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Early Dark Energy: A Possible Solution to the Hubble Tension

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Up until the 1920s, astronomers had no evidence that the Universe extends beyond our galaxy, or that it ever looked any different than it appeared at the time. To the naked eye, the objects in the night sky seemed largely unchanged. Thus, the logical conclusion was that the state of the universe is perpetually fixed. Even Albert Einstein once embraced this idea and produced mathematical models to describe a static universe in 1917. Without evidence—only speculation—of other galaxies, Einstein's universe reached no further than the outskirts of the Milky Way. This proposed static model leaves very little room to debate the cosmic origins of the Universe. If we assume the Universe never grows, shrinks, or changes on any large scale, then perhaps it has always existed. Simply, remaining in a perpetually fixed state eliminates the need for the Universe to have a birthday.

It was not until 1923 when Edwin Hubble discovered proof of extragalactic objects and 1927 when George Lemaitre suggested that the Universe has a finite age. In 1929, Hubble found evidence that distant galaxies appear to fly away from the Earth. He observed that light emitted from these galaxies stretch toward longer redder wavelengths on the electromagnetic spectrum (Figure 1). This is a phenomenon called redshift, quantified by z, the fractional change in the wavelength. Redshift is caused by the Doppler effect, where the frequency of waves emitted by an object moving away from the observer is decreased. Furthermore, he discovered that the higher the redshift value, the farther away an object is from Earth and the higher its recession velocity.

From the perspective of an observer on Earth, it appears that most distant galaxies are moving away from us. However, since

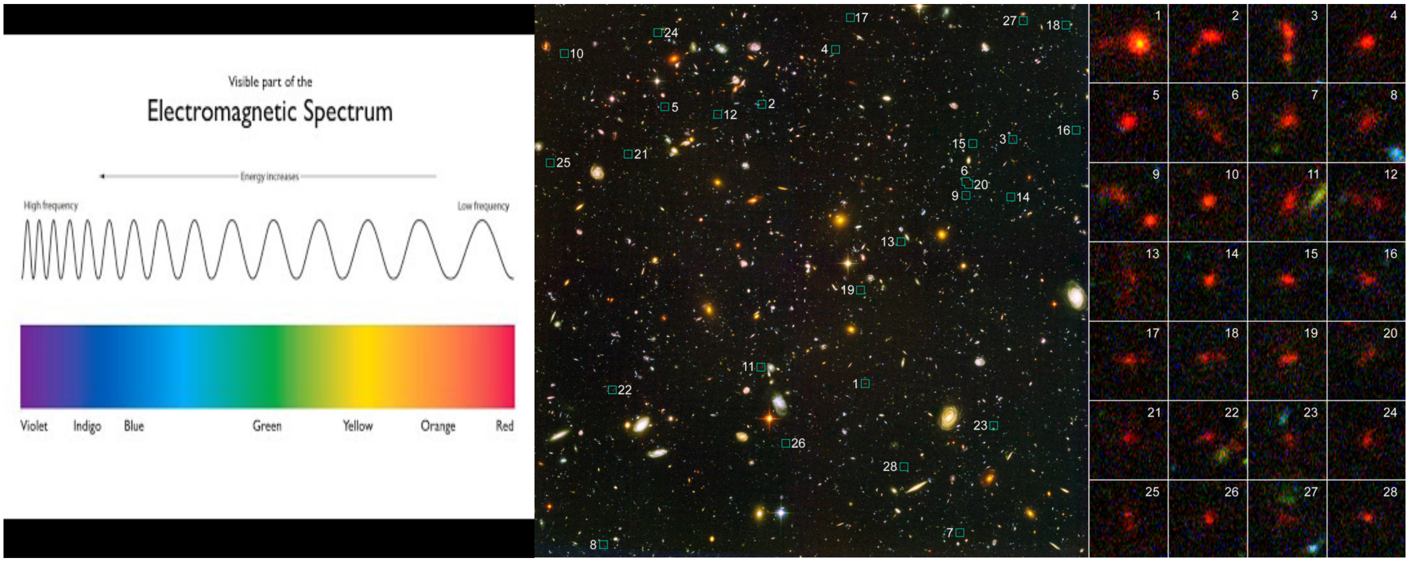

Figure 1: (left) Visible light on the electromagnetic spectrum: wavelength increases and energy decreases from the violet to red end of the spectrum (right) Redshifted galaxies as seen in the 2006 Hubble Ultra Deep Field.

our Galaxy is not the center of the Universe, the most natural explanation is that these galaxies are actually receding from one another, carried by the uniform expansion of space itself. Therefore, the Universe cannot be static. It must have expanded from an initial state, or more simply, had a beginning.

