

BIG BANG ACOUSTICS – SOUND IN THE EARLY UNIVERSE

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Despite its title – “The Big Bang” – the modern scientific description of creation has, until recently, been paradoxically lacking in any acoustic content. The original term was coined by Fred Hoyle in 1950 and refers to the “explosive” quality of the Universe’s early expansion, rather than to sound itself. As the decades passed, many other qualities of creation have been studied, and even popular accounts now bring them to life – the enormously high temperature and density of the first moments; the sequence of eras – quark, hadron, lepton, radiation, matter – which track the changing content; moments of cathartic transition, as matter and antimatter annihilate, as thermonuclear fusion turns hydrogen into helium, as the Universe turns transparent. Creation, it turn out, is wild and wonderful, and the modern story is rich and fascinating. But the scenes described have all been silent ones.

Why has sound been such a latecomer to the story? Because sound involves variations in properties from place to place. As with many branches of physics, understanding average properties is much easier than understanding perturbations. But with the average properties now well understood, there is growing interest in perturbations, of which sound is a particular kind. Why are perturbations and their growth so important? Because they take an initially smooth Universe and turn it into the incredibly lumpy Universe of today, with its stars and galaxies dotted throughout an ocean of vacuum. Primordial sound, then, plays a crucial role in the origin of all structure – without it there would be no galaxies, stars, planets or people.

The full story of the growth of perturbations is fascinating and complex, and too long a tale to tell here. But given the readership of Echoes, let’s zero in on some of the more overtly acoustic aspects of the story. A more complete account, which is aimed at a popular audience and which includes all the associated sounds, can be found on my website at <http://www.astro.virginia.edu/~dmw8f>.

First, the observations. The picture (minus the ear!) shows the full sky as seen by NASA’s microwave telescope, WMAP. These microwaves have been travelling for almost 14 billion years and they provide the most distant and ancient picture of the Universe we have – dating from 380,000 years after the Big Bang (for a human, that’s just 12 hours after conception). The image is contrast stretched to show very slight patchiness in microwave brightness, which in turn traces variations in temperature and pressure. Hence, these patches are (mostly) peaks and troughs of sound waves moving through the hot glowing gas (the bright optical glow is converted into microwaves by the enormous redshift associated with Universe’s expansion).

Choosing $\Delta P/P$ as our measure of loudness, the peak pressure variations are about 0.01% or roughly 110 dB – rock concert volume! Despite the relatively fine scale of the acoustic patchiness, the enormous distance to the microwave sky implies giant wavelengths – up to 200,000 light years. Thus, even with a very high sound speed (60% light speed, see below), the frequencies are incredibly low, about 10^{-12} Hz, and they only become audible to humans after an up-shift of about 50 octaves. This is as one might expect, an object as vast as the Universe

itself does indeed have an exceedingly deep voice. Perhaps the most remarkable feature of these primordial sounds is that their spatial power spectrum shows a fundamental and harmonics! In some sense, the Universe acts like a resonator – though a rather poor one, since the harmonics are quite broad and the sound is more like a roar than a note. Why should there be any harmonics? Whereas a normal resonator selects its preferred modes of vibration by being spatially bounded, the Universe is unbounded spatially but bounded temporally – it has a finite age. At the time of the microwave sky, harmonic peaks in the spatial power spectrum denote regions which have experienced an integral number of oscillations since the Big Bang – they are caught at phases of maximum compression/rarefaction. Interestingly, because gravity also affects sound production, the amplitudes of the odd (maximum compression) harmonics grow faster than the even (maximum rarefaction) harmonics, and ultimately only the odd harmonics survive – indeed, one can even detect in the present day tapestry of galaxies the faint residual signal of the first (odd) harmonic coming from those early times.

What kind of fluid do the pressure waves move through? Nothing like our atmosphere! At the time of the microwave sky, the temperature and density have dropped to just 3000K and 100 protons and electrons per cubic centimeter at a pressure of a tenth of a femto-bar. Prior to this time, the gas is sufficiently hot to be ionized and is therefore opaque, or foggy. Since the Universe was also immensely bright, does light, trapped in the fog, affect the propagation of sound? It most certainly does! With a billion photons per proton, light’s pressure is a billion times greater than the gas pressure, and the sound waves are really waves in the pressure of light – great surges in brilliance, which course through the glowing fog. In fact, light is so dominant that it contributes significantly to the total density, and so the speed of a pressure wave is almost that of a purely relativistic gas, namely $c/\sqrt{3}$ or about 170,000 km s⁻¹. This is indeed an unusual fluid!

