GRESHAM COLLEGE

The Music of the Spheres
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"In space, no one can hear you scream". The chillingly accurate tagline of Ridley Scott's 1979 space horror classic, Alien, is often belied in science fiction movies, forgetting that in space there is no air, and hence no sound. Space today is terrifyingly silent. But it wasn't always thus: the early universe was filled with hot plasma in which sound waves could travel. The cosmos was quivering with the aftershocks of the Big Bang.

This lecture investigates some of the surprising ways in which sound waves are found in the cosmos: the leftover light from the Big Bang, the patterns of galaxies in the sky, and an entirely different kind of "sound", namely the gravitational waves "chirping" of black holes duetting before blending into each other. The universe is actually filled with more astounding sounds than "The Music of the Spheres" the ancients had imagined.

<u>"Holst in excelsis"</u>

With the celebratory headline "Holst in Excelsis", the *Truth* newspaper reported on the hugely popular performance of the "picturesque" seven-movements orchestral suite *The Planets*, conducted by the composer himself, Gustav Holst, at the opening of the Queen's Hall Symphony Concerts in London on Oct 13th, 1923. Each of the movements is named after one of the solar system planets: Mars, The Bringer of War; Venus, the Bringer of Peace; Mercury, the Winged Messenger; Jupiter, the Bringer of Joy; Saturn, the Bringer of Age; Uranus, the Magician; and Neptune, the Mystic. As the titles let on and Holst himself explained, the planetary portraits were inspired by "astrological associations and horoscopes", rather than astronomical notions: the martial character of Mars, the ethereal beauty of Venus, the lightning movement of Mercury, and so on. Audiences and critics loved it: the anonymous reviewer in the *Truth* compared favourably Holst to Edgar, and raved about "the mystical quality" of the last movement. His opinion was in contrast with Samuel Langford's, the *Manchester Guardian*'s music critic, who three years earlier was lukewarm about the five first movements, perhaps because, as he bemoaned, "music is in an experimental stage, […] the floodgates are opened and the bounds of music less defined than ever before". Indeed, in 1923 the fade-out ending of *Neptune* was so novel that it mystified the public: a chorus of women singing from a room away from the stage, their voices fading further and further as the door was "to be slowly and silently closed" at the last bar (according to the score), "until the imagination knew no difference between sound and silence", in the words of Holst's daughter.

The enduring popularity of *The Planets* is perhaps due in no small part to Holst's ambition to translate into music the imagined essences of the solar system bodies (excluding the luminaries, the Sun and the Moon, but including the two outmost planets, Uranus and Neptune, unknown in ancient times) – in some sense, re-interpreting with his musical sensibility the "harmony of the spheres". Holst couldn't have known that what were for him artistic means of expression, sound and rhythm, would soon become a tool of discovery for astronomers and physicists.

Exactly a week before Holst's London performance at the baton, the astronomer Edwin Hubble had captured another kind of cosmic rhythm that at a stroke expanded the confines of the known cosmos manifold. While observing the Andromeda galaxy with the 100-inch Hooker telescope at Mount

Wilson Observatory, California (at that time the most powerful instrument in the world), Hubble was delighted to spot a kind of regularly pulsating star, called a Cepheid variable. Thanks to its rhythmic variation in luminosity, he would measure the distance to Andromeda and so determine beyond doubt that it was a galaxy outside our own (see my Nov 2020 Gresham lecture “Understanding the Universe with AI”). In the century that followed, hitherto unsuspected sounds from space carried music of a kind that only the most discerning ears could appreciate: a symphony featuring a 13.7 billion years old orchestra of sub-atomic particles, choruses of galaxy clusters surfing cosmic sound crests, and lethal duets by pairs of chirping black holes.

The curtain had opened on a truly cosmic performance.

A Silent, Frozen Darkness

“In space, no one can hear you scream”. The chillingly accurate tagline of Ridley Scott’s 1979 space horror classic, *Alien*, is often belied in science fiction movies, where we routinely hear mighty spaceships swoosh by, and space battles rage to an accompaniment of deafening explosions.

