CULTURAL ANTHROPOLOGY

GRAVITY'S REVERB: Listening to Space-Time, or Articulating the Sounds of Gravitational-Wave Detection

STEFAN HELMREICH
Massachusetts Institute of Technology
http://orcid.org/0000-0003-0859-5881

I heard gravitational waves before they were detected.[1]

I was sitting in a pub in May 2015 with MIT physicists Scott Hughes and David Kaiser, my headphones looped into a laptop. Hughes was readying to play us some interstellar sounds: digital audio files, he explained, that were sonic simulations of what gravitational waves might sound like if, one day, such cosmic undulations arrived at detection devices on Earth. Gravitational waves are tiny but consequential wriggles in space-time, first theorized by Einstein in 1916—vibrations generated, for example, by such colossal events as the collision of black holes or the detonation of supernovae. Listening to Hughes's .wav representations of black holes spiraling into one another, I heard washing-machine whirs, Theremin-like glissandos, and cybernetic chirps—noises reminiscent, I mused, of mid-twentieth century sci-fi movies (see Taylor 2001 on space-age music).

00:00 00:16

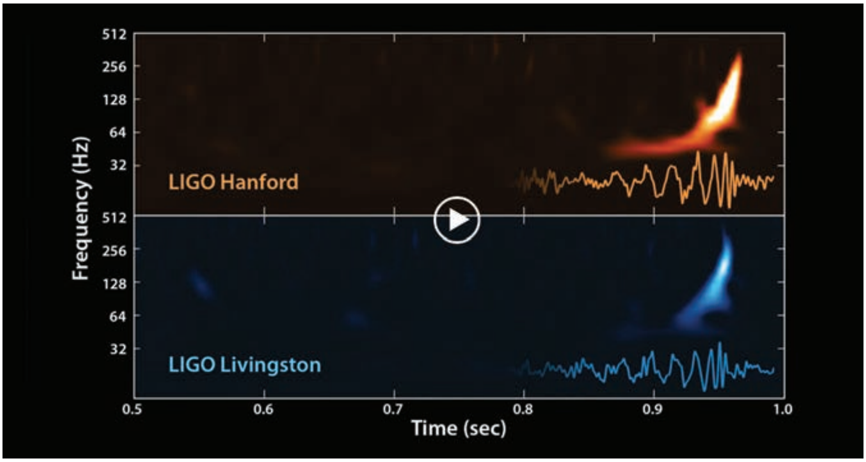
Audio 1. Circular inspiral, spin 35.94% of maximum, orbital plane 0°, 0° viewing angle. Created by Pei-Lan Hsu, using code written by Scott Hughes.

00:00 00:09

Audio 2. Generic inspiral, eccentricity $e = 0.7$, inclination $i = 25°$. Created by Pei-Lan Hsu, using code written by Scott Hughes.

CULTURAL ANTHROPOLOGY, Vol. 31, Issue 4, pp. 464–492, ISSN 0886-7356, online ISSN 1548-1360. *DOI: 10.14506/ca31.4.02*

These were sounds that, as it turned out, had a family resemblance to the actual detection signal that, come February 2016, would be made public by astronomers at the Laser Interferometer Gravitational-Wave Observatory (LIGO), an MIT-Caltech astronomy collaboration anchored at two massive antennae complexes, one in Hanford, Washington, another in Livingston, Louisiana. The sonic imprint of that detection, described by astronomers as a "chirp," had arrived in September 2015, and, before making its way into the media, had been double-checked and sonically streamlined. The audio file that then circulated was joined with an evocative graphic, a paired set of left-to-right waveform readouts, aligned with bright spectrogram swoops (suggesting nothing so much as ghostly nebulae against a space-dark background).



Video 1. A visualization of the chirp pattern detected on September 14, 2015. Created by LIGO.

What *are* gravitational-wave detection sounds, predicted and actual? How do they operate as auditory evidence and argument in today's astronomy and what can they tell us about the cultural valences of astronomical and other scientific audition? There are historical answers: astronomy has long been tuning its observations to different wavelengths—to optical, infrared, X-ray, radio, ultraviolet, and gamma-ray radiation (see Munns 2013 on radio astronomy). Gravitational waves open a sonically accessible channel of apprehension, though they also promise to take astronomy into a novel realm, since these waves are not, as are electromagnetic and acoustic waves, vibrations that travel *through* space-time. Rather, they are warpings *in* space-time. There are sociological answers: such sounds bear the imprint of community debates about what can count as a proper machine registration of gravitational waves (Collins 2004). There are philosophical and technical answers: fixing gravitational waves as part of the ontology of the universe has required well-structured and well-elaborated wave analogies and correspondingly calibrated technologies of waveform capture (Kennefick 2007).

There are answers to be sought, too, by approaching these sounds anthropologically, as I do here. I ask: How do established and up-to-the-minute metaphors, models, and machines shape how such cosmic vibrations come into audibility? What symbolic significance does listening to the universe hold for scientists? How do encounters of humans with a cosmically scaled phenomenon—an encounter with what philosopher Timothy Morton (2013, 1) would call a *hyperobject*, a thing that is "massively distributed in time and space relative to humans"—summon up cognitive, practical, and affectual strategies for grappling with the gap between cosmic and human scales? In this essay, drawing on conversations with a few LIGO scientists at MIT and on popular representations of gravitational-wave sound, I sketch the outlines of a gravitational-wave science *acoustemology*, which the anthropologist of music Steven Feld has defined as a "sonic way of knowing and being" (Feld and Brenneis 2004, 462; see also Feld 1996).

Astronomers have been scouting for gravitational waves for decades, first in small-scale experiments in the 1960s, famously conducted by the physicist Joseph Weber, and then, starting in 1992, at LIGO with the support of the National Science Foundation (Bartusiak 2000; Collins 2004; Levin 2016). Although these waves are not acoustic pressure waves (like ordinary sound waves in air)—but are theorized, rather, as squeezes and stretches in the very stuff of space-time—their frequencies, captured by detection instruments, coincidentally map onto the human auditory range (though, by the time they arrive at Earth, at vanishingly low amplitudes, one one-thousandth the diameter of a proton, much diminished from their initial, gargantuan sizes).[2] Scientists like Hughes have employed acoustic analogies to anticipate what gravitational waves might sound like to a detector, and have been creating audio simulations of possible discovery events. In this way, the black hole collision sounds I heard though headphones in May 2015 might be described as mathematically precise *sonic science fictions*, audio animations of scenarios derived from Einstein's theory of general relativity.

In 2016, the LIGO team described the sound of their gravitational-wave detection as a "chirp," a sound wave speedily swooping up in frequency. Much was made of this auditory representation. As the LIGO scientist Szabolcs Marka framed the matter in the *New York Times* (Overbye 2016), "Everything else in astronomy is like the eye. . . . Finally, astronomy grew ears. We never had ears before."[3] Or, as the physicist Gabriela González, the LIGO Scientific Collaboration spokesperson at Louisiana State University, elaborated when the detection was announced, "The frequencies of these waveforms are in the human hearing range. . . . We are not only going to be seeing the universe, we are going to be *listening* to it" (NSF 2016).

How do scientists turn gravitational-wave detection into sound and meaning? To preview: gravitational-wave scientists do not take detection sounds to be acoustic emanations of the cosmos. Rather, they take these sounds to be encodings—mediations—of vibrations, even as these sounds, for some astronomers, also make "visceral" for them the detection of gravitational waves; such detections thus have an emotional charge. Thinking through the meanings of these sounds often sees scientists reaching for analogies to do with auditory experience. Some suggest that interpreting these sounds requires them to develop a "vocabulary," a trained judgment about how to listen for the meanings behind particular waveforms. Gravitational-wave detection sounds, I argue, are thus *articulations*—articulations of theories with models and of models with instrumental captures of physical phenomena. Following Stuart Hall, I take an articulation to be both a speech act and a linking together of entities, a form of "connection that can make a unity of two different elements, under certain conditions" (Grossberg 1986, 53). Mike Fortun and Herbert J. Bernstein (1998, 39) offer a science-studies elaboration, writing that a linguistic articulation seeks "to give words to, to try to express, describe, or invent something that wasn't previously a part of language or thought" and that a physical articulation operates as a "corporeal, an organic or mechanical . . . structure in which different parts meet and rub up against each other" (compare Kockelman 2013, 57, 143 on "inferential articulation," an articulation that emerges when people interpreting a network of signs agree that relations among signs are bound by infrastructures of logical inference). Gravitational-wave sounds emerge from semiotically and technologically specific articulations of humans with machines with nonhuman phenomena.