For terrestrial sounds, there is always a driving mechanism – the air blown across the flute, or the stick which strikes the drum. What drives the primordial sound? The kneejerk thought that “the initial explosion was simply a big BANG”, while superficially satisfying, fundamentally misunderstands the nature of creation. First, the expansion is really an expansion of space, not an expansion into space. Second, the expansion is pure and “radial” – each location moves away from its neighbor location, so no part is catching up any other part, so there are no initial pressure waves. Creation, it turns out, was utterly silent. However, for reasons we’ll get to, the early Universe was not entirely smooth – there were slight variations in density from place to place. Now imagine a region adjacent to a density enhancement – a gravitational “valley”. This region is born on the brink of falling down into the valley – which it soon does, at the speed of sound. As it falls in, it becomes compressed, overshoots equilibrium, heats, gets brighter, and the radiation over-pressure pushes the fluid back out; where it overshoots again, cools, loses its pressure, so falls back in again. In this way, gravitationally driven standing pressure waves form and grow. Gravity is the driver, and the naturally undulating “landscape” provides a set of cavities within which sound is generated.

What shapes the landscape? Whatever dominates the density. For the first 50,000 years light is dominant, and we have a peculiar situation in which the mass carried by sound waves provides its own driving force. Later on, as light’s density wanes, the dominant substance becomes “dark matter” – about which we know very little, except that it behaves like a transparent dense pressureless fluid. Its own self-gravity causes concentrations to grow, and as the atomic gas falls into these concentrations its sound volume steadily increases. Ultimately, when the

fog clears and the gas can finally move freely, it falls into these concentrations and collapses to make the first generation of stars.

Let's now track the evolution of sound pitch. There is a curious phenomenon associated with times shortly after creation: history is finite, and processes that require time to develop cannot occur until sufficient time has elapsed. For example, the gravitational creation of sound across a valley 1000 light years in size can only occur after the Universe is 1000 years old. Why? Because it takes at least this long for gravity's pull, travelling at light-speed, to cross the region allowing it to "wake-up" and respond to its own gravity. This gives an interesting quality to the primordial sound: as time passes, its pitch drops as longer waves are added to the mix. In the recordings I have made, this is clearly heard as a descending scream.

Of course, there must be more to the story. Why was the Universe born slightly lumpy? What carved out the initial landscape, with its hills and valleys? This question has proved a tough nut to crack, though cosmologists are beginning to feel they have the answer. It seems that in the exceedingly early Universe, quantum fluctuations of space-time were amplified by an extraordinary period of exponential expansion, called inflation, driven by energy released when the vacuum relaxed from a higher to a lower energy state. The cosmic roughness is therefore a relic of quantum roughness deep the sub-atomic world, writ large by inflation's amazing amplifier. This is a truly bold idea, that all structures, from stars to galaxies to the cosmic tapestry, arise more or less directly from the ghostly world of quantum foam.

Let's pursue these initial moments one step further. Although it takes time for sound to get started – first short waves, then longer ones – that delay is just a quirk of a Universe with a finite past. One can imagine cheating time and releasing all wavelengths at once, creating the "sound" of the initial landscape – the sound of that first rich silence. This is a holy grail in cosmology – the so-called "Initial Power Spectrum" – since it embodies essentially everything that is to come. What did it sound like? Was it melodic, harmonic, beautiful to our ears? No! It was pure noise. The initial power spectrum is a featureless powerlaw: $P(k) \propto k^n$ (k is the wave vector, $n \sim 1$) which produces a formless "hiss". On reflection this is just as it should be, since no scale is yet preferred over any other, and so no "features" are introduced to the power spectrum. Furthermore, with an index $n \sim 1$, this spectrum has the remarkable property of creating structures on all scales – from stars to galaxies. Even if it wasn't "music" to our ears, Nature certainly made an extremely wise and creative choice.

Let's end by looking at why Big Bang Acoustics has received so much attention, quite apart from the fun of "listening" to creation. One hardly needs to mention to readers of Echoes that the sound an object makes contains a massive amount of information about the nature of the object. So too with the Universe. Like a struck bell, the Universe was subject to an initial noise-like perturbation, to which it responded and continues to respond 14 billion years later. As with any material object, the response can be studied using power spectra which, in the case of the Universe, we can observe at two times: today in the cosmic tapestry of galaxies; and 380,000 years after the Big Bang, in the microwave sky (the latter is the richer source of information because all the oscillations are still linear and the physics of the fluid is well understood). Now, in close association with the observational developments, theorists have been constructing highly sophisticated computational models of the evolving perturbations which include most of the relevant physics. As in many sciences, one can study reality by matching model calculations to observations. In practice, cosmologists add three other datasets to the two acoustic ones,

and from these they have been able to derive high precision (2-10% accuracy) measurements of such quantities as the Universe's age, geometry, expansion history, composition, and other, more abstract, properties. Impressive though this is, it is the basic agreement between the theoretical models and the observational datasets which provides such a powerful indication that the overall framework must be close to the truth.

Modern cosmology is in a golden era. Each decade sees great strides forward, in both observations and theoretical understanding. While there are sometimes wonderful surprises, it really does seem that a coherent and detailed picture is emerging. The most recent and exciting contribution has undoubtedly come from the power spectrum of the microwave sky. Remarkably, this yields to a sophisticated acoustic analysis, which in turn has provided some of the most precise measurements of cosmic properties to date.