

From the Big Bang to the Multiverse: Translations in Space and Time

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An End to Modernity

The Big Bang is an extraordinarily difficult subject for visual representation. When Josiah McElheny and I met for the first time, in September 2004, we began by examining his sketch for the piece that would become, over the following year, *An End to Modernity*. In this sketch, inspired by the spectacular Lobmeyr chandeliers that hang in the Metropolitan Opera House, a central sphere supports a starburst of metal rods, which in turn support clusters of glass pieces and lamps. This seemed a perfect depiction of the popular conception of the Big Bang, a tremendous explosion that flings fragments of matter in all directions from a central point. But the Big Bang is *not* an explosion of material into space; it is the origin of space and time itself, initiating an expansion that occurs everywhere and has no center. How could any static sculpture, no matter how intricate, depict *that*?

During the ensuing three-hour conversation, the solution emerged: retain the basic structure of the sketch, but change the *interpretation* of that structure by using a spatial dimension to represent time. The center of the sculpture would then become the primordial cosmos and the outer edge the present day, and the passage from one to the other would trace the 14 billion year history of the expanding universe. With this space-to-time translation, *An End to Modernity* could incorporate many of the key features of cosmic evolution that have been revealed by astronomical observations over the last four decades, following prescriptions that Josiah and I worked out over many months of meetings, emails, and phone calls. In the finished work, each of the 230 radiating rods emerges in a random direction with a randomly selected length and terminates in a cluster of hand-formed glass disks and blown-glass globes, representing a cluster of galaxies, or else in a single lamp, representing a quasar. The rules that govern the form, size, and contents of the cluster, or the brightness of the lamp, depend on the length of the rod, and thus on the cosmic epoch that corresponds to its termination point. The clusters are surrounded, we must imagine, by clouds of invisible “dark matter,” subatomic particles whose identity remains unknown but whose existence is inferred from their observed gravitational effects on the rotations and motions of galaxies.

The central aluminum sphere that supports the cluster and lamp rods also represents one of the crucial concepts of modern cosmology: the Last Scattering Surface. The early universe was so hot that hydrogen atoms were broken apart into their constituent protons and electrons. The free electrons scattered light much like the water molecules of a dense fog, making the universe opaque. When the expanding cosmos cooled to a temperature of 3000°C some 500,000 years after the Big Bang, all free electrons disappeared into atoms, and the universe became transparent. The most distant source of “light” that we can see is the opaque “surface” nearly 14 billion light years away. The 1965 discovery of the cosmic microwave background, the faded glow of this surface now cooled to a mere three degrees above absolute zero, provided the key piece of evidence for the hot early universe postulated by the Big Bang theory.

In *An End to Modernity*, the Big Bang itself is a conceptual point at the center of the sculpture, time zero, hidden by the aluminum sphere just as the electron fog of the last scattering surface shields the earliest epochs of the cosmos from our direct view. From the central sphere outwards, the sculpture incorporates a logarithmic mapping between distance from the center and the size of the universe. Every 7.2” of distance corresponds to a factor of two in cosmic expansion, and the 6-foot span from the central sphere to the outer edge of the sculpture represents a 1000-fold growth in each spatial dimension.

At the epoch of last scattering, the universe was filled with smoothly distributed hot gas, with no galaxies or stars or living creatures to admire them. Over time, gravity amplified small fluctuations created in the first trillionth of a second of cosmic history into the galaxies and larger structures that we observe today. In *An End to Modernity*, the first galaxies appear three feet out from the central sphere, 100 million years after the Big Bang. Like our own Milky Way, these early galaxies have the disk-like shapes that are the generic final state of a cooling, rotating cloud of gas. Moving outward towards the present, three things change. First, the galaxies get bigger, as they attract gas from their surroundings and process it into stars. Second, gravity pulls the galaxies themselves into ever larger structures, galaxy clusters and superclusters. Finally, a new type of galaxy begins to appear, rounded elliptical systems formed by chaotic collisions of the rotationally ordered disks. Elliptical galaxies, depicted by glass spheres, reside mainly in the dense clumps where collisions are most common, while the extended, filamentary superclusters are populated mainly by disks.

The lamps that illuminate *An End to Modernity* represent quasars, the brightest objects in the universe. Quasars are powered by supermassive black holes, up to ten billion times the mass of the Sun, which reside at the centers of galaxies. As gas falls into these black holes, it collides with itself at speeds close to the speed of light, heats up, and emits light, X-rays, and other forms of radiation. When a supermassive black hole is actively devouring gas, it can outshine the combined starlight of its host galaxy by a factor of 1000. The first quasars are faint because there has not been time to build the most massive black holes. The height of the quasar era is the period 2-4 billion years after the Big Bang. At later times, the population slowly fades because the galactic disturbances that feed gas to the black holes become less common, so that most galaxies harbor only a dark remnant of their former glory. In *An End to Modernity*, this history is encoded by the changing frequency and brightness of the quasar lamps.

