The Archeology of Relic Sound Waves

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Introduction

In this paper I review the role that sound played in the early universe and what information it can provide us today. Many scientists have worked on this problem in the past few decades, and many more in the past five years. What follows is a distillation of some of the essential points and results from this large body of work. I have found the recent article "Cosmic sound waves rule" by Daniel J. Eisenstein and Charles L. Bennett in *Physics Today*, p. 44-50, April 2008 to be a very well written resource in preparing this paper.

Sound in the Cosmos: Then and Now

Any student of physics can tell you, sound does not travel through the vacuum of space (thunderous exploding "Death Stars" in the movies aside). However, there was a time when sound waves filled the entire universe, and recent astronomical studies have found the imprint of these waves embedded in the fabric of the cosmos. The reason sound waves can exist in air and not a vacuum is that they are a sequence of regions where the air is slightly over and under the background atmospheric pressure. Because the molecules in the air are colliding more frequently in the high pressure regions, those molecules (on average) are pushed toward the lower pressure regions, somewhat like a row of falling dominoes. This is what causes the sound wave (or pressure wave if you like) to travel or propagate through the air. The speed of this propagation in air is around 334 meters per second or 772 mph. Now this is fast, but not so fast that you can not notice the lag between seeing a baseball player hit the ball and hearing the crack of the bat from the outfield. Of course in the near vacuum of space, molecules are too few and far apart to collide, like separating those dominoes by more than their height. This means there is nothing to drive a sound wave to propagate, so sound can not exist in space as it stands today.

However during a period in the early evolution of the universe known as Inflation, the state of things was quite different than it is today. Soon after the Big Bang, matter in the rapidly expanding universe was so hot that all the electrons were separated from the atoms, forming a state of matter called a plasma. In addition to all these free charges flying around, there was also a copious amount of light which can be thought of as little bundles of energy called photons.

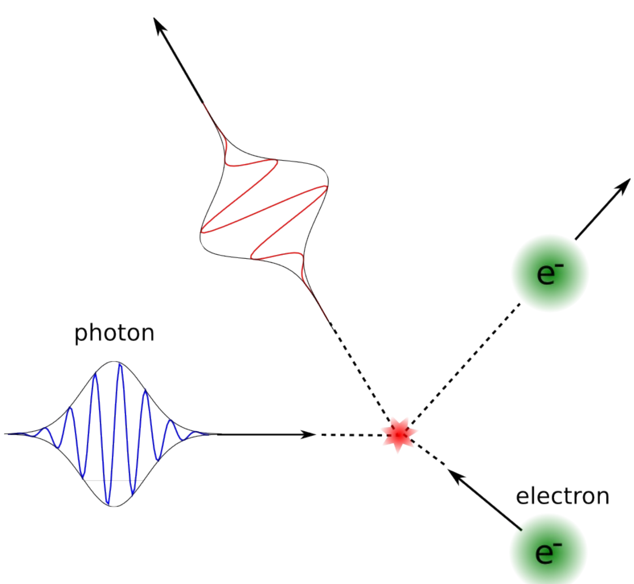

Figure 1: Collision of light (a photon) and an electron. These collisions created pressure which allowed for the existence of sound waves.

Now a curious result of quantum mechanics is that light (photons) have *momentum*, even though they do not have any mass. This means a photon can collide with an electron and they can exchange momenta, like two billiard balls colliding. In physics, this is known as the Compton effect. [See Figure 1] Millions of these collisions give rise to a sort of pressure known as *radiation pressure*. So now we have a way for sound, in the sense of a propagating pressure wave, to exist in the early universe. The source of these cosmic sound waves was small fluctuations in energy which originated VERY shortly after the Big Bang, the nature of which is not really understood but is deeply rooted in the mysteries of quantum mechanics and general relativity. We do know however that these sound waves traveled very fast – a little over ½ the speed of light!

