Cosmology Today

David N. Spergel

Abstract: We seem to live in a simple but strange universe. Our basic cosmological model fits a host of astronomical observations with only five basic parameters: the age of the universe, the density of atoms, the density of matter, the initial "lumpiness" of the universe, and a parameter that describes whether this lumpiness is more pronounced on smaller physical scales. Our observations of the cosmic microwave background fluctuations determine these parameters with uncertainties of only 1 to 2 percent. The same model also provides an excellent fit to the large-scale clustering of galaxies and gas, the properties of galaxy clusters, observations of gravitational lensing, and supernova-based measurements of the Hubble relation. This model implies that we live in a strange universe: atoms make up only 4 percent of the visible universe, dark matter makes up 24 percent, and dark energy – energy associated with empty space – makes up 72 percent.

Cosmology is a historical science. Because light travels at a finite speed, when we look out in space, we look back in time. We see the sun as it was eight minutes ago, and we see nearby stars as they were five, ten, or a hundred years ago. It takes light approximately 2.5 million years to travel from the Andromeda galaxy to our eyes, so when we stare at our nearest major neighbor with a telescope, we observe Andromeda as it was back before the dawn of man. The farther out we look, the farther back we look in time. When the Hubble Space Telescope observes a distant galaxy, it sees the galaxy as it was perhaps 12 billion years ago. Our observations of the cosmic microwave background involve the oldest light, photons that formed only one year after the Big Bang and last interacted with atoms just four hundred thousand years after the Big Bang. This light travels for 13.7 billion years before reaching us, and it brings us our universe's baby picture.

Our basic model of cosmology rests on Einstein's nearly century-old theory of general relativity. As my late academic great grandfather Johnny Wheeler used to teach, "General Relativity consists of two simple ideas: matter tells space how to curve and space tells matter how to move." On the scale of our

DAVID N. SPERGEL, a Fellow of the American Academy since 2012, is the Charles A. Young Professor of Astronomy on the Class of 1897 Foundation and Professor of Astrophysical Sciences at Princeton University. He is a theoretical astrophysicist with interests ranging from the search for planets around nearby stars to the shape of the universe.

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solar system, the mass of the sun curves space around it, and our Earth moves on a nearly circular orbit in this curved space. On the cosmological scales, the distribution of matter is nearly uniform. General relativity implies that a nearly uniform universe must be either expanding or contracting. Since Edwin Hubble's observations in the 1920s, we have known that our universe is expanding.

As the universe expands, the distance between galaxies grows. Today, it takes light roughly fifty million years to travel to the Virgo cluster. Eight billion years ago, the distance between objects was a factor of two smaller, so light would have taken only twenty-five million years to travel from our galaxy to the Virgo cluster. As we go farther back in time, objects get closer and closer together. Thus, the early universe was much denser than today's universe.

This expansion of the universe not only increases the distance between galaxies, but also stretches light. Light emitted from a distant galaxy is "redshifted." If a galaxy eight billion years ago emits blue light, the radiation's wavelength is stretched as it travels toward us, and we observe the light as red. Because astronomers can easily measure the wavelength of light detected from a distant galaxy, we can determine its redshift and then use general relativity (and our cosmological model) to relate the redshift of a galaxy to its age. Today, our universe is 13.8 billion years old. When we observe a galaxy at redshift 1, the wavelength of the light has been stretched by a factor of two due to the expansion of the universe. It took light 8 billion years to travel from the galaxy to us, so we observe this distant galaxy as it was 5.7 billion years after the Big Bang. Yellow light emitted by the galaxy at redshift 1 at a wavelength of 550 nanometers will appear to us in the infrared at 1100 nanometers. The most distant known galaxy is at redshift 10. When optical light left this infant galaxy 13.3 billion years ago, it was only 500 million years after the Big Bang. Today, we see this light as infrared radiation and use our observations to study the properties of early galaxy formation.

General relativity relates the expansion rate of the universe to the density and geometry of the universe. If the energy in expansion exceeds the self-gravity of the matter in the universe, then the universe is negatively curved and will expand forever, growing increasingly cold and empty. On the other hand, if the energy in expansion is less than the self-gravity of the universe's matter, the expansion will slow down and reverse, and the universe will collapse in a future big crunch. As Robert Frost prophesized, the universe will end in either fire or ice.

