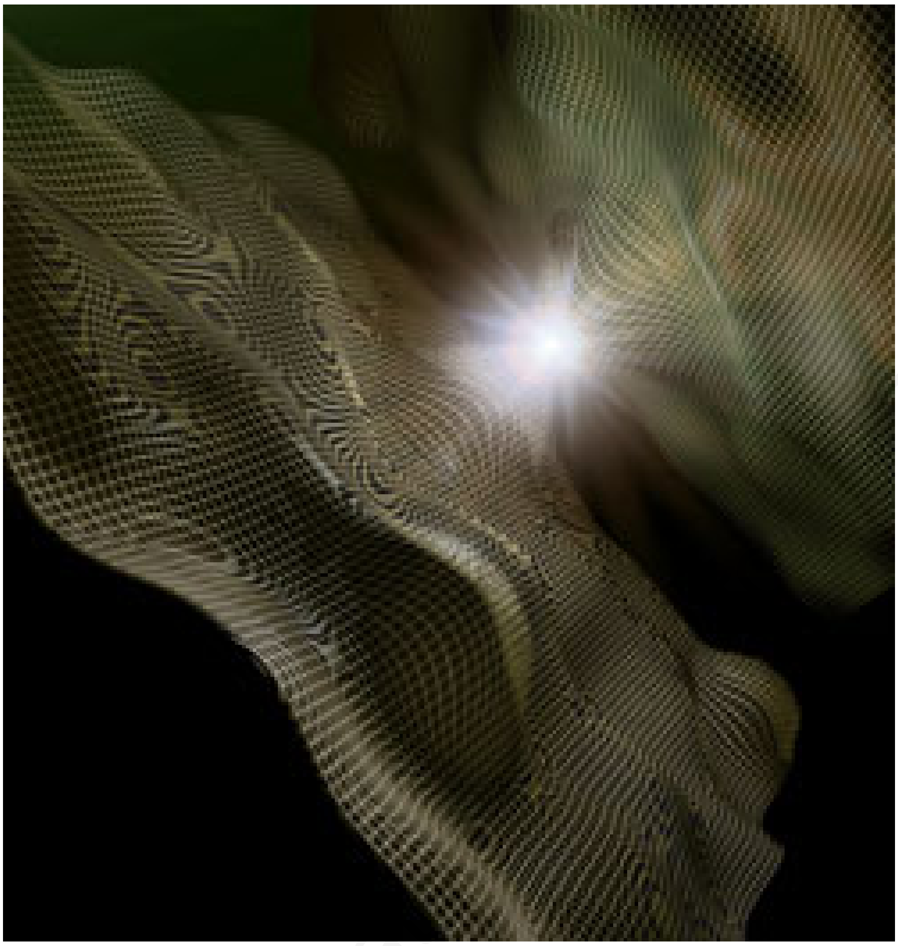

A Dissertation on Modern Physics

"The Ekpyrotic Universe"

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Introduction to Physics II (PY 1101)

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Index

Ekpyrosis *noun*:

1. A large and destructive fire; a general burning.
2. Something like a conflagration; cataclysmic fire; conflict; war.

Introduction

From ancient times, Man has searched answers for his roots. Questions like where do we come from, how did life come to exist, what was before life. His search has taken him from the physical to the metaphysical world. And if, by time, we have come to a point to answer convincingly a lot of them, we still haven't agreed or know how the cosmos or the universe began. Certain questions arise on this matter. Is the universe infinite or finite? Is it eternal or will there be an end of time? Did it arise from something else, or did it simply pop out of nothingness? Cosmologists have tried over the years to give the truth.

The Universe, The "Big Bang" and Cosmic Inflation

The Universe is everything that exists: the entirety of space and time, all forms of matter, energy and momentum, and the physical laws and physical constants that govern them. In a well-defined, mathematical sense, the universe can even be said to contain that which does not exist; according to the path-integral formulation of quantum mechanics, even unrealized possibilities contribute to the probability amplitudes of events in the universe. The universe is sometimes denoted as the *cosmos* or *Nature*, as in "cosmology" or "natural philosophy".