Death of a Cosmic Sound Wave

So how did we get from a universe filled with sound to a silent one? The switch over occurred quite suddenly. As the universe expanded and cooled, eventually the electrons were captured by the nuclei to form the sort of electrically neutral atoms of which we are all made – an event known as Recombination. At this point, the number of free electrons zipping around colliding with photons dropped by a factor of 10,000, thus dropping the radiation pressure. This essentially made it impossible for sound to propagate anymore. A fascinating aspect of this sequence of events is that the little fluctuations in matter and energy pressure at the moment of Recombination were "frozen" in time. It's a bit like throwing a handful of pebbles in a pond, watching the chaotic ripples travel along, forming patterns on the surface, and then flash freezing the pond. [See Animation 1] NASA has built an instrument that can see the imprint of these relic sound waves in the form of tiny fluctuations in the general microwave background, temperature in a sense, of the night sky. This instrument is called the Wilkinson Microwave Anisotropy Probe or WMAP and has been making measurements for the past five years.

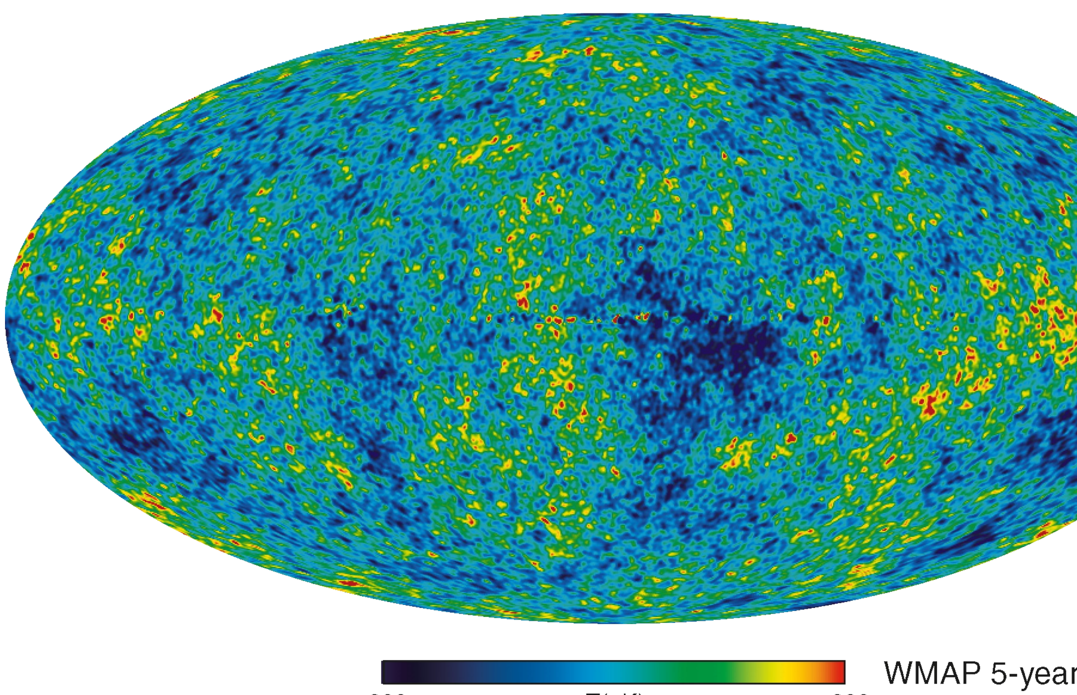

Figure 2: Temperature fluctuations in the night sky as measured by the NASA WMAP. The fluctuations are tiny, but unlock a great deal of information. [courtesy of NASA WMAP Science Team]

Interpreting the Map from WMAP

Figure 2 shows a map of the night sky with the tiny fluctuations in temperature color coded on it. This map captures the over and under pressure regions in the universe at the moment of Recombination and reveals a great deal of information. Looking at the map, one might notice that the sizes of the "hot" (red) and "cold" (blue) pockets are not random, but appear to have a characteristic size. The size of these pockets is determined by the distance a sound wave traveled from it's inception at the Big Bang until the waves were frozen at Recombination. Figure 3 shows that this characteristic size looks about 0.6º wide to us, which translates into about 480 million light-years across in the today's universe. The red curve in the graph below is a mathematical model with parameters that can be adjusted to best match the observations, thus providing good estimates for the values of those parameters. And here lies the real power of understanding the relic acoustic waves that once filled our universe.

