Inflationary Big Bang Cosmology and the New Cosmic Background Radiation Findings

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A trio of new findings lends strong support to a powerful idea called "inflation" that explains many of the observed characteristics of our universe. The findings relate to the slight variations in the faint microwave energy that permeates the cosmos. The size and distribution of these variations agree well with the theory of inflation, which holds that the entire universe underwent an incredibly brief period of mind-bogglingly vast expansion (a hyper-charged Big Bang) before slowing down to the slower rate of expansion observed today.

Combining the new findings about the cosmic microwave background radiation with inflation, cosmologists (the scientists who study the origin of the cosmos) believe they also have a compelling explanation for why stars and galaxies have their irregular distribution across the observable universe.

Some cosmologists now believe that not only is the irregular distribution of "ordinary matter" related to the nature of these variations in the cosmic background radiation, but through inflation, both are related to the conditions within that incredibly dense and hot universe at the instant of its creation. (Such ordinary matter includes the elements that make up our Sun and our Earth and, ultimately, human beings.)

Cosmologists have long believed that every bit of matter in the entire observable Universe – all the planets, stars, and galaxies, which we can see through powerful telescopes, as well as all the things we can't see directly but know must be there due to the effects they produce – was once compressed together into a very dense and very hot arbitrarily small volume. Smaller than an atom, it not only contained what would become every bit of matter and energy, both seen and unseen, but was itself space.

The word "observable" is key to understanding this picture, though, because while the "observable" universe can be thought of as expanding outward from an arbitrarily small volume, the same cannot necessarily be said of the entire universe, which in fact may be infinite.

This is a confusing point that arises because what we see as the universe is probably just a minute, even infinitesimal, fraction of the entire universe. We see only those objects whose light has had time to reach us, so in this way, the observable universe can be thought of as a sphere or a ball of radius roughly 14 billion light years extending in every direction from Earth. What exists beyond that we don't know because we can't see it yet, since the light from objects in it has not had time to reach us. Furthermore, the entire universe may be "unbounded" or infinite – a situation the current cosmic background radiation findings suggest. This means that if two rays of light were sent out on parallel paths into the universe, they would travel on a straight line forever (assuming they weren't bent by local distortions causing by objects with gravitational attraction).

What we are left with is the odd picture of an observable universe that "exploded" out of a volume smaller than an atom, but an entire universe that may now be infinite in extent. And whether or not that entire universe was initially also compressed into such a small volume is unanswerable. If the inflationary model is true, this means that virtually all of what was in the universe at its first instant of creation was forever "inflated" away from what we see in the observable universe, which has a finite size that is expanding at the speed of light.

Not only can we not ask what existed outside of our universe, we cannot even know what the vast majority of our own universe looks like – just the small "observable" part that we can see (out to a radius of about 14 billion light years). All we can say is that prior to inflation, everything that exists in our observable universe was compressed into an incredibly small, incredibly hot, and incredibly dense volume.

Cosmologists have strong reason to believe that the universe that we inhabit – both the observable part and the part beyond what can see and ever will be able to see – began to expand very rapidly within an incredibly tiny fraction of a second after its creation.

When the universe was just 10^{-34} seconds old (that's one tenth of one billionth of one trillionth of one trillionth of a second), it underwent an awesome expansion whose source of energy was space itself – before gravity could reverse the expansion. Within another 10^{-34} seconds, the universe expanded by an order of 10^{43}, meaning that any two objects (i.e. the super-exotic particles that preceded energy and matter) that were one unit of distance apart before inflation were now 10^{43} units apart.

Although just an example, if that unit were one inch, then any two objects one inch apart before inflation would be 10^{43} inches apart after inflation. Since one light year (the distance light travels in one year) is 5.866 trillion miles, this corresponds to a size of about 27 septillion (that's 2.7×10^{25}) light years. By contrast, today's observable universe is "just" 14 billion (that's 1.4×10^{10}) light years extending in every direction from Earth. Using this number of one inch would mean the "entire" universe just after inflation would have already been 10^{15} times bigger than what we can see even now 14 billion years after the fact. Light would need another 10^{15} years to reach us for us to be able to see this part of the universe.

