The Sounds of the Universe
Transcript

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Professor Carolin Crawford

Introduction

Astronomy is a very visual subject. We're all familiar with – and captivated by – the stunning images of stars, nebulae and galaxies from both ground-based and space-based telescopes, or pictures direct from the surface of Mars taken by robotic spacecraft. But vision is only part of the whole human experience. In this talk I am going take a different approach to appreciating the universe, through the sense of sound. Astronomers have long realised that sound waves are 'out there', and that they play a part in the physical processes going on in space. But it's only over the last twenty last years or so that the various roles of sound in space has been recognised and actively pursued in astronomical research.

In this talk I'll be looking at how:

• Sound can be used a diagnostic of cosmic phenomena, indirectly tracing the behaviour of astronomical objects: whether the presence of lightning on Jupiter, or the physical structure inside distant stars.

• Sound can itself be an important physical process, capable of transferring significant amounts of energy across vast volumes of space; for example, the transfer of energy from a black hole out into a surrounding cluster of galaxies.

• Sound can be used to convey and illustrate some aspects of astronomy very effectively, particularly radio signals converted into sound. It's much easier to appreciate features of a signal like the variation in its frequency, or detect the pattern of a repeated beat by 'hearing' it.

Warning

One should be clear at the start that hardly any of the sounds I'll play can be straightforwardly heard. We don't detect astronomical sound like we do most noises here on Earth, and even the most sensitive microphone will be useless. There is only one sound that included in this lecture that one could actually hear exactly as it will be played. Even the real astronomical sounds I feature have a far lower pitch than anything we could hear, and so have been speeded up (sometimes by enormous factors) to be made audible. In addition, I should re-emphasise that some of the sounds I'm going to play for you never existed as sounds in the first place. They are conversions to sound of natural radio signals which are part of the electromagnetic spectrum, and thus a form of light, or are representations of periodic phenomena converted into sounds so they can be appreciated.

Some Introductory Physics of Sounds

We are often told that there is no sound in space; this is not entirely true. Sound needs to travel through something, as (unlike light) it works by the compression and rarefaction of a medium, such as the air in this room. All you need to create a sound is a vibration that pushes on the air, squeezing it together slightly in one place. The higher pressure in this region then pushes onto the gas immediately next to it, squeezing it to be at higher pressure just as the first region relaxes back. If the original disturbance repeats itself rhythmically, we end up with rippling waves of pressure spreading out and away from the source. These are a sound wave.

In order that you can hear the sound of my voice, many things have to happen. The air expelled from my lungs passes over my vocal cords, making them vibrate, and the speed of vibration is controlled by surrounding muscles which can open/close/stretch the cords. These vibrations push on the air just above them, are amplified in my mouth, and then carried out through the air to your ear. As the vibrating air molecules strike your eardrum, the oscillations of this membrane are amplified in the middle ear, and transformed into nerve signals by the cochlea before they can be interpreted as sound by your brain.

Note that the individual particles taking part in a sound wave don't move far at all, they just oscillate to and fro, as its more a case that the wave moves out through the particles. A simple analogy is to a Mexican wave, where in a packed audience – such as those in a sports stadium – each successive column of spectators briefly stands and raises their arms before promptly sitting back down again. Even though no one person has moved from their seat, a wave signal has travelled right along the side of the stadium. In the same way, a sound wave is a disturbance spreading through space by particles which don't individual move much; and it carries energy with it.

We characterise waves in a number of ways, the simplest of which is the wavelength, measured as the distance between two successive compressions or rarefactions. We also use the term frequency, particularly in the case of sound, to specify an exact note being heard, as it tells how densely packed the compressions or rarefactions are. For sound waves travelling at the same speed (and note that the speed of sound depends on the physical properties of the medium it travels through, such as its density and temperature), it's how many such 'cycles' travel past you per second. In a wave with a short wavelength, many more cycles pass by you than would if it had a longer wavelength, so it is said to have a higher frequency. Waves with a long wavelength have a low frequency. Our ears detect sounds with a frequency between 20 to 20,000 such cycles per second. There are, of course, are many more sounds that are inaudible to us, because their frequency is much higher or lower than this range.

