SONIFICATION STRATEGIES FOR THE FILM *RHYTHMS OF THE UNIVERSE*

Mark Ballora

Penn State University
School of Music/School of Theatre
Music Bldg I, University Park, PA 16802-1901, USA
ballora@psu.edu

ABSTRACT

Design strategies are discussed for sonifications that were created for the short film *Rhythms of the Universe,* which was conceived by a cosmologist and a musician, with multi-media contributions from a number of artists and scientists. Sonification functions as an engagement factor in this scientific outreach project, along with narration, music, and visualization. This paper describes how the sonifications were created from datasets describing pulsars, the planetary orbits, gravitational waves, nodal patterns in the sun's surface, solar winds, extragalactic background light, and cosmic microwave background radiation. The film may be viewed online at [1], and the sonifications described here may be downloaded at [2].

1. INTRODUCTION

This is a description of a science outreach project, a 21:00 film titled *Rhythms of the Universe.* It is a collaboration between musician/ethnomusicologist Mickey Hart and cosmologist George Smoot III, with contributions from personnel at Lawrence Berkeley Labs, Meyer Sound, and Penn State University. It is a poetic and scientific speculation on humankind's innate desire to understand the cosmos, featuring narration by Hart and Smoot, along with a shifting collage of music, videos, visualizations, and sonifications.

The film has the benefit of name recognition of its creators. Mickey Hart was one of the drummers for the Grateful Dead, and has received acclaim for his releases of world music recordings and books on ethnomusicology. George Smoot was a recipient of the 2006 Nobel Prize in Physics. The film premiered September 29, 2013 at the Smithsonian Air and Space Museum in Washington, DC [1]. At this writing, further distribution possibilities are being explored.

The film might be termed a piece of "edutainment," a descriptor that seems to have come into common parlance in the 1970s to describe programming that was meant to educate through entertainment, such as nature documentaries, science television programs, or health awareness programs. For *Rhythms of the Universe*, the design goal was to create sonifications that were viscerally compelling and potentially informative.

It is interesting to note that interpretation is an essential component of information displays of all kinds. For example, astronomical photographs are commonly treated with filters, coloration, and superimposition of various spectral ranges. And during the discussion that followed the film's premiere, George Smoot remarked that all complex information – whether it be the history of the universe or the mapping of the human genome, is rendered in such a way as to fit onto something the size of a book or newspaper. This is what the human mind can take in. Aesthetic interpretations are vital to creating informative renderings.

Following a review in Section 2 of prior work done in this area, Section 3 will describe seven sonification examples from the film, followed by Concluding Remarks in Section 4. Audio examples may be downloaded from [2]. Sonification work for this film has been described previously [3], although this paper focuses mostly on different design approaches than those described there.

2. EARLIER WORK

Linking sounds to the cosmos is an idea that dates back at least to the ancient Greeks, and has had particular resonance in Western civilization [4].

Sound has led to a number of discoveries about the cosmos, such as cosmic microwave background radiation [5], information on Saturn's rings [6], and the search for evidence of gravitational waves [7]. Many scientific research and outreach projects involve the use of sound. NASA has supported audifications of the sun's heliosphere [8]. A spectral renderer designed for use by a blind astronomer was also used by sighted colleagues due to the ability to readily hear patterns [9]. Sound is used to introduce various astronomical phenomena to young and non-specialist audiences, such as the nature of helioseismology [10, 11], cosmic microwave background radiation [12], the relative orbital times of our solar system's planets [13], and the gravitational waves that would presumably result from large-scale events such black holes or supernovae [14, 15].

In addition to musical works that were created by sonifying the cosmos [16, 17, 18], sonification seems to appear with increasing frequency in installations and in artist residency projects such as Collide@CERN [19].

Many of the sonifications created for *Rhythms of the Universe* used these examples as starting points, and will be discussed in the next section.

3. SONIFICATION STRATEGIES

This section will describe strategies used in the creation of seven sonification types used in the film. All of the sonifications were created using SuperCollider software [20].

3.1. SuperCollider

This general-purpose audio programming language can render auditory displays based on any approach being taken, whether the data is being audified or sonified.