Whether or not the entire (as opposed to just the observable) universe was "compressed" into something smaller than an atom, we do not know. What we see today, though, after inflation, is a universe that is essentially flat – meaning two rays of light sent out next to each other will remain (assuming no local gravitational influences) parallel essentially *forever*. Whatever curvature the universe may have had has long since been flattened away – much as a tiny ant would perceive a big beach ball it chanced to walk on. The nature of cosmic background radiation as indicated in the three findings support just such a view: the size of the cosmic background radiation variations reaching us indicates that the universe is indeed flat.

So even if the entire (as opposed to the observable) universe were compressed into a tiny, closed volume, inflation would have opened up and flattened out that volume forever – much as a tiny ant would perceive on a rapidly inflating balloon

[Furthermore, the inflationary model of the universe and other exotic (but not unreasonable theories) suggest that our "infinite" universe may in fact be one of an infinite number of other universes that span numerous dimensions and in each of which different "laws of nature" apply. Think of a drop of water. If our observable universe is just one molecule of water in the drop of water, the entire drop represents the entire universe (although even this may not be a good analogy, since the drop itself is finite in size). All we can know is the one molecule of water, not the whole drop itself. Now put that drop into an ocean – where each drop in that ocean represents another universe. This gives us some sense of the power of the term "infinite."]

In the inflationary Big Bang model of the universe, there was no central point from which all matter "exploded" outward since it was space itself that was expanding everywhere. Even today, galaxies are flying away from each other as the "stretching" of space itself continues. Astronomers are able to measure how fast galaxies are moving away (receding) from each other, and they have determined that the farther away a galaxy is, the faster it is moving as the stretching of space continues.

The extreme conditions of that initial universe produced powerful electromagnetic waves (photons) that were mostly forged in the first few instants of the Big Bang and have persisted throughout the history of the universe, traveling around in all directions. These waves have gradually lost their extremely high energy, corresponding to a gradual decrease in their frequencies (i.e. the wavelengths have become longer). Whereas once they were incredibly energetic X-rays, they have gradually weakened to microwaves today. These microwaves form what is known as the cosmic background radiation.

While cosmic background radiation's existence has been known since the 1960s, the variations in the radiation, which can be measured as either variations in frequency/wavelength or in absolute (Kelvin) temperature, have only been known since 1991, when NASA's Cosmic Background Explorer satellite first roughly measured them. (In the Kelvin scale, 0 Kelvin is the temperature at which all molecular motion ceases – it is never actually reached – and it corresponds to –273C).

This past April, three teams of scientists presented their findings on variations in the cosmic background radiation at an American Physical Society conference in Washington, D.C. Each of the teams measured the cosmic background radiation in different parts of the sky and at somewhat different wavelengths. Two of the three teams had already presented preliminary findings on the largest variations in the background radiation last year.

The experiments are each known by their acronyms: DASI, BOOMERANG, and MAXIMA.

The first stands for Degree Angular Scale Interferometer, and it used 13 distinct ground-based radio telescopes at the South Pole to measure cosmic background radiation frequencies in the low energy part of the electromagnetic spectrum (weak microwaves). The other two were both balloon-borne experiments that measured the cosmic background radiation at slightly higher frequencies in the millimeter region.

BOOMERANG, short for the Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics, consisted of a very sensitive millimeter telescope that was carried by a large balloon 120,000 feet or about 37 kilometers high into the upper atmosphere over Antarctica. The balloon and its attached instruments circumnavigated the Antarctic continent over almost an 11 day period from late December 1998 to early January 1999, measuring the cosmic background radiation.

MAXIMA, the Millimeter Anistrophy eXperiment IMaging Array, also measured the background radiation in the millimeter region, but it flew for just a seven-hour period on the night of August 2, 1998 high above Texas.