A recap of what scientists claimed the LIGO detection indicated: A long time ago in a galaxy far, far away, a pair of black holes that had been orbiting each other for billions of years hurtled into one another, releasing in a fraction of a second a train of gravitational waves—the conversion into energy of much of the mass that these former stars jettisoned as they combined into one enormous black hole. When this energy arrived to Earth on September 14, 2015, 1.3 billion years after its cataclysmic origin, it interfered with beams of laser light ricocheting off mirrors in the LIGO apparatus. That phase displacement was translated into a sine wave sound that slid in two tenths of a second up from 35 Hz to 150 Hz. This was the chirp (see Hughes 2016). When Caltech's LIGO Laboratory executive director, David Reitze, announced the detection on February 11, 2016, at the National Press Club in Washington, D.C., he offered an explication at once clarifying and poetic:

> What LIGO does is it actually takes these vibrations in space-time, these ripples in space-time, and it records them on a photo-detector, and you can actually hear them. So, what LIGO has done, it's the first time the universe has spoken to us through gravitational waves. And this is remarkable. Up till now, we've been deaf to gravitational waves, but today we are able to hear them. (NSF 2016)

Reitze's announcement makes clear that gravitational-wave signals require a chain of mediations to appear, even as their sounded translations also invite more informal acoustic descriptions (the word *spoken* here suggesting that gravitational-wave sounds are already articulations). If the analogy of gravitational waves to sound waves is secured instrumentally in LIGO's techniques of signal registration, it permits commentators, scientific and popular, to glide toward more fanciful metaphorical accounts.[4] The mathematico-computational *formalisms* and technological forms through which gravitational waves are known and made audible—Einstein's equations, interferometric observatories, sound files—thus operate alongside less fully disciplined collections of acoustic, auditory, and even musical similes and metaphors, which I will call *informalisms*. Those informalisms can then bounce or reflect back on the original articulations, leading to a kind of rhetorical reverb, in which articulations, amplified through a range of similes, metaphors, and analogies, become difficult to fully isolate (for scientists as well as their ethnographers) from the rhetorical reflections they generate.

I tell a three-part story. In the first section, I discuss the rhetorical and technical apparatuses that have over the last half-century or so prepared scientists to imagine (and, through the mediation of their instruments, experience) the cosmos as a sounded space. In the second, I work through Hughes's premonitory gravitational-wave simulations, developing the claim that these predictive sounds are articulations and audio animations of models and theory in physics. In the third section, I zero in on the detection event of 2015, asking how its sonic aspect bolstered gravitational waves' claim to reality. I report on conversations with scientists who told me that they used the infrastructural rumbling and buzzing of

LIGO as a "diagnostic" of whether the detectors were working, and that hearing the chirp on top of this noise made the event "visceral." Gravitational-wave sounds are not the unvarnished sounds of nature. Even as they tell a story about the cosmos, I conclude that they are also the articulated sounds of human-technological-ahuman assemblages.

PREVERBERATION

For centuries, space was either a zone of the harmonic, cosmic sublime or of vast silence. The stage for a modern, noisier cosmos was set in the middle of the twentieth century, in the years around the theorization of the Big Bang. In *Making Noise: From Babel to the Big Bang and Beyond*, Hillel Schwartz (2011) suggests that the Big Bang, emerging from the thinking of Georges Lemaître and George Gamow on the (backward-in-time) implications of an expanding universe, was of its cultural moment, echoing anxieties about what Oppenheimer called the "big bang" of the atom bomb, as well as keying in to a world ever more saturated by sound, static, distortion, and noise (the term "Big Bang" was coined in 1949 by the astronomer Fred Hoyle, and is often understood to have been a jibe at theories of cosmic evolution, which Hoyle found unpersuasive). Schwartz (2011, 823) writes, "The Big Bang became such an audicon of astrophysics and so constant a cosmological figure in popular discourse because of the omnipresence and everyhowness of noise." Schwartz listens back before the full arrival of the Big Bang theory, too, reporting on metaphors describing cosmic rays, in, for example, Harvey Lemon's 1936 book, *Cosmic Rays Thus Far*, in which Lemon wrote, "now and then, here and there, in the great solitudes and silences of interstellar, intergalactic space, an atom, perhaps of hydrogen, is born of radiation . . . [cosmic rays are] the wail of newborn atoms" (Schwartz 2011, 818). As the universe became imaginable in sound, it became populated with noises—pops and chirps against the hum of the cosmic microwave background, that field of radiation left over from the early universe. Schwartz (2011, 827) also offers a 1980 quotation from a reflection by Rudolf Kippenhahn, the director of the Max Planck Research Institute for Astrophysics in Munich:

> At a lecture I gave around 1960, I asked the audience to imagine an instrument capable of transforming all the incoming radiation from space into audible sound. We would hear the constant rushing of the starlight and the radio eruptions of the sun as well as the rushing of the radio waves. . . . [Now, twenty years later], we could hear the heterodyne ticking of the

> pulsars—the low humming of the Cancer pulsar for instance, emitting pulses of very high energy from a spherical star cluster. . . . There is not only rushing to be heard in space, there is ticking and drumming, humming, and cracking.

The idea of a universe available for technical audition, then, was in place by at least the mid-1960s. A proper historical accounting would track the technical choices, institutional infrastructures, and funding regimes that enabled Kippenhahn's call to "imagine" "radiation from space" as "audible sound" to be realized in detection techniques that can in fact produce sound as one of their outputs.

Sonic descriptions of cosmic phenomena—and of gravitational waves in particular—now suffuse popular representations. In her history of gravitational-wave science, *Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time*, Marcia Bartusiak (2000, 9) writes that since gravitational waves have a "frequency [that] happens to fall in the audio range," their detection "will at last be adding sound to our cosmic senses, turning the silent universe into a 'talkie,' one in which we might 'hear' the thunder of colliding black holes or the whoosh of a collapsing star."[5] Bartusiak's scare quotes, particularly around the word *talkie*—a term used after the era of silent film to refer to motion pictures with sound—make evident that the universe is not itself a movie or sound object, but is rather apprehensible as such only through technologies of representation. As Alexandra Supper (2014, 37) writes in her study of scientists turning data from sunspot detections into sound, it is important to be cautious about "the usage of metaphors to suggest that the sounds are inherent to the phenomena being sonified rather than the outcome of a series of human-technological interventions."

The Columbia University physicist and cosmologist Jenna Levin (2011, 9:32–12:12) makes manifest how such metaphors may sometimes collapse toward the literal. In an online TED talk originally delivered in 2011, she navigates through thickets of mixed metaphors to guide her listeners toward an intuition that gravitational waves are *real* sounds: "The universe has a soundtrack and that soundtrack is played on space itself, because space can wobble like a drum. It can ring out a kind of recording throughout the universe of some of the most dramatic events as they unfold." Gravitational waves, Levin proposes, are:

> literally the sounds of space ringing. . . . If you were standing near enough, your ear would resonate with the squeezing and stretching of space. You would literally hear the sound. . . . I'd like to play for you the sound that we predict. . . . Imagine a lighter black hole falling into a very heavy black

> hole. The sound you're hearing is the light black hole banging on space each time it gets close. It . . . comes in like a mallet and it literally cracks space, wobbling it like a drum. And we can predict what the sound will be. We know that as it falls it gets faster and it gets louder.
>
> [*Plays sound, a rhythmic tapping that speeds up until it ceases*]
>
> . . . and it's gone. Now, I've never heard it that loud—it's actually more dramatic. At home it sounds kind of anticlimactic. It's sort of like "ding, ding, ding." . . . Now that chirp is very characteristic of black holes merging—that it chirps up at the end. . . . But the sound is too quiet for any of us to ever hear.

Levin here compresses an explanatory map onto empirical territory—her repeated use of the word *literally* presents sounds as research findings rather than as mediated data or interpretations, setting up a rhetorical reverb that requires a certain listening *through* or *past* to get at the more staid technical claims that she and her colleagues might otherwise articulate when talking among themselves. The rhetorical reverb here reinforces a sense of space as sounded, as a transductive medium (cf. Helmreich 2007), full of signal and noise (a sense of reality as a suffusing space of vibration, from the body to the cosmos, gathers force with wave theories of the late nineteenth and early twentieth centuries; see Beer 1996; Trower 2012; Brain 2015).

Whether the sound of the universe is imagined as loud—Kippenhahn's "eruptions"—or quiet—"low humming"—adds an additional dimension to cosmic listening. The sober solitude culturally associated with astronomical enterprise resonates aesthetically with the relatively modest sounds delivered by gravitational-wave astronomy (Overbye 1991; see also Aubin, Bigg, and Sibum 2010 on the quasi-monastic space of the observatory). Levin's remark that she usually hears gravitational-wave audio simulations "at home" as "anticlimactic"—she is impressed at her TED talk by hearing a simulation "that loud"—points to the affects awakened by gravitational-wave sounds (see Thompson and Biddle 2013 on sound as affect). As cleaned-up sounds never to be played back too loud, gravitational-wave sounds are not terrifying cosmic roars, but subtle and well-mannered sounds of precise science. The quiet that follows them becomes an invitation to contemplation.