Scientific experiments have yielded several general facts about the observable universe. The age of the universe is estimated to be 13.7±0.2 billion years. The universe is very large, possibly infinite, being at least 93 billion light years across, and consisting mainly of matter, rather than antimatter. The luminous matter within it is sparse and consists principally of galaxies, which are distributed uniformly when averaged over length-scales longer than 300 million light years. On smaller length scales, however, the galaxies tend to clump together into clusters, superclusters and even larger structures. The light arriving from distant galaxies is detectably redshifted, with the redshift increasing with the galaxy's distance from Earth. The universe is bathed in a microwave radiation that is highly isotropic (uniform across different directions), and corresponds to a blackbody spectrum of roughly 2.7 Kelvin. The relative percentages of the lighter chemical elements — especially hydrogen, deuterium and helium — is apparently the same throughout the universe. However, only 4% of the matter and energy in the universe is luminous, that is, directly observable from its emitted electromagnetic radiation; the remainder consists of dark energy (73%) and dark matter (23%), both of which are mysterious. The universe is believed to be expanding, in the sense that space itself is expanding with time; even objects initially at rest to one another will appear to fly apart because new space is being created between them. The universe has three spatial dimensions and one temporal (time) dimension, although extremely small additional dimensions cannot be ruled out experimentally; spacetime appears to be smoothly and simply connected, with very small curvature, so that Euclidean geometry is generally accurate throughout the universe. The universe appears to be governed by the same physical laws and constants throughout its extent and history.

Throughout their recorded history, humans have proposed several cosmologies and cosmogonies to account for their observations of the universe. The earliest quantitative models were developed by the ancient Greeks, who proposed that the universe possessed infinite space and had existed eternally, but contained a single set of concentric spheres of finite size (corresponding to the fixed stars, the Sun and various planets) rotating about a spherical but unmoving Earth. Over the centuries, more careful astronomical observations and improved theories of gravity led to the present theory of the Big Bang and, more specifically, the Lambda-CDM model, which accounts for the available data. According to such theories, everything in the universe — all forms of matter and energy, and even spacetime itself — came into being at a single event, a gravitational singularity; as space expanded with time, the matter and energy cooled sufficiently to allow the stable condensation of elementary particles into the primordial nuclei and atoms. Once atoms formed, matter became mostly transparent to electromagnetic radiation; the ambient microwave radiation observed today is the residual radiation that then decoupled from the matter.

However there is a classic conundrum of the big bang cosmology: why does the universe appear flat, homogeneous and isotropic in accordance with the cosmological principle when one would expect, on the basis of the physics of the big bang, a highly curved, inhomogeneous universe? Cosmic inflation seems to answers this riddle. It is the idea that the nascent universe passed through a phase of exponential expansion that was driven by a negative-pressure vacuum energy density. As a direct consequence of this expansion, all of the observable universe originated in a small causally-connected region. Inflation also explains the origin of the large-scale structure of the cosmos. Quantum fluctuations in the microscopic inflationary region, magnified to cosmic size, become the seeds for the growth of structure in the universe. Inflation was proposed by American physicist and cosmologist Alan Guth in 1981 and was given its modern form independently by Andrei Linde, and by Andreas Albrecht and Paul Steinhardt.

This theory leaves many unknowns hanging. It does not explain why the Big Bang happened and what, if anything, existed before. It also does not explain the nature of the unidentified energy field that is causing our universe to accelerate.

The Cyclic Model and Brane Cosmology

In the 1930s, theoretical physicists, most notably Einstein, considered the possibility of a cyclic model for the universe as an alternative to the Big Bang. However, work by Richard C. Tolman showed that these early attempts failed because of the entropy problem that, in statistical mechanics, entropy only increases because of the Second law of thermodynamics. This implies that successive cycles grow longer and larger. Extrapolating back in time, cycles before the present one become shorter and smaller culminating again in a Big Bang and thus not replacing it.

In 2001, one new cyclic model came to help explain the creation of the universe and shed some light in the questions created by the Big Bang Theory. The theory describes a universe exploding into existence not just once, but repeatedly over time. The theory could potentially explain why a mysterious repulsive form of energy known as the "cosmological constant", and which is accelerating the expansion of the universe, is several orders of magnitude smaller than predicted by the standard Big Bang model. It was developed by Neil Turok of Cambridge University, Burt Ovrut of the University of Pennsylvania, and Paul Steinhardt and Justin Khoury of Princeton University, and was based in brane cosmology. The central idea is that the visible, four-dimensional universe is restricted to a brane inside a higher-dimensional space, called the "bulk". The additional dimensions may be taken to be compact, in which case the observed universe contains the extra dimensions, and then no reference to the bulk is appropriate in this context. In the bulk model, other branes may be moving through this bulk. Interactions with the bulk, and possibly with other branes, can influence our brane and thus introduce effects not seen in more standard cosmological models. It was a 67 page long cosmological scenario called “The Ekpyrotic Universe: Colliding Branes and the Origin of the Hot Big Bang”.