So every sound requires a medium to carry it. Sound does thus not travel though a vacuum; but few regions in space are a complete vacuum. There is matter lying between the stars – and even between galaxies – in space. These may not form an ‘atmosphere’ as we would obviously recognise it, as such regions are at much lower densities than we ever experience on Earth. The air molecules in this room only occupy about 1/1000 of the space – the rest is nothing – meaning the molecules are separated by about 10 times their size. Atoms of the interstellar medium are spaced at a separation more like 10 million to their size. But so long as there is some kind of atmosphere, even a very sparse one, there is a medium though which sounds waves can be carried. The subtlety is that not all notes can be transmitted.

In order for an original disturbance to produce a sound, the particles it pushes on need to travel far enough to successfully collide with more particles. If the material is densely packed, the smallest of displacements will start propagating a sound wave through the medium. But if the medium is sparsely populated, small displacements will not have any effect. The only sounds that will successfully propagate are where the wavelength of the sound is longer than the mean distance between particle collisions. So in the interstellar medium, where the particles are widely spaced, only very long wavelength / low frequency sounds can carry. Yes, in space no one can hear you scream; the wavelength of the sounds that a human produces is too short to be transmitted. But there are still sounds in space.

Whistlers on Earth and Jupiter

Credits: Don Gurnett, University of Iowa / European Space Agency / NASA VLF information at www.spaceweather.com

Even within Earth’s atmosphere there are natural radio emissions all around us that we are unaware of, but which can be detected and readily converted into sounds using a radio receiver. We can very obviously hear the dramatic sound of thunder that accompanies a lightning strike, but the electrical energy generated and flowing through the clouds in a strike also sets up electromagnetic waves of radiation. In the visible wavebands this emission manifests as the flash of lightning; but radiation is also produced right down to very low frequency radio waves. All lightning strikes emit short snappy/popping signals called sferics (short for ‘atmospherics’), which can be picked up by radio receivers within several hundred kilometres. To travel further from their point of origin, sferics can be carried through the upper ionized layers of our atmosphere known as the ionosphere. This disperses the signal, so that the lower frequencies travel slower than the high frequencies. As a consequence, not all frequencies arrive at their destination simultaneously, and the sound gets distorted into something called a tweek. But there is a very distinctive radio signal generated by a sferic that has been dispersed more widely into a whistler.

Rarely lightning strikes can occur high up between clouds rather than reaching down to the Earth. Many of the radio waves generated in such a strike are directed to travel away from the earth and into the ionosphere, where they are guided along and back down to the Earth along magnetic field lines. On this much longer journey, the radio frequencies are very widely dispersed so that the high frequencies arrive at a destination first, followed by successively lower ones to produce a characteristic falling/descending tone that lasts a few seconds and that is known as a whistler. All sferics, tweeks and whistlers are examples of ‘natural radio’ emission that has been converted into a sound signal so we can appreciate them, and they vary on the same timescale as heard. As whistlers are produced by radio waves propagating a long way along the Earth’s magnetic field, they are carried between Northern and Southern hemisphere. Thus a lightning strike in Africa can generate whistlers detected in the UK, or vice versa. The study of whistlers enables scientists to gather information about the earth’s ionosphere and magnetosphere over long distances.

Of course the Earth is not the only place in the Solar System that has storms. There are much stronger, dramatic storms in the atmospheres of the gas giants, such as the Great Red Spot on Jupiter, along with many other smaller, hurricane-style storms. These storms create lightning, particularly deep in the lower cloud layers containing water ice. The Galileo spacecraft took images of the night side of Jupiter, where the upper layers of clouds dimly reflect the light off Jupiter's moon Io and you can see bright flashes of lightning strikes some hundred or so km below. But long before such direct pictures of lightning on Jupiter were taken, scientists knew it was present in the clouds from the detection of whistler radio signals by the Voyager 1 and 2 spacecraft. It’s a much noisier signal, but the characteristic falling tone is apparent.