When datasets were audified, they were loaded into a Buffer object and iterated at various rates to create audio files of corresponding transpositions. When datasets were rendered as parameter-based sonifications, the sounds themselves were created as SynthDefs. The particular sound synthesis design was usually based on an intuitive connection to the data domain ("What should space stretching sound like? How should an aurora borealis sound?") These SynthDefs were typically designed with a good number of control inputs to allow the data to be reflected in as many characteristics of the sound as possible. Sonic characteristics (pitch, panning, volume, vibrato rate, etc.) may be considered as sound dimensions. With higher dimensionality to the sound rendering, there is increased capability for spontaneous and unexpected formation of auditory gestalts, wherein unrealized patterns in the data can emerge.

The datasets were saved as arrays, rescaled to value ranges suitable for the audio parameters to which they would be applied, and then iterated with a Task. At each iteration, either a sounding synth could be updated to reflect the current data values (a change applied to a drone); or a new instance of a SynthDef could be created based on the current data value (a data point corresponding to note played on an instrument).

3.2. Pulsar

Pulsars, an accidental discovery resulting from the adoption of the radio telescope, are spinning neutron stars. Their spinning motions cause radiation to appear to blink on and off regularly, with the precision of an atomic clock. Data used for sonifications of the pulsar B0531+21 in the Crab Nebula were obtained from the European Pulsar Network Database Browser [21]. The dataset consists of changes in two types of values over time. One type of data describes intensity values for eight of the frequencies emitted by the pulsar (Figure 1). The second type consists of Stokes parameters (Q, U, V), which were converted into spherical coordinates of the form (*radius, azimuth angle, zenith angle*).

The sonification of the intensity values is simple additive synthesis: Eight sine wave oscillators play transpositions of the eight frequencies. The dataset's intensity values trace an amplitude envelope for each oscillator, but slowed in time, so that the pulsar's actual period of 0.03 seconds is played over a period of 9 seconds. The cycles repeat, just as the data represents one or two periods of a repeating pattern being emitted by the pulsar. To add variety to the sound, the eight oscillators were splayed across the stereo field and sent through reverb.
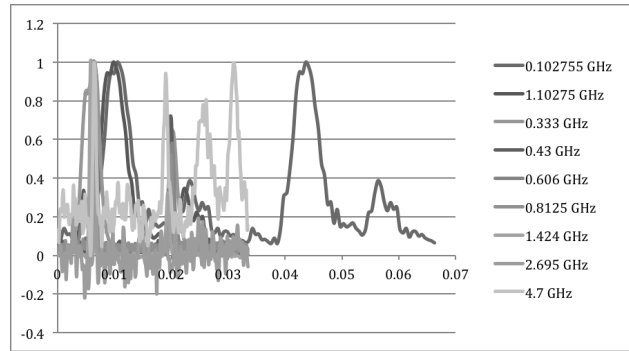

Figure 1: Intensity values for eight frequencies from the spectrum of pulsar B0531+21 [21].

For each of the eight frequencies, a second sound layer was created from the azimuth and zenith coordinates, which were determined from the Stokes coordinates. A pair of detuned, glassy-sounding wavetables was sent through a bandpass filter and a panner. The wavetables were set to a frequency two octaves below that of the corresponding sine oscillator. The beating rate and filter bandwidth were both mapped from the zenith value, and the pan position was mapped from the azimuth value.

The result was a pulsing, quavering sound that is a fairly literal rendition of the data values, and serves as an effective complement to video of the pulsar.
[AUDIO FILE: pulsar-allGHz.aif]

3.3. Planets of the Solar System

This is perhaps better described as an auditory diagram than as a sonification. It was extrapolated from the website SolarBeat [13], which shows an image of the planets orbiting the sun. Each planet has an associated pitch that sounds at the completion of each of its orbits. A different pitch is played for each planet as they complete their orbits, which allows comparison of the relative orbit times of the planets, as the inner planets' pitches sound more frequently than those of the outer planets.

The measurements used for *Rhythms of the Universe* reflect the elliptical shape of the orbits used for these diagrams. Data was obtained from the National Space Science Data Center's planetary fact sheets [22] describes each planet's orbit time, axis length, and eccentricity. As a reference to Pythagoras and the Music of the Spheres [4], a scale of pitches was derived from ratios representing the relative orbital distances of the nine planets from the sun. These pitches were played repeatedly by a string-like sound, which was created from a Karplus-Strong string model [23]. Each was "plucked" at timing intervals proportional to the planets' orbital periods, with the earth's orbit time being set at one second, and the others at corresponding rates: for example, Mercury's pluck occurred 4.15 times for every single Earth pluck, while Pluto's pluck occurred every 247 seconds.