Sound is made of trains of periodic disturbances that travel through a medium in the same direction as the wave, by alternating regions of compression and expansion. Physicists talk of “pressure” or “longitudinal” waves. On Earth, sound waves travel through air at a speed of about 340 m per second. This is much slower than the speed of light, which travels at 300,000 km per second — the distance from the Earth to the Moon, which astronauts in the Apollo missions took three days to cover. This difference in speed between sound and light accounts for the familiar phenomenon of seeing lightning strike in the distance first, followed by the roll of thunder a few seconds later.

But in space there is no air, and hence no sound. As we move up from the Earth’s surface, the atmosphere becomes thinner and thinner, until eventually, at an altitude of about 100 km, the blue gives way to the blackness of space. Above that point, in the absence of a medium dense enough to carry sound, space today is terrifyingly silent. It is not, however, entirely empty: apart from large astronomical bodies (such as stars, planets, asteroids and comets), it also contains a great deal of particles of various kinds. Inside galaxies (including our own), there are regions filled with small grains of dust, leftovers from the formation of planetary systems, and gas clouds (mostly made of a hydrogen, the simplest of elements, being made of a solitary proton). There are also various kinds of particles: at an average 413 per cubic centimetre, the most abundant particles in the universe are photons (i.e., the particles that make up light), followed by neutrinos (a ghostly particle that hardly ever interacts with anything else, see my February 2021 Gresham lecture “Neutrino: the particle that shouldn’t exist”), at 112 per cubic centimetre. We have also good reasons to believe that space is teeming with another crop of invisible particles, called “dark matter”. According to current ideas regarding the make-up of the universe, 12 million dark matter particles stream through our hand every second — and yet, we are completely unaware of them. This is because dark matter, like neutrinos, almost never bumps into normal particles, and hence is able to travel forth, unnoticed and almost undetectable.

Although the density of matter is extremely high in some places (like on the Earth, for example), the almost totality of space is very nearly empty. If we were to scatter all the ordinary matter in the universe uniformly around, its average density would be very small indeed: for a fine grain of sand in London, the next one would be found in Sydney, ten thousand miles away. This makes space an almost perfect vacuum, perfectly silent and almost entirely cold: the average temperature of space is a mere 3 Kelvin above absolute zero.

The Big Bang Rumble

But things were not always thus. The universe is expanding, powered by the mighty blast of the Big Bang, the moment when the cosmos was brought into being 13.7 billion years ago. If we imagine rewinding the cosmic movie, we would see a smaller universe in the past than today. There comes a point, a long time ago in the cosmos' history, when the universe was a billion times denser and a thousand times hotter than today. At this moment in time, a mere 380,000 years after the Big Bang, the universe was still in its infancy: galaxies had not had time to form yet, nor stars, let alone planets (which would come into being much later, by recycling heavier elements produced in the thermonuclear furnace of the first two generations of stars) or crawling, living things. The baby universe was filled with a hot plasma, made of hydrogen atoms whose electrons were kicked off their atomic orbits by collisions with photons. For each atom, a billion photons were bouncing around like lightning fast, untiring quantum balls in an over-crowded pinball machine. As a result, the plasma was heated up at a temperature of 2,700 degree Celsius – sufficient to vaporize gold, had gold existed at that point in time, and glowed a shade of yellow similar to the flesh of a ripe mango, had human eyes existed to contemplate it at that point in time. Our fictitious average distance between grains of sand was reduced to 10 miles, and despite the rarefied nature of the plasma the constant collisions with photons created a suitable medium for sound waves to travel through.

The baby universe was a gigantic, three-dimensional bass drum, ready to be played. The beater that got the music going was quantum mechanics: tiny fluctuations in energy at the very beginning of time transmuted into little heaps of plasma that enjoyed higher-than-average energy, and therefore higher-than-average density. In an early universe game of the rich get richer, gravity further amplified these compression points by pulling more of the surrounding plasma in, like minuscule seeds that just in virtue of being initially denser became ever more so. But as plasma heaped up, it dragged photons along until their light-speed kicks reversed the compressing motion, creating a spherical sound wave traveling outwards at 60% of the speed of light.