Until recently, cosmologists thought that the expansion rate of the universe would slowly decelerate. The expansion rate of the universe is proportional to the square root of the density of the universe. Since the density of matter decreases as the universe expands, astronomers assumed that the expansion rate of the universe has been slowing with time.

But over the past thirty years, there has been growing evidence that the expansion rate of the universe has been increasing with time.[1] This result has shocked physics: the equivalent of throwing a ball upward and finding that gravity makes it accelerate away from the point of release. If general relativity is correct, this cosmic acceleration implies that most of the energy in the universe is in the form of dark energy: energy associated with empty space. In the late 1990s, measurements of the relationship between the distance and the redshift to supernova – powerful explosions of nearly uniform brightness that can be seen at very large distances – provided the strongest evidence for this strange phenomenon.[2] Soon afterward, measurements of the cosmic microwave background fluctuations confirmed this surprising cosmology.[3]

Dark energy is different from "dark matter." Ever since Fritz Zwicky's work in the 1930s, astronomers have suspected that stars are not the dominant form of matter in galaxies. By the 1970s, astronomers had assembled several independent lines of argument all implying that dark matter was neither gas nor stars. Dark matter appears to be some new type of particle that has not yet been found in our particle accelerators. Dark energy is even stranger: it does not cluster in galaxies, nor does it seem to respond to any of the natural forces. Dark energy affects the universe only through changing its expansion rate.

The cosmic microwave background radiation is the oldest light in the universe, the leftover heat from the Big Bang. This radiation fills all space and was once the dominant form of energy in the universe. The expansion of the universe cools the cosmic background radiation. Today, the temperature of the radiation is 2.73 degrees K. When the distance between galaxies was half its present value, the temperature of the cosmic background radiation was twice its present value. When the distance between galaxies was a tenth its present value, the temperature of the cosmic background radiation was ten times its present value.

As we go farther back in time and closer to the moment of the start of the Big Bang expansion, the universe is ever hotter. One second after the Big Bang, the temperature of the universe was 10 billion degrees C, and the universe was a nearly uniform sea of electrons, protons, neutrons, dark matter, and radiation. At that time, most of the energy density in the universe was in the form of radiation. Three minutes after the Big Bang, the temperature of the universe was about 500 million degrees C. During this period in the universe's evolution, most of the deuterium and helium in the universe was synthesized from neutrons and protons. Our measurements of the abundance of these two cosmic fossils are a direct determination of the density of the atoms at this early epoch.

During the first three hundred thousand years of cosmic history, almost all of the atoms in the universe were ionized into a plasma of electrons, protons, and helium ions. The cosmic background photons were frequently colliding with the electrons in this primordial plasma, so both atomic matter and photons were coupled together in a single fluid. As the universe cooled, the protons and helium ions were able to combine with electrons and form neutral hydrogen and helium atoms. By four hundred thousand years after the Big Bang, most of the electrons had combined with ions, and the universe was mostly neutral. Since the cosmic background photons do not interact with these neutral gases, they were able to propagate freely. The photons that we observe when we look at the cosmic background radiation last interacted with atoms at this very early time. Thus, when we observe the background radiation, we are directly measuring physical conditions at this early moment in the history of the universe.

In 1964, astronomers Arno Penzias and Robert Wilson detected the cosmic background radiation with their horn antenna at Bell Laboratories. Twenty-five years later, the COBE satellite found that this nearly uniform microwave radiation had exactly the spectral properties predicted by the hot Big Bang model. This measurement of the cosmic background is one of the foundational observations for the hot Big Bang model.

