Acoustics and Astronomy

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The universe has a sound foundation!

Introduction

Two famous science fiction movies have left the general public a little bit conflicted about whether the words "sound" and "space" (as in "outer space") belong together. The promotion for the movie *Alien* touted the phrase, "In space, no one can hear you scream," whereas in the popular *Star Wars* movies, the whine of the Empire's "TIE fighters" is an iconic sound. Of course, in the rarefied interstellar medium in which both *Alien* and *Star Wars* occur, *Alien* wins on the question of "correct physics" hands down. The TIE fighters' sound (which is a wonderful mixing of the sound of a car on wet pavement and a screeching elephant, including Doppler effects as the fighters pass by; see http://acousticstoday.org/fsounds) simply does not exist in the near vacuum of interstellar space.

The basic reason for this is simple: sound requires a reasonably substantial material medium for its propagation. A typical density of atoms (mostly hydrogen) in interstellar space is about 10 per cubic centimeter, with a temperature of about 100 K, and thus a root-mean-square (RMS) velocity of about 1 km/s. Under such conditions, an atom of hydrogen collides with another roughly once every billion seconds! Assuming that a sound wave has to be as less than or equal to the frequency of the atomic/molecular collisions, we see that we are looking at a billionth of a hertz sound. Not exactly in the range of possible human hearing, for which 20-20,000 Hz is a generous bandwidth estimate.

However, the universe is both vast and old (by human standards), and sound has actually been produced in the universe at many different places and at various times. Moreover, sound is also an incredibly useful tool for studying the universe.

In doing a grand tour through space and time (because the farther out in space we look, the farther back in time we go), it makes sense to organize the tour in some orderly fashion. Our chosen ordering will be to start at home in our present solar system and then work our way outward.

Sound on Earth

Because you are reading *Acoustics Today*, you are likely familiar with the properties and many uses of sound on Earth. Sound provides one of the most common bases of communication between animals (with light and chemical communication being the other prominent means). More important to this article, sound also provides an excellent tool for remote sensing of solids, liquids, gases, and even plasmas (ionized gases). By first looking briefly at how we study sound on Earth and use it for environmental sensing, we can set the stage for how to expand this knowledge outward.

Let us start with our atmosphere. A very standard acoustic atmospheric probe is sonic detection and ranging (SODAR), the acoustic backscattering version of radar in air. In addition to ranging, SODAR can give very good vertical profiles of temperature, wind speed, and turbulence. Another (hybrid) acoustic technique used to measure the atmosphere is the radio acoustic sounding system (RASS). This technique combines an acoustic beam with Doppler radar to provide a vertical profile of the speed of sound and thus temperature. "Sonic anemometers" have been workhorses in providing information on the atmosphere, and because they have no moving parts, it is easy to shield them from destructive effects.

Looking at the ocean technologies available, we first see an immediate transcription between SODAR in air and sound navigation and ranging (SONAR) in water. Acoustic current meters also abound, going from small, single-point, time-of-flight acoustic current meters (ACMs) to vertically profiling acoustic Doppler current profilers (ADCPs). Long-distance, horizontal acoustic propagation paths can sensitively average ocean temperature. Multiple, crossing acoustic tracks are used for acoustic tomography, which has produced 4-D (3-D space plus time) images of ocean processes.

Finally, we come to the solids, earth and ice, that can support both shear and compressional waves. High-frequency acoustic backscatter can be used to probe small-scale ice features like roughness, and low frequencies, which introduce a variety of shear-coupled ice plate waves, are used to study large regions. Studying the solid earth, one uses both surface waves like Rayleigh waves locally and body waves (pressure [P] and shear [S] waves), which traverse entire planetary scales, at low frequencies. The times of flight of these waves and their amplitudes, when used in inverse schemes, provide a look at a planet's layering structure as well as interior inhomogeneities.

Given that we have a rich variety of acoustic instrumentation developed to measure earth, ocean, and atmosphere on Earth, we should be able to take these into space and do more of the same. Right? No! It's not that easy! Space exploration has a large set of constraints that need to be met, and many of the techniques we use on Earth are not (at least at present) transportable. Let's discuss this briefly.