The Big Bang rumble had begun, and it kept grooving for the next 380,000 years. These sounds were not meant to be heard by human ears: the base note has a wavelength of half a million light years, approximately twice the diameter of the Milky Way. To play this sound on a piano, you would need to extend its range by 65 octaves to the left of the keyboard! Nevertheless, this triumph of science (and music) rivals in beauty anything written by Bach.

Just like a bell ringing inside a vacuum chamber goes silent when the air is pumped out,
the primordial rumbling stopped when the plasma it needed for its propagation vanished as the universe cooled and became black. But the sound waves that were produced by the plucking of quantum physics at the beginning of time have left their oscillatory imprint in the temperature of the leftover light from the Big Bang: this is literally sound transformed into light. In one of the most remarkable achievements of modern cosmology, we are today able to observe the afterglow of the primordial plasma through which the Big Bang rumble reverberated (Figure 1), and map the temperature that still bears the statistical signature of the cosmic sounds it once contained. By tuning into this cosmic symphony, we can measure with great precision the properties of the drum that produced it – the universe itself.

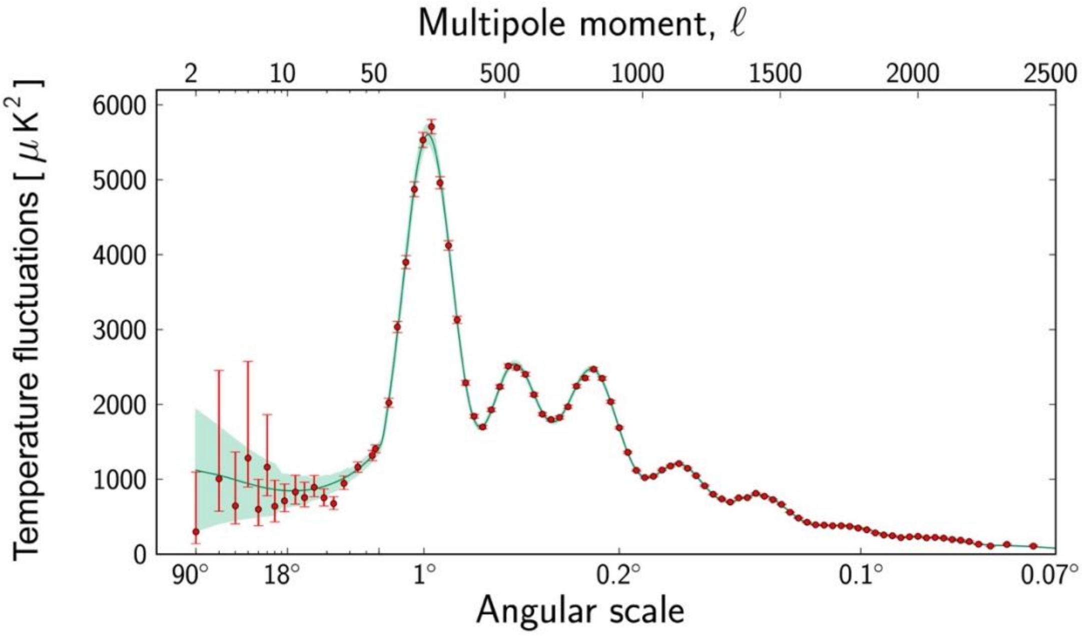

Figure 1: The signature of cosmic sound imprinted in the light echo from the Big Bang. The red dots with errorbars (indicating measurement uncertainty) are the data from the Planck satellite; the green line is the theoretical prediction; the green-shaded band shows the theoretical uncertainty. Credit: ESA/Planck Team (2013).

<u>Surfing The Cosmic Wave</u>

Sound may have been extinguished from space, but that does not mean that its consequences don't surround us still. Like an insistent melody we keep whistling under our breath unconsciously hours after the music has stopped, cosmic sound has left a distinct memory of its presence onto the 50 billion galaxies that fill the visible universe. When the plasma vanished and sound waves were halted, regions of space that happened to host a crest of the sound wave (i.e., regions of compression of the plasma) found themselves filled with more atoms than average. Around such regions gravity immediately set to its silent work, tirelessly assembling more and more gas, therefore making the region denser and denser. At the same time, most of the gas was being sucked back by the stronger pull of dark matter, five times more abundant than normal matter back then as it is now. Dark matter pulled the gas towards the region of space where the sound wave had initially started from – towards the point where the beater first struck the drum. The result of this tug-of-war was that while most of the gas ended up at the location of dark matter, some stayed behind where the crest of the sound wave had come to a halt. Five hundred million years later, the first stars would ignite out of the gas, and galaxies assemble at these same locations, separated, on average, by the distance that the sound wave crests had managed to cover before the music stopped.