While the cosmic microwave background radiation is nearly uniform, there are tiny variations in the temperature of the radiation. These variations are primarily due to the fluctuations in the density and temperature of the universe four hundred thousand years after the Big Bang, the period when the electrons and protons combined to make hydrogen. COBE made the first detection of the micro-Kelvin-level variations in the microwave background temperature.[4] Subsequent observations by ground-based and balloon-based radio antennas mapped this background with ever improving technologies. In 2003, NASA's WMAP released its first detailed all-sky map of the fluctuations.[5] In 2013, ESA's Planck satellite team provided an even more detailed map that traces the same fluctuations.[6] Observations from WMAP, Planck, and ground-based telescopes such as the Atacama Cosmology Telescope in Chile and the South Pole Telescope in Antarctica give a remarkably consistent picture of the physical conditions in the early universe.[7]

The few millionth-of-a-degree temperature variations in the microwave background radiation seen by these experiments trace variations in the density and temperature of the early universe. Because the microwave background photons have been traveling to us with minimal interactions with intervening matter since four hundred thousand years after the Big Bang, these fluctuations reflect physical conditions at these early times.

Four hundred thousand years after the Big Bang, the early universe was a simple place. Electron, protons, and photons were bound together into a warm 3000 K plasma. Tiny variations in the density of the universe generated sound waves in this plasma. The distance that the sound waves could move in four hundred thousand years imparted a characteristic scale on the universe, and the self-gravity of the plasma and the dark matter determined the height of the peaks. Because these variations were small, cosmologists can use linear theory to accurately predict the relationship between the statistical properties of the fluctuations and the conditions in the early universe.

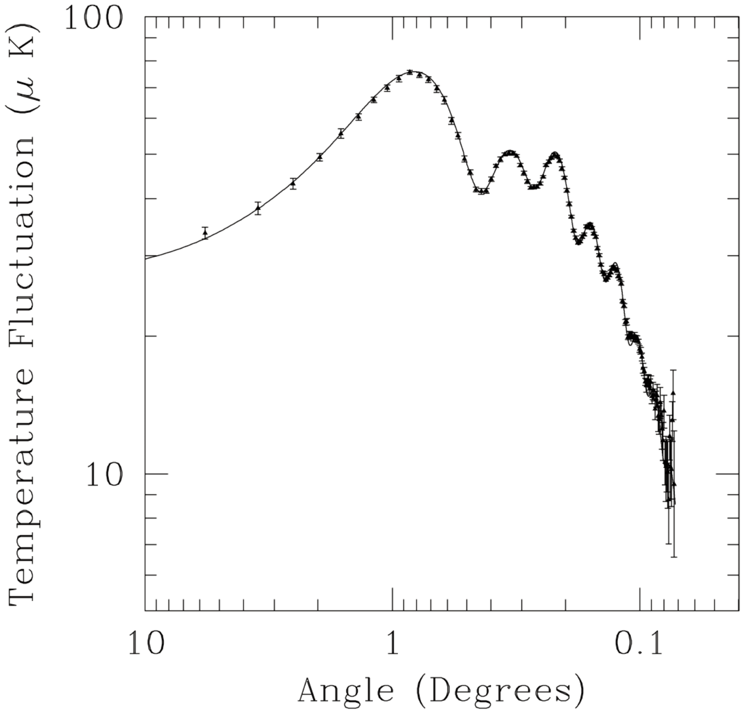
Cosmologists quantify the properties of these fluctuations by measuring their statistical properties. These fluctuations have very simple statistical properties: they are spatially homogenous and can be characterized almost entirely through measurements of the point correlation function of the data or, equivalently, the angular power spectrum. Figure 1 shows the measured angular power spectrum from the Planck satellite. The x-axis on this plot shows the angular size of the fluctuations; the y-axis shows the amplitude of the temperature fluctuations.

We can use the measurements of the amplitude of the peaks in the temperature angular power spectrum to infer the basic parameters of modern cosmology. The ratio of the height of the first peak to the second peak depends on the density of atoms in the early universe. The position of the peaks depends on the geometry of the universe. The height of the third peak is sensitive to the total density of matter. With our current observations of the cosmic microwave background, we can pin down all of the basic parameters to the precision of one part in a hundred.