The Ekpyrotic Scenario

Astronomical evidence clearly indicates that the observable universe has been expanding for the past 13.7 billion years. In the inflationary Big Bang model, the universe was hot and dense at the outset, and then immediately went through a period of hyperexpansion. Steinhardt and his colleagues considered a very different possibility: What if the universe actually started out cool and vacuous?

If that were the case, the idea of branes colliding in a hidden dimension might provide a simpler explanation for the ongoing expansion. To find out whether the idea made sense, the pair took on the daunting task of mastering the equations of superstring theory and applying them to their theory. For simplicity, the researchers assumed that the branes were flat and parallel to each other. They also assumed that the branes contained no matter. That didn't mean the branes were voids: Quantum theory asserts that even the total vacuum of empty space is seething with "virtual" subatomic particles that constantly wink in and out of existence. In aggregate, these virtual particles add up to a huge amount of latent energy—which, according to Einstein's theory of special relativity, is equivalent to an astounding amount of mass. So a crash between two empty branes would still be a collision of gigantic proportions.

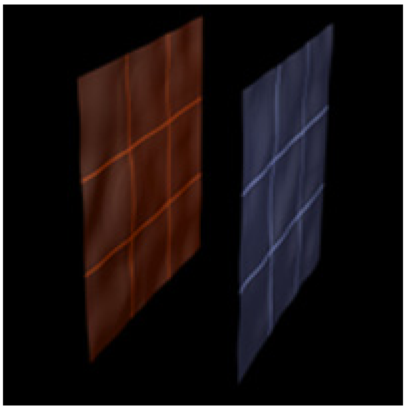
The research team subsequently turned its attention to what would happen in the branes after a collision. Calculations suggested that the crash would generate a universe-wide fireball of pure energy within each brane. That blast would drive the two branes apart again. Then, as the fireball suffusing our brane began to cool, its underlying energy would undergo a phase transition, like water freezing into ice. This transition would unleash a force that would make the universe start to expand. The hot spots of the fireball would congeal into clumps of matter that would eventually become clusters of galaxies. The cold spots would become the empty voids that lie between the clusters.

This theorizing agrees with what we can see in our universe now. The ekpyrotic model leads to a scenario a lot like the fireball of the Big Bang, but there is no episode of inflation. From the outset, the cosmos experienced just one force that accelerated the expansion. That force is still at work today, which means that instead of coasting to a stop, the universe is expanding faster today than it was a billion years ago and will be expanding faster a billion years from now. In short, that one force would also explain the enigmatic force that astronomers have recently named dark energy. Further calculations by Steinhardt and Turok suggest we're at the beginning of a very long process that will eventually result in what appears to be an empty universe. Trillions of years from now, matter will be so widely spread out that its average density will be much less than a single electron per quadrillion cubic light-years of space. That's so close to zero density that there's no meaningful difference.

In the far future, another three-dimensional world still lurks nearby, similarly emptied out after its encounter with ours, invisible and imperceptible to us. Although they bounced apart after the collision, the two branes will exert a force on each other that's analogous to gravity, and they will ultimately meet in another crash, triggering another Big Bang. The cycle of such collisions would be eternal.

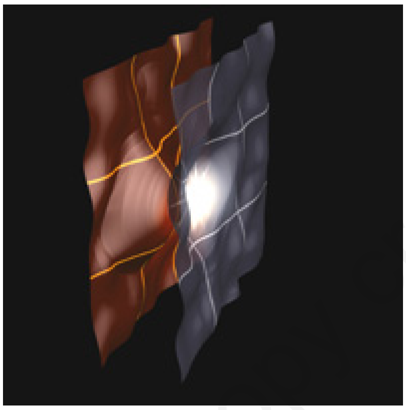
In this new cyclic model, the universe starts essentially empty each time. That means virtually no matter gets recycled. So entropy doesn't increase, and there is no beginning or end to time.