The minute variations in the cosmic background radiation recorded by all three experiments are a very significant finding. As noted, today's cosmic background radiation is a faint "echo" of the much more intense radiation that filled the universe several hundred thousand years after the Big Bang/inflation event when it had cooled just enough to permit ordinary matter to form. This radiation was last scattered when the plasma existed, and since then, it has been moving in all directions across the universe (only very tiny bits of it intercepted by matter). The radiation has "cooled" over the age of the universe – roughly 14 billion years – from about 4,000 Kelvin at the "time of last scattering" to about 2.74 Kelvin, which falls in the microwave region of the electromagnetic spectrum. (By contrast, the Sun radiates most strongly in the visible light wavelength with a corresponding temperature of roughly 5,000 Kelvin.)

In these earlier findings, each had found that the cosmic background radiation alternated between "hot" and "cold" patches on the order of 50 millionths to 100 millionths of a Kelvin (i.e. 50 to 100 micro-Kelvins) and at a spatial separation of about a half a degree (which is about the size of the full moon as seen in the sky).

The refined findings by two of the teams combined with the new findings by a third team showed more detailed structure within the hot and cold patches. Much like a musical note as a fundamental "harmonic", the new findings showed additional harmonics.

The analogy to sound waves is actually rather apt. In the early universe, before it cooled enough to allow ordinary matter to form and instead was a hot plasma (with negatively charged electrons moving too fast to be captured by positively charged protons), minor fluctuations in the plasma behaved like acoustic (sound) waves. Areas of compression in the plasma density corresponded to hotter patches and areas of expansion in the plasma density corresponded to colder patches. In this way, the cosmic background radiation that fills space today is a slowly fading echo of those sound waves that permeated the plasma.

These density fluctuations also allowed matter, once it had formed, to clump together. Without such fluctuations, matter could not have collected together and gravity could not have worked to further cluster more matter together. Ultimately, it allowed stars to form, which in turn allowed galaxies and clusters of galaxies and clusters of the clusters (called super-clusters) to form. What is referred to as "large-scale structure" in the cosmos, with matter showing a "lumpiness" in its distribution across the universe, arose from such fluctuations.

However, the question remains, why were there any fluctuations in this young plasma-filled universe? The answer, some cosmologists believe, lies in inflation. Recall that with inflation, something that was exceedingly small was expanded over 43 orders of magnitude in size in an incredibly brief fraction of a second (one trillionth of one trillionth of one hundred millionth of a second, or a decimal point and 34 zeros followed by a one).

Because of this inflation, the quantum fluctuations that existed when the universe was very dense were almost instantly stretched out to incredibly vast distances. The quantum fluctuations thus became the plasma density fluctuations, which, in turn, produced the observed variations in the cosmic background radiation and the lumpiness of ordinary matter.

Inflation thus appears to answer the question of why the early hot, dense universe gave rise to structure – quantum fluctuations were inflated out to vast distances. Without inflation, it becomes much harder to explain why an early hot universe with more or less uniform density should have given rise to any structure.

In addition, some cosmologists say that inflation explains why the cosmic background radiation has essentially a uniform value of 2.74 Kelvin with variations of just a few thousandths of a Kelvin. How was it possible for the entire universe, they ask, to come to the same temperature, given that the universe is not old enough since the time that matter formed, which is when today's cosmic background radiation was last scattered off the "fog" of plasma?

This is the flip side of the question, which previously asked about where did the minor variations in background radiation come from. Despite these variations, the remarkable fact is that the background radiation is so uniform in all directions. This means that at the time the plasma disappeared – the time of last scattering of the cosmic background radiation – the temperature of the plasma must have been the same in all directions. But this immediately poses the problem that not enough time had elapsed for such a large area to reach an equilibrium temperature.

To understand this, one must first picture the plasma as a sort of opaque fog of light that exists on a spherical "shell" surface centered about the Earth at a radial distance of roughly 14 billion light years. This spherical shell of plasma extends in every direction from the Earth, the light having left every point on it simultaneously 14 billion years ago (back when the universe was only a few hundred thousand years old). The 14 billion light year distance is determined by the speed of light multiplied by the time since the plasma last existed. The sphere is moving away from the Earth at the speed of light. We can see the scattering effect it produced on the cosmic background radiation that reaches us today.