We can use observations of the nearby universe to infer the same parameters through very different methods:

- Measurements of the abundance of deuterium and helium 4 provide determinations of the density of atoms accurate to 10 percent and consistent with the density inferred from the height of the peaks in the microwave background angular power spectrum.[8]
- Measurements[9] of the distances to nearby supernovae and Cepheid stars measure the expansion rate of the universe to be 74 km/s/Mpc, within 10 percent

Figure 1
Amplitude of Temperature Fluctuations as a Function of Angular Scale



The curve is the best-fit model based on the data from the Wilkinson Microwave Anisotropy Probe and the Atacama Cosmology Telescope; the points and their error bars are computed from a combination of the publicly available Planck satellite 217 GHz and 545 GHz data. Source: David Spergel, Raphael Flauger, and Renee Hlozek, "Planck Data Reconsidered," submitted to *Journal of Cosmology and Astroparticle Physics* (2013), arXiv:1312.3313.

of the value inferred from the cosmic microwave background observations. Cepheids are variable stars with a known relationship between their period and their luminosity. Because the intrinsic luminosity of supernovae and Cepheids are known, they are used as standard candles to measure distance. A mild discrepancy between these two measurements is a subject of active discussion at cosmology meetings.

- Supernova observations can also be used to trace the relationship between distance and expansion. These observations[10] also yield the cosmological parameters consistent with the cosmic microwave background observations and require a universe filled with dark matter, dark energy, and atoms. In 2011, the Nobel Prize for Physics committee recognized the leaders of these observations for their discovery of cosmic acceleration. In our simplest cosmological models, dark energy is the driver of this cosmic acceleration.

- Measurements[11] of the abundance of rich clusters of galaxies provide an alternative method of measuring the density of the matter and the amplitude of the primordial fluctuations. These measurements again fit our basic cosmological model with a consistent set of parameters.

- The same sound waves that produce a characteristic scale in the microwave sky also produce a characteristic scale in galaxy clustering. Using the Sloan Digital Sky Survey, astronomers have now measured the positions of millions of galaxies. They can compute the statistical correlations of these galaxies and infer the density fluctuations in matter in the nearby universe.[12] These measurements agree remarkably well with the cosmic microwave background observations.

Despite the remarkable success of the Big Bang model in describing the evolution of the universe and the growth of fluctuations, the model is incomplete. Intriguingly, inflation – currently the most popular extension of the Big Bang model – not only addresses these problems but also makes predictions that we can test with our cosmic microwave background observations.[13]

The standard Big Bang model has a number of profound philosophical problems: it does not explain why our universe is so large, why the kinetic energy of our universe nearly perfectly balances the gravitational energy, or why the universe is nearly (but not perfectly) uniform. Our universe is more than 13.7 billion light years across, yet the "characteristic" scale set by general relativity and quantum mechanics is the Planck length, only 10^{-36} meters. Our nearly flat universe is at an unstable fixed point. Today, the kinetic energy of the universe (the energy in the expanding galaxies) is within 1 percent of the gravitational energy of the universe. Since these two quantities tend to rapidly evolve away from each other in the standard cosmology, they would have to be finely tuned to be nearly identical to more than twenty digits at the epoch of nucleosynthesis, the period of the universe three minutes after the Big Bang, when most of the deuterium and helium in the universe was synthesized.

The near, but not perfect, uniformity of the early universe is another puzzle in Big Bang cosmology. Different regions of space that were never in causal contact in the Big Bang model have nearly identical densities. The solution to the problem must explain this near, but not perfect, equality; for if the early universe were perfectly uniform, it would still be uniform today.

The inflationary paradigm offers an answer to these questions. It posits that the very early universe underwent an extremely rapid period of exponential expansion. Cosmologists call this very rapid period of expansion "inflation." This rapid expansion stretched the universe to a very large size. During this rapid period of expansion, the kinetic energy of the universe was driven to match the gravitational energy, and this enormous stretching erased any initial fluctuations in the early universe. When the inflationary paradigm was proposed thirty years ago, cosmologists recognized that the model not only solved these Big Bang cosmology problems, but also offered a mechanism to produce the fluctuations that would grow to form galaxies.

During the inflationary expansion, tiny quantum mechanical fluctuations in density were amplified enormously. Some regions of the universe had slightly higher densities while other regions of the universe had slightly lower densities. The regions with slightly higher densities spent more time in the exponential expansion phase and exited inflation later. After the universe cooled and became dominated by matter, these denser regions grew and eventually collapsed to form galaxies, stars, and planets. Thus, the inflationary model implies that the origin of all of the structure in the universe was the tiny quantum mechanical fluctuations amplified during the first moments of the Big Bang.