The first, and perhaps most stringent, constraint is payload. Getting equipment into space can cost hundreds of thousands of dollars per kilogram, and many acoustics techniques (especially those involving low-frequency sources) require very heavy equipment. Second, there is the power budget of the equipment. In space, there are no wall outlets, and so one needs to rely on heavy batteries, generators, or solar panels to provide "juice." Third, there is the Darwinian competition between methods. Electromagnetism and gravity do not require a material medium to propagate and so allow remote sensing as opposed to acoustics, which requires in situ instrumentation. And finally, there is the fact that acoustic methods don't necessarily have the same response on other planets and moons as they do on Earth. The pressures, temperatures, densities, and chemical makeups of the solid, liquid, and gaseous parts of other worlds are generally very different from what is found on Earth. As to this last point, let me heartily recommend an *Acoustics Today* article about this by Leighton and Petculescu (2009). It contains not only some great discussion but also recordings of what voices and music would sound like on Mars, Venus, and Titan. If you think Bach's "Toccata and Fugue in D Minor" (the old *Phantom of the Opera* music) sounds slightly demonic on Earth, wait until you hear it elsewhere!

Given the above, where do all these constraints leave us? Well, maybe with the first rule of conversation: listen. Microphones, hydrophones, and geophones listening to the ambient soundscape (natural sources) satisfy the "smaller, lighter, cheaper, and less power hungry" requirements and also can provide some very good scientific results. Let's look at one of the most productive examples to date: geophones listening to the music of our own moon.

Exploring the Moon

Humans have been observing the moon for millennia and, by the time of the ancient Greeks, had good estimates of its size, distance, and orbital characteristics. But only with the advent of the telescope and Galileo's drawings of mountains and craters on the moon was there any appreciation that the moon had structure beyond that of a mottled sphere. With the invention of Kepler's and Newton's orbital mechanics, the moon's mass and mean density could also be estimated, but we were still limited to observing the surface structure of just one side of our "tidally locked" companion. (Tidally locked implies that the period of rotation is equal to the period of revolution and is due to Earth distorting the moon's shape ever so slightly, which slowed its rotation.) It would take until 1959 for the Soviet space program to have a man-made object (Luna 2) impact the moon and also see its surprising far side (Luna 3). In 1970, Luna 16 finally brought lunar material back to Earth for direct study. These were spectacular initial results, but the floodgates had really just begun to open.

The US Apollo program, in which Apollo 11 through 17 (except 13) landed on the moon, installed instruments, and brought back samples, was the first intense phase of in situ lunar investigation. Heat and magnetism sensors (among

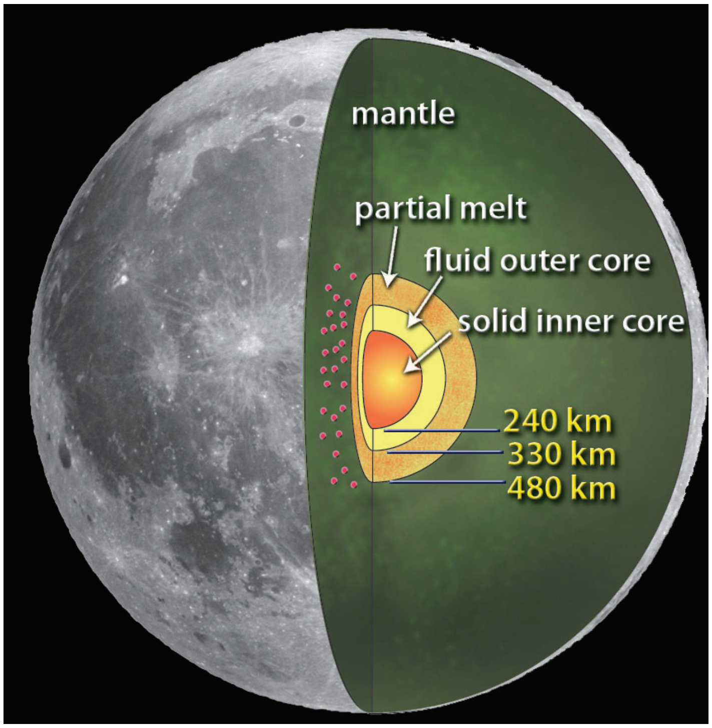

Figure 1. *The layering structure of the moon as inferred by lunar seismic measurements. Courtesy of NASA.*

many others) were deployed by the crews along with seismic sensors, which are our main interest here. Surface temperature, magnetism, and sound measurements can all be utilized to give maps of interior structure, but of the three, the sonic measurements give the best interior resolution due to their richness of possible acoustic path structures. These deployments included "active" (man-made source) seismic experiments, in which a "thumper" source and mortar rounds created waves that were sensed by a small line array of geophones (a very standard configuration on Earth) and also a "passive" (natural source) system that listened for intrinsic lunar seismic activity.