Step One: EMPTY UNIVERSE



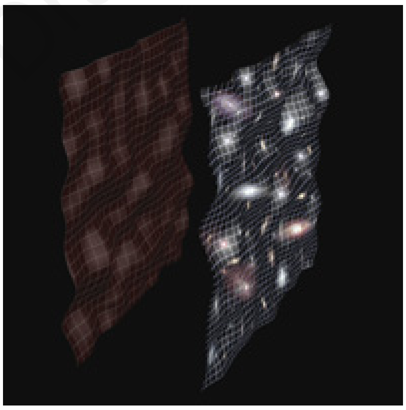
Each panel represents a three-dimensional membrane. The observable universe exists within the panel on the right; the other membrane is invisible to us. At the end of one cosmic cycle—after about a trillion years of accelerating expansion—matter is so spread out that space is essentially empty. This stage corresponds to the distant future of our universe. All is not static, however: The membranes still contain energy, and a force of attraction gradually draws them together again.

Step Two: FIERY COLLISION



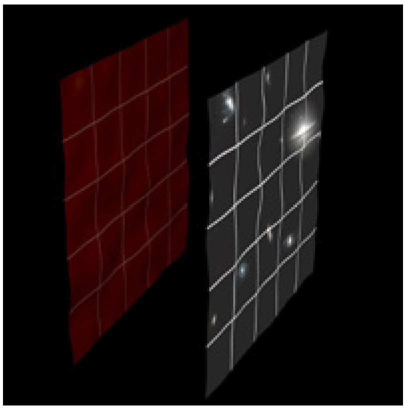
As the two membranes draw nearer to each other, they ripple and distort so that the surfaces come together in different places and at different times. As the membrane surfaces crash into each other, vast amounts of energy are released (white zone). Called ekpyrosis—the Greek word for conflagration—the colossal collision gives birth to a baby universe in our membrane (right). The force of the impact causes space to expand rapidly and also pushes the two membranes apart.

Step Three: GALAXY FILLED UNIVERSE



After the two membranes collide, they move apart. The initial fireball expands and cools, with the ripples of the membrane leading to the small temperature fluctuations in microwave background radiation observed in our universe. The subsequent sequence of events echoes the Big Bang model: Lumps of gas give rise to galaxies and other cosmic structures, and space continues to expand. This roughly corresponds to the current state of our universe.

Step Four: OLD UNIVERSE



Toward the end of one cosmic era, space has expanded to such an extent that galaxies have drifted very far apart. After about a trillion years, most of the stars have burned out, and our universe is nearly empty. But this is not the end of the story. The continued attraction between the neighboring membranes draws them together again, setting the stage for another colossal collision and an ekpyrotic rebirth of our universe. The cycle of collisions between membranes continues into eternity.

Epilogue

Others have embraced this theory and others are still skeptic. One reason is that at the moment of collision, the extra dimension separating the two branes goes from vanishingly small to literally zero. That creates what physicists call a singularity, a point at which the laws of physics break down. Although superstring theory might help explain what happens in a singularity, it hasn't done so yet. Steinhardt and Turok respond that their theory could gain credence from LISA, a proposed space probe that would look for gravity waves from the early universe. Gravity waves are ripples in the fabric of space-time that were predicted by Albert Einstein. So far, they are theoretical. But by 2020, the LISA experiment—pairs of free-flying satellites that would move apart and together with each passing wave—could either find confirming evidence of inflation or find nothing and thus tip the scales toward ekpyrosis. Regardless of whether it is a correct model of the origin of the universe, it is an excellent indication of the new possibilities opened up by the development of brane cosmology.

When Ptolemaic theorists discovered that the planets did not appear to be moving in a simple pattern around Earth, they added epicycles—tiny circular movements on top of the grand orbital circles. Closer examination showed that this didn't quite explain observations either, so the theorists added epicycles on top of epicycles until the model did work. The final result was also very complex. Then Copernicus came along with the idea of a sun-centered cosmology, and Johannes Kepler realized that planets actually move in ellipses. Suddenly, planetary motions made sense without the complexity of epicycles, and the old theory was dropped. Maybe we are on the verge of an equal magnitude "revelation". And all will suddenly become clear.

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