As the sound studies theorist Jonathan Sterne (2003) argues, sound has, at least in European and American epistemological settings, long been associated with embodied, even intimate, knowledge. Sterne (2003, 15) describes the contrasting associations between hearing and vision that have animated this acoustemology. Whereas "hearing is concerned with interiors, vision is concerned with surfaces . . . hearing tends toward subjectivity, vision tends toward objectivity . . . hearing is a sense that immerses us in the world, vision is a sense that removes us from it." The prospect of listening to gravitational waves thus offers for persons invested in this acoustemology a meeting place between subjective and objective, a way of making inhumanly scaled phenomena experientially available to the bodies of hearing scientists and their audiences.

There is an aesthetic component to informal descriptions of space sound. When writers deliver depictions of the universe as a piece of symphonic music, they bring the science into the realm of elevated intellectual appreciation. Bartusiak, in her book, offers an extended comparison of Einstein to a great German composer. At a later moment in her text, the "talkie" universe morphs into a kind of modernist symphony, perhaps one written by Stravinsky:

> The LIGO detectors on each coast are best receptive to frequencies from 100 to 3,000 hertz. On the musical scale that roughly extends from an extremely low A note to a very high F-sharp. . . . Given the audio range of the signal, there might be single cymbal crashes from exploding stars, periodic drumbeats from a swiftly rotating pulsar, and extended glissando—a rapid ride up the scale—from the merger of two black holes, as well as a faint background hiss. (Bartusiak 2000, 153)

The "background hiss" is suggestive of the noise of a recording medium, pointing to the fact that hearing cosmic music happens against an infrastructure, which itself has a noise. Bartusiak's phrasing may remind readers of a certain age cohort of "tape hiss," the background sound made by magnetic cassette tapes, indicating that sonic metaphors key closely to their historical moments. Consider Albert Lazzarini, a 1974 MIT graduate with a physics degree, whose comments on a recording of a possible gravitational wave Bartusiak (2000, 165) quotes. Lazzarini's words track the aesthetics of tape-recorder noise and make a canonical countercultural reference to nonhuman sound: "It sounds like a hiss. . . . Actually, a hiss with warbles in it, due to the suspension. It's eerie, in some ways like whale songs." In these framings, the universe is variously a romantic composition or a nonhuman song; consider Janna Levin's (2016) book *Black Hole Blues and Other Songs from Outer Space* (by now, we have been through most of the master metaphors for organized sound in the West: symphonies, compositions, instruments, soundtracks, background noise, the blues . . .). Notably, the black-hole universe is almost never imagined in the key of menacingly noisy heavy metal—or, better, ambient death metal—which one could imagine as fitting, given the cosmic catastrophes that something like the chirp is meant to index.

SIMULATION

When David Kaiser and I listened to Scott Hughes's simulated gravitational-wave sounds, Hughes (n.d.) pointed back to his website, which provided an analogical warrant for posing gravitational waves as akin to sound waves:

> The waves that [gravitational waves] generate will have wavelengths of thousands or tens of thousands of kilometers. We cannot even in principle use this radiation to form an *image* of its source; thinking about what GWs can help us "see" is just not a well-posed analogy. A more fruitful analogy can be formed based on sound. The sounds that our ears are sensitive to have wavelengths that can be many meters or tens of meters, far too long to form images of the sources that generate them.

Listening to Hughes's sounds, I recollected *Einstein's Unfinished Symphony*, in which Bartusiak (2000, 199) described what these sounds might resemble: "a sort of whine, a series of waves that rapidly rise in pitch, like the sound of an ambulance siren that is swiftly approaching." What, though, was I listening *to* when I listened to sound files meant to portray gravitational-wave detections? Take this auditory anticipation of what a detection might sound like if it were to capture gravitational-wave vibrations generated by a small black hole spiraling into a massive one, something not too far from what LIGO captured:

Audio 3. Circular inspiral, spin 99.8% of maximum, orbital plane 20°, 0° viewing angle. Created by Pei-Lan Hsu, using code written by Scott Hughes.

Hughes and an undergraduate physics major, Pei-Lan Hsu, created this simulation in 2007. What *is* this .wav file?[6] To begin, such gravitational wave files are not: recordings (direct, pitch-shifted, amplified, or otherwise) of actual events; synthesized waveforms created from scratch, in the mode of the electronic synthesizer, using the manipulation of electronic oscillators, voltage-control filters, and envelope modulators; or sonifications that map the numerical to the sonic in arbitrary, if calibrated, ways (as sonifications of, say, the stock market might; the stock market is not itself a waveform, even if its rises and falls can be mapped as one). Hughes's audio waveforms are, rather, sonic indexes of ideal-typical events—they have relations of analogy, of close contiguity, to waveforms that might be produced by gravitational waves. A file like "Circular Inspiral" is an index—in Charles Sanders Peirce's semiotic sense—of a simulation, an impression of the coming into being of a physical object (of course, for nonphysicists, Hughes's sounds might still be reminiscent of synthesizer sounds, or they might be experienced as what the *musique concrète* composer Pierre Schaeffer in 1966 called *acousmatic*: sounds without an apparent cause in the common-sense world [see Kane 2014]).

David Kaiser and I asked Hughes how the simulated sound artifact was made. The recipe involves theoretical abstractions, mathematical formalisms, computational simulations, and translations of all these into sound (rather than into images). The steps go like this:

1. Start with Einstein's general relativity equations.
2. Employ equations from this set to model a scenario that creates gravitational waves (in, e.g., a binary star system in which stars spiral into collision with one another).
3. Translate the equations describing this system into a computational formalism in FORTRAN 90 or C++ that can be moved forward step by step, in computational time, and that can thereby simulate the propagation of gravitational waves.
4. Transduce the wave frequency value outputs into audible data in the audio spectrum.
5. Format this data as a digital sound file (mp3, AIFF, .wav).

In the making here is not only a sound simulation but also, more foundationally, an animation, in sound, of a theory of gravitational-wave phenomena.[7] Hughes agreed that such sounds were "not theory-agnostic"—and, indeed, as Daniel Kennefick (2000) has shown, there have been battles in gravitational-wave science about what it is that theory should and can predict about black hole coalescence. Hughes's files are, I suggest, *audio animations*: stepped, frame-by-frame representations (audifications) of a system meant to be captured by a one-to-one mapping between an ideal or empirical reality and a schematized, moving depiction.[8]

The sequence of events that makes this animation is a chain of what the media scholars Jay Bolter and Richard Grusin (1999) call *remediations*, transformations in the media that carry information from one domain to another (from scientific papers to computers to speakers). These transformations also follow what the historian of science Stephanie Dick (2014) would call a series of *reformalisms*: changes in the form of inscription across formats (from nonlinear equations to computer languages to those transduced vibrations that many of us define as "sound"). There exist for these files, then, what Jonathan Sterne (2012, 19–21) would call a "perceptual technics," a format that assumes a particular kind of listener, just as the mp3 format instantiates a specific psychoacoustic model. As the sound studies scholar Tara Rodgers (2011) would also point out, these waves have been cleaned up, made pure, and as such emerge from an audio-technical tradition that has treated sounds as individuals—individuals whose lifetimes can be graphed, whose properties can be purified (think sine wave), and whose growth and decay can be formally known and represented (think heartbeats in electrocardiograms) through the narrative form of the waveform. This purity is consequential—it makes the sounds *sound* like mathematical abstractions. No wonder these files make me imagine sci-fi movie oscilloscopes—and remind me of what James Wierzbicki (2014), in his taxonomy of sounds in science fiction films, calls the sounds of "futuristic" technologies, "made up of bleeps and blips that cover a wide pitch range and are devoid of recognizable rhythmic patterns" (see also Taylor 2001 on space-age sounds, which Taylor tracks not only in labs, but also through histories of hi-fi recordings meant to appeal to audiophiles).

Hughes's simulations await a prepared—or trainable—listener. They provide information to those who know how to listen. When he was interviewed in the *Atlantic* just after the gravitational-wave detection, Hughes offered that detection sounds could be understood as parts of something like a language: "I like to think of it in a linguistic way," he said. "The vocabulary of the [event] is imprinted on the wave" (Adams and Chapman 2016). In an audio accompaniment to the *Atlantic* piece, Hughes used his voice to imitate detection sounds: "If the two black holes are nonspinning, you get a very simple chirp: *whoop!* If the two bodies are spinning very rapidly, I have that same chirp, but with a modulation on top of it, so it kinda goes *wooooo woooo wooo woo re ri!* It's the vocabulary of spin, imprinted on this waveform." Earlier, Hughes had offered a similar account in my own conversation with him: "It's this idea that the spin causes this sort of *RrRR RrRR RrRR*. I consider that to be almost like a vocabulary. And that is telling me a lot about the evolution and the dynamics of this system."