How fast is space expanding and what is causing it?

The rate of expansion of the Universe today—the Hubble constant H_0—is inferred by two main methods, the results from which have disagreed for decades. However, the margins of error surrounding the two values were significant, and it was expected that the two constants would converge as instrumentation improved and measurements became more precise. This has not been the case. In fact, as the margins of error around each value have diminished, the gap between them has only become more pronounced. This problem has been dubbed the "Hubble tension."

The Cosmic Distance Ladder Method

The expansion of the Universe can only be observed at extremely large distance scales which we are currently only able to measure indirectly. In one method, the Hubble constant is inferred by a "three-step distance ladder" (Figure 2), where vast extragalactic distances are measured by building on several shorter distances—the "rungs" of the ladder.

Distances to the first "rung"—Cepheid variable stars in the nearby Large Magellanic Cloud, a satellite galaxy 158,000 ly (lightyears) away—are linked to the second "rung"—distances to objects such as Type Ia supernovae and Cepheids in galaxies ~10^6 ly away. Each Cepheid has a pulsation period, meaning they brighten and dim over regular intervals, from which the luminosity is determined via the Leavitt Law. Type Ia supernovae are stellar explosions roughly 5 billion times more luminous than the Sun, making them extremely useful benchmarks for calculating extragalactic distances. The third "rung" builds upon the previous measurements, reaching Type Ia supernovae in galaxies hundreds of millions of lightyears away from Earth where the expansion of the Universe can be observed. The distances to these objects are determined from the luminosity (intrinsic brightness) and the apparent brightness.

The Hubble constant is then calculated using these distances and the redshift, inferred using the light spectra of wavelengths traveling from the object to the observer stretched by the expansion of space. The cosmic distance ladder Hubble constant was recently constrained to $H_0 = 73.04 \pm 1.04$ km/s/Mpc by the SH0ES (Supernovae and H_0 for the Equation of State of dark energy) team using the Hubble Space Telescope.[1]

The Cosmic Microwave Background Method

Contrary to the distance ladder method, which probes vast distances by building on increments of measurements starting closer to Earth, this method begins with a snapshot of the Universe captured in its infancy. The Big Bang, the rapid expansion of space from an extremely hot and dense state, occurred approximately 13.8 billion years ago. However, this event left behind a signature 380,000 years later—a sea of radiation that permeates the entire Universe (Figure 3). This leftover glow from the Big Bang is called the Cosmic Microwave Background (CMB) and its average temperature is 2.725 K (-270 °C), though it contains tiny temperature fluctuations. The CMB depicts the Universe as matter was able to cool and form into the first atoms.