Although both worked, the passive system took the prize for the most spectacular result. The seismic traces soon revealed monthly "moonquakes" generated not by plate tectonics as on Earth (because the moon has no tectonic system) but by the lunar tides! These moonquakes, like earthquakes on Earth, provided a strong, natural, deep-source signal that could be used to explore greater depths in the lunar interior. Interestingly, although the seismic and other experiments were shut off in 1977 for budgetary reasons, the data from the seismic sensor were revisited in 2010 with modern computing power, and the reanalyzed data revealed a completely new view of the lunar core: a solid core surrounded by a liquid outer core, in turn surrounded by a layer of partially melted magma (**Figure 1**).

The success of the seismic program on the moon strongly recommends its use on other moons and planets if knowledge of the interior is what is desired. And natural sources and simple receiving equipment can satisfy the stringent payload and power requirements.

As to the exploration of the rest of the solar system by acoustics, it is such a vast topic that space forbids trying to treat it here. However, if one is interested in this topic and is amenable to looking at the somewhat more advanced technical literature, there is an excellent August 2016 special issue on "Acoustic and Related Waves in Extraterrestrial Environments" in *The Journal of the Acoustical Society of America* (*JASA*; see http://acousticstoday.org/ee). The papers therein and their references should be an excellent starting place for this topic.

Sound in the Sun

Because there is a lot of "empty space" [*sic*] between Earth and the sun, nobody really expected to hear sounds on Earth from the sun. (Which turns out to be wrong but more of that later!) However, there also was little doubt that sound existed on the sun, likely a broadband roar due to the turbulence of the hot gas in its upper regions. What the real nature of the sound field was like on the sun, however, and how useful it would prove to be turned out to be a real surprise.

The story of how the solar sound field was elucidated, and later used, begins with a rather standard investigation that was being made of solar "granules," which are convective cells on the sun, each about the (horizontal) size of the state of Alaska. One sees bright spots, where hot gas is rising, surrounded by dark lines, where gas that has cooled is falling back down. To study the speed, depth, and lifetimes of these convective cells, astronomers looked at the intensities, Doppler shifts, and spectral line splitting of the solar Fraunhofer lines of the bright and dark regions, a standard type of analysis called a dopplergram. This should have been a nice, straightforward piece of science. But, in 1960, Robert Leighton of Caltech noticed that if you made a dopplergram across the entire solar disk, the Doppler velocities didn't eventually decorrelate with separation in space or past the roughly 10-minute lifetime of a granule but showed a regular pattern. The sun, in fact, appeared to be a regular oscillator with a period of 300 seconds! This was an entirely novel and unexpected result, far beyond what was expected from the examination of the granules.

The story of how the "mystery of the solar oscillations" was solved is entertaining but again somewhat long and involved. In the interest of space, I refer the reader to the literature. My favorite popular book is the excellent *Sunquakes: Probing the Interior of the Sun* by J. B. Zirker (2003). It has both history and science and is a wonderful introduction to the modern field of "helioseismometry."