Audio 4. Excerpt from an interview with Scott Hughes, conducted by Stefan Helmreich.

I hear evidence in this clip from my ethnographic interview with Hughes of how he thinks in a material and semiotic way about what I have been describing as linguistic-technical articulation. His voice becomes a medium for thinking about listening.

Hughes's recurring metaphor of vocabulary suggests, to underline the point, that sound representations are articulations, not just findings (recall Miller's [1993, 379] definition of metaphor as "a comparison statement with parts left out"; here, parts are *added*, as linguistic comparisons are swapped in for mathematical ones). If Levin poses her wave sounds as "literal," as data, Hughes offers his as indexical sounds that emerge where signals meet an articulatory apparatus (thereby taking for granted that gravitational waves exist, which is the datum that Levin seeks in her talks primarily to establish). Elinor Ochs, Patrick Gonzales, and Sally Jacoby (1996, 330), in their linguistic-anthropological account of how physicists use hands and voices to explain their research, can help us understand how scientists like Hughes use gesture and sound both to "express their subjective involvement . . . by foregrounding their role as practitioners of scientific activity" and to "express involvement more extremely by taking the perspective (empathizing with) some object being analyzed," thus "involving themselves in graphic (re)enactments of physical events" (see also Myers 2015 for examples of gesturally made knowledge in the life sciences). Hughes's enactment offers a sonically embodied inferential articulation, saturated with rhetorical reverb.

What might be learned from gravitational-wave soundings? One question that comes up in discussions of transforming data into sound is whether this adds anything epistemologically novel or offers merely a popularization (see Supper 2014). Hughes offered an argument for sound as more than an impressionistic tool:

> We have two ears, and I can make these sounds in stereo. I put one polarization in the left ear, one in the right ear. And you can hear in some of these sources, they evolve in slightly different ways, which turns out to be connected to the orientation of the source with respect to line of sight, or line of hearing. Stereo can help illustrate what information is being carried by these polarizations.

In other words, assigning the two polarizations of gravitational waves to the two sides of a stereo mix takes advantage of the two-earedness of humans. The twoness of gravitational-wave polarization and the twoness of human ears, however, as David Kaiser helped me understand, is a serendipitous coincidence.[9] What results is not a sound *image* of gravitational waves (as Levin might have it), but rather a sound *graph* or *diagram*—one you have to learn to read through listening, one for which you need what Hughes calls a "vocabulary" (cf. Rice 2010, on learning how to hear through stethoscopes). As Hughes put it to me, "It's a new dimension of hearing." Hughes's strategic stereophony now demands abstractly formalist rather than indexical listening (cf. Hirschkind 2004, 137 on pious listening, in which sermon audiences use "disciplined ears" to hear divine truth not *in* but *through* the words of religious orators). Placing x coordinates in one ear and y coordinates in another makes this file not really a stereo image at all, but a file with different aspects of the same sound piped to different ears—as if one had, analogously, glasses that let one see only blue in one eye and only red in another. Listening itself becomes a kind of articulation.

REALIZATION

When LIGO delivered the detection news, the signal presented sounded much like Hughes's audio anticipations. Work of the sort Hughes did turned out to be essential for scientists to know what they were listening for. The detection was informed by audio animations. As a team of researchers who simulate black holes explained, "Scientists develop possible waveforms that could be detected in their instruments. Each of these 'template' waveforms is then tested in a computer against the detector data to see if the template rings sympathetically" (SXS n.d.). Or, as the physicist Kip Thorne put it when the news arrived:

> The colliding black holes that produced these gravitational waves created a violent storm in the fabric of space and time. . . . We have been able to deduce the full details of the storm by comparing the gravitational-wave forms that LIGO saw with the wave forms that are predicted by supercomputer simulations. (NSF 2016)

The use of so-called matched filtering evidences what science-studies scholars might term theory-laden observation (see Hanson 1958; Kennefick 2000), with theories necessarily built right into detection tools.[10] In an older anthropological idiom—giving gravitational waves something of an animist spin—a template might also be understood as a trap, "both a model of its creator, the hunter, and a model of its victim, the prey animal. . . . the trap embodies a scenario, which is the dramatic nexus that binds these two protagonists together, and which aligns them in time and space" (Gell 1996, 27).[11]

Although much of the discussion of gravitational waves operated in the domain of the auditory, images were far from absent.[12] Indeed, the sound was often explicated using left-to-right graphs, with time along the x axis and amplitude (of strain) along the y. Figure 1 of the detection paper (Abbott et al. 2016) looked like this:

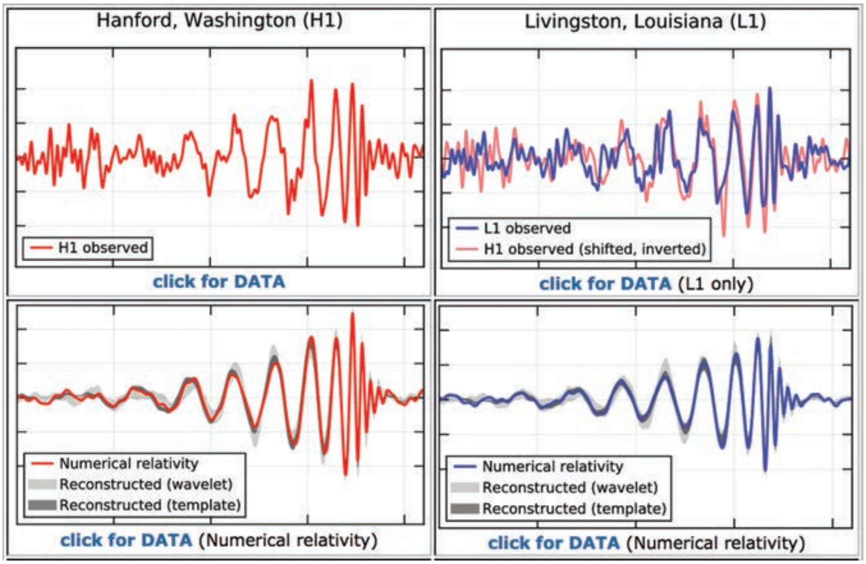


Figure 1. In the top row, the gravitational-wave event GW150914 as observed by the LIGO Hanford and Livingston detectors. GW150914 arrived at Livingston first and then at Hanford 6.9 ms later. To permit comparison, Hanford data are visually superimposed on the Livingston data, but shifted by 6.9 ms and, to account for the detectors' physical orientations, inverted. In the bottom row, an ideal-typical projection of gravitational-wave strain onto each detector, mapping a numerical relativity waveform consistent with GW150914 parameters. As with gravitational-wave sounds, these gravitational-wave graphics reflect the neatening up and articulation of data. Created by LIGO.

In the wake of the detection, I contacted two MIT players in the LIGO story: Nergis Mavalvala, a MacArthur Prize–winning astrophysicist who has spent her career developing and implementing technological innovations for the LIGO detectors, and who has spent many years at the Washington and Louisiana sites, and Matthew Evans, an astrophysicist specializing in the making and testing of the LIGO apparatus, involved in engineering and troubleshooting the instruments.

When I met with Mavalvala, I saw she had stereo speakers in her office. "I have a good amplifier and good speakers," she explained, "because sometimes someone will just send me a signal file. And I can look at it on my screen as a graph, or I can encode it as a sound." Although she emphasized that gravitational-wave phenomena were not themselves acoustic, she said translating them into sound could aid in judging a signal significant:

> Some compact stars can be spinning at frequencies we can hear. You could have one sitting right at middle C. And you would just hear a single tone, *mmmmm*. Sometimes you might have a companion star that's near enough to slightly perturb its orbit. And then you'll get exactly the same thing, but you might get a little envelope as the star feels its gravity a little bit. And then you'll see the same single tone, but modulated, *mmnnmmnnmm*, like that. All of those things tell us about what the source is. It's actually vocabulary, within the language of signal.