Radio Signals from Aurorae

Credits: Don Gurnett, University of Iowa / European Space Agency

All natural radio signals are created by moving charged particles, which can of course originate from sources outside of our atmosphere. One very strong source is the Sun, which emits a wash of charged particles such as energetic protons and electrons from its upper layers in the ‘solar wind’. This wind continually replenishes a very thin atmosphere known as the interplanetary medium, which fills the space between the planets in our Solar System. Its average density is only a tiny fraction of that of the Earth’s atmosphere, at only about 400 particles per cubic centimetre. The charged particles of the solar wind perpetually rain onto the upper atmosphere, although most are deflected away by the shield of Earth’s magnetic field. Occasionally – and particularly if the Sun is active – some of the particles leak into the magnetosphere, where they are then guided along Earth’s magnetic field to reach deeper into the atmosphere. Here they collide with the oxygen and nitrogen molecules of the air, to produce a luminous green and red glow that is the aurorae (Northern or Southern lights), most easily observed at polar latitudes, where the lines of magnetic field are concentrated and directed down. The moving charged particles that create the northern lights also produce intense radio emission at very low frequencies. We can 'hear' the aurorae as a busy chatter when these radio signals are converted to sound, again varying on the real timescale that you can hear.

The Earth is, of course, not the only planet with a strong magnetic field and aurorae. There are very complicated interactions between the solar wind and the magnetospheres of the giant planets Jupiter and Saturn, which can cause hydrogen molecules to fluoresce to be detected as aurorae at the poles in UV light. These aurorae are also accompanied by radio signals. Saturn is a particularly strong source of intense radio emission, which has been detected by scientific instruments on the Cassini spacecraft, and which displays an incredible range of variation in frequency and time. In this instance the frequency of the radio emissions convert to sounds that are above the audio frequency range, so have been slowed by a factor of 260 to be made audible.

<u>Cassini Crossing Saturn's Rings</u>
Credit: European Space Agency
In my last lecture I detailed some results from the international Cassini mission that has been closely studying Saturn, its moons and rings from close orbit since 2004. As part of the manoeuvre to put it in orbit around Saturn, the spacecraft had to move through Saturn's rings twice, using the largest of the gaps in the rings as a passage. Such 'gaps' are not really empty, but still contain millions of tiny solid particles, comparable in size to particles of cigarette smoke, and Cassini ploughed through them at a relative speed of around 20 kilometres a second. Its dish antenna was turned to face the direction of travel so it would act as a protective shielf (a successful move, as no damage was done to the spacecraft or its instruments). One of the onboard science instruments recorded the rate of dust impacts onto this antenna, which reached a maximum of about 700 hits per second. Scientists at the University of Iowa have then converted the rate of these impacts into audible sounds that resemble hail hitting a tin roof.

<u>The Winds of Titan</u>
Credit: European Space Agency
One of the first things that Cassini did after arriving at Saturn was to jettison the Huygens probe to parachute down through the smoggy methane atmosphere of Saturn's largest moon, Titan. A small microphone on the outside of the probe recorded the descent, primarily the sound of the winds in the atmosphere rushing around it as it fell. From the drift of the probe, the speed of these winds has been estimated at around 6-7 kilometers per hour. This is the only sound I shall play you in this lecture that you would hear like this if you were actually there. The sound of the wind quietens as the probe nears the ground, ceasing completely as the little spacecraft settles to the surface to become the furthest human-made object landed on the surface of a Solar System body.