Because light travels at a finite speed, astronomical telescopes function as time machines: when we observe distant objects, we see them not as they are today but as they were when they emitted their light. This fortunate feature of physics allows us to build an empirical picture of the history of the universe from observations at the present day. *An End to Modernity* represents the principal elements of this picture — the Last Scattering Surface, the growth, transformation, and clustering of galaxies, and the rise and fall of the quasar population — in idealized but qualitatively accurate form. From our earthbound vantage point, the history of the universe is traced through a series of concentric shells, with the earliest epochs seen at the greatest distances. *An End to Modernity* inverts this perspective, and it invites us to view the history of the cosmos as though we stand outside of it. However, if current astronomical inferences are correct, the universe will expand forever, at an ever accelerating rate, driven outwards by the repulsive gravitational effect of “dark energy” that fills otherwise empty space. Thus, wherever we stand to regard *An End to Modernity*, we are implicitly enveloped by the future.

The Last Scattering Surface

An End to Modernity depicts, in idealized form, the entire history of the cosmos. *The Last Scattering Surface* zeroes in on two special moments of that history: the present day, and the epoch of recombination, when the formation of hydrogen atoms lifted the free electron fog that had prevailed for the preceding half million years. With the space-to-time translation that underlies both *An End to Modernity* and *The Last Scattering Surface*, the epoch of recombination is represented by the central aluminum sphere, the opaque barrier that conceals the early universe within. But the real last scattering surface is not merely a screen; it glows with the heat of the primordial cosmic fireball. At the recombination temperature of 3000° C, this glow would have a dull orange color. The subsequent expansion of the universe has stretched the primordial light to millimeter

wavelengths, where it is no longer visible to our eyes but can be measured by microwave radio telescopes. For more than 25 years after its initial discovery, steadily improving observations showed that the cosmic microwave background is almost perfectly uniform across the sky. This uniformity tells us that the early universe was full of smoothly distributed hot gas, with no galaxies, stars, or planets, or living beings to admire them.

In 1992, the *Cosmic Background Explorer (COBE)* satellite made the first detection of intensity variations on the last scattering surface, finding minute temperature differences of one thousandth of one percent from one point on the sky to another. These temperature differences are the imprint of tiny variations in the underlying density of matter. Over the last 14 billion years, gravity has pulled matter into the denser regions, a snowballing process that amplified the tiny seeds present at recombination into the large scale cosmic structure that we observe today. The intensities of the lamps that illuminate *The Last Scattering Surface* are chosen based on the *COBE* image of the microwave sky — there is a one-to-one mapping between the locations of the lamps and points on the true celestial sphere. The clusters of glass pieces at the outer edge represent present-day clusters of spiral and elliptical galaxies, just as they do in *An End to Modernity*.

The structure observed in the cosmic microwave background is “scale-invariant”: if we blur the *COBE* map, smoothing over its small scale roughness, then the level of intensity variation barely decreases. This scale-invariance carries through to *The Last Scattering Surface*: if a lamp’s neighbors are bright, then it is more likely than average to be bright as well. We see variations from one lamp to the next, but also patches that are coherently bright or dim, and even, as we walk around the perimeter, whole octants of the sphere that are “hot” or “cold.” The scale-invariance of primordial fluctuations, processed subsequently by the gravity of radiation and matter, is the reason that galaxies do not pepper the universe randomly but are instead drawn into an intricate filamentary web.

A perfectly smooth universe could remain perfectly smooth, and perfectly boring, forever. *The Last Scattering Surface* depicts the subtle imperfections of the primeval cosmic glow, and the rich, beautiful structures that emerged from them.

The End of the Dark Ages

After the expanding cosmos cooled to 1000° C, the background radiation stretched to infrared wavelengths, and the universe was devoid of visible light. Where the initial concentration of atoms and dark matter was unusually high, gravity pulled matter together into dense, slowly spinning clumps. Some 5-10 million years after the Big Bang, the cores of the densest contracting gas clouds heated to the temperature needed for nuclear fusion to begin, and the first stars in the universe were born.

