is, either. Th difference between the two is that the dark energy causes repulsive gravity and is smooth distributed; the dark matter behaves like ordinary matter in terms of its gravitational properties—it attractive and it clusters, but we don’t know what it’s made of. The stuff we do know about—proton neutrons, ordinary atoms and molecules—appear to comprise only about 5 percent of the mass of th universe.

The moral of the story is we have a great deal to learn. At the same time, the theories that we hav developed so far seem to be working almost shockingly well.

2 The Cyclic Universe

Paul Steinhardt

Theoretical physicist; Albert Einstein Professor of Science, Princeton University; coauthor (wit Neil Turok), *Endless Universe: Beyond the Big Bang*

If you were to ask most cosmologists to give a summary of where we stand right now in the field, the would tell you that we live in a very special period in human history where, thanks to a whole host advances in technology, we can suddenly view the very distant and very early universe in ways w haven't been able to do ever before. For example, we can get a snapshot of what the universe looke like in its infancy, when the first atoms were forming. We can get a snapshot of what the univers looked like in its adolescence, when the first stars and galaxies were forming. And we are now gettin a full detail, three-dimensional image of what the local universe looks like today. When you p together this different information, which we're getting for the first time in human history, you obta a very tight series of constraints on any model of cosmic evolution.

If you go back to the different theories of cosmic evolution in the early 1990s, the data we'v gathered in the last decade has eliminated all of them save one, a model that you might think of toda as the consensus model. This model involves a combination of the Big Bang model as developed the 1920s, '30s, and '40s; the inflationary theory, which Alan Guth proposed in the 1980s; and a rece amendment that I will discuss shortly. This consensus theory matches the observations we have of th universe today in exquisite detail. For this reason, many cosmologists conclude that we have final determined the basic cosmic history of the universe.

But I have a rather different point of view, a view that has been stimulated by two events. The fir is the recent amendment to which I referred earlier. I want to argue that the recent amendment is n simply an amendment but a real shock to our whole notion of time and cosmic history. And secondl in the last year I've been involved in the development of an alternative theory that turns the cosm history topsy-turvy: All the events that created the important features of our universe occur in different order, by different physics, at different times, over different time scales. And yet this mod seems capable of reproducing all the successful predictions of the consensus picture with the sam exquisite detail.

The key difference between this picture and the consensus picture comes down to the nature time. The standard model, or consensus model, assumes that time has a beginning that we normal refer to as the Big Bang. According to that model, for reasons we don't quite understand, the univers sprang from nothingness into somethingness, full of matter and energy, and has been expanding an cooling for the past 15 billion years. In the alternative model, the universe is endless. Time is endles in the sense that it goes on forever in the past and forever in the future, and in some sense space endless. Indeed, our three spatial dimensions remain infinite throughout the evolution of the universe

More specifically, this model proposes a universe in which the evolution of the universe is cycli That is to say, the universe goes through periods of evolution from hot to cold, from dense to unde dense, from hot radiation to the structure we see today, and eventually to an empty universe. Then, sequence of events occurs that cause the cycle to begin again. The empty universe is reinjected wi

energy, creating a new period of expansion and cooling. This process repeats periodically foreve
What we're witnessing now is simply the latest cycle.

The notion of a cyclic universe is not new. People have considered this idea as far back as record history. The ancient Hindus, for example, had a very elaborate and detailed cosmology based on cyclic universe. They predicted the duration of each cycle to be 8.64 billion years—a prediction wi three-digit accuracy. This is very impressive, especially since they had no quantum mechanics and n string theory! It disagrees with the number I'm going suggest, which is trillions of years rather tha billions.

The cyclic notion has also been a recurrent theme in Western thought. Edgar Allan Poe an Friedrich Nietzsche, for example, each had cyclic models of the universe, and in the early days relativistic cosmology Albert Einstein, Alexander Friedmann, Georges Lemaître, and Richard Tolma were interested in the cyclic idea. I think it's clear why so many have found the cyclic idea to b appealing: If you have a universe with a beginning, you have the challenge of explaining why it beg and the conditions under which it began. If you have a universe that's cyclic, it's eternal, so you don have to explain the beginning.

During the attempts to try to bring cyclic ideas into modern cosmology, it was discovered in th 1920s and '30s that there are various technical problems. The idea at that time was a cycle in whic our three-dimensional universe goes through periods of expansion beginning from the Big Bang an then reversal to contraction and a Big Crunch. The universe bounces, and expansion begins again. O problem is that every time the universe contracts to a crunch, the density and temperature of th universe rises to an infinite value, and it is not clear if the usual laws of physics can be applied.