This is such a simple experiment to undertake, you may wonder why it's not been done before! Well it's been tried – originally with the 1999 Mars Polar Lander, which unfortunately is one of the (many) missions that didn't make it to the Martian surface. The later Phoenix lander to Mars also had a microphone installed, but it was never deployed during its mission. So far, no spacecraft has successfully captured the sounds of Mars, but hopefully this will be achieved in the not too distant future. We can expect noises on Mars to sound similar to those on Earth, but more muted, as the Martian air is a 100 times thinner and so with fewer particles to carry the sound. The atmosphere is also at much lower pressure, lowering the sound speed, making all sounds carry at a lower pitch than if they were heard on Earth.

<u>A Humming Sun</u>
Credit: Alexander Kosovichev, Stanford University
Apart from its role in creating the interplanetary medium, the Sun is itself a humming ball of sound waves. The Sun is a star - not a solid body, but a large sphere of turbulent hot plasma. Nuclear fusion reactions deep in its core generate phenomenal amounts of energy. Material lying above the core is heated, and then rises steadily up through the cooler outer layers of the Sun as large streams of hot plasma. As these rivers reach the Sun's surface they cool, sinking back down to form a convection cell, in the same way that water boiling in a saucepan moves energy from where the heat is applied at the bottom of the pot to the cooler surface. In the Sun, however, these cells are thousands of kilometres across.

The continual turbulent convection motions inside the star set up vibrations and thus sound waves. When these strike the surface of the Sun, they make it oscillate in and out, in the same way that striking a bell or gong will cause it to vibrate and ring. Here, however, the vibrations are not caused by a single strike, but continuously occurring small strikes, and the difference to a bell or gong is that these sound waves are generated internally rather than externally. Reflected by the surface of the sun, most of them remain trapped inside the star. Under the influence of these continual small strikes, the surface of the Sun moves to and fro in a periodic fashion. The velocities of this motion are small, only about 15-20 cm/s, but can still be tracked by the Doppler effect, whereby a slight change in the spectrum of the light can reveal how fast the emitter is moving towards or away from you. Astronomers use precise measurements of these surface motions as a powerful diagnostic of the internal structure of the Sun. The sound waves start close to the surface and propagate downwards into the Solar interior; but deeper in the Sun, the physical conditions change. Most obviously, the temperature increases, which in turn increases the sound speed. Thus waves will move faster the deeper they penetrate, and the resulting refraction of sound waves slowly bends their path around so that they turn back to head back out to the surface before reaching the centre of the Sun. At the surface the sound wave is reflected as if by a mirror to be redirected back down. Hence small variations in the original direction of propagation direct different sound waves to penetrate to different depths in the Sun.

There are many possible curved paths that the sound waves can follow through the Solar interior. The longest wavelength/period tones sample the region deep down towards the core, while higher frequency tones rattle around the layers closer to the surface. The resonant frequencies detected are thus determined by the way that physical conditions change in the interior of the Sun. For example, if you have two oscillations of slightly different frequencies, the lower frequency penetrates a little deeper into the Sun on its journey than the higher frequency waves. The difference in frequency between the two oscillations therefore says something about that region of the Sun that only the lower frequency wave passed through. Scientists examine the vibration of the sun's entire surface at once, sorting out the individual patterns and amplitudes of the all the resonant vibrations. This is not a trivial problem, as there are over 100,000 oscillations all happening at the same time! But by determining which frequency of sound wave went through which part of the Sun, it is possible to establish what the sound speed is in every part of the Sun that the sound waves have passed through, and so assemble a detailed picture of the physical conditions in the solar interior. By monitoring the Sun's vibrating surface, 'helioseismologists' can probe the stellar interior in much the same way that geologists use seismic waves generated by earthquakes to probe the inside of our planet. It is considered the best method for verifying theories of stellar structure and evolution of the Sun.

Although these vibrations of the Sun are genuine sounds, their frequencies are much too low for the human ear, and they can be made audible only by speeding them up some 42,000 times; 40 day's worth of vibrations (monitored by the SOHO satellite) need to be compressed into a few seconds.