So, while similar information could be extracted from a visual reading of the data, audification adds another dimension. Mavalvala went on: "The very first thing that happens is a computer algorithm tells you, 'I hear something loud.' And then you say, 'oh, what do you hear?' to the computer algorithm, and then you plot it, and then if it looks interesting, then you might do the right filtering, and put it into sound." Of the detection, she said, "It's very *viscerally* a *thump*, compared to seeing a squiggle on a screen. Graphs may have all kinds of frequencies, and then somehow our ears, because of the way that filtering happens, pick something up that our eyes didn't pick up."[13]

Mavalvala's account of such *articulate listening* suggests a question: *who* or *what* is doing the listening in gravitational-wave astronomy? At some moments, scientists will propose that it is a discipline or field—recall LIGO scientist Szabolcs Marka remarking that "finally, astronomy grew ears." At other moments, it may be the LIGO experimental system as a whole, tuning to the "epistemic thing" (Rheinberger 1997) of the gravitational wave. At still others, the listener may be a computer program—as when Mavalvala gives voice to a computer algorithm: "I hear something loud." And, of course, in many instances the listeners are scientists, plugged into an articulated listening relay, making sense and sensibility from signals.

For such signals to be discerned at all (by machines or people), the ambient hums and noises of the detector have to be controlled, held steady, if not fully quiet. The detector, a massive device distributed across two physical sites—

Washington and Louisiana—is constantly vibrating owing to seismic, ambient, and quantum fluctuations. Before a signal can be registered, Matt Evans told me, scientists must draw up a "noise budget," a catalog of all the sounds that need to be listened *through* or filtered out. A graphical representation of such a budget hung on Evans's wall:

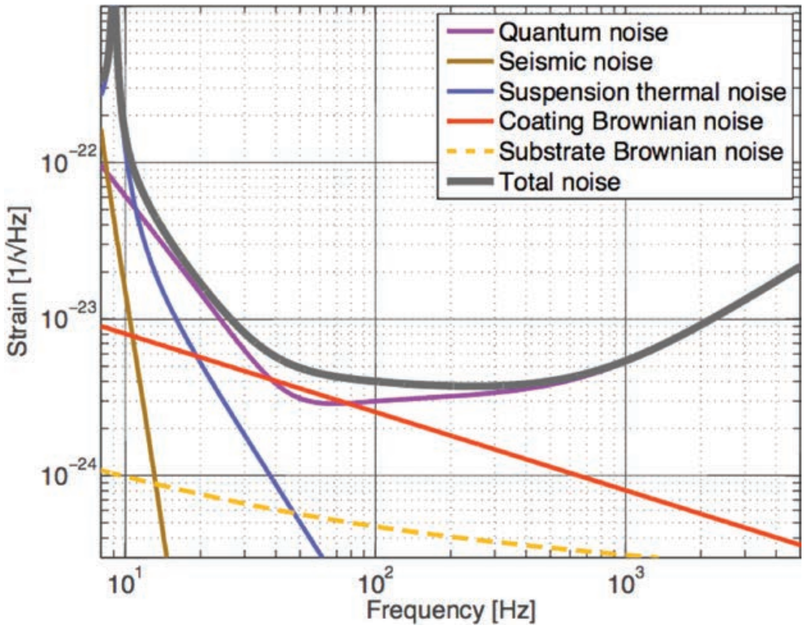


Figure 2. Noise budget for LIGO. Figure from "The Advanced LIGO Gravitation Wave Detector, by S. J. Waldman, https://arxiv.org/abs/1103.2728.

Evans played me, in succession, the different "noises" of the LIGO detector at work, the frequencies that had to be accounted for in a noise budget. He played me the following files:

Audio 5. Seismic noise. Created by LIGO.

Audio 6. Thermal noise. Created by LIGO.

Audio 7. Quantum noise. Created by LIGO.

The first, seismic noise, was "just sort of a low rumbling." The second, thermal noise, was "like waves on a beach." And the third, quantum noise, was "like hard rain on a sidewalk." He also played me the sound of the LIGO machine at the ready, resonating with what he called "violin modes."

Audio 8. Violin modes. Created by LIGO.

These resonances were so named because the thin glass fibers that suspend the central interferometer mirrors oscillate, when at rest, with a clear string tone at around 500 Hertz. All these sounds inform LIGO operators' embodied sense of whether the instrument is working properly (cf. Mody 2005). As Mavalvala told me:

> We use this not just as an analogy, we actually use this in our work. When we're sitting there diagnosing our detectors, we will encode sound into a loudspeaker or headphones. And the different kinds of sound allow us to diagnose what's troubling the detector. We can assemble a vocabulary of maladies.

Evans elaborated:

> We listen to the sound, and when the detector is "locking" to get the control system operating, it thumps in a particular pattern—clicks and bumps and things like this, going through various transitions. And then at some point you get the nice humming sound of the detector. That's sort of a peaceful moment, when you know that you have the thing operating and in a happy state, and you can hear the violins going.

"We use our ears," he emphasized, "to diagnose the interferometer performance. We listen to the output of the detectors on the speakers in the control room. That came naturally to me. I used to have an old '67 Camaro and I would never turn on the stereo when I was driving the car." Evans and others frequently walk around the LIGO facility searching for sources of unwanted vibration. One source of scattered light, he told me, "sounded like these big howler monkeys or apes." The Louisiana observatory is built on a swamp, which gives it distinct resonant frequencies in the seismic register. It is also close to truck and train traffic. As Rainer Weiss (2016), a key MIT scientist behind LIGO, put it in a recent colloquium talk, "Noise comes from the Earth, from anthropogenic things . . . mostly *people*."

Once noise is stabilized, it becomes possible to operate with a background against which to detect a signal. And the "noise" is noisy—staticky, buzzy, hummy, a fuzz against which to pick out a clean signal. LIGO observatories, Evans told me, are "like giant hearing aids." Just like Mavalvala, Evans thought detection could be aided by listening:

> Your ears are roughly equivalent to a fraction-of-a-second fast Fourier transform. So, rather than opening up a program and looking at this thing, and trying to figure out what the features are, your ears just pick all those things out without any trouble. There are things which happen in the spectrum that are there if you know what to *look* for, but without thinking about it or learning how to do it, you can *listen* to it, and hear very obviously the clicks and bumps.

Evans's metaphor of the hearing aid might be tweaked. LIGO may be more like a cochlear implant, a frequency analyzer that anticipates what those phenomena *are* that these devices need to capture and then builds these deeply *into* the infrastructure of machine listening. In this light, LIGO director David Reitze's comment about astronomy having been "deaf" can be understood as flagging a disciplinary condition that requires a technical fix (see Friedner and Helmreich 2012 on the acoustemology of cochlear implants). That vibratory capture, then heard by hearing humans, has a phenomenological dimension. The rumble that accompanies detection provides a sense that *something is happening*. Scientists are not listening against digital silence, but rather against a hum that tells them that the detector is on. As Ragnhild Brøvig-Hanssen and Anne Danielsen (2016) argue in their book on digital sound, each recording and playback medium—wax, tape, vinyl, digital—has its own distinctive silence, usually a characteristic set of whirrs, clicks, hisses, and pops. It is no different with LIGO. The noise/silence, I suggest, adds reality to the signal. The chirp—a clean, abstract, mathematically streamlined sound, like a Theremin whoop—is juxtaposed, emerges from, and therefore acquires the reality effect of the rumble, roar, and hiss that LIGO is always creating and that is always being sonically documented.

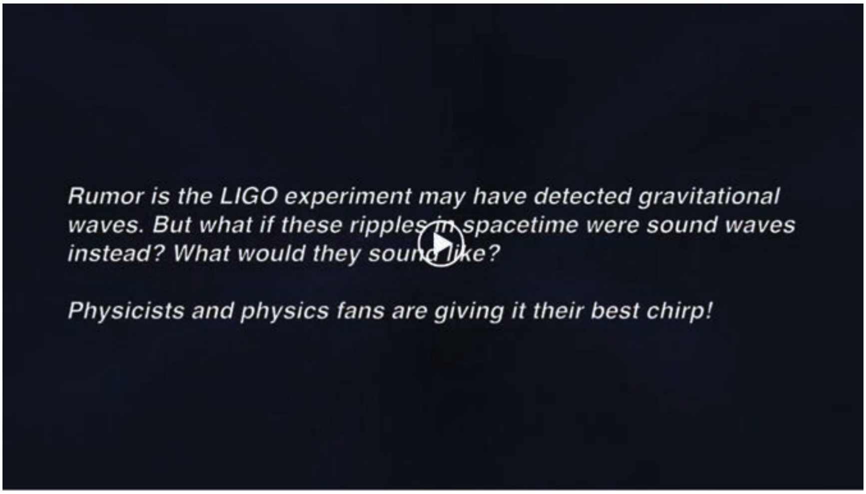
Why is the signal sound called a chirp? The term originates in radar research, describing a pulse-compressed signal that shows a sweeping increase (or decrease) in frequency, a sweep that radar engineers in the 1950s likened to the chirp of a bird, bat, or insect (the *Oxford English Dictionary* defines *chirp* as "the short sharp shrill sound made by some small birds and certain insects; a sound made with the lips resembling this; a chirrup"). The term was coined in 1951 in a Bell Lab memo entitled "Not with a Bang, but a Chirp," a reference to the final line of T.S. Eliot's 1925 poem "The Hollow Men," which famously reads "Not with a bang, but a whimper" (see Klauder et al. 1960). By the time LIGO scientists used the term, it had a formalized meaning and measure in signal science—though these are not in fact carried over into the gravitational-wave usage, which has a different mathematical form, making the use of the word *chirp* here more metaphorical than exact.