The End of the Dark Ages zeroes in on the first one billion years of cosmic history, when the diffuse glow of the Big Bang faded and the first stars, galaxies, and quasars filled the universe with discrete sources of visible light. In structural terms, it is like the inner regions of *An End to Modernity*, expanded in scale and detail to allow closer inspection. All of its galaxies are small, since they have not yet had time to grow to larger size. Nearly all of them have the disk-like form expected from the collapse of spinning gas clouds, since they have not had time to fragment completely into stars and merge with each other to create disordered elliptical systems. Lamps mark the first quasars, massive black holes that glow as they swallow gas from their galactic hosts. These early quasars outshine the surrounding galaxies, but they are not as massive or as bright as the super-luminous systems that will succeed them two billion years later. The first galaxies and quasars are clustered on large scales because they form at rare locations, the high mountain peaks

of the primordial matter distribution that are most susceptible to early collapse. However, gravity has not yet arrayed the galaxies into filamentary superstructures.

Astronomers define the end of the cosmic “dark ages” as the time when ultraviolet radiation from hot stars and accreting black holes penetrated into the depths of intergalactic space, breaking the hydrogen atoms that resided there back into protons and electrons. This “epoch of reionization” — the inverse of the recombination that formed the last scattering surface — appears to have occurred 400–800 million years after the Big Bang. However, even the deepest images from *Hubble Space Telescope* and the largest ground-based telescopes reach only to the end of the reionization epoch. The structure of *The End of the Dark Ages* is therefore based mainly on theoretical modeling, computer calculations that draw on what we know about atoms, dark matter, and ripples in the cosmic microwave background to predict how the first stars and galaxies formed. *Hubble’s* successor, the *James Webb Space Telescope*, is designed to penetrate further in space and deeper in time, to open the dark ages to direct observation.

At the end of the dark ages, the universe was simpler than the one we inhabit today, the smooth skin of its youth only lightly wrinkled by gravity. But for the first time in cosmic history, an alien being on a young world could have looked up and seen a night sky much like our own, sparkling with stars, and with galaxies beyond.

Island Universe

Space is big. This claim may seem intuitively obvious, but it can be made precise: the observable universe contains roughly 10^{78} atoms and 10^{87} cosmic microwave photons, numbers that are straightforward to calculate but impossible to envision. Despite the richness of structure traced by galaxies and clusters of galaxies, on large scales the universe is remarkably uniform. We see the same kinds of structures whatever direction we look in, and the cosmic microwave background itself is smooth to one part in 100,000.

In the big bang cosmology of the 1960s and 1970s, the size and smoothness of the observable universe were accepted as initial conditions — just the way it is. In 1980, Alan Guth proposed the theory of cosmic inflation, which *explains* this size and smoothness as a consequence of exponential expansion during the first billionth of a billionth of a trillionth of a second of cosmic history. This ultra-fast, accelerating expansion ironed out any wrinkles present in the pre-inflationary universe. At the end of the inflation, the universe heated to high temperature and thereafter followed the track of the standard hot big bang theory. Quantum noise — the inevitable consequence of the famous Heisenberg Uncertainty Principle — was stretched from subatomic distances to macroscopic scales during inflation, providing the seeds of cosmic structure that would grow to fruition billions of years later.

Guth’s proposal was quickly adapted and refined by other physicists including Andreas Albrecht, Richard Gott, Stephen Hawking, Andrei Linde, Alexei Starobinsky, and Paul Steinhardt. The most exotic of these refinements is the “eternal inflation” scenario proposed by Linde in 1982, according to which our entire observable universe is but one of many (perhaps infinitely many) “bubbles” in an inflationary sea, whose continuing exponential expansion pulls bubbles away from each other so rapidly that they have no chance to collide. What appears to us as the “big bang” origin of the cosmos is really just the moment when our bubble separated out from the inflationary background, heated up, and switched to decelerating expansion.

The theory of inflation has been highly successful, providing an explanation for the size and smoothness of the universe and accurate quantitative predictions for the wide variety of structures that it contains. The “multiverse” implied by Linde’s eternal inflation model is far more speculative, and the existence of many disconnected cosmic bubbles may not be testable even in principle. The

multiverse scenario becomes still more exotic when one allows the possibility that each bubble has distinct physical properties, because of different durations of inflation, different amounts of dark matter and dark energy, perhaps even different fundamental laws governing atoms and elementary particles, or different numbers of spatial dimensions.

It is this big, multi-faceted cosmos that *Island Universe* depicts. Each of the five sculptures represents its own bubble universe, with the same conceptual structure and visual language as *An End to Modernity*: an opaque last scattering surface, quasar lamps, galactic clusters composed of glass disks and spheres, and time increasing from the center to the outside. We should imagine that each of these bubbles will continue to expand and grow new structures at its future edge, but that the room in which we view them is filled with energy whose repulsive gravity accelerates the bubbles away from each other, so that their expanding surfaces can never meet. The lowest of the spheres began growing earliest and has reached the largest size, while the uppermost sculpture is small because it has had the least time to grow.