<u>Asteroseismology</u>
Credits: Kepler spacecraft mission / Aerts et al, European Southern Observatory
Helioseismology is comparatively easy as the Sun is the brightest thing in the Sky. Extending this science to other stars has had to await advances in sensitive instrumentation. Observations of a star's colour and brightness can be easily related to its temperature and brightness, and show that there are many stars very different from our Sun. However, the only way to understand the internal structure of a star is through asteroseismology. As they're much further away, the light from other stars is much fainter than that from the Sun, so detecting the vibrations provoked on their surface is much harder.

Over the last few years this science has been greatly assisted by a satellite currently in orbit around the Earth known as Kepler. Its main purpose is to detect planets around other stars, by timing the tiny but regular dimmings of a star's brightness that could be caused by the silhouette of a planet moving across its disc. But it is also sensitive to the rhythmic variations in brightness caused by stellar sound waves, and is currently gathering information on many stars, with potentially enough to allow more statistical studies of intrinsic stellar properties over a wider range of physical properties such as mass, age or luminosity. Such observations will allow astronomers to much more closely constrain theoretical models for the inner structure and evolution of stars considerably unlike our Sun.

So there are other stars we can listen to, for example:

• ALPHA CENTAURI A is a member of the binary star system which are the next closest stars to the Sun (after their likely companion Proxima Centauri). It's very similar to the Sun in age, and only slightly larger in mass, radius, luminosity, rotation and temperature.

• HD 49933 is another Solar-like star, but slightly larger in mass and radius; it's hotter and brighter – and much younger, at an age of only 2.4 billion years

• XI HYDRA is very different, at ten times the width and sixty times the luminosity of the Sun. Although the movements of the stellar surface are larger, the soundwaves take much longer to travel through the stellar interior and up to the stellar surface than they do in a solar-like star. The movement of the surface is slower, and thus more difficult to detect, and it displays oscillations with several periods of around 3 hours.

<u>Pulsars</u>
Credit: Andrew Lyne, Jodrell Bank
There are even stranger types of star in our Galaxy whose behaviour can be illustrated best through sound, and these are a particular class of neutron stars known as pulsars. When a massive star runs out of fuel to feed the fusion reactions at its core, it can no longer prevent its eventual collapse under self-gravity. The outer layers are blasted into space in a supernova explosion, leaving the central core to collapse down and become packed so tight that individual atomic nuclei are broken down. The electrons and protons are squeezed together to form neutrons. However, neutrons resist being squeezed too tightly, and exert an outward pressure that is able to stem the inward pull of gravity. At this point matter is so tightly packed that one teaspoon of neutron star material weighs about a billion tons. The original star will have had a radius of a few million km, yet much of its bulk is now packed down into an object only a few tens of km across. The star would also have been rotating, and be laced through with strong magnetic fields. But once it has collapsed and shrunk inward, the magnetic fields have become much more concentrated, and it will spin far more rapidly (due to the conservation of rotational momentum).

The neutron star is surrounded by a magnetosphere, where electrons and other charged particles are accelerated by the extraordinarily strong magnetic field to move at velocities close to the speed of light. This results in narrow twin beams of powerful radiation directed out from the magnetic poles of the star. So if one imagines a neutron star as a giant bar magnet, the magnetic poles – and the beams of radiation aligned along them – are then tipped at an angle to the axis of rotation. When the geometry is favourable, the beam sweeps over the earth each time the star rotates and we detect a pulse of radiation; this is a pulsar. (Many neutron stars may never be seen as pulsars simply because their beams do not sweep through the direction towards the Earth.) For every pulse we detect, the pulsar has revolved once around its axis, and so the rapidity of the pulsation reveals the rotation rate of the neutron star. The rates are far too fast to be ‘seen’ as twinkling in real time, but can be appreciated by ear if one changes each radio pulse to a sound. For example:

• PSR 0329+54 is a typical pulsar – as one of the stronger pulsars, it was one of the first to be discovered. With a pulse period of 0.714519 seconds, you can hear the individual pulses clearly.