How do we discern the Hubble constant from the CMB? We can crudely think of

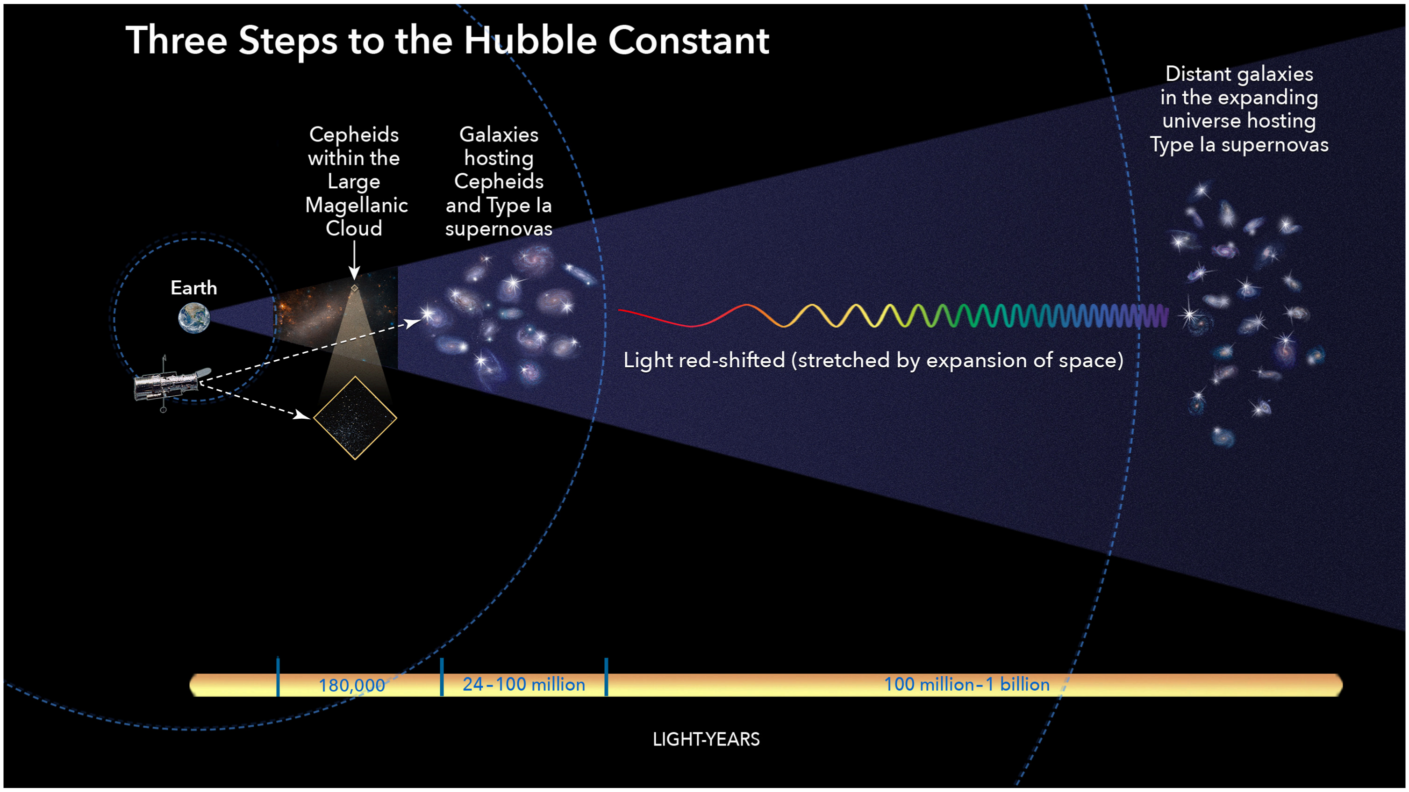

Figure 2: The three-step distance ladder is an indirect way of measuring vast extragalactic distances using Cepheid variable stars and Type 1a supernovae.

this like any equation with a set of knowns and unknowns. The CMB is known; it is observational evidence of the Big Bang theory. The other parameters: the contents and the expansion rate of the Universe, are variables and when put together, must be able to produce the CMB result, or in other words, must solve the equation. The contents of the Universe are described by the ΛCDM (Lambda Cold Dark Matter) model, which is the most widely accepted model of Big Bang cosmology. Three notable components of the ΛCDM model are dark matter, dark energy, and normal atomic matter. Essentially, the Hubble constant can be indirectly inferred by the best fit solution of the ΛCDM to the CMB observations. Recent results from the Planck Collaboration yield H_0 = 67.4 ± 0.5 km/s/Mpc.[2]

Both of these methods approach the Hubble constant from different angles and have been improved by significant advancements in observational techniques that have yielded more accurate and comprehensive surveys of the Universe. And while scientists have constrained each individual value within error bars of <1.1 km/s/Mpc, there has been no empirical progress to close the gap between them. This is the essence of the Hubble tension. However, in a study published in the Annual Review of Nuclear and Particle Science, scientists Marc Kamionkowski and Adam Reiss from Johns Hopkins University discuss a unique model of dark energy called early dark energy (EDE), which could be a factor in resolving the Hubble tension.[3]

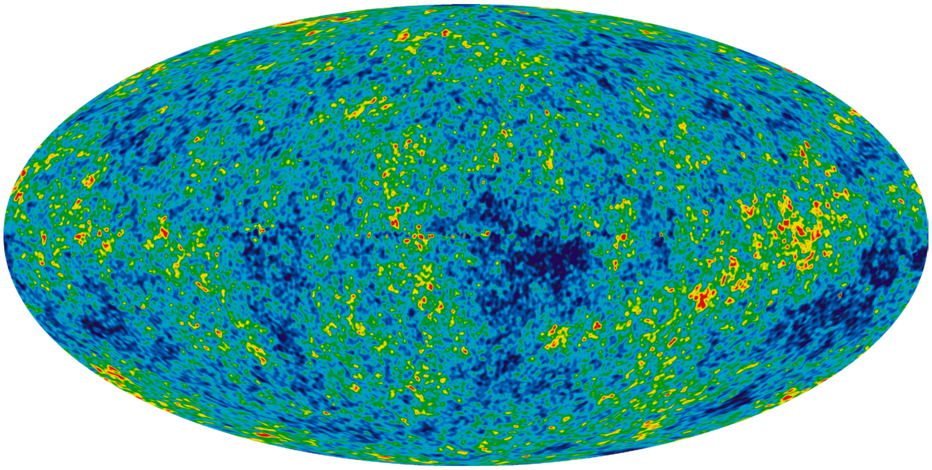

Figure 3: The Cosmic Microwave Background is a nearly uniform sea of radiation originating from the Big Bang. Temperature fluctuations are shown. Blue corresponds to colder regions while red corresponds to hotter regions.