This brings us back to the question of why the cosmic background radiation has an energy that is equivalent to 2.74 Kelvin (plus or minus 0.000005 to 0.000010 Kelvin) in every direction. In order for the background radiation to have such a nearly uniform energy, the plasma had to have had essentially the same temperature in every direction. Otherwise, the cosmic background radiation, which had an energy corresponding to an absolute temperature of roughly 4,000 Kelvin at the time of last scattering, could not cooled uniformly to 2.74 Kelvin, as observed today.

Why? Because not enough time had elapsed from the time of the Big Bang (when inflation occurred) to the time the early universe cooled enough and the opaque fog was replaced by the transparency of space (and matter was able to form). In that roughly 300,000-year period, not enough time had elapsed to allow each bit of the plasma to exchange energy with each other bit, and thus come to an "equilibrium" temperature. Consider a hot cup of tea cooling on a table. The tea will eventually exchange enough heat energy with the surrounding air that it cools to the temperature or the air. (Actually, the tea will cool substantially while the air in the room warms ever so slightly, but in the end, the air and the tea will be in thermal equilibrium.) With something as large as the universe, even as it existed 300,000 years ago, and in the absence of inflation, not enough time would have elapsed to allow for a thermal equilibrium to occur. But such an equilibrium did occur, otherwise today's cosmic background radiation wouldn't be so uniform. The *only* way this was possible, some cosmologists say, is if every piece of the plasma were initially in close contact with every other piece and then abruptedly inflated out to unimaginably vast distances.

Finally, another very compelling reason for the existence of inflation, according to its proponents, as revealed in the cosmic background radiation findings is the fact that the observable universe appears "flat" in every direction. Flatness means a beam of light sent out from an emitter in any direction would move in a straight line through space forever, assuming it never encountered any local curvature effects due to stars or planets or other "mass-ive" objects. Furthermore, two beams of light emitted parallel to each other would remain forever parallel, again assuming no local curvature. The reason for this is that this universe, even if it began as a tiny "ball", has been stretched out to such incredibly vast distances that the portion we call the observable universe (the part we can see because light has had time to reach us) is so miniscule in comparison that it is basically a flat surface. Think of a tiny flea standing on the surface of a large balloon. To the flea, the horizon is basically flat, much like it appears to us when standing on the beach, looking out at the ocean. The part of the balloon visible to the flea, or the part of the Earth visible to us, is tiny in comparison to the whole.

The importance of the recent cosmic background findings is that the sizes of the hot and cold patches are what is predicted if the (observable) universe is flat. Were the observable universe "closed" – like the surface of the balloon is – than the radiation reaching us should bend inward. The result would be that the hot and cold patches would appear larger than they actually are. This is analogous to putting a magnifying lens in front of your eyes: the image appears bigger than it actually is.

Other physical parameters appear to be satisfied by the inflationary hypothesis, most notably the "tilt". The tilt refers to whether there are more hot and cold temperature (or density) fluctuations on the larger scale than on the smaller scale. Put another way, tilt refers to whether or not matter would tend to clump together more in smaller regions of space than in larger regions of space. This is sometimes referred to as the invariance question: are the density fluctuations throughout the universe scale-invariant, meaning density perturbations are the same at all spatial scales. No tilt means there is no preference and density perturbations, and hence structures containing matter, are just as likely to form at the small scale as at the large scale. Inflation predicts that there should be zero tilt, which is defined as a tilt parameter equal to unity. The new findings support such a tilt parameter.

Taken together, there appears to be strong experimental and theoretical support for the notion that the universe underwent such an inflation in the first infinitesimally small fraction of a second after its creation. The result is a universe in which matter is distributed irregularly across the cosmos and in which cosmic background radiation displays the variations observed.