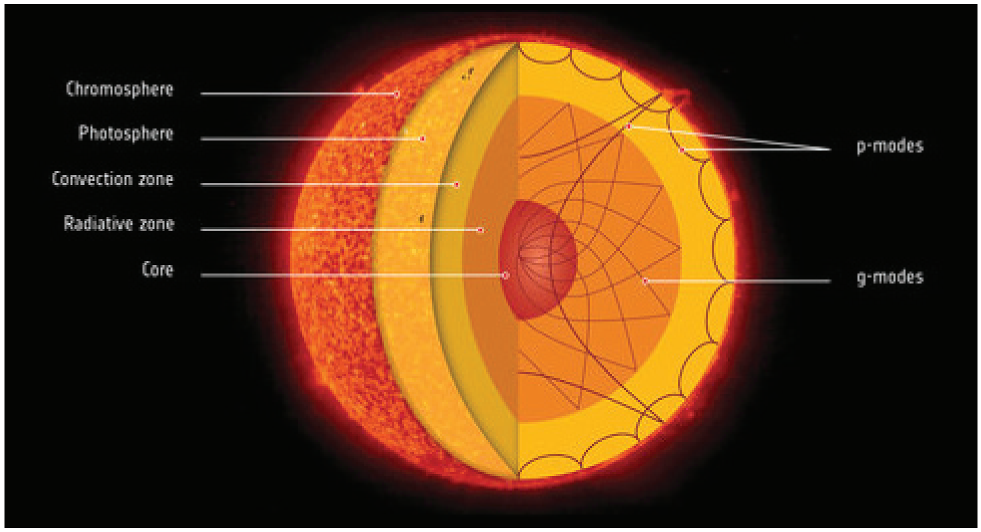

Figure 2. *A picture of the sun showing its layering structure and the paths that sound takes traveling through it. Paths with an integer number of loops (which) reinforce constructively and create the spherical harmonic modes seen on the surface. p-modes, Pressure modes; g-modes, gravity modes. Courtesy of the Solar and Heliospheric Observatory (SOHO; collaboration between the European Space Agency [ESA] and NASA).*

So, cutting to the answer, What were the oscillations? It is found that the sound, which is produced by the turbulent motions in the convective zone, is trapped in the convective zone! Just below the top of the convective zone (**Figure 2**), the gas temperature drops off quickly, which causes the upward moving sound to be reflected back down into the convective zone. At depth below, the speed of sound and temperature increase drastically, and this refracts downward-going sound back upward into the convective zone. The sound is thus trapped above and below. This creates vertical (radial) normal modes, a phenomenon well-known in earthly acoustics and seismics. However, the sun is a sphere, and any such modes also need to be quantized, positively reinforcing modes in the north-south and east-west directions as well. These modes are well known from physics and are the so-called "spherical harmonics." In terms of the ray picture in **Figure 2**, this corresponds to rays that circle around the sun an integer number of times.

There are a few interesting factoids to add to this picture. First, because the sun is a fluid, it cannot support shear waves, and so this is a pure acoustics problem (the p-mode in **Figure 2** is the pressure mode). Second, underneath the convection zone, in the radiative zone and core, the restoring force for wave motion is gravity (the buoyancy force; g-mode), not pressure, and so these are not acoustic waves but are instead like the internal wave motions seen in the earth's ocean. These g-mode waves are damped out in the convective zone and so are not seen at the surface, making it hard to get information about the core. However, recently, these faint waves may have been observed, suggesting that the core rotates every seven days, which is much faster than the radiative and convective zones. Finally, it seems that there is indeed an acoustic signal from these solar modes that is detectable from Earth! Seismic records on Earth contained a mysterious "hum" that recently has been identified with the solar p-modes and that is likely transmitted from the sun to Earth by the interplanetary magnetic field and the solar wind. Thus, we do hear the sound of the sun on Earth (Thompson et al., 2007; Fossat et al., 2017)!

From the Sun to the Stars: Asteroseismology

If helioseismology works well on the sun, why not use the same technique on the stars? Well, just like transplanting our earthly acoustics instruments elsewhere, it's not quite the same problem or conditions. The stars don't present a finite disc like the sun, and so the signals we get are integrated (averaged) over the surface of the star, reducing them. The intensity changes seen are on the order of one part per million. For Earth-based systems, atmospheric turbulence wreaks havoc with such low-level signals, and more over any time series made are interrupted every day and every season by the diurnal and seasonal sky changes. This means going into space if you want to pursue asteroseismology.

Luckily for the star researchers, the "exoplanet revolution," which also needed to detect very tiny fluctuations in star's intensities, was also in full swing (and still is!). A very symbiotic relationship between the asteroseismologists and the

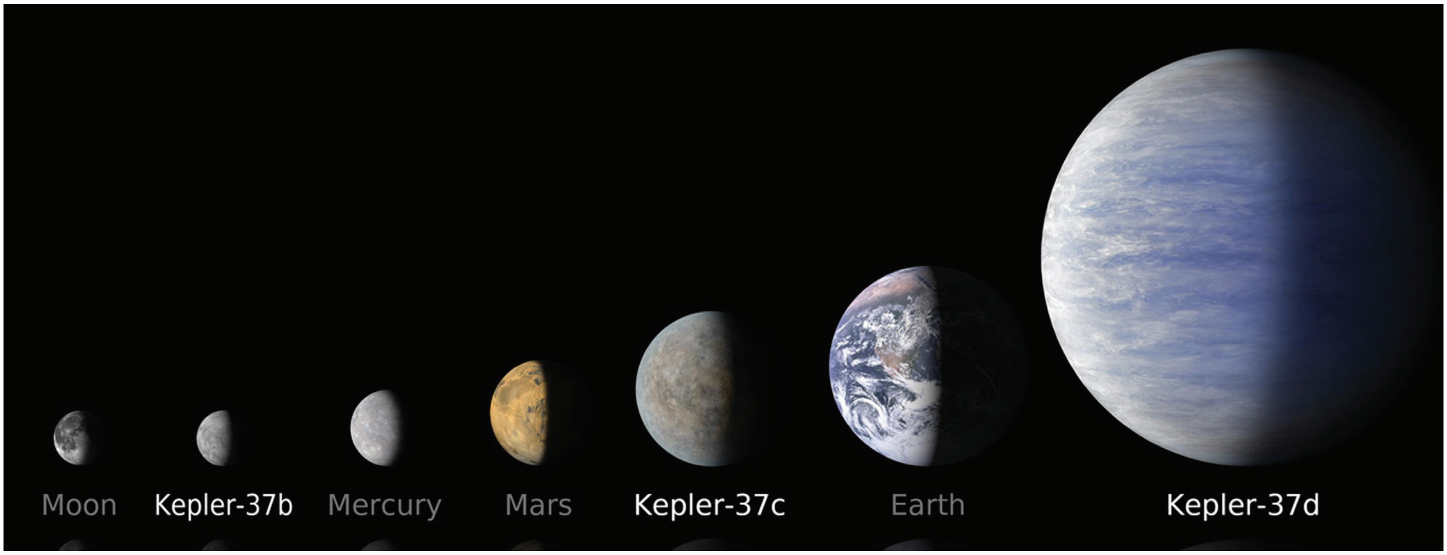

Figure 3. *Three "earth-sized" exoplanets found around the star Kepler-37 compared with solar system planets. Courtesy of NASA.*

exoplanet researchers sprang up, starting with two Canadian and French satellite efforts, microvariability and oscillations of stars (MOST) and convection, rotation, and planetary transits (CoRoT), and culminating with NASA's superbly equipped Kepler spacecraft.

The symbiosis between the two fields comes about because, to measure an exoplanet's size from transit data (where the planet crosses in front of the star), you need to know the star's size. This would seem hard to get from the "point source" stars we see at our distance, and this is where asteroseismology comes in. The time series data about the stars oscillations that asteroseismology collects also allows one to create a stellar model for each star; stellar structure is a rather well-developed field. Such stellar models produce, among many other things, an estimate of the star's size and age. This directly gives the planet's size and, moreover, an estimate of its age (about the same as the star's).

One of the major goals of the Kepler mission, and its modified K2 mission, was to find earthlike exoplanets by looking at smaller stars like the sun. The star Kepler-37, 220 light years away in the constellation Lyra, was one of its nicer success stories. Three planets roughly comparable to Earth in size (see **Figure 3**) were found orbiting a star with a diameter 77% that of the sun (measured to an astounding 4% accuracy!). Finding out if these planets are suitable for life is a larger, further story, but asteroseismology lets us know the first-order details that get us in the game.

Like any other technique, asteroseismology can produce more information when used in combination with other techniques. When used in combination with spectroscopic data, it produces stellar masses accurate to about 6% and diameters accurate to 2%! This technique has been used on hundreds of smaller and medium-sized stars to date.

When used on larger, red giant stars, asteroseismology has been able to distinguish between two different evolutionary stages of hydrogen and helium burning that could not be separated before and show that the interior core rotated at least 10 times faster than the surface.

And as a final gem, asteroseismology found a new, interesting class of stars, now called "heartbeat stars," which produce brightness time series that look very much like the waveforms found in human electrocardiograms (Matthews, 2015). The reason for this similarity is actually rather simple. Many stars are in binary systems, with orbits that are highly eccentric (pronouncedly elliptical). As the companions draw close together in the perigee part of the orbit, large tides that ring the oscillation modes of the stars once per orbital period are raised. These modes die out as the stars eventually move apart, flattening the brightness curve back to its undisturbed state. By monitoring these unique oscillations in both intensity and motion (Doppler), even more information can be obtained about stellar structure.

Creating Our Universe with Sound: The Big Bang

At this point in time, it is accepted that our universe was created in a singular event mockingly called (by one of its most famous opponents, Fred Hoyle) "The Big Bang." This theory, to Hoyle's dismay, was confirmed by Penzias' and Wilson's accidental 1964 discovery of the cosmic microwave background (CMB) radiation, which is the observable relic radiation from that event. The CMB also provides us with direct evidence of acoustic waves in the early universe, but it takes another entity, the "theory of inflation," to provide a plausible mechanism for the source of the acoustic waves. (Inflationary theory is extremely solid in having many of its predictions verified, but there are still competing theories, and it is not yet a fully *proven* theory, so there is the teensiest bit of squishiness in this part of this story!)

The story of the acoustic waves, in very crude terms, goes like this. Just 10^{-37} seconds after the "instant of creation," a field that has been dubbed the "inflaton" field, quickly decayed from a very symmetric, high-energy state into an asymmetric, lower energy state, creating all the matter and energy in the universe toward the end of the process. (This process of "symmetry breaking" is a familiar one in phase transitions, only here the whole universe was making a transition!) This process also expanded the universe enormously, much faster than the speed of light (really), meriting the name "inflation." Inflation theory accounts for why space is, to a very high degree, flat (Euclidean) and solves the "horizon problem" (which is, Why are the number and size of density fluctuations the same on opposite sides of the universe, which are separated by greater distances than the speed of light times the age of the universe?). So it is, as has been mentioned, a pretty believable theory, if not yet proven. But there was also another benefit to the theory. In this theory, density fluctuations, which occurred due to the uncertainty principle of quantum mechanics, were magnified into the seeds of large-scale structure in the later universe. These seeds showed up as very slightly overdense and underdense (relative to the mean) regions of the primordial hot, expanding plasma containing dark matter, baryons, electrons, photons, and neutrinos (Dodelson, 2003).

Considering an overdense region of the primordial plasma quickly provides a physical model for the sound waves. The overdensity region attracts matter toward it where the heat of the photon-matter interaction provides an outward force. The gravity force and the pressure force counter each other and create oscillations, very analogously to how sound in air is created by pressure differences. The speed of these acoustic waves is relativistic, however, a bit more than half the speed of light!

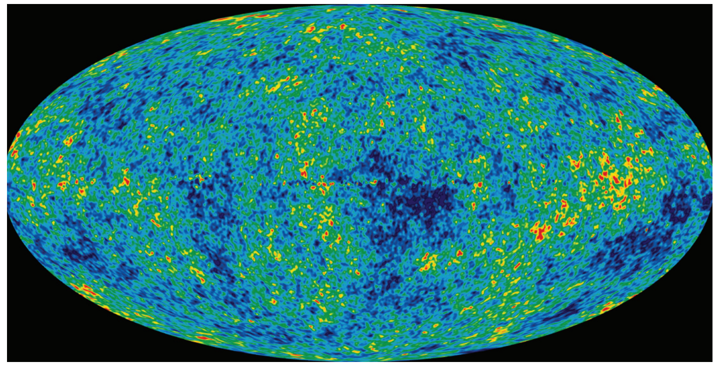

Figure 4. *Nine-year map of the cosmic microwave background radiation fluctuations from the Wilkinson Microwave Anisotropy Probe (WMAP) satellite. The basic 2.725 K blackbody spectrum has been subtracted off this picture to just show the fluctuations. Hot colors (**yellow** and **red**) indicate warmer temperatures; cool colors (**blue**) indicate colder temperatures. These translate to over- and underdense regions. Courtesy of NASA.*

At about 380,000 years into the history of the universe, the expanding plasma had cooled down enough (below 3000 K) that electrons and protons could combine together into neutral hydrogen atoms and not be immediately dissociated by collisions. Before this, the charged matter and the photons interacted strongly via what is called Thomson scattering, and one couldn't get very far away from the other; they were "coupled." However, when the universe cooled enough for neutral atoms to exist, a time gloriously mislabeled as "recombination" (as there was no previous combination!), the photons of light were free to travel their merry way without any significant scattering because the neutral atoms did not scatter light significantly. When this happened, the distribution of the overdensity and underdensity regions (the acoustic waves) became imprinted or "frozen" on the surface of last scattering and thus encoded into the microwave background radiation. (It is worth noting that the photons *weren't* in the microwave region then, but at higher optical frequencies; the expansion of the universe has redshifted these photons since then.)

The map of the CMB fluctuations as one looks out over the entire celestial sphere is one of mankind's premier achievements, and, as acousticians, we should be aware that we are looking at a map of the acoustic modes of oscillation of the young universe, which is probably the most important data we have to understand the universe as a whole. But what does this map tell us in particular?

One bit of acoustics it tells us is that because the intensity fluctuations are 10^{-4} to 10^{-5} smaller than the mean, the $\Delta p/p$ of the radiation pressure was of that order, which corre-

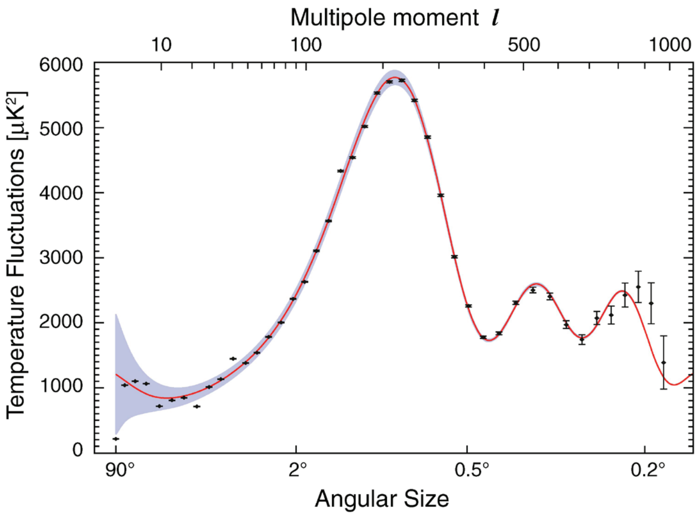

Figure 5. *Power spectrum of the cosmic microwave background fluctuations. Angular size is the most interesting quantity here. The multipole moment (l), which is a more proper mathematical description, is simply given by* 1~180 (*angular size*). *Courtesy of NASA.*

sponds acoustically to about 110 dB. These are fairly substantial sound waves!

Perhaps more importantly, the small density disturbances shown in **Figure 4** are pictures of the seeds of future structure. Galaxies and clusters of galaxies that are a million times denser than the universe's mean density formed from the overdense regions, whereas vast cosmic voids formed from the less dense parts. The exact way this "amplification" occurred is still an active research area.

To get at some of the other physics contained in the CMB, we need to further distill the spatial image seen in **Figure 4** into a spatial power spectrum. This means doing a decomposition similar to the spherical harmonic analysis that was done for helioseismometry. (Only because space is basically isotropic, we don't have the north-south versus east-west distinction we have for the sun. So there is one less modal index to consider.) A power spectrum versus angular size is shown in **Figure 5**.

The peaks in the CMB power spectrum contain a wealth of information. The angular scale of the first peak is a measure of the curvature of the universe and says (in good agreement with inflation theory) that the universe has a flat geometry. The ratio of the next peak to the first (or odd-to-even peaks in general) gives the baryon density, whereas the third peak informs about the dark matter density.