A coefficient value for the SuperCollider's Karplus-Strong unit generator produces a quality that gives the sound a harsh or muted quality. For purposes of this rendering, the coefficient

for each planet's string pluck was mapped from its relative distance from the sun, so that the inner planets sounded more pointed (like a harder, faster pluck of a string), while the outer planets sounded duller (like a gentler pluck of a string).

Each planet's motion was represented by a spinning whistling sound, created from noise filtered at the planet's pitch. From the axis length and eccentricity values for each orbit, a sequence of distances for 360° was created, with a whistling sound event occurring at each degree position. The whistle "notes" overlapped, forming a continuous swirling sound, with pan positions that cycle through the stereo field once every 360°.

The rotation rate and pitch varied slightly according to changing distance, in order to simulate Doppler effects. This was done by taking the distance from the sun (one of the ellipse's foci) at each degree position and dividing this distance by the distance value for the last degree position, and then multiplying the inverse of this ratio by the planet's base frequency. Since the planets move more quickly when they are closer to the sun, the frequency of the swirling noise varies according to position, going up slightly when the planet is near the sun, and falling slightly when it is more distant.

The iteration rate was also mapped from these distances, as the traversal through the 360° went slightly faster when the radius from a focus was smaller, and slightly slower as the radius increased. Most planets' orbits are close to being circular, so this was a subtle effect.

The inclination of each planet's orbit relative to the plane of the earth's orbit was reflected in a rich harmonic waveform. The pitch was that of the planet's pluck, transposed down two octaves. The number of harmonics was a mapping of the inclination angle, and varied at a rate that matched the planet's orbit time, so that its sound became slightly brighter and more muffled once per orbit. [AUDIO FILE: SolarSystemOrbit.aif]

3.4. Gravitational Waves

The phenomenon theorized by Einstein that has remained undetected until just recently [24] are gravitational wave fluctuations, which are ripples in space-time [7]. These are presumably everywhere, but typically in amounts so minute as to be undetectable. Special gravitational telescopes such as the Laser Interferometer Gravitational-Wave Observatory (LIGO) were created in the hope of being able to detect such fluctuations originating from distant, extraordinarily large events such as supernovae or black holes. Since these fluctuations are expected to be at frequencies within the auditory regions, one approach among researchers is to listen for patterns that might be detected. Thus, some theoretical cosmologists calculate simulated gravitational fluctuations and audify them [14, 15].

The sonifications created for this film were created from the audification examples at [15] (an example is shown in Figure 2). Rather than being treated as literal audio samples, data values functioned as control streams for the synthesized instrument. The instrument was synthesized based on the idea of a "cosmic jaw harp," created from a combination of a band limited impulse generator and Brown noise, which was sent through a resonant highpass filter. Changes in the data were reflected timbrally as changes to the cutoff frequency. The

highpass filtered signal was, in turn, passed through a set of five bandpass filters, with center frequencies that were roughly coincident with the spectra that form the vowel "OH." These center frequencies oscillated in a manner determined by the data, which changed the quality of the quasi-vowel. The panning also oscillated around a central point in a manner determined by the data.
[AUDIO FILE: gravwaves_Hughes_page12_1.aif]

This sonification approach is more musical than direct audification, wherein many of the wave's subtleties are averaged by the auditory system so that a percussive, noisy sound is perceived. Audifications also literally flatten the data: the ripples in space are multi-dimensional, while the renderings behind the audifications consist of only one dimension of amplitude values as a function of time. The sonification approach allows variations in the shape of the wave to be perceived, since the iteration rate can be slowed down when the data is meant to be modulating a sound, rather than producing the literal audio samples. And the application of the wave to a number of parameters of the sound (pitch, pan, filter, frequency, vowel type) creates a higher level of dimensionality than can be derived with audification.
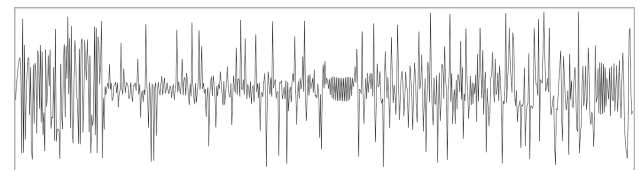

Figure 2: The knocking inspiral of two black holes, as their orbit draws them closer and closer [15].