The universe is much more than meets the eye

When one looks up on a clear night sky, there seems to be an infinite number of stars out there. It turns out that careful observations and calculations by astronomers and cosmologists have shown that there must be much MORE "stuff" out there than we can see – that is, matter that does not give off light. This so called *cold dark matter* has mass like regular matter, but does not interact with light and is not bound together with the same fundamental forces as normal matter. One of the parameters mentioned above is the ratio of this strange dark matter to normal matter in the universe, and the model fits to the acoustic oscillations tell us that there is almost exactly *five times* as much dark matter as normal matter! Moreover, cosmologists have known that the rate of expansion of the universe is larger than the contracting pull of gravity should allow. The cause for this extra expansive boost has been termed *dark energy*, which is very far from being understood. However the acoustic oscillations revealed by WMAP are emerging as one of the primary tools for unlocking the mysteries of this significant component of our universe.

It is easy to see why the WMAP project was declared the scientific *Breakthrough of the Year* in 2003. This is an exciting and dynamic time in cosmology with ever more detailed measurements of the texture of these ancient sound waves providing insights that continue to revolutionize our understanding of the structure and evolution of our universe.

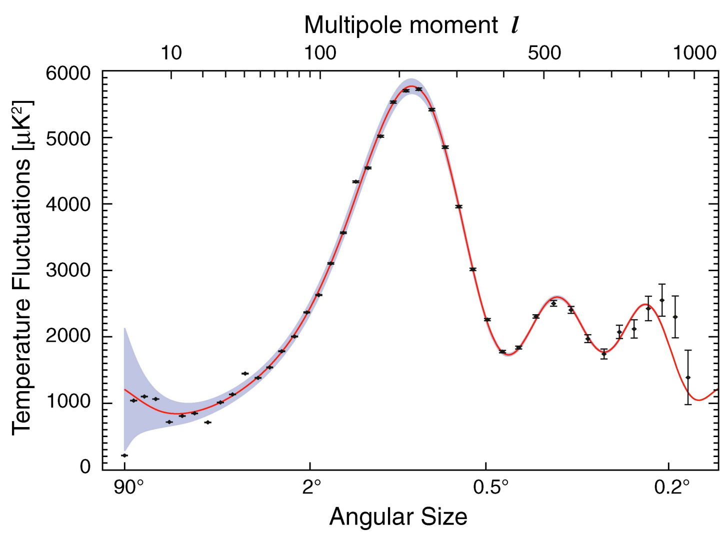

Figure 3: A graph of the intensity of temperature fluctuations for different sizes (measured by angles). The big hump around 0.6º (or 480 million light years across) came from the earliest sound waves. [courtesy of NASA WMAP Science Team]

Animations
The following animations were created by the NASA WMAP Science Team and can be found on their website (listed below in the references).

Animation 1: Cosmic Ripples
An analogy between traveling sound waves in the early universe and ripples on a pond generated by throwing in some pebbles. It then relates these ripples to the what is seen in the WMAP data shown in Figure 2.
[Link: http://map.gsfc.nasa.gov/media/030658/index.html]

Animation 2: Universe Evolution
This animation illustrates the evolution of the universe after the end of the sound era at Recombination. It shows how the pockets of higher matter density (or pressure) at that time eventually evolved into the clusters of stars and galaxies we see today.
[Link: http://map.gsfc.nasa.gov/media/030651/index.html]

A Few References
Images and animations used in this paper can be found at the NASA WMAP website:
http://map.gsfc.nasa.gov/

A good review article is:
"Cosmic sound waves rule" by Daniel J. Eisenstein and Charles L. Bennett in *Physics Today*, p. 44-50, April 2008.

Official technical paper of the latest WMAP observations:
G. Hinshaw, *et al.*, "Five-Year Wilkinson Microwave Anisotropy Probe Observations: Data Processing, Sky Maps, and Basic Results", Astrophysical Journal Supplement, in press (2008).

Acknowledgments
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