Gabriela González presented the sound at the 2016 detection announcement, guiding listeners in how to hear:

> I wanted to play the gravitational wave for you to hear, but it's so short that it's just a *thump*. So, what we have done is taken the real signal and shifted a bit in frequency, but it's still the real signal. Did you hear the chirp? There's a rumbling noise, and then there's a chirp. . . . *Whoop!* That's the chirp we've been looking for. This is the signal we have measured. (NSF 2016)

González's account starts by identifying the gravitational-wave detection event with the gravitational wave itself, but then explains that the low thump extracted from the observational apparatus had to be pitched up in frequency so that humans could hear it well. Her next step was to make sure her listeners knew what they were listening for: "Did you hear the chirp? There's a rumbling noise, and then there's a chirp." Thinking back to Hughes's suggestion that gravitational-wave sound signatures offer a "vocabulary," we can think of the chirp—with its reference to bird vocalization and to organized radar signals—as an *articulate* sound, a sound that emerges from a structured source (and one that has already been anticipated, since the word *chirp* was used to describe candidate signals even before they were detected).[14]

This may explain why González vocalizes along with the data playback: "*Whoop!* That's the chirp we've been looking for."[15] Alexandra Supper (2015) calls such performances "data karaoke." On the day of the announcement, the YouTube user Unruly Curiosity posted a video of people voicing the chirp sound, performing this sound as a human-nonhuman articulation (a reading reinforced by the fact that some chirps were offered by guinea pigs and dogs; see Fortun and Bernstein 1998, 40 on material-semiotic scientific articulations as "lobsterlike entities made out of disparate, heterogeneous elements").



Video 2. Chirp for LIGO supercut trailer. Created by Unruly Curiosity, uploaded to YouTube on February 11, 2016, https://www.youtube.com/watch?v=0uzicC9qujg.

This practice of listening through vocalizing has something in common with what Steven Feld (1990) has described among the Kaluli of Papua New Guinea: a practice of listening by singing along, as when someone sits by a river and sings along with it as a way of hearing it (see also Eidsheim 2015). It underscores what the LIGO detection sound is: an index of human apprehension (see also Connor 2014 on sobs, hums, and stutters). At the same time, the *inarticulate*, animal character of the chirp offered by scientists embodies an argument that human imitators are aping or parroting a phenomenon beyond the human.[16] The fact that the chirp is funny when humans and animals make it emphasizes the uncanniness of the science—"a hybridization of machine and organism that, inevitably, makes one laugh" (Doyle 2003, 24).

REVERBERATION

In *Gravity's Shadow*, his sociology of the search for gravitational waves, Harry Collins (2004) chronicles a long history dating back to the 1960s of scientists' attempts to capture signs of gravitational waves. Thomas Pynchon's novel *Gravity's*

Rainbow—on which the title of *Gravity's Shadow* plays—grappled with the unsteady character of human scientific and social mastery over forces atomic and subatomic. *Gravity's Shadow* details how setting thresholds of gravitational-wave detection has been a scientific and social balancing act, ever shadowed by the prospect of high-stakes failure or success. What I call "gravity's reverb" in the title of this article points to a less grand subject. Reverberation is "a propagation effect in which a sound continues after the cessation of its emission. Reflections of the sound on surfaces in the surrounding space are added to the direct signal" (Augoyard and Torgue 2006, 111). The reverberations I listen for in this article are echoes and reinforcements of auditory analogies, echoes and reinforcements of explicit similes and implicit metaphors that can both add to and blur the "original" human-machine articulation of the sounds of gravitational waves.

In *Echo and Reverb: Fabricating Space in Popular Music Recording, 1900–1960*, Peter Doyle (2005) suggests that reverb originates in attempts to render in sound the emptiness of vast landscapes, particularly the frontier American West (as in such pieces as Vaughn Monroe's 1949 "Ghost Riders in the Sky"). Gravity's reverb, of the sort astronomers reported detecting from the universe, might be a sign of the vastness of the universe, making of the cosmos an echoing space of waves. But such reverb also echoes the history of astronomies dedicated to transposing data across wavelengths, the history of purifying sound, and the history of cleaning up sound recordings. There is something incongruous, then, about the match between the outsized scale of gravitational waves generated by black holes and the delicateness of a chirp sound, which, with its evocations of little birds, is almost an audicon of sonic smallness (cf. Mowitt 2015 on pings, whispers, and gasps). The modesty of the detection sound becomes a sound of sensible, not sublime, science.

Gravitational waves, then, are not precisely what Morton calls hyperobjects, outsized entities like climate or the Anthropocene that are, in his terms, viscous, nonlocal, temporally undulating, and phasing. Gravitational waves, at least as scientists know them through sound, are not fully beyond-the-human. They are articulations of human, technological, and cosmological vibration. While the cosmic time that LIGO speaks to may be vast and vibratory, the history that LIGO records is a human history—of instruments, institutions, and technologies fashioned as sensory adjuncts and extensions (see Weiss 2016).[17] Human apperceptions of gravitational waves are articulations, formalisms suffused by reverberating informalisms. Gravity's reverb is the sound of humans, listening.

ABSTRACT

In February 2016, U.S.-based astronomers announced that they had detected gravitational waves, vibrations in the substance of space-time. When they made the detection public, they translated the signal into sound, a "chirp," a sound wave swooping up in frequency, indexing, scientists said, the collision of two black holes 1.3 billion years ago. Drawing on interviews with gravitational-wave scientists at MIT and interpreting popular representations of this cosmic audio, I ask after these scientists' acoustemology—that is, what the anthropologist of sound Steven Feld would call their "sonic way of knowing and being." Some scientists suggest that interpreting gravitational-wave sounds requires them to develop a "vocabulary," a trained judgment about how to listen to the impress of interstellar vibration on the medium of the detector. Gravitational-wave detection sounds, I argue, are thus articulations of theories with models and of models with instrumental captures of the cosmically nonhuman. Such articulations, based on mathematical and technological formalisms—Einstein's equations, interferometric observatories, and sound files—operate alongside less fully disciplined collections of acoustic, auditory, and even musical metaphors, which I call informalisms. Those informalisms then bounce back on the original articulations, leading to rhetorical reverb, in which articulations—amplified through analogies, similes, and metaphors—become difficult to fully isolate from the rhetorical reflections they generate. Filtering analysis through a number of accompanying sound files, this article contributes to the anthropology of listening, positing that scientific audition often operates by listening through technologies that have been tuned to render theories and their accompanying formalisms both materially explicit and interpretively resonant. [sound; articulate listening; gravitational waves; acoustemology; space-time]

NOTES

Acknowledgments I thank my MIT physicist interlocutors, Matt Evans, Scott Hughes, and Nergis Mavalvala, whose work with LIGO and on gravitational waves has made epochal contributions to astronomy. For close readings and commentary from colleagues in anthropology, sound studies, and science and technology studies, I thank Stephanie Dick, Steven Feld, Graham Jones, Lisa Messeri, Heather Paxson, Sophia Roosth, Nick Seaver, Alma Steingart, Jonathan Sterne, and Trevor Pinch. Audiences at the University of California, Santa Barbara (particular thanks to David Novak) and at "Periods and Waves: A Conference on Sound and History," held at Stony Brook University (and organized by Ben Taussig and Erika Honisch), made many useful observations about this material. Thanks to Claire Webb for key transcriptions. I thank Dominic Boyer and Cymene Howe at *Cultural Anthropology* for soliciting this article, as well as two anonymous reviewers of the piece. Finally, I thank David Kaiser, physicist and historian of science, for his guiding wisdom in getting me properly tuned into these spacey topics.

1. Apologies to Douglas Kahn (2013, 1), whose *Earth Sound Earth Signal: Energies and Earth Magnitude in the Arts* opens with the sentence, "Radio was heard before it was invented."
2. Different detectors are sensitive to waves in different frequency ranges. For outer space–based detectors, sought-after frequencies will be much lower, from 10 millihertz to one-tenth of a hertz.
3. Metaphors of astronomical listening appear earlier with radio telescopes (Munns 2013),

but this is the first instance in which the captured frequencies sat in a human audio range.