3.5. Helioseismology

The convection processes taking place within the sun boil to the surface, tapping it constantly from within, like microscopic strikes within a spherical gong. Helioseismologists study vibrational nodes that form within the sun. These acoustical vibrations appear as spherical harmonics. Datasets are available from the Global Oscillation Network Group (GONG) [25].

There are three node types, shown in Figure 3. Harmonic nodes are those forming horizontally on the surface, along planes that are perpendicular to the line connecting the north and south poles. Azimuthal nodes are those that form vertically, as planes that pass through the poles and the equator. The radial order refers to subsurface nodes falling between the surface and the core. Some ten million different vibrational patterns have been observed. As the number of harmonic nodes (the harmonic degree value) increases, so too do the number of radial nodes per harmonic degree, and so in turn do the number of azimuthal nodes per radial node.

Patterns of the sun's resonant vibrations are commonly shown on an *l-nu diagram*, in which the horizontal axis shows the number of harmonic nodes, and the vertical axis shows frequency, and brightness level represents intensity (akin to a spectrogram). While lower numbers of harmonic nodes produce widespread low intensity vibrations, as the plots are read along the horizontal axis from the left, and the number of horizontal nodes reaches a quantity on the order of about ten, clear resonant frequency patterns can be observed. As the number of

horizontal nodes increases, regular high-intensity vibrations can be observed. The patterns of resonant frequencies form arc-like shapes as they are plotted as a function of the number of harmonic nodes (Figure 4).
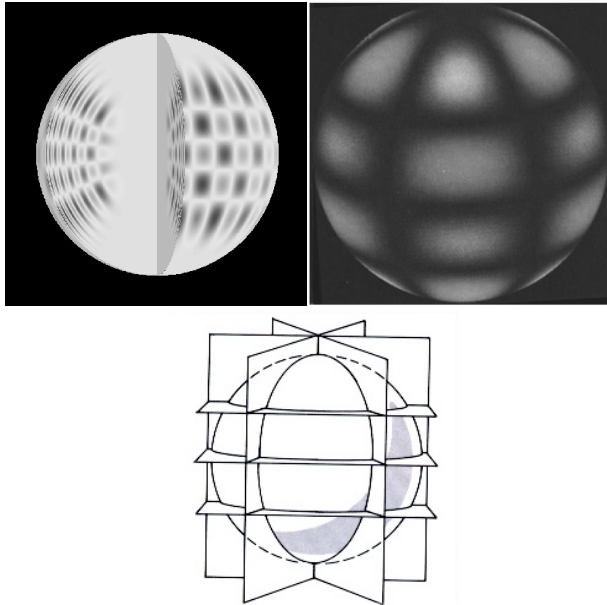

Figure 3: The three node types commonly observed in helioseismology [11].
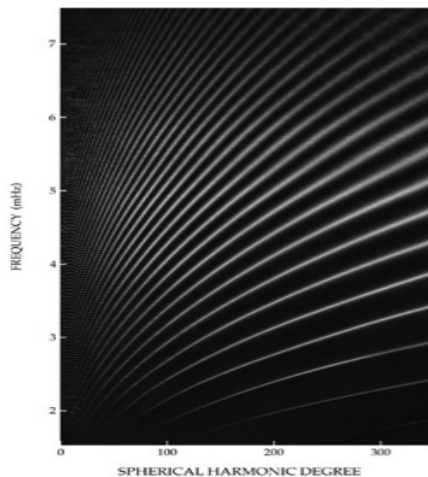

Figure 4: l-nu diagram [11]

The datasets consist of frequency and amplitude values for each harmonic, radial degree, and azimuthal degree. When the frequency and amplitude were plotted as a function of degree number, the resonance patterns shown in the figure became clear, and by tracing these from dataset to dataset, a contour could be formed that corresponded to the striped patterns found in the l-nu diagram. By using these contours as pitch envelopes applied to spectrally rich droning sounds, the contour of each arc could be heard. Given the high number of data points

involved, some compression was necessary. The pitch envelopes were created by taking the resonant nodes of every tenth dataset (out of a total of 150), so that 15-point trajectories were created. Each arc was sonified separately, so that they could be assembled as desired for the film.

Two rendering approaches were taken. In the first, the arcs lasted on the order of 5 seconds, and had a percussive quality. This approach gave a quick overview of the contour of the nodal plots.

In the second approach, the sonification of each arc was extended to last on the order of 18 seconds. The radial and azimuthal node values for each of the 15-point trajectories were represented as a series of quick sound grain splashes that sounded when the pitