The article

In Defense of the Big Bang

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An important scientific innovation rarely makes its way by gradually winning over and converting its opponents....What does happen is that its opponents gradually die out and that the growing generation is familiarized with the idea from the beginning.

Max Planck, 1936

What, you might ask, could possibly induce a rational astrophysicist to believe that all the matter, energy, and space of the universe began fifteen billion years ago in a primeval fireball packed into a volume smaller than a marble that has been expanding ever since? The answer is simple: regardless of what you may have read or heard, the big bang is supported by a preponderance of evidence and has become the most successful theory ever put forth for the origin and evolution of the universe.

Scientific evidence in support of a theory sometimes takes you places where your senses have never been. Common sense is that human ability to assess a situation you have never seen before by invoking life experiences derived from your five senses. But twentieth-century science has largely been built upon data that was, and continues to be, collected with all manner of tools that enable us to see the universe in decidedly uncommon ways. As a consequence, while we have always required that a theory make mathematical sense, we no longer require that a theory make common sense. We simply demand that it be consistent with the results of observations and experiments. This posture has enabled profound, yet remarkably counterintuitive branches of physics, such as relativity, quantum mechanics, and big bang cosmology to arise.

Of all the theories about how the physical world works, the general public seems to be most intrigued by the big bang. Who wouldn't? Ideas about the origin of things have always made fascinating science. But I have found some people that vehemently oppose the big bang while being generally uninformed about its fundamental tenets. A well-constructed theory should explain some of what is not understood and, more importantly. predict previously unknown phenomena that can be tested. A successful theory is one where experiments consistently confirm its predictions.

Some like to claim that the big bang is "just a theory" and should therefore be discounted. Don't be fooled. The beginning of the twentieth century saw the end of labeling successful theories as "laws." This change of vocabulary came when new experimental domains revealed the predictions of previous physical laws to be incomplete. The change was the physicist's humble recognition that data from newer and better equipment might provide a deeper realization of the physical world. This is why pre-1900 we had Kepler's *laws* of planetary motion, Newton's *laws* of gravity, and the *laws* of thermodynamics, whereas after 1900 we have Einstein's *theory* of relativity, quantum *theory*, big bang *theory*, and so forth.

Confidence in big-bang cosmology is derived from the strengths of many arguments. Let us start with Edwin Hubble's 1929 observation that we live in an expanding universe, where distant galaxies recede from us faster than the near ones in direct proportion to their distances. Further support came from Albert Einstein's theory of gravity, better known as the general theory of relativity, which predicted an expanding universe as one of its solutions with the precise expansion pattern found by Hubble. Since Einstein's theory preceded Hubble's discovery (by thirteen years), Einstein cannot be accused of putting

Questions

Before reading the article, what does the title make you think about? Why? What do you expect from this article based upon your knowledge of the author?

Explain why the author would choose to begin the essay with this quote.

What does this first paragraph tell you about the essay?

What does the author mean when he says “we no longer require that a theory make common sense?

How does the content of this paragraph compare with the definition of “theory”?

Does the author believe the big bang “just a theory”? Why or why not?

Why is it important that Einstein’s theory came before Hubble’s observation? How does this fact fit in with the explanation of a theory used earlier in the essay?

forth an after-the-fact explanation.

For any theory, one should not hesitate to question every possible assumption, no matter how basic they are. If you happen to have a gripe with the claim that objects with high velocity of recession, are farther away than objects with low velocity of recession then consider the existence of gravitational lenses as a simple test-case. As first predicted by Einstein, the gravity of a high-mass foreground object can distort space in its vicinity so that an object which, by chance, falls along the line of sight in the background , can look as though it is split into two or more images. These optical antics have been observed in dozens of galaxies all around the sky and the "lensed" object (presumed to be in the background simply because it was the one that got lensed) always has a higher recession velocity than the object whose gravity is serving as the lens itself.

Perhaps it's some kind of an illusion that very distant galaxies have very high recession velocities. We measure the velocities from the increase in wavelength (and associated decrease in frequency) in the spectrum of the light emitted by the galaxy. If indeed the galaxies are receding and have shifted spectral features because of it then they ought to measurably exhibit a stretching of time intervals. Recently, supernovae discovered in distant galaxies have been found to take more time to explode and decline in luminosity than counterpart supernovae in nearby galaxies. That extra time happens to be precisely what you would expect from the wavelength and frequency shifts of the spectral features.

The most powerful supporting argument for the big bang derives from the "cosmic microwave background." Shortly after the Second World War, and shortly after the notion of a hot, explosive origin for the universe was proposed by the physicist George Gamow, the physicists Ralph Alpher and Robert Herman invoked simple principles of thermodynamics and particle physics to infer that the density of matter and energy of the universe must have been higher in the past, concluding that there should be a leftover signal from an earlier time, when the ambient temperature of the universe was thousands of degrees. That leftover signal, by virtue of the expanding universe, should have cooled appreciably and would appear today as an omni-directional bath of microwave energy with a characteristic temperature of a few degrees on the Kelvin absolute temperature scale. In 1965 a part of this background signal serendipitously revealed itself in data obtained by the microwave antennae of two Bell Labs physicists, Arno Penzias and Robert Wilson, for which they were jointly awarded the 1978 Nobel prize in physics.

How did Penzias and Wilson provide evidence for the idea of Gamow?

How is the relationship between Penzias/Wilson and Gamow similar to the relationship between Hubble and Einstein?

If you have a gripe with the claim that some accidentally discovered microwaves are the cooled remnant of a youthful, hot universe, then consider that the big bang predicts a specific mixture of energy for this bath of microwaves that characterizes a single temperature. By similar reasoning, the specific mixture of energy emitted by the Sun (including the relative amounts of infrared, visible and ultraviolet light), characterizes a single temperature (6000 kelvins) at its surface. In 1990, the COBE satellite (COsmic Background Explorer) measured this background and indicated a single temperature (2.726 kelvins) to an accuracy of two-tenths of one percent.

You might be skeptical about whether this single-temperature assortment of microwaves actually came from the early universe. You might prefer to think they were created by your neighbor's microwave oven or a police radar gun or by some microwave-emitting wall of interstellar material nearby in space. But we know that the gravity of galaxy clusters slightly reduces the energy of light that passes through them. And when we look for what the microwave background does in the line of sight to these distant clusters we see a slight drop in energy, implying that the microwave background indeed hails from beyond these clusters and not in front of them.

You may not be convinced that the universe was hotter in the past than it is today, as it must have been in the big bang picture. Consider distant galaxies, which, because of the light travel time between the galaxy and us, we see not as they are but as they once were. If big bang cosmology is correct, these distant galaxies should be bathed in a hotter cosmic background than what is measured in the present. Sensitive measurements of molecules that react differently to different background temperatures have allowed us to infer a temperature for the cosmic background from distant galaxies that is in precise accord with the predicted temperature of the universe at the time the light that we measured left these galaxies.

Just for fun, let's turn back the big bang clock, and use current laws of physics to extrapolate the behavior of the universe to a time when it was much smaller, denser, and hotter--when the background was upwards of a trillion degrees. (Our current theories of physics actually allow us to describe the behavior of the universe starting from the first 0.000000000000000000000000000000000000000000000001 seconds of its existence all the way up to 15 billion years and beyond. Times earlier than this 10^{-43} seconds have no meaning in quantum mechanics.) At these early times and high temperatures, all atoms were broken apart into their component nuclear particles. Combining all that we know of quantum mechanics, particle physics, and all we have learned from busting atoms to smithereens in particle accelerators, we conclude that as the cosmic soup expanded and cooled, nuclear particles recombined to make a specific and predictable assortment of atoms: the universe was born with 75 percent of its mass as hydrogen and about 25 percent as helium. These are bold extrapolations, but surveys of the most helium-deficient galaxies (those that have undergone very little star formation and hence suffered very little contamination) routinely find between 22 and 27 percent helium, in good agreement with big bang predictions.

The author believes galaxies with relatively few stars provide evidence that cosmologists were accurate in their estimates of the proportion of hydrogen and helium in the early universe. Why would galaxies with fewer stars provide a better indication of the proportion of hydrogen to helium in the early universe than galaxies with many more stars?

A few other light elements are predicted to have formed in trace amounts during the first several moments of the universe. Among these are "heavy" hydrogen (which is simply a proton and a neutron), "light" helium (which is simply helium that is missing a neutron from its nucleus), and lithium (the third lightest element on the periodic table of elements). The measured quantities of these light elements in the universe are also consistent with the predictions from the big bang.

We didn't just make this stuff up. It represents an unprecedented marriage of astrophysics and particle physics where a coherent cosmic picture has emerged from a minimum of assumptions that tells us the galaxy velocities are real, the galaxy distances are real, the expanding universe is real, relativity is real, quantum mechanics is real, and the big bang is real. Whenever different sub-branches of a science support the same theory then the confidence you bestow upon the theory is greatly enhanced.

Why do you think the author chose to make the statement, “We didn’t just make this stuff up”?

But alas, all is not perfect in paradise. There remains a few holes in big bang theory.

Most importantly, the density of mass in the universe today implies an initial value that is remarkably close to the critical density, which is the density that packs just enough mass for the universe to live at the boundary between one that will ultimately recollapse and one that will expand forever. The fine-tuning that this requires among the values for many of the cosmological parameters in the early universe could not have happened randomly.

And going deeper than the simple extrapolations of the big bang we find that the microwave background is far too uniform from one patch of the sky to the next to have emerged from the conditions thought to have been present in the early universe.

Unfortunately, the early, rapid expansion of the universe does not leave enough time for the galaxies to form as we think they should form; and the big bang cannot tell us what happened before 10^{-43} seconds, or for that matter, what happened before zero seconds--or why the laws of physics are what they are.

Why does the author choose to divulge problems with the big bang theory?

Do we throw away the big bang along with the bath water because of these complications? Or do we retain the big bang's successful predictions and see if there is room to modify the theory's details in an attempt to solve these problems? These sorts of questions have arisen before. In the mid-sixteenth century, the Polish astronomer Nicolaus Copernicus proposed a model of the known universe with the Sun as the center of all motion rather than Earth. This heliocentric model was much, much simpler than the competing geocentric model because it removed the need for complex epicycles to account for the motions of the planets in the sky, especially during their occasional retrograde motion. But there was a problem. The predicted paths of the planets in the heliocentric model continually deviated from the actual paths of the planets in the sky. Should Copernicus have therefore discarded the entire idea of a Sun-centered universe, or should he have modified some of the model's details? Copernicus' heliocentric view was, of course, basically correct. The problems arose because he naively assumed that the planets orbited the Sun in perfect circles rather than in ellipses the concept of gravity was not yet invented. It would be two hundred years before Isaac Newton's universal law of gravitation supplied a bigger picture that modified and completely subsumed Copernicus' view of the world.

In what way are problems with the big bang similar to problems faced by Copernicus? Do you think this is a fair comparison for the author to make?

Progress has already been made to resolve some of the problems with the big bang model. The most significant modification is known as inflationary cosmology, where the energetics of the very early universe passes through a phase that spontaneously triggers an period of extremely rapid expansion. Inflation naturally accounts for what was thought to be an embarrassingly fine-tuned "critical" density. It also allows the cosmic microwave background to be as uniform as it is measured to be. Introduced in the early 1980s by the American physicist Alan Guth, inflation is a natural consequence of the principles of quantum mechanics when applied to the fabric of space and time in the early universe and thus has no household analog. Inflation's main prediction is that the universe was born with its mass density equal to the critical value and continues today have the critical mass density. Current observations have recovered anywhere from 20 to 40 percent of the mass necessary to reach the critical density. Inflation enthusiasts are fervently looking for the rest.

One class of inflationary theories describes a mega-universe with multiple areas of expansion where each region looks like a big bang universe from within, and where different regions of expansion can sustain laws of physics that differ from the ones we know. If this model can be tested and supported then inflation will have subsumed the entire big bang into a larger cosmological picture.

If you choose to discard the big bang entirely then step lightly, you will be forfeiting an impressive array of successful predictions--far more than most theories-in-progress enjoy. Nearly everyone in the community of astrophysicists has chosen to work with it, recognizing that our efforts may lead to an even deeper understanding of the universe where the big bang becomes the core idea of something even bigger.

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Was this essay effective at achieving its purpose? Explain.

Write three questions you would like to ask the author based on this essay.