4. I take analogy to be an alignment of two objects or domains for comparison. Simile and metaphor are expressions of analogy. Following a glossary of rhetorical terms offered by the Department of Modern and Classical Languages, Literatures, and Cultures at the University of Kentucky, I take simile to be "an explicit comparison between two things using 'like' or 'as,'" and metaphor to be "implied comparison achieved through a figurative use of words." A metaphor may also be defined as "a comparison statement with parts left out" (Miller 1993, 379). In practice, of course, these rhetorical devices shade into one another. If, as Marilyn Strathern (1992, 47) writes, "culture consists in the way people draw analogies between different domains of their worlds," it also consists of how those analogies often operate in incomplete and unanticipated ways.
5. Bartusiak (2000, 126) writes of the gravitational wave scientist Rainer Weiss, whose "career began with a determination to get rid of the noises in a hi-fi system, only to transfer that interest to reducing the noises that could mask a gravity wave, whose wavelength happens to be in the audio range." Not all metaphors are sonic. The French physicist Thibault Damour has gone culinary, likening gravitational waves to wiggles in jellied veal: "Finalement, il faut voir notre Univers plutôt comme du 'veau en gelée,' comme aime à le dire Thibault Damour, professeur spécialiste de relativité générale à l'Institut des hautes études scientifiques" (Larousserie 2016). Thanks to Noémie Merleau-Ponty for this reference.
6. .wav is the Waveform Audio File Format, employed on PCs for uncompressed audio (sampled 44,100 times per second with sixteen bits per sample). Microsoft created it for Windows 3.1 in 1992.
7. For arguments about theories, animated, in the life sciences, see Kelty and Landecker 2004.
8. The audio animation I have in mind does not immediately apply to sequenced music, whether created using piano rolls (see Seaver 2011) or electronic sequencers. Such music, while unfolding frame by frame, automates abstract, conventional representations of musical notation, not sound analogs/indices of continuous phenomenological events (though this distinction would get muddied if audio sampling were thrown into the stew).
9. In personal communication with the author, David Kaiser explains that, "in 'pure' general relativity, GWs [gravitational waves] have precisely two independent polarization states. But alternatives/generalizations of general relativity exist in which GWs have up to five independent polarization states. In general, GWs are understood to be represented by a spin-2 tensor field, which in general has $2\times2+1=5$ independent degrees of freedom, but in the limit that the mass of the particles associated with the field vanishes—as it does in general relativity—several of these degrees of freedom (polarization states) become indistinguishable, leaving only two independent polarization states. So GWs needn't have only two independent polarizations; they happen to have exactly two in general relativity."
10. David Kaiser observes that, in this particular case, the signal was strong enough to detect without template matching. Inferring the source of the waves (the collision of two black holes of specific masses and orbits), however, did require matched filtering. Gravitational-wave detections that pinpoint signal origins might be seen as technologies that make *place* in outer space (see Messeri 2016). These locative operations can be contrasted with the disorientation that often accompanies experiential encounters with the cosmos (see Battaglia, Valentine, and Olson 2012).
11. I am indebted to Nick Seaver, Alberto Corsín Jiménez, and Rane Willerslev for this metaphor.
12. Seeing sound explicated through image reminds me of Ferdinand de Saussure's (1916) founding text in linguistics, in which he explains that language should properly be imagined as a set of contrasts in sound, but makes the claim stick by offering diagrams of how sounds might differ from one another. For kindred ethnographic work on remote

sensory apprehensions and embodiments of otherworldly phenomena—work that focuses on technologies of vision—see Vertesi 2015.

13. Mavalvala continued: "I don't know if I would ever think of sound as part of the discovery process. It's part of diagnostics." By this, I take it that she meant that the discovery was the result of the complex tuning of various instruments and that listening, even if informative, may not in the end be necessary to confirming signals.
14. Compare Sophia Roosth's (2009) analysis of sonocytology, in which scientists listen to cells and then report on them as "screaming" or otherwise voicing their agency.
15. The *Oxford English Dictionary* defines *whoop* as "a natural exclamation consisting of a voiceless *w* followed by an *o* or *u* sound, concluded by closure of the lips. The phonetic significance of some early forms is uncertain."
16. This expert vocalization is not akin to the statements of hyperarticulate wine connoisseurs, whose translation of one sensory mode, taste, into another, sound, means to evidence a refined human capture of nature, rather than a tongue-tied wonder before it (see Silverstein 2006).
17. The temporality of a black hole collision from 1.3 billion years ago thus does not demand that we theorize a billion years of music (playing here on the title of Tomlinson 2015, which seeks the origins of music in the worlds of *Homo erectus*). Gravitational waves only exist as sound when there is someone or something to hear them.

REFERENCES

Abbott, B. P. et al.
2016 "Observation of Gravitational Waves from a Binary Black Hole Merger." *Physical Review Letters* 116, no. 6. http://dx.doi.org/10.1103/PhysRevLett.116.061102.

Adams, Allan, and Sasha Chapman
2016 "What Gravitational Waves Sound Like." *Atlantic*, February 11. http://www.theatlantic.com/science/archive/2016/02/what-gravitational-waves-sound-like/462357.

Aubin, David, Charlotte Bigg, and H. Otto Sibum, eds.
2010 *The Heavens on Earth: Observatory Techniques in the Nineteenth Century*. Durham, N.C.: Duke University Press.

Augoyard, Jean-François and Henry Torgue, eds.
2006 *Sonic Experience: A Guide to Everyday Sounds*. Montreal: McGill-Queen's University Press.

Bartusiak, Marcia
2000 *Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time*. New York: Berkley Books.

Battaglia, Debbora, David Valentine, and Valerie Olson, eds.
2012 "Extreme: Humans at Home in the Cosmos." Special issue, *Anthropological Quarterly* 85, no. 4.

Beer, Gillian
1996 "Wave Theory and the Rise of Literary Modernism." In *Open Fields: Science in Cultural Encounter*, 295–318. New York: Oxford University Press.

Blanchet, Luc, Thibault Damour, Bala R. Iyer, Clifford M. Will, and Alan G. Wiseman
1995 "Gravitational-Radiation Damping of Compact Binary Systems to Second Post-Newtonian Order." *Physical Review Letters* 74, no. 18. http://dx.doi.org/10.1103/PhysRevLett.74.3515.

Bolter, Jay David, and Richard Grusin
1999 *Remediation: Understanding New Media*. Cambridge, Mass.: MIT Press.

Brain, Robert Michael
2015 *The Pulse of Modernism: Physiological Aesthetics in Fin-de-Siècle Europe*. Seattle: University of Washington Press.

Brøvig-Hanssen, Ragnhild, and Anne Danielsen
2016 *Digital Signatures: The Impact of Digitization on Popular Music Sound*. Cambridge, Mass.: MIT Press.

Collins, Harry
2004 *Gravity's Shadow: The Search for Gravitational Waves*. Chicago: University of Chicago Press.

Connor, Steven
2014 *Beyond Words: Sobs, Hums, Stutters and Other Vocalizations*. London: Reaktion Books.

Dick, Stephanie Aleen
2014 "After Math: (Re)configuring Minds, Proof, and Computing in the Postwar United States." PhD dissertation, Harvard University.

Doyle, Peter
2005 *Echo and Reverb: Fabricating Space in Popular Music Recording, 1900–1960*. Middletown, Conn.: Wesleyan University Press.

Doyle, Richard
2003 *Wetwares: Experiments in Postvital Living*. Minneapolis: University of Minnesota Press.

Eidsheim, Nina Sun
2015 *Sensing Sound: Singing and Listening as Vibrational Practice*. Durham, N.C.: Duke University Press.

Feld, Steven
1990 *Sound and Sentiment: Birds, Weeping, Poetics, and Song in Kaluli Expression*. 2nd edition. Philadelphia: University of Pennsylvania Press.
1996 "Waterfalls of Song: An Acoustemology of Place Resounding in Bosavi, Papua New Guinea." In *Senses of Place*, edited by Steven Feld and Keith H. Basso, 91–135. Santa Fe, N.M.: School of American Research Press.

Feld, Steven, and Donald Brenneis
2004 "Doing Anthropology in Sound." *American Ethnologist* 31, no. 4: 461–74. http://dx.doi.org/10.1525/ae.2004.31.4.461.

Fortun, Mike, and Herbert J. Bernstein
1998 *Muddling Through: Pursuing Science and Truth in the Twenty-First Century*. Washington, DC: Counterpoint.

Friedner, Michele, and Stefan Helmreich
2012 "Sound Studies Meets Deaf Studies." *Senses and Society* 7, no. 1: 72–86. http://dx.doi.org/10.2752/174589312X13173255802120.

Gell, Alfred
1996 "Vogel's Net: Traps as Artworks and Artworks as Traps." *Journal of Material Culture* 1, no. 1: 15–38. http://dx.doi.org/10.1177/135918359600100102.