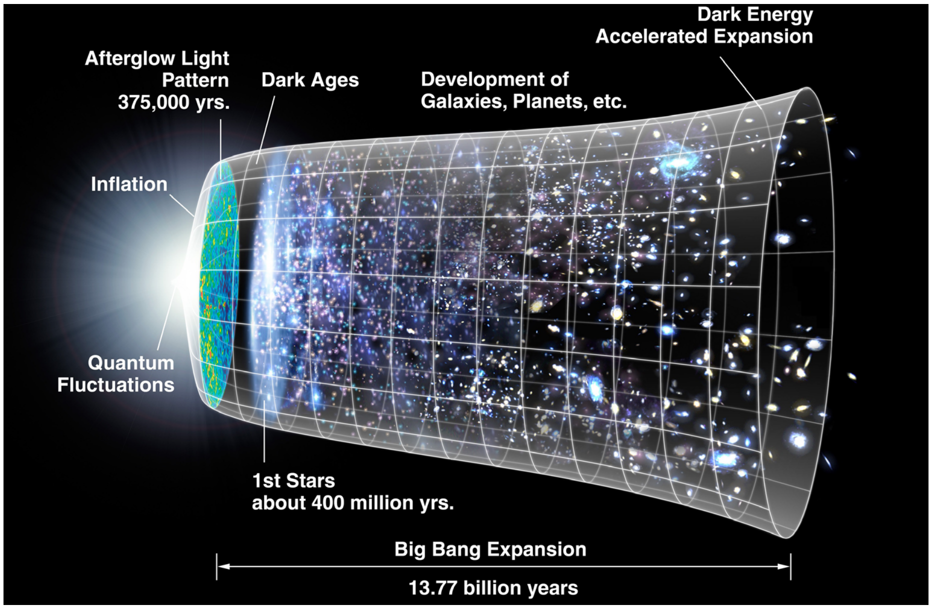

Figure 4: The different regimes of the Universe from the Big Bang to the present.

What is dark energy?

Let's return to the ΛCDM model. Normal matter actually only comprises around 5% of the energy density of the Universe. Dark matter, an invisible non-atomic substance that does not observably interact with the electromagnetic force, currently comes in second at 27%, while dark energy makes up the bulk of the universe at 68% of its energy density.[2]

Dark energy, with a name befitting its elusive nature, drives the accelerated expansion of space, causing galaxies to appear as though they are flying away from one another. Its physical qualities and particle nature (if any) are unknown. Consensus currently dates the beginning of the dark energy dominated regime of the Universe to about 5 billion years ago, which is why the expansion of the Universe is observed to be accelerating. However, dark energy, like the Hubble constant, only affects the Universe on the largest distance scales. For example, while almost all observable galaxies are moving away from us, our nearest neighbor, the Andromeda galaxy, is headed on a collision course with our Galaxy in 4.5 billion years.[4] Thus, the gravitational attraction between the Milky Way and Andromeda is strong enough to overtake the expansion effects of dark energy.

What is early dark energy and how is it different from dark energy?

Early dark energy affects the Universe with the same principles as dark energy; however, the key difference lies in *when* it dominates. Unlike dark energy, which dominates the late universe, early dark energy would alter the physics of the early Universe, the era between the Big Bang and the CMB (roughly the first 380,000 years).

Descriptions of the early Universe generally include atomic matter, dark matter, and radiation as the main crucial components. EDE would be an extra ingredient in this mixture, a catalyst for a burst of expansion that caused the hot plasma originating from the Big Bang to cool and form atoms faster. This would drive the Hubble constant—as determined indirectly from the CMB—closer to the results obtained via the cosmic distance ladder. This proposed EDE model would have comprised roughly 10% of the energy density of the Universe during this early period, then have rapidly decayed into matter and radiation.[3] This is a particularly intriguing solution to the Hubble tension because if EDE only dominates for a few hundred thousand years pre-CMB, it does not require making drastic changes to how we understand the Universe in its current regime.

At the present moment, early dark energy is a theoretical solution to the Hubble tension and certainly not the only possibility out there. Adding an extra energy component to the early Universe is a daunting prospect, however one could argue that it is no more daunting than the vast amount that is still unknown about the Universe. It is an exciting time for cosmology. As the Hubble tension becomes solidified from both sides of the aisle, it becomes clearer every day that there is a well of unknown physics waiting to be tapped.

Acknowledgments

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