Second, every cycle of expansion and contraction creates entropy through natural thermodynam processes, which adds to the entropy from earlier cycles. So at the beginning of a new cycle, there higher entropy density than the cycle before. It turns out that the duration of a cycle is sensitive to th entropy density. If the entropy increases, the duration of the cycle increases as well. So, going forwa in time, each cycle becomes longer than the one before. The problem is that, extrapolating back time, the cycles become shorter until, after a finite time, they shrink to zero duration. The problem avoiding a beginning has not been solved; it has simply been pushed back a finite number of cycles. we're going to reintroduce the idea of a truly cyclic universe, these two problems must be overcom The cyclic model I will describe uses new ideas to do just that.

To appreciate why an alternative model is worth pursuing, it's important to get a more detaile impression of what the consensus picture is like. Certainly some aspects are appealing. But what want to argue is that, overall, the consensus model is not so simple. In particular, recent observatio have forced us to amend the consensus model and make it more complicated. So, let me begin with overview of the consensus model.

The consensus theory begins with the Big Bang: The universe has a beginning. It's a standa assumption that people have made over the last fifty years, but it's not something we can prove present from any fundamental laws of physics. Furthermore, you have to assume that the univer began with an energy density less than the critical value. Otherwise, the universe would sto expanding and recollapse before the next stage of evolution, the inflationary epoch. In addition, reach this inflationary stage, there must be some sort of energy to drive the inflation. Typically this assumed to be due to an inflation field. You have to assume that in those patches of the universe th began at less than the critical density, a significant fraction of the energy is stored in inflation energ so that it can eventually overtake the universe and start the period of accelerated expansion. All these are reasonable assumptions, but assumptions nevertheless. It's important to take into accou these assumptions and ingredients, because they're helpful in comparing the consensus model to th challenger.

Assuming these conditions are met, the inflation energy overtakes the matter and radiation after few instants. The inflationary epoch commences, and the expansion of the universe accelerates at furious pace. The inflation does a number of miraculous things: It makes the universe homogeneous, makes the universe flat, and it leaves behind certain inhomogeneities, which are supposed to be th seeds for the formation of galaxies. Now the universe is prepared to enter the next stage of evolutio with the right conditions. According to the inflationary model, the inflation energy decays into a h gas of matter and radiation. After a second or so, there form the first light nuclei. After a few tens o thousands of years, the slowly moving matter dominates the universe. It's during these stages that th first atoms form, the universe becomes transparent, and the structure in the universe begins to form- the first stars and galaxies. Up to this point, the story is relatively simple.

But there is the recent discovery that we've entered a new stage in the evolution of the univers After the stars and galaxies have formed, something strange has happened to cause the expansion the universe to speed up again. During the 15 billion years when matter and radiation dominated th universe and structure was forming, the expansion of the universe was slowing down, because th matter and radiation within it is gravitationally self-attractive and resists the expansion of th universe. Until very recently, it had been presumed that matter would continue to be the domina form of energy in the universe and this deceleration would continue forever.

But we've discovered instead, due to recent observations, that the expansion of the universe speeding up. This means that most of the energy of the universe is neither matter nor radiatio Rather, another form of energy has overtaken the matter and radiation. For lack of a better term, th new energy form is called dark energy. Dark energy, unlike the matter and radiation we're famili with, is gravitationally self-repulsive. That's why it causes the expansion to speed up rather than slo down. In Newton's theory of gravity, all mass is gravitationally attractive, but Einstein's theo allows the possibility of forms of energy that are gravitationally self-repulsive.

I don't think either the physics or cosmology communities, or even the general public, have ful absorbed the full implications of this discovery. This is a revolution in the grand historic sense— the Copernican sense. In fact, if you think about Copernicus—from whom we derive the wo "revolution"—his importance was that he changed our notion of space and of our position in th universe. By showing that the Earth revolves around the sun, he triggered a chain of ideas that led to the notion that we live in no particular place in the universe; there's nothing special about where are. Now we've discovered something very strange about the nature of time: that we may live in special place, but we do live at a special time, a time of recent transition from deceleration acceleration; from one in which matter and radiation dominate the universe to one in which they a rapidly becoming insignificant components; from one in which structure is forming in ever larg scales to one in which now, because of this accelerated expansion, structure formation stops. We a in the midst of the transition between these two stages of evolution. And just as Copernicus' propos that the Earth is no longer the center of the universe led to a chain of ideas that changed our who outlook on the structure of the solar system and eventually to the structure of the universe, it shouldn be too surprising that perhaps this new discovery of cosmic acceleration could lead to a whole chan in our view of cosmic history. That's a big part of the motivation for thinking about our alternativ proposal.