Grossberg, Lawrence, ed.
1986 "On Postmodernism and Articulation: An Interview with Stuart Hall." *Journal of Communication Inquiry* 10, no. 2: 45–60. http://dx.doi.org/10.1177/019685998601000204.

Hanson, Norwood Russell
1958 *Patterns of Discovery: An Inquiry into the Conceptual Foundations of Science*. New York: Cambridge University Press.

Helmreich, Stefan
2007 "An Anthropologist Underwater: Immersive Soundscapes, Submarine Cyborgs, and Transductive Ethnography." *American Ethnologist* 34, no. 4: 621–41. http://dx.doi.org/10.1525/ae.2007.34.4.621.

Hirschkind, Charles
2004 "Hearing Modernity: Egypt, Islam, and the Pious Ear." In *Hearing Cultures: Essays on Sound, Listening, and Modernity*, edited by Veit Erlmann, 131–51. New York: Bloomsbury.

Hughes, Scott A.
n.d. "The 'Sound' of Spacetime: Overview." http://gmunu.mit.edu/sounds/sounds.html.
2016 "Music of the Spheres." *London Review of Books* blog, February 23. http://www.lrb.co.uk/blog/2016/02/23/scott-hughes/music-of-the-spheres.
Kahn, Douglas
2013 *Earth Sound Earth Signal: Energies and Earth Magnitude in the Arts*. Berkeley: University of California Press.
Kane, Brian
2014 *Sound Unseen: Acousmatic Sound in Theory and Practice*. New York: Oxford University Press.
Kelty, Christopher, and Hannah Landecker
2004 "A Theory of Animation: Cells, L-systems, and Film." *Grey Room*, no. 17: 30–63. http://dx.doi.org/10.1162/1526381042464536.
Kennefick, Daniel
2000 "Star Crushing: Theoretical Practice and the Theoretician's Regress." *Social Studies of Science* 30, no. 1: 5–40. http://dx.doi.org/10.1177/030631200030001001.
2007 *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves*. Princeton, N.J.: Princeton University Press.
Klauder, J. R., A. C. Price, S. Darlington, and W. J. Albersheim
1960 "Theory and Design of Chirp Radars." *Bell System Technical Journal* 39, no. 4: 745–808. http://dx.doi.org/10.1002/j.1538-7305.1960.tb03942.x.
Kockelman, Paul
2013 *Agent, Person, Subject, Self: A Theory of Ontology, Interaction, and Infrastructure*. New York: Oxford University Press.
Larousserie, David
2016 "Les ondes gravitationelles en quatre questions." *Le Monde*, February 11. http://www.lemonde.fr/cosmos/article/2016/02/11/les-ondes-gravitationnelles-en-quatre-questions_4863835_1650695.html.
Levin, Janna
2011 "The Sound the Universe Makes." *TED* talk, March. https://www.ted.com/talks/janna_levin_the_sound_the_universe_makes.
2016 *Black Hole Blues and Other Songs from Outer Space*. New York: Knopf.
Messeri, Lisa
2016 *Placing Outer Space: An Earthly Ethnography of Other Worlds*. Durham, N.C.: Duke University Press.
Miller, George A.
1993 "Images and Models, Similes and Metaphors." In *Metaphor and Thought*, 2nd edition, edited by Andrew Ortony, 357–400. New York: Cambridge University Press.
Mody, Cyrus C. M.
2005 "The Sounds of Science: Listening to Laboratory Practice." *Science, Technology, and Human Values* 30, no. 2: 175–98. http://dx.doi.org/10.1177/0162243903261951.
Morton, Timothy
2013 *Hyperobjects: Philosophy and Ecology after the End of the World*. Minneapolis: University of Minnesota Press.
Mowitt, John
2015 *Sounds: The Ambient Humanities*. Berkeley: University of California Press.
Munns, David P. D.
2013 *A Single Sky: How an International Community Forged the Science of Radio Astronomy*. Cambridge, Mass.: MIT Press.

Myers, Natasha
2015 *Rendering Life Molecular: Models, Modelers, and Excitable Matter*. Durham, N.C.: Duke University Press.
National Science Foundation (NSF)
2016 "LIGO Detects Gravitational Waves." Press conference, National Press Club, Washington, DC, February 11. http://mediaassets.caltech.edu/gwave.
Ochs, Elinor, Patrick Gonzales, and Sally Jacoby
1996 "'When I come down I'm in the domain state': Grammar and Graphic Representation in the Interpretive Activity of Physicists." In *Interaction and Grammar*, edited by Elinor Ochs, Emanuel A. Schegloff, and Sandra A. Thompson, 277–327. New York: Cambridge University Press.
Overbye, Dennis
1991 *Lonely Hearts of the Cosmos: The Story of the Scientific Quest for the Secret of the Universe*. New York: HarperCollins.
2016 "Gravitational Waves Detected, Confirming Einstein's Theory." *New York Times*, February 11. http://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einstein.html.
Rheinberger, Hans-Jörg
1997 *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube*. Stanford, Calif.: Stanford University Press.
Rice, Tom
2010 "Learning to Listen: Auscultation and the Transmission of Auditory Knowledge." *Journal of the Royal Anthropological Institute* 16, S1: S41–61. http://dx.doi.org/10.1111/j.1467-9655.2010.01609.x.
Rodgers, Tara
2011 "'What, for me, constitutes life in a sound?': Electronic Sounds as Lively and Differentiated Individuals." *American Quarterly* 63, no. 3: 509–30. http://dx.doi.org/10.1353/aq.2011.0046.
Roosth, Sophia
2009 "Screaming Yeast: Sonocytology, Cytoplasmic Milieus, and Cellular Subjectivities." *Critical Inquiry* 35, no. 2: 332–50. http://dx.doi.org/10.1086/596646.
Saussure, Ferdinand de
1916 *Cours de linguistique génerale*, edited by Charles Bally and Albert Sechehaye, with the assistance of Albert Riedlinger. Lausanne, Switzerland: Payot.
Schwartz, Hillel
2011 *Making Noise: From Babel to the Big Bang and Beyond*. New York: Zone Books.
Seaver, Nick
2011 "'This is Not a Copy': Mechanical Fidelity and the Re-enacting Piano." *differences: A Journal of Feminist Cultural Studies* 22, nos. 2–3: 54–73. http://dx.doi.org/10.1215/10407391-1428843.
Silverstein, Michael
2006 "Old Wine, New Ethnographic Lexicography." *Annual Review of Anthropology* 35: 481–96. http://dx.doi.org/10.1146/annurev.anthro.35.081705.123327.
Simulating eXtreme Spacetimes (SXS)
n.d. "Needles in the Haystack: Hearing the Cosmic Symphony." http://www.black-holes.org/the-science-gravitational-waves/gravitational-wave-astronomy/needles-in-the-haystack.
Sterne, Jonathan
2003 *The Audible Past: Cultural Origins of Sound Reproduction*. Durham, N.C.: Duke University Press.
2012 *MP3: The Meaning of a Format*. Durham, N.C.: Duke University Press.
Strathern, Marilyn
1992 *Reproducing the Future: Anthropology, Kinship, and the New Reproductive Technologies*. New York: Routledge.

Supper, Alexandra

2014 "Sublime Frequencies: The Construction of Sublime Listening Experiences in the Sonification of Scientific Data." *Social Studies of Science* 44, no. 1: 34–58. http://dx.doi.org/10.1177/0306312713496875.

2015 "Data Karaoke: Sensory and Bodily Skills in Conference Presentations." *Science as Culture* 24, no. 4: 436–57. http://dx.doi.org/10.1080/09505431.2015.1052390.

Taylor, Timothy D.

2001 *Strange Sounds: Music, Technology, and Culture*. New York: Routledge.

Thompson, Marie, and Ian Biddle, eds.

2013 *Sound, Music, Affect: Theorizing Sonic Experience*. New York: Bloomsbury.

Tomlinson, Gary

2015 *A Million Years of Music: The Emergence of Human Modernity*. New York: Zone Books.

Trower, Shelly

2012 *Senses of Vibration: A History of the Pleasure and Pain of Sound*. New York: Continuum.

Vertesi, Janet

2015 *Seeing Like a Rover: How Robots, Teams, and Images Craft Knowledge of Mars.* Chicago: University of Chicago Press.

Weiss, Rainer

2016 "One Hundred Years of Gravitational Waves: Observation of a Binary Black-Hole Collision." Presentation at the MIT Physics Colloquium, Cambridge, Mass., February 25.

Wierzbicki, James

2014 "The Imagined Sounds of Outer Space." *Journal of Sonic Studies* 8. https://www.researchcatalogue.net/view/109621/109622.