The Milky Way is one such galaxy, born through gravity while surfing time on the crest of a cosmic sound wave long gone.

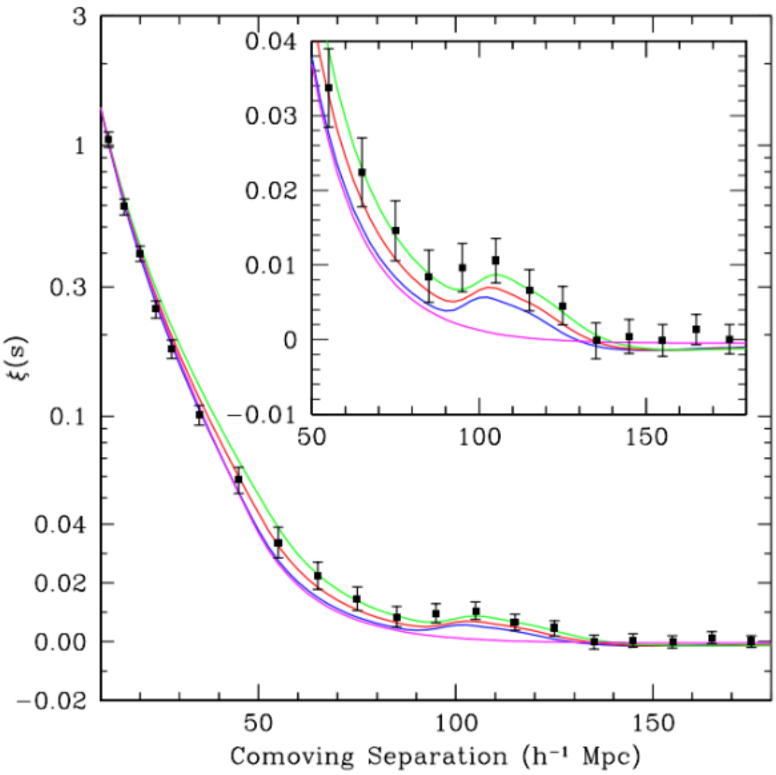

Figure 2: Probability of finding two galaxies in the universe as a function of their separation (horizontal axis). The slight bump in the data (black squares), which is more evident in the inset in the upper right, reflects the location of the crests of the cosmic sound wave with respect to their origin. The coloured lines represent various theoretical models. Credit: Eisenstein et al (2005).

Thanks to the twin key technologies of digital cameras and robotic telescopes, in the last 20 years we have mapped out the location of millions of galaxies in the sky. The average distance between crests of the primordial sound waves has kept growing since the plasma disappeared, as regions of space have been pulled apart by the continuing expansion of the universe (which, incidentally, for the past 6 billion years appears to have been accelerating, a puzzling effect that we ascribe to something called "dark energy"). We expect that distance to have ballooned to 450 million light years, about 1% of the diameter of the visible universe. By inspecting the location of the many million galaxies we have now collected, we can bring out the slight bump showing a tiny excess of galaxies separated by the average distance of crests in the cosmic sound (Figure 2). Like an elaborately embroidered tapestry where the weaver has secretly threaded in an invisible geometric motif, the rich pattern of galaxies around us thus bears the faintest of marks from soundwaves in the infant universe.

<u>From Death, Music</u>

While Gustav Holst was busy writing the last movements of *The Planets* at St Paul's Girls' School in London, Albert Einstein in Berlin was publishing a prediction ensuing from his newly unveiled theory of General Relativity. The creation and transmission of waves through space was central to it – but this time, it was waves of a kind no-one had imagined before.