With these thoughts about the consensus model in mind, let me turn to the cyclic proposal. Sin it's cyclic, I'm allowed to begin the discussion of the cycle at any point I choose. To make th discussion parallel, I'll begin at a point analogous to the Big Bang; I'll call it the Bang. This is a poi in the cycle where the universe reaches its highest temperature and density. In this scenario, thoug unlike the Big Bang model, the temperature and density don't diverge. There is a maximal, fini temperature. It's a very high temperature, around 10^{20} degrees Kelvin—hot enough to evapora atoms and nuclei into their fundamental constituents—but it's not infinite. In fact, it's well below th so-called Planck energy scale, where quantum gravity effects dominate. The theory begins with a ba and then proceeds directly to a phase dominated by radiation. In this scenario you do not have th inflation one has in the standard scenario. You still have to explain why the universe is flat, you sti have to explain why the universe is homogeneous, and you still have to explain where the fluctuatio came from that led to the formation of galaxies, but that's not going to be explained by an early sta of inflation. It's going to be explained by yet a different stage in the cyclic universe, which I'll get to

In this new model, you go directly to a radiation-dominated universe and form the usual nucle abundances; then go directly to a matter-dominated universe in which the atoms and galaxies a larger-scale structure form; and then proceed to a phase of the universe dominated by dark energy. the standard case, the dark energy comes as a surprise, since it's something you have to add into th theory to make it consistent with what we observe. In the cyclic model, the dark energy moves center stage as the key ingredient that is going to drive the universe, and in fact drives the univers into the cyclic evolution. The first thing the dark energy does when it dominates the universe is wh we observe today: It causes the expansion of the universe to begin to accelerate. Why is th important? Although this acceleration rate is 100 orders of magnitude smaller than the acceleratio that one gets in inflation, if you give the universe enough time it actually accomplishes the same fe that inflation does. Over time, it thins out the distribution of matter and radiation in the univers making the universe more and more homogeneous and isotropic—in fact, making it perfectly so- driving it into what is essentially a vacuum state.

Seth Lloyd said there were 10^{80} or 10^{90} bits inside the horizon, but if you were to look around th universe in a trillion years, you would find on average no bits inside your horizon, or less than one b inside your horizon. In fact, when you count these bits, it's important to realize that now that th universe is accelerating, our computer is actually losing bits from inside our horizon. This something that we observe.

At the same time that the universe is made homogeneous and isotropic, it is also being made fla If the universe had any warp or curvature to it, or if you think about the universe stretching over th long period of time, although it's a slow process it makes the space extremely flat. If it continu forever, of course, that would be the end of the story. But in this scenario, just like inflation, the da energy survives only for a finite period and triggers a series of events that eventually lead to transformation of energy from gravity into new energy and radiation that will then start a new peri of expansion of the universe. From a local observer's point of view, it looks like the universe go through exact cycles; that is to say, it looks like the universe empties out each round and a new matt and radiation is created, leading to a new period of expansion. In this sense it's a cyclic universe. you were a global observer and could see the entire universe, you'd discover that our three dimensio are forever infinite in this story. What's happened is that at each stage when we create matter a radiation, it gets thinned out. It's out there somewhere, but it's getting thinned out. Locally, it loo like the universe is cyclic, but globally the universe has a steady evolution, a well-defined era which, over time and throughout our three dimensions, entropy increases from cycle to cycle.

Exactly how this works in detail can be described in various ways. I will choose to present a ve nice geometrical picture that's motivated by superstring theory. We use only a few basic elemen from superstring theory, so you don't really have to know anything about superstring theory t ~~understand what I'm going to talk about, except to understand that some of the strange things~~ I' going to introduce I am not introducing for the first time. They're already sitting there in superstrin theory waiting to be put to good purpose.

One of the ideas in superstring theory is that there are extra dimensions; it's an essential eleme to that theory, which is necessary to make it mathematically consistent. In one particular formulatio of that theory, the universe has a total of eleven dimensions. Six of them are curled up into a little ba so tiny that, for my purposes, I'm just going to pretend they're not there. However, there are thre spatial dimensions, one time dimension, and one additional dimension that I do want to consider. I this picture, our three dimensions with which we're familiar and through which we move lie along hypersurface, or membrane. This membrane is a boundary of the extra dimension. There is anoth boundary, or membrane, on the other side. In between, there's an extra dimension that, if you lik only exists over a certain interval. It's like we are one end of a sandwich, in between which there is so-called bulk volume of space. These surfaces are referred to as orbifolds or branes—the latt referring to the word "membrane." The branes have physical properties. They have energy an momentum, and when you excite them you can produce things like quarks and electrons. We ar composed of the quarks and electrons on one of these branes. And, since quarks and leptons can onl move along branes, we are restricted to moving along and seeing only the three dimensions of o brane. We cannot see directly the bulk or any matter on the other brane.

In the cyclic universe, at regular intervals of trillions of years, these two branes smash togethe This creates all kinds of excitations—particles and radiation. The collision thereby heats up th branes, and then they bounce apart again. The branes are attracted to each other through a force th acts just like a spring, causing the branes to come together at regular intervals. To describe it mo completely, what's happening is that the universe goes through two kinds of stages of motion. Whe the universe has matter and radiation in it, or when the branes are far enough apart, the main motion the branes stretching, or, equivalently, our three dimensions expanding. During this period, the brane more or less remain a fixed distance apart. That's what's been happening, for example, in the last 1 billion years. During these stages, our three dimensions are stretching just as they normally would. A a microscopic distance away, there is another brane sitting and expanding, but since we can't touc feel, or see across the bulk, we can't sense it directly. If there is a clump of matter over there, we ca feel the gravitational effect, but we can't see any light or anything else it emits, because anything emits is going to move along that brane. We only see things that move along our own brane.

Next, the energy associated with the force between these branes takes over the universe. From o vantage point on one of the branes, this acts just like the dark energy we observe today. It causes th branes to accelerate in their stretching, to the point where all the matter and radiation produced sin the last collision is spread out and the branes become essentially smooth, flat, empty surfaces. If yo like, you can think of them as being wrinkled and full of matter up to this point, and then stretching b a fantastic amount over the next trillion years. The stretching causes the mass and energy on the bran to thin out and the wrinkles to be smoothed out. After trillions of years, the branes are, for all inten and purposes, smooth, flat, parallel, and empty.

Then the force between these two branes slowly brings the branes together. As it brings them together, the force grows stronger and the branes speed toward one another. When they collide, there a walloping impact—enough to create a high density of matter and radiation with a very high, albe finite, temperature. The two branes go flying apart, more or less back to where they are, and then th new matter and radiation, through the action of gravity, causes the branes to begin a new period o stretching.

~~In this picture, it's clear that the universe is going through periods of expansion and a funny~~ kin of contraction. Where the two branes come together, it's not a contraction of our dimensions but contraction of the extra dimension. Before the contraction, all matter and radiation has been sprea out, but, unlike the old cyclic models of the 1920s and '30s, it doesn't come back together aga during the contraction, because our three dimensions—that is, the branes—remain stretched out. On the extra dimension contracts. This process repeats itself cycle after cycle.

If you compare the cyclic model to the consensus picture, two of the functions of inflation- namely, flattening and homogenizing the universe—are accomplished by the period of accelerate expansion that we've now just begun. Of course, I really mean the analogous expansion that occurre one cycle ago, before the most recent Bang. The third function of inflation—producing fluctuations the density—occurs as these two branes come together. As they approach, quantum fluctuations caus the branes to begin to wrinkle. And because they're wrinkled, they don't collide everywhere at th same time. Rather, some regions collide a bit earlier than others. This means that some regions rehe to a finite temperature and begin to cool a little bit before other regions. When the branes come apa again, the temperature of the universe is not perfectly homogeneous but has spatial variations left ov from the quantum wrinkles.

Remarkably, although the physical processes are completely different and the time scale completely different—this is taking billions of years, instead of 10^{-30} seconds—it turns out that th spectrum of fluctuations you get in the distribution of energy and temperature is essentially the san as what you get in inflation. Hence, the cyclic model is also in exquisite agreement with all of th measurements of the temperature and mass distribution of the universe that we have today.

Because the physics in these two models is quite different, there is an important distinction what we would observe if one or the other were actually true—although this effect has not bee detected yet. In inflation when you create fluctuations, you don't just create fluctuations in energy an temperature but you also create fluctuations in spacetime itself, so-called gravitational waves. That a feature we hope to look for in experiments in the coming decades as a verification of the consensu model. In our model, you don't get those gravitational waves. The essential difference is th inflationary fluctuations are created in a hyperrapid, violent process that is strong enough to crea gravitational waves, whereas cyclic fluctuations are created in an ultraslow, gentle process that is to weak to produce gravitational waves. That's an example where the two models give an observation prediction that is dramatically different. It's just difficult to observe at the present time.

What's fascinating at the moment is that we have two paradigms now available to us. On the o hand, they are poles apart in terms of what they tell us about the nature of time, about our cosm history, about the order in which events occur, and about the time scale on which they occur. On th other hand, they are remarkably similar in terms of what they predict about the universe toda Ultimately what will decide between the two is a combination of observations—for example, th search for cosmic gravitational waves—and theory, because a key aspect to this scenario entai assumptions about what happens at the collision between branes that might be checked or refuted superstring theory. In the meantime, for the next few years, we can all have great fun speculatin about the implications of each of these ideas and how we can best distinguish between them.

3

The Inflationary Universe

Alan Guth

Paul Steinhardt did a very good job of presenting the case for the cyclic universe. I’m going describe the conventional consensus model upon which he was trying to say that the cyclic model is a improvement. I agree with what Paul said at the end of his talk about comparing these two models; it yet to be seen which one works. But there are two grounds for comparing them. One is that in bo cases the theory needs to be better developed. This is more true for the cyclic model, where one h the issue of what happens when branes collide. The cyclic theory could die when that problem final gets solved definitively. Secondly, there is, of course, the observational comparison of th gravitational-wave predictions of the two models.

A brane is short for “membrane,” a term that comes out of string theories. String theories bega purely as theories of strings, but when people began to study their dynamics more carefully, the discovered that for consistency it was not possible to have a theory which discussed only string Whereas a string is a one-dimensional object, the theory also had to include the possibility membranes of various dimensions to make it consistent, which led to the notion of branes in genera The theory that Paul described in particular involves a four-dimensional space plus one tim dimension, which he called the bulk. That four-dimensional space was sandwiched between tw branes.

That’s not what I’m going to talk about. I want to talk about the conventional inflationary pictur and in particular the great boost that this picture has attained over the past few years by the somewh shocking revelation of a new form of energy that exists in the universe. This energy, for lack of better name, is typically called dark energy.

But let me start the story further back. Inflationary theory itself is a twist on the conventional B Bang theory. The shortcoming that inflation is intended to overcome is the basic fact that although th Big Bang theory is called the Big Bang, it is in fact not really a theory of a bang at all; it never wa The conventional Big Bang theory, without inflation, was really only a theory of the aftermath of th Bang. It started with all of the matter in the universe already in place, already undergoing rap expansion, already incredibly hot. There was no explanation of how it got that way. Inflation is a attempt to answer that question, to say what “banged,” and what drove the universe into this period enormous expansion. Inflation does that very wonderfully. It explains not only what caused th universe to expand but also the origin of essentially all the matter in the universe at the same time. qualify that with the word “essentially” because, in a typical version of the theory, inflation need about a gram’s worth of matter to start. So inflation is not quite a theory of the ultimate beginning, b it is a theory of evolution that explains essentially everything we see around us, starting from almo nothing.

The basic idea behind inflation is that a repulsive form of gravity caused the universe to expan General relativity, from its inception, predicted the possibility of repulsive gravity; in the context general relativity, you basically need a material with a negative pressure to create repulsive gravit According to general relativity, it’s not just matter densities or energy densities that crea gravitational fields, it’s also pressures. A positive pressure creates a normal attractive gravitationa field, of the kind we're accustomed to, but a negative pressure would create a repulsive kind gravity. ~~It also turns out that according to modern particle theories, materials with a negative pressu~~ are easy to construct out of fields that exist according to these theories. By putting together these tw ideas—the fact that particle physics gives us states with negative pressures, and that general relativi tells us that those states cause a gravitational repulsion—we reach the origin of the inflationa theory.

By answering the question of what drove the universe into expansion, the inflationary theory ca also answer some questions about that expansion that would otherwise be mysterious. There are tw very important properties of our observed universe that were never really explained by the Big Ba theory; they were just part of one's assumptions about the initial conditions. One of them is th uniformity of the universe—the fact that it looks the same everywhere, no matter which way you loo as long as you average over large enough volumes. It's both isotropic, meaning the same in a directions, and homogeneous, meaning the same in all places. The conventional Big Bang theory nev really had an explanation for that; it just had to be assumed from the start. The problem is th although we know that any set of objects will approach a uniform temperature if they're allowed to s for a long time, the early universe evolved so quickly that there wasn't enough time for this to happe To explain, for example, how the universe could have smoothed itself out to achieve the uniformity temperature we observe today in the cosmic background radiation, one finds that in the context of th standard Big Bang theory it would be necessary for energy and information to be transmitted acro the universe at about a hundred times the speed of light.

In the inflationary theory, this problem goes away completely, because, in contrast to th conventional theory, it postulates a period of accelerated expansion while this repulsive gravity taking place. That means that if we follow our universe backward in time toward the beginning usi inflationary theory, we see that it started from something much smaller than you ever could hav imagined in the context of conventional cosmology without inflation. While the region that wou evolve to become our universe was incredibly small, there was plenty of time for it to reach a unifor temperature, just like a cup of coffee sitting on the table cools down to room temperature. Once th uniformity is established on this tiny scale by normal thermal-equilibrium processes—and I'm talki now about something that's about a billion times smaller than the size of a single proton—inflatio can take over and cause this tiny region to expand rapidly and become large enough to encompass th entire visible universe. The inflationary theory not only allows the possibility for the universe to b uniform but also tells us why it's uniform: It's uniform because it came from something that had tim to become uniform and was then stretched by the process of inflation.

The second peculiar feature of our universe that inflation does a wonderful job of explaining, a for which there never was a prior explanation, is the flatness of the universe—the fact that th geometry of the universe is so close to Euclidean. In the context of relativity, Euclidean geometry not the norm, it's an oddity. With general relativity, curved space is the generic case. In the case of th universe as a whole, once we assume that the universe is homogeneous and isotropic, then this issue flatness becomes directly related to the relationship between the mass density and the expansion ra of the universe. A large mass density would cause space to curve into a closed universe in the shape a ball; if the mass density dominated, the universe would be a closed space with a finite volume a no edge. If a spaceship traveled in what it thought was a straight line for a long enough distance, would end up back where it started from. In the alternative case, if the expansion dominated, th universe would be geometrically open. Geometrically open spaces have the opposite geometr properties from closed spaces. They're infinite. In a closed space, two lines which are parallel w start to converge; in an open space, two lines which are parallel will start to diverge. In either cas ~~what you see is very different from Euclidean geometry. However, if the mass density is right~~ at th borderline of these two cases, then the geometry is Euclidean, just like we all learned about in hig school.

In terms of the evolution of the universe, the fact that the universe is at least approximately fl today requires that the early universe was extraordinarily flat. The universe tends to evolve away fro flatness, so even given what we knew ten or twenty years ago—we know much better, now, that th universe is extraordinarily close to flat—we could have extrapolated backward and discovered tha for example, at one second after the Big Bang the mass density of the universe must have been equa to an accuracy of fifteen decimal places, to the critical density where it counterbalanced the expansio rate to produce a flat universe. The conventional Big Bang theory gave us no reason to believe th there was any mechanism to require that, but it has to have been that way, to explain why the univers looks the way it does today. The conventional Big Bang theory without inflation really only worked you fed into it initial conditions which were highly finely tuned to make it just right to produce universe like the one we see. Inflationary theory gets around this flatness problem, because inflatio changes the way the geometry of the universe evolves with time. Even though the universe alway evolves away from flatness at all other periods in the history of the universe, during the inflationa period the universe is actually driven towards flatness incredibly quickly. If you had approximatel 10^{-34} seconds or so of inflation at the beginning of the universe, that's all you need. Inflation woul then have driven the universe to be flat closely enough to explain what we see today.

There are two primary predictions that come out of inflationary models, which appear to b testable today. They have to do (1) with the mass density of the universe, and (2) with the properti of the density nonuniformities. I'd like to say a few words about each of them, one at a time. Let m begin with the question of flatness.

The mechanism that inflation provides that drives the universe toward flatness will in almost a cases overshoot, not giving us a universe that is just nearly flat today but a universe that's almo *exactly* flat today. This can be avoided, and people have at times tried to design versions of inflatio that avoided it, but those versions of inflation never looked very plausible. You have to arrange fo inflation to end at just the right point, where it's almost made the universe flat but not quite. requires a lot of delicate fine-tuning, but in the days when it looked like the universe was open, som people tried to design such models. But they always looked contrived and never really caught on.