The history and form of structure in each island universe is distinct, corresponding to varying levels of quantum noise at the end of inflation or to varying amounts of gravitationally attractive dark matter and gravitationally repulsive dark energy. After two days of discussions at the Institute for Advanced Study, in fall 2006, Josiah and I had covered a wall's worth of blackboards with sketches and notes about the five cosmic bubbles we had chosen to represent. We gave each universe a working title, and these initial names, despite imperfections, have stuck throughout the project. The central sculpture, "Heliocentric," follows the same rules as *An End to Modernity*, adjusted for its slightly smaller size. This sphere represents our own cosmic island, and the Milky Way could be any one of the glass disks at its surface. Or perhaps it is another bubble universe, much like our own but unimaginably distant, and forever beyond our reach.

In "Small Scale Violence," the largest and lowest sphere, inflation has produced intense ripples on small scales, seeds that grow quickly to produce the first galaxies soon after the epoch of last scattering. These galaxies are strongly clustered, and frequent gravitational collisions of disks lead to a large population of elliptical galaxies. Compared to "Heliocentric," "Small Scale Violence" has a high proportion of short rods that contain these early forming galaxies, and, uniquely among the five *Island Universe* sculptures, it contains more spheres than disks. Violent mergers also feed the rapid and sustained growth of supermassive black holes. This universe is bright with quasars, represented by a large number of high-intensity lamps. From its inner epochs to its outer edge, "Small Scale Violence" is rich with large scale structure, containing the most complex and populous clusters of *Island Universe*.

In "Frozen Structure," a high proportion of dark energy truncates the growth and clustering of galaxies soon after it has begun. The first galaxies again form soon after recombination, clusters of small disks on short rods. Once dark energy starts to drive accelerated cosmic expansion, the gravitational attraction of dark matter cannot pull fresh material into the galaxies or pull the galaxies together into larger structures. "Frozen Structure" does contain a handful of long rods, but the galaxies and clusters that they hold are like those of the shorter, earlier rods. With few disordering collisions, this universe is dominated by disk galaxies. After a brief quasar era, its undernourished black holes fade away, and only the inner zones of "Frozen Structure" have illuminating lamps. In a universe dominated by dark energy, galaxies speed away from each other to evolve in quiet isolation.

As viewed from Earth, the stars of our own Galactic disk form a diffuse band of light, like a trail of milk spilled across the sky. Only when large telescopes allowed us to map the distribution of distant galaxies did we learn that our cosmos becomes uniform on large scales. In "Directional Structure," the fourth island, an incomplete end to inflation has left the universe anisotropic on the largest scales, and rods emerge only along a tilted equatorial belt. Galaxies and quasars form

only within this thick, disk-shaped zone, and even this is unbalanced, with the largest clusters all on one side. As astronomers in this universe trained their telescopes beyond the nearby stars, they would find that distant galaxies were themselves arrayed in a cosmic scale Milky Way, and that peering perpendicular to this “Super-Galaxy” would reveal only formless darkness.

“Late Emergence,” the highest and smallest sculpture, has the lowest amplitude of inflationary ripples at recombination — a last scattering surface that is ten times smoother even than our own. This universe has a prolonged dark age, billions of years with no stars or galaxies to illuminate it, so even the shortest of its rods extend nearly to the “present day.” The spherical arrangement of these rods reflects the large scale uniformity of this cosmos. Eventually, gravity can grow structure even from small seeds, and this universe may have a rich future ahead. At the moment captured by *Island Universe*, it is bursting into bloom for the first time.

In 1905, Albert Einstein made the startling discovery that time is relative, its flow depending on the state of motion of the timekeeper. In a homogeneous universe, there is a natural choice of timekeepers, those “go-with-the-flow” observers (like ourselves) who follow the cosmic expansion and see an isotropic cosmos. We can therefore speak unambiguously about the passage of time and the history of structure within any one cosmic bubble. In eternal inflation, however, the universe becomes radically inhomogeneous on scales far beyond our cosmic horizon, and there is no one privileged set of observers to run the clocks. In *Island Universe*, therefore, there is no clear way to reconcile the time of an individual bubble, which increases radially outward from its center, with the time of another bubble, or with the “global” time that increases from the floor to the ceiling. As we walk among the islands, wandering superluminally through an inflationary sea whose smooth expanse and bubbling froth must extend far beyond the gallery walls, we assume vantage points that can exist only in the abstract realms of science, mathematics, and art.