Einstein had long been thinking about electromagnetic waves, i.e., light, and this sparked the revolution that was relativity. At the beginning of the 19th century, it was widely held that light, being a wave, needed an inert, elastic medium to propagate through, and so that space must be filled with such an invisible, immobile substance: the "luminiferous ether". The experimental search for the ether was unfruitful, and with Special relativity first and General relativity later, Einstein paired away at its alleged properties until nothing of it was left: we now think of light as of an electromagnetic wave that travels through vacuum.

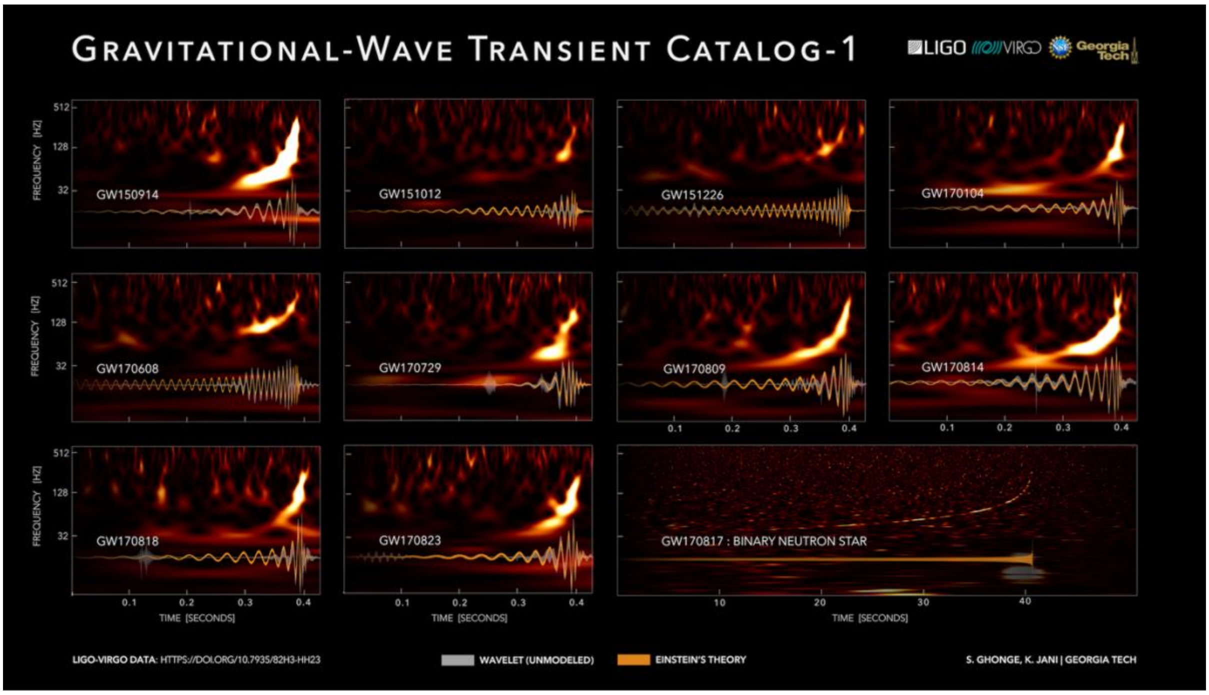

Figure 3: some of the gravitational wave signals observed to date. The horizontal axis represents time, while the vertical axis is the "tempo" of the wave's oscillation. The colours indicate the data, while the orange lines are the theoretical prediction from Einstein's general relativity that best match each observation. The "chirping" of the black holes or neutron stars pair is seen as the increase in tempo towards the end of the inspiralling. Credit:LIGO Scientific Collaboration and Virgo Collaboration/Georgia Tech/S. Ghonge & K. Jani.

But the consequences of General relativity ring through space in a surprising way: a star possesses mass, and therefore generates gravity. More precisely, from Einstein's point of view, it deforms the shape of spacetime around it, and this changes the trajectory of free-falling bodies in its vicinity – creating the "force" we call gravity. If you spin a perfectly spherical star, nothing changes in its gravitational field[1]. But if you imagine gluing the star to the tip of a rod and spinning it around like in Olympic hammer throwing, the star generates ripples in spacetime – oscillations with the properties of waves, perpendicular to the direction of travel and that propagate outwards at the speed of light.