The generic inflationary model drives the universe to be completely flat, which means that one the predictions is that today the mass density of the universe should be at the critical value that mak the universe geometrically flat. Until three or four years ago, no astronomers believed that. They to us that if you looked at just the visible matter, you would see only about 1 percent of what you neede to make the universe flat. But they also said they could offer more than that: There's also dark matte Dark matter is matter that's inferred to exist because of the gravitational effect it has on visib matter. It's seen, for example, in the rotation curves of galaxies. When astronomers first measure how fast galaxies rotate, they found they were spinning so fast that if the only matter present was wh you saw, galaxies would just fly apart.

To understand the stability of galaxies, it was necessary to assume that there was a large amount dark matter in the galaxy—about five or ten times the amount of visible matter—which was neede just to hold the galaxy together. This problem repeats itself when one talks about the motion galaxies within clusters of galaxies. The motion of galaxies in clusters is much more random an chaotic than the spiral galaxy, but the same issues arise. You can ask how much mass is needed t hold those clusters of galaxies together, and the answer is that you still need significantly more matt than what you assumed was in the galaxies. Adding all of that together, astronomers came up onl with about a third of the critical density. They were pretty well able to guarantee that there wasn't an more than that out there; that was all they could detect. That was bad for the inflationary model, b many of us still had faith that inflation had to be right and that sooner or later the astronomers wou come up with something.

And they did, although what they came up with was something very different from the kind matter we were talking about previously. Starting in 1998, astronomers have been gathering evidenc for the remarkable fact that the universe today appears to be accelerating, not slowing down. As I sa at the beginning of this talk, the theory of general relativity allows for that. What's needed is material with a negative pressure. We are now therefore convinced that our universe must b permeated with a material with negative pressure which is causing the acceleration we're now seein We don't know what this material is, but we're referring to it as dark energy. Even without knowin what it is, general relativity by itself allows us to calculate how much mass has to be out there cause the observed acceleration, and it turns out to be almost exactly equal to two-thirds of the critic density. This is exactly what was missing from the previous calculations! So, if we assume that th dark energy is real, we now have complete agreement between what the astronomers are telling about the mass density of the universe and what inflation predicts.

The other important prediction that comes out of inflation is becoming even more persuasive tha the issue of flatness: namely, the issue of density perturbations. Inflation has what in some ways is wonderful characteristic: that by stretching everything out—and Paul's model takes advantage of th same effect—you can smooth out any nonuniformities that were present prior to this expansio Inflation does not depend sensitively on what you assume existed before inflation; everything the just gets washed away by the enormous expansion. For a while, in the early days of developing th inflationary model, we were all very worried that this would lead to a universe that would b absolutely, completely smooth.

After a while, several physicists began to explore the idea that quantum fluctuations could save u The universe is fundamentally a quantum mechanical system, so perhaps quantum theory w necessary not just to understand atoms but also to understand galaxies. It's a rather remarkable ide that an aspect of fundamental physics like quantum theory could have such a broad sweep. The poi is that a classical version of inflationary theory would predict a completely uniform density of matt at the end of inflation. According to quantum mechanics, however, everything is probabilistic. Ther are quantum fluctuations everywhere, which means that in some places the mass density would b slightly higher than average and in other places it would be slightly lower than average. That's exact the sort of thing you want, to explain the structure of the universe. You can even go ahead an calculate the spectrum of these nonuniformities, which is something that Paul and I both worked on the early days and had great fun with. The answer that we both came up with was that, in fac quantum mechanics produces just the right spectrum of nonuniformities.

We really can't predict the overall amplitude—that is, the intensity—of these ripples unless w know more about the fundamental theory. At the present time, we have to take the overall factor th multiplies the predicted intensity of these ripples from observation. But we can predict the spectru —that is, the complicated pattern of ripples can be viewed as ripples of many different wavelength lying on top of each other, and we can calculate how the intensity of the ripples varies with the wavelengths. We knew how to do this back in 1982, but recently it has actually become possible fo astronomers to see these nonuniformities imprinted on the cosmic background radiation. These we first observed back in 1992 by the COBE satellite, but back then they could only see very broa features, since the angular resolution of the satellite was only about 7 degrees. Now they've gotte down to angular resolutions of about 1/10 of a degree. These observations of the cosmic backgrour radiation can be used to produce plots of the spectrum of nonuniformities, which are becoming mo and more detailed.