• PSR 0833-45 is the neutron star resulting from the Vela supernova some 10,000 years ago, and spins with a period of 89.3 milliseconds, and one can again hear the pulses clearly

• PSR 0531+21 is the Crab pulsar, and is not the youngest known, but it was the first to be discovered in 1967. It rotates about 30 times a second, emitting a double pulse in each rotation

• PSR 0437-4715 is ‘millisecond pulsar’, rotating about 174 times a second. It is an old pulsar which has been spun up by the accretion of matter from a companion star.

• PSR 1937+21 is one of the fastest known pulsars, spinning on its axis every 1.56 milliseconds. This is so fast that the surface of this star is moving at about a seventh of the speed of light!

<u>The Humming Black Hole in the Persues Cluster</u>
Credit: Andy Fabian et al, University of Cambridge
There are even more extreme objects that produce not just radio signals, but real sounds. Black holes are even more gravitationally-collapsed masses than neutron stars, and are responsible for regions of the most extreme gravity around them. Many are formed from the remnants of massive stars, but there are also super-massive black holes – black holes of up to one billion solar masses – which are lurk in the cores of the largest and most massive galaxies in the Universe, central cluster galaxies. Galaxies cluster together under gravity, but the stars in these galaxies that we see with optical telescopes represent only a tiny fraction of the total matter present. There is at least ten times as much mass contained in a hot tenuous gas that lies in between the galaxies of a cluster. So even between galaxies in a cluster there is matter forming an atmosphere, known as the intracluster medium. It’s detectable in clusters of galaxies as they are the largest and most massive structures in the Universe, and their enormous gravitational field squeezes and heats the gas to temperatures of millions of degrees. It’s not detectable in visible light, but only through its X-ray emission.

One such supermassive black hole sits at the centre of the brightest galaxy at the heart of the Perseus cluster of galaxies, one of our nearest and best studied clusters. It is ‘only’ around 250 million light-years distant from Earth, and contains hundreds of fat round galaxies all crowded into a region about 10 million light-years across. When viewed in X-ray light rather than optical light, the galaxies are no longer visible, and the image consists only of a smooth puddle of X-ray gas centred on the massive central dominant galaxy. Detailed X-ray images of the intracluster medium within the Perseus cluster show complicated structures centred on the central galaxy. The atmosphere is no longer smooth, but shows clear disturbances to either side of the galaxy, with a bright source marking the position of the black hole. In particular, large bubbles are apparent in the X-ray gas, which are surrounded by larger circular ripple features, centred on the core of the cluster.

These ripples are sound waves, travelling by the compression and rarefaction of the hot atmosphere. When the X-ray gas in the intracluster medium is squeezed, it becomes denser, causing it to emit more X-ray emission and appear brighter. Regions of lower pressure and density are fainter. The disturbance responsible for creating these sound waves is caused by jets issued by the supermassive black hole. An active black hole, it is powered by the continuous accretion of matter from its immediate surroundings. The accretion isn’t completely efficient, and some of the energy escapes to power jets of relativistic plasma. These push through the surrounding galaxy and out into the intracluster medium where they excavate bubbles. (The observed cavities are not really empty, but are filled with high-energy particles and magnetic fields rather than the hot X-ray gas.)

As the radio-emitting plasma in these jets pushes aside the X-ray gas, like all other motions in an atmosphere, it sets up a wave of compression. Continuous puffing of matter inflates these cavities further to create a regular motion setting up a series of pressure waves. Of course, the timescales are such that we don’t actually see the waves moving. All we have is a snapshot, where a pattern of ripples betrays that a regular disturbance has occurred. The sound generated in this cluster is not just noise, but a fairly pure note, as the ripples are relatively evenly spaced. The observed wavelength is around thirty thousand light years – allowing us to estimate the frequency. This is far below anything we’re used to thinking of as a sound; rather than cycles per second, we’re talking here about one cycle every 10 million years. It translates to a B♭note, but a B♭fifty-seven octaves below middle C!