Just like moving positive and negative charges back and forth inside an antenna generates electromagnetic waves, hurling masses around produces gravitational waves: a kind of cosmic radio that transmits both in AM and FM, encoding its signal as a fluttering of spacetime. Gravitational waves are the trembling of spacetime announcing a catastrophe that played out in utter silence millions or even billions years ago: two neutron stars or two black holes in a tight orbit around each other, spinning at each end of an invisible rod, lose energy by emitting gravitational waves. As they do so, their orbit tightens – the imaginary rods shortens, and so they splurge more and energy into gravitational waves, the tempo of their pirouetting about each other increasing, their orbital embrace becoming ever tighter, until they merge violently, then settle into a single, diminished body. In the last few milliseconds of their drama, their gravitational waves distress signal becomes louder and shriller. The two objects, soon to lose their individual identities, cry out in unison in a last chirp: the gravitational waves oscillations become faster and the amplitude increases (Figure 3). After that, eternal silence.

[1] This is not entirely accurate, as General relativity predicts tiny distortions in the spacetime around a rotating mass, which however are irrelevant for our discussion here.

Einstein first described gravitational waves in 1916, though he remained long unconvinced of their actual physical existence. Twenty years later, he wrote a paper arguing against his own earlier prediction, only to be persuaded to change his mind back later. It took a hundred years before our technology became sufficiently sophisticated to register the tiny disturbances to the fabric of spacetime that Einstein struggled to accept. On 14 September 2015, the first ever such burst was detected on Earth by the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration. This ground-breaking discovery opened a new window on the universe, enabling astronomers to listen in to the death of black holes and other very dense objects, such as neutron stars, for the first time, so momentous that it was awarded the Nobel Prize for Physics in 2017. Since then, such extraordinarily difficult measurements have become almost routine: we have now overheard the final, dramatic moments of the life of over twenty binary systems; black holes for the most part, and a couple of neutron stars pairs.

Already now, information gleaned from gravitational waves has upended our understanding of how black holes form. Astronomers have also begun to use them as 'cosmic sirens' – naturally occurring musical signposts in the universe. Just like a fog horn helps seafarers estimate their distance from a dangerous shoreline when visibility is poor, the blare of merging black holes or neutron pairs can be used to determine how remote they are from us. This in turn helps establish how fast the universe has been expanding over time. For a given distance from us, the gravitational wave volume – whether we hear it as a *forte* or a *pianissimo* – depends on the combined mass of the stars or black holes involved, which is unknown. Fortunately, the final chirping of the signal encodes information about the mass, so by combining both the volume of the wave and its "melody", we can unambiguously locate the sources – without needing to see them (which is anyways very difficult). Like the chorus singing from offstage at the end of Holst's *Neptune,* we strain to hear their sound even though we cannot see its authors – until the difference between sound and silence disappears.

Astronomy for All

For millennia, astronomy has been a purely visual science. The discovery of gravitational waves means that it is now an audible one, too. Of course, gravitational waves are not literally sound waves, but the analogy is helpful both in thinking about them and as a vehicle for communicating to a wider public the exciting discoveries that this new field is bringing.

Sounds *of* the universe (as opposed to sounds *in* the universe) are also helpful in translating data and images into a different format that is more accessible and inclusive, for example for people with visual impairment. Many initiatives have rendered astronomical phenomena into scientifically accurate and generally accessible soundscapes: images of the Milky Way as seen in optical light, infrared and X-rays (in the latter two cases, translating light that is invisible to humans into sounds that are audible to us), the leftover radiation of the Big Bang that we encountered earlier, plasma density data from the Voyager probes, the vibrations of starquakes, radio emissions from Saturn, Jupiter's magnetosphere, and many more.

Two and a half millennia ago, the Pythagoreans believed that each of the seven "planets" (including the Moon and the Sun), as it revolved around the Earth, produced a sound that stood in perfect harmony with all the others, the universal *diapason*, or the concordance of all the notes. They could not have imagined how 21st century science would reveal a much more intricate, but equally beautifully concordant, cosmic symphony.

Further reading (and some listening)

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