The most recent data set was made by an experiment called the Cosmic Background Imager, whic released a new set of data in May that is rather spectacular. This graph of the spectrum is rath complicated, because these fluctuations are produced during the inflationary era but then oscillate the early universe evolves. Thus, what you see is a picture that includes the original spectrum plus a of the oscillations that depend on various properties of the universe. A remarkable thing is that thes curves now show five separate peaks, and all five of the peaks show good agreement between theo and observation. You can see that the peaks are in about the right place and have about the rigl heights, without any ambiguity, and the leading peak is rather well-mapped-out. It's a rathe remarkable fit between actual measurements made by astronomers and a theory based on wild ide about quantum fluctuations at 10^{-35} seconds. The data are so far in beautiful agreement with th theory.

At the present time, this inflationary theory, which a few years ago was in significant conflict wi observation, now works perfectly with our measurements of the mass density and the fluctuations. Th evidence for a theory that's either the one I'm talking about or something very close to it is very, ver strong.

I'd just like to close by saying that although I've been using "theory" in the singular to talk abo inflation, I shouldn't, really. It's important to remember that inflation is really a class of theories. inflation is right, it's by no means the end of our study of the origin of the universe, but still it's reall closer to the beginning. There are many different versions of inflation, and in fact the cyclic mod that Paul described could be considered one version. It's a rather novel version, since it puts th inflation at a completely different era of the history of the universe, but inflation is still doing many the same things. There are many versions of inflation that are much closer to the kinds of theories v were developing in the '80s and '90s, so saying that inflation is right is by no means the end of th story. There's still a lot of flexibility here, and a lot to be learned. And what needs to be learned wi involve both the study of cosmology and the study of the underlying particle physics, which essential to these models.

4

A Balloon Producing Balloons Producing Balloons

Andrei Linde

Theoretical physicist, Stanford University; father of eternal chaotic inflation; inaugural winne Milner Foundation Fundamental Physics Prize

I should probably start by explaining what happened during the last thirty years in cosmology. Th story will begin with old news: the creation of inflationary theory. Then we will talk about t relatively recent developments, when inflation became a part of the theory of an inflationa multiverse and the string theory landscape. Then—what we expect in the future.

Let me start by saying that many, many years ago—and I mean like almost a century ago- Einstein came up with something called the cosmological principle, which says that our universe mu be homogeneous and uniform. And for many years people used this principle. In fact, it wa formulated even much earlier, by Newton. The universe is still represented this way in current boo on astrophysics, where you can find different versions of the cosmological principle.

For a while, this was the only way of answering the question of why the universe is everywhere t same—in fact, why it is the universe. So we did not think about the multiverse, we just wanted explain why the world is so homogeneous around us, why it is so big, why parallel lines do n intersect. Which is, in fact, part of the same question: If the universe was tiny, like a small globe, a you drew parallel lines perpendicular to the equator of the globe, they would intersect at the south a the north poles. Why has nobody ever seen parallel lines intersecting?

These kinds of questions, for many years, could seem a bit silly. For example, one may wond what happened before the universe even emerged. The textbook of general relativity that we used Russia said that it was meaningless to ask this question, because the solutions of the Einste equations cannot be continued through the singularity, so why bother? And yet people bothered. The are still trying to answer these kinds of questions. But for many people such questions look metaphysical, not to be taken seriously.

When inflationary theory was invented, people started taking these questions seriously. Alan Gu asked these questions and proposed the theory of cosmic inflation, a framework in which a consiste answer to these questions could be found. The problem was, as Guth immediately recognized, that h own answer to these questions was incomplete. And then, after more than a year of work, I proposed new version of inflationary theory, which helped to find a way to answer many of these questions. first it sounded like science fiction, but once we found possible answers to the questions whi previously were considered metaphysical, we couldn't just forget about it. This was the first reason f us to believe the idea of cosmic inflation. So let me explain this idea.

Standard Big Bang theory says that everything begins with a big bang, a huge explosion. Terroris started the universe. But when you calculate how much high-tech explosives these guys would have have at their disposal to start the universe formation, they would need 10^{80} tons of high-te explosives, compressed to a ball smaller than 1 centimeter, and ignite all of its parts exactly at t same time with a precision better than 1 in 10,000.

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