This is not just a novelty story of a humming black hole, but demonstrates that sound can be an important physical process. The energy these enormous sound waves carry is colossal, and represents a hitherto vast and unseen energy flow in the Universe. For many years astronomers had been wondering why the intracluster medium remains so hot – after all, the hot gas is losing energy all the time because it is emitting high-energy X-rays, and so should have substantially cooled over much of the lifetime of the Universe. Yet it stays hot, and the discovery of sound waves spreading out from the cavities in clusters such as this provides a viable heating mechanism. The energy escaping from the black hole is carried out into the far reaches of the intracluster medium by the sound waves, where it dissipates as heat in the cluster gas to prevent it from cooling.

Soundwaves in the Early Universe
Credit: Mark Whittle, University of Virginia
Finally we move to the most important soundwaves of all – those that originated in the very early Universe, and which are responsible for the distribution of all the galaxies, clusters of galaxies and the empty spaces between them, that we see around us today. During the first 350,000 years or so of its existence, the early Universe was tiny, comprising an incredibly hot 'soup' of charged particles such as protons and electrons. It was also full of light, but all the photons were trapped, unable to travel any distance before interacting with these particles. As the Universe grew it cooled down, until at an age of about 380,000 years it reached temperatures low enough that all the charged particles started combining to form atoms. They thus no longer interacted with the photons, which were free to stream directly towards us and give us the earliest light we can see in the Universe. This is a snapshot at the Universe at this time, which we call the cosmic microwave background (CMB). Even though the early Universe was very hot, it has expanded so much by today that all the CMB photons have had their wavelengths stretched by enormous factors, and now the temperature of this radiation is now only a few degrees above absolute zero; consequently it shines brightest at microwave wavelengths.

Maps of the CMB do not show the intensity of the light, but instead the colours used represent the temperature of the radiation. The mottling of the image is therefore showing tiny fluctuations in temperature, on the scale of a departure of 1 part in a hundred thousand away from the average of 2.75K. However, these inhomogeneities in temperature trace variations in the density of the energy/matter mix at this instance: slightly denser regions than average were also slightly warmer than average, and less dense regions slightly cooler. Thus the fluctuations in temperature show the compressions and rarefactions of sound waves travelling through the 'hot soup' at the precise instant that it combined to form atoms and set the photons free. Within all the hot soup of the early Universe, there are minute overdensities of mass that have slightly stronger gravity that then pull on their neighbouring regions. Dark matter clumps together easily under gravity; ordinary matter takes longer to follow as it is also influenced by other forces, and it tends to bounce around a bit before settling into the condensations. It is these motions that set up the oscillations and thus the sound waves that course through the medium of the early Universe. The overdensities provide a focus for gravitational attraction that eventually builds the seeds that may go on to develop later into giant structures such as the galaxies. The size and density of the cosmos permitted only some acoustic waves to propagate, and so only some of these waves grew to become part of the large scale structure we see today.

The size of these variations in temperature enable one to infer the frequencies of the sound waves propagating through the universe at the time of the CMB. The Universe will continue to expand, and we can follow what will happen to the soundwaves as the whole of space is stretched – the wavelength increases and the frequency falls. Obviously the sound is far too low to be audible, unless it is speeded up. The following recording follows the loudness and pitch of these soundwaves during the first few million years of the Universe... compressed into only 10 seconds; this entails the speeding up of the signal by some 100,000 billion billion times.

Acknowledgement
This talk builds on the work of many astronomy teams around the world; you can follow links to access all the original web-pages for the sounds included today (and many others besides) from
http://www-xray.ast.cam.ac.uk/~csc/sounds.html
Today's talk has grown from a lecture originally devised and presented in collaboration with Prof AC Fabian (Institute of Astronomy, Cambridge).