Another acoustic result that is very useful in modern cosmology is how the "baryon acoustic oscillations" (sound waves) we discussed create a rather useful "standard ruler" for the universe. If one considers a single acoustic wave from an overdense region originating in the center of the primordial plasma, it is easy to show that at the time of decoupling/recombination, when the photons start moving away from the baryonic matter, there is an overdense shell of this matter left at a fixed radius. This radius is called "the sound horizon," and as a result of it, when the universe evolves further, cosmologists expect a local maximum in the number of galaxies separated by that scale. That is indeed what was found by the Sloan Digital Sky Survey of galaxies and confirms the CMB observations that the sound horizon is ~150 megaparsecs (1 parsec = 3.2 light years), which can then be used as a standard ruler. This ruler, combined with the CMB observations, can be used to study the mysterious "dark energy" that seemingly comprises 70% of our universe (Morgan, 2014)!

Seeing with Sound: Sonification

Another astronomical use of sound is its use in "visualizing" various types of data that have features that are sometimes better detected by our ears than by our eyes. As an example, our eyes can detect differences in images that are presented at a frame rate of about 50 Hz, but our ears can sense up to 20 kHz. Also, our ears can be sensitive to nuances that are not readily visible in time series plots or spectra; the brain has some very good signal processing capabilities! Sound is also something we can viscerally relate to, especially if we turn up the bass! So data on many of today's astronomical phenomena have been "translated" into sonic representations. Let's look at a few.

Perhaps the most famous recent sonification has been from the Laser Interferometer Gravitational Wave Observatory (LIGO) observations of merging black holes. These astounding observations actually show gravity wave arrivals that occur in the same frequency range as acoustics and so are natural candidates for sonification. The first observations showed a 0.2-second up-chirp that one could hear easily at the original frequency and when slightly shifted up in frequency sounded like a bird chirp. The two subsequent observations also show a similar structure (as the black holes spiral in faster and faster). (For example, see http://acousticstoday.org/bh).

Another favorite sonification is "the sound of the big bang." A nice example of this can be found on the website of John G. Cramer of the University of Washington (http://acousticstoday.org/cramer). It is based on models of the universe's evolution over a 760,000-year time period that are constrained to correctly describe the CMB spectrum that is seen in **Figure 5**. As the universe expands, it becomes more and more of a bass instrument (which reflects the

CMB photons being redshifted physically). This sonification shifts the real frequencies by a factor of 10^{26} upward to match our human hearing range! The universe, even back then, was a big place and the wavelengths that fit within it were huge.

Moving back in closer to home, space physicist Don Gurnett has sonified the plasma density data from the Voyager probe traveling out of the solar system from the heliosphere to interstellar space. The pitch and frequency of the sound waves indicated the density of gas surrounding the spacecraft (which was sensed by a plasma probe) and made discerning the slow transition much easier. In the heliosphere, the tones were about 300 Hz, corresponding to plasma waves propagating through the (more rarefied) solar wind. When Voyager broke through to the interstellar medium, the frequency jumped to 2-3 kHz, making the jump clear to the researchers.

Within the solar system, Timothy Leighton has recommended the following excellent NASA website for sonification, http://acousticstoday.org/space. It features a dozen completely "otherworldly" sounds!

And finally, back at home, MIT's Building 54 (the "Green Building") was outfitted with a battery of 35 loudspeakers until mid-September 2017, which translated the temporal variability of the ions and electrons in the ionosphere into acoustic signals that were broadcast outside the building (http://acousticstoday.org/iono). This is a conscious merging of art and science for the MIT community's and public's benefit. Given that the music of the universe is a glorious merger of art and science, this is a perfect way to end this story.

Postscript

This article comes from a talk I gave as a member of the Cape Cod Astronomical Society, a very good group of amateur astronomers from my home region of Cape Cod. When they learned I did acoustics research and teaching for a living, one member quipped that "astronomy is a long way from acoustics!" I said that was untrue and would give a lecture to the club to prove it. This article is an expansion of that talk.

Acknowledgments

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Biosketch

Jim Lynch is president of the Cape Cod Astronomical Society, editor in chief of the Acoustical Society of America publications, and senior scientist emeritus at the Woods Hole Oceanographic Institution. He is a physicist by training and not an astronomer per se. His credentials are simply those of a very interested amateur with a science background. He again thanks his reviewers for checking this article.

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