This remarkable explanation for the origin of structure is testable. The inflationary model is highly predictive about the statistical properties of these fluctuations. This instability during the inflationary phase led to a very specific prediction for the statistical properties of the variations in density: the fluctuations should be "Gaussian random phase, adiabatic, nearly scale-invariant" fluctuations. Gaussian random phase fluctuations have very simple statistical properties and are described entirely by their two-point correlation function. Adiabatic fluctuations have the same ratio of photons, electrons and protons, and dark matter everywhere. Scale-invariant fluctuations have the same amplitude on all scales. Thus, the inflationary model predicts that the statistical properties of the temperature of the tens of millions of points in the Planck satellite maps and the statistical properties of the positions of millions of galaxies can be described by only two numbers: an amplitude and a small deviation from scale invariance.

One of the predictions of the inflationary model is that there should be equal numbers of hot and cold spots in the microwave sky, and that the statistical properties of hot spots and cold spots should be identical. Analyses of both the WMAP and Planck satellite data reveal no evidence for this symmetry. Quantifying this through constraints on the three-point function, analyses show that the primordial fluctuations are symmetric to better than one part in a thousand. Any detection of these features would have been a significant challenge to the inflationary model. The statistical properties of these observations also show a remarkably strong agreement with the predictions of the inflationary scenario: the fluctuations are adiabatic, Gaussian, nearly scale-invariant, and coherent over scales that are larger than the "horizon" scale (the distance that light can travel). The statistical properties of the millions of points in the sky are described by two basic numbers, an amplitude and a scale-dependence – a remarkable success for the inflationary scenario.[14]

Another prediction of the inflationary model is that the geometry of the universe should be very close to flat. There should be nearly equal amounts of kinetic energy and gravitational energy. At the time that the inflationary universe was proposed, most astronomers would argue that the gravitational energy associated with the known galaxies was too small to balance the kinetic energy in expansion. In the 1980s, most cosmologists would have argued that the observations implied that the ratio of the two, usually called Ω, was 0.2 – 0.3. Inflationary models predicted $\Omega = 1$. While a number of theorists noted the possibility that this discrepancy could be resolved if the universe was filled with dark energy, this possibility was considered exotic, the last refuge of the scoundrels who wanted to preserve the inflationary model. Today, the observational situation is very different. The WMAP and Planck satellite observations imply that $\Omega = 1$ to better than 1 percent. When these cosmic microwave observations are combined with observations of large-scale structure, the current best measurements imply that $\Omega = 1$ to better than 0.1 percent, another remarkable success for the inflationary model.

Despite these many predictive successes, the inflationary model faces a number of theoretical challenges. The inflationary scenario does not explain the origin of the universe and requires special initial conditions. For inflation to match the observed large size of the universe and the low amplitude of initial fluctuations, the parameters in the model must be fine-tuned. Since inflation occurs in the first moments of the Big Bang and at energy scales far beyond those accessible in the laboratory, our exploration of its physics stretches our basic understanding of the underlying nature of matter, space, and time.

Over the past few decades, cosmologists have developed a remarkably successful cosmology model that fits a host of astronomical observations. However, while this model addresses many of the previously unsolved questions of cosmology, it raises a new set of questions:

- Why is the universe accelerating? What is the nature of dark energy? Are we seeing the breakdown of gravity on cosmological scales?
- What is the nature of dark matter?
- Did the early universe also undergo a period of acceleration? If so, what was the mechanism that drove this early period of inflation?

There are many different routes toward addressing these questions. Developments in string theory and other attempts at unifying physics may provide new insights into the nature of space and time. Future observations of the geometry of the universe, the statistics of the primordial fluctuations, as well as the gravitational waves predicted in the inflationary scenario will either confirm this basic model or challenge its underlying tenets. Searches for dark matter could reveal the nature of these unknown particles. Astronomical measurements of distances or the growth rate of structure will test the notion that vacuum energy drives cosmic acceleration.

Of course, if we can address any of these questions, the answers will likely point toward even deeper and more profound mysteries.

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