Dark Energy and Cosmic Sound

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The Universe today is marked by a vast array of stars and galaxies. The galaxies themselves are not distributed randomly but are instead arranged into larger structures: galaxy clusters, super-clusters, and voids. One of the major goals in cosmology is to understand how the galaxies and the larger structures came to be.

The young Universe was much hotter and denser than today's Universe. At times within 400,000 years of the Big Bang, the Universe was sufficiently hot that all of the electrons were stripped out of the hydrogen atoms. The resulting state of matter is known as a plasma, and in this plasma, light is essentially trapped into the soup of electrons and nuclei.

Around 400,000 years after the Big Bang, the Universe cools to below 5000 degrees Farenheight, permitting the hydrogen nuclei and electrons to combine into a neutral gas. In this gas, the glowing heat of the universe is suddenly able to travel long distances, and indeed it travels essentially unabated to our telescopes, where we record it as the cosmic microwave background radiation. When we make an image of the cosmic microwave background (such as was done with the COBE and WMAP satellites), we are looking back 13 billion years and taking a picture of the Universe as it was at an age of 400,000 years.

This picture reveals that the early Universe was remarkably smooth, with density differences of only 1 part in 1000 from one place to another. This is very different from the Universe today, where the galaxies are a million times denser than the cosmic mean and even patches 50 million light years across vary by factors of two. Our standard theory for the mechanism for this growth of structure is gravity. Overdense regions attract their neighbors more than underdense regions, and so the overdense regions become slightly more dense. This process repeats itself, building the fluctuations from a part in a thousand to order unity and more.

However, in the plasma of the young Universe, the gravitational attraction of the overdense regions is offset by a different force, namely the pressure imbalance from the light and heat trapped in the plasma. This pressure is so large that density differences, which are thought to be initiated in the first second of the Universe, do not grow by gravity but instead oscillate like sound waves. This is analagous to the sound waves in air: overdense packets of air have more pressure and therefore expand, overshooting to become underdense with less pressure, and back again.

The early Universe creates sound waves of all wavelengths, but like an organ pipe picking up a resonant frequency, the end of the plasma era at 400,000 years imposes a fixed size and therefore selects a resonant wavelength. This preferred scale is spectacularly confirmed by observations of the microwave background, which find a characteristic scale for hot and cold patches of about 1 degree.

Equivalently, one can think of these sound waves as being emitted from initially overdense regions. A given location might begin overdense in both dark matter and gas. However, the overdense gas also has too much pressure, and as a result, a spherical sound wave is driven into the surrounding medium. In the first million years of the universe, this sound wave expands to a radius that *today* is 500 million light-years across[1]. After this first million years, there is a overdense region at the original location, because the dark matter hasn't moved much, and a small spherical ring of overdensity at 500 million light-years radius caused by the gas. Both of these regions begin to attract additional matter, such that by today, both are more likely regions to form galaxies. Of course, the Universe is composed of many overdense regions whose spherical waves have overlapped. If one region is like throwing a pebble in a pond and seeing the expanding ripple, then the Universe is like throwing a handful of gravel in pool. Nevertheless, the basic radius can still be detected statistically, and we predict that galaxies are slightly more likely to be separated by 500 million light-years than they are to be separated by 400 or 600 million light-years.

We have now detected this signature. Our measurements are based on a large sample of galaxies drawn from the Sloan Digital Sky Survey. Our map consists of 46,748 galaxies covering 9% of the sky and a volume equal to a cube 4 billion light-years on a side. The Sloan Digital Sky Survey has been collecting this data for over 5 years at a dedicated state-of-the-art telescope at Apache Point Observatory in New Mexico.

By demonstrating that this imprint of the early universe survives the 13 billion years of growth to exist in the clustering of galaxies today, we have confirmed the theory for the gravitational growth of structure.

However, this is only half the story. The physics of the sound propagation in the early universe is sufficiently simple that we can predict exactly what the resonant wavelength of sound is. This means that we know how big the signature we're detecting is supposed to be. By measuring the angular extent on the sky of the signature, we can infer how far away the galaxies in our sample must be.

The measurement of distance is a major problem in cosmology. Most types of astronomical objects, like galaxies, come in a wide variety of sizes and luminosities, so that when we observe one on the sky we are unsure as to whether we are seeing a small, dim galaxy nearby or a big, luminous galaxy far away. The expansion of the universe causes the distant galaxies to appear to be moving away from us, and we can measure this velocity very accurately with the Doppler shift of their light. We use the Doppler shift (or "redshift") to sort the galaxies into different ages. In the local universe, this leads to Hubble's famous relation that distance is proportional to velocity. However, this relation had always been expected to change at higher velocities because gravity should cause the expansion of the universe to change while the light propagated to us.

In the last six years, measurements of distant supernovae found that they were a little dimmer and hence further away than had been expected from their Doppler shift. This

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[1] Remember, the Universe itself is expanding. When we say that the sound wave expands, we mean that it expands relative to a set of positions that are themselves passively expanding with the Universe. It's like walking on a moving train.

required that the expansion of the universe wasn't slowing down in time, as one would get from an attractive gravity. Instead, the expansion is accelerating faster over time! Gravity on the largest scales somehow is repulsive.

There have been many proposed explanations for the acceleration of the universe — Einstein's cosmological constant, a new type of matter-energy, or a fundamental change to gravity itself — but all of them are stiff challenges to our standard views of particle physics. Indeed, the acceleration of the universe is probably the most profound observational mystery in current physics.

To try to diagnose the exotic new physics that is causing the acceleration, we need much more precise measurements of the cosmological distance scale. This is very difficult because the required accuracy is hard to prove. For example, perhaps supernovae are slightly different in the past than today?

By using the imprint of the early sound waves in our galaxy data, we can measure the distance to these galaxies using a simple geometrical test, namely the angular extent of a feature of known size. We find the same distance as had been found by the supernovae, which is important because it confirms this very important measurement using a completely different and highly robust method.

In the future, large surveys of more distant galaxies will measure the imprint of cosmic sound as a function of distance, thereby allowing us to map the expansion of the universe in more detail. This and other methods will give a detailed probe of the mysterious acceleration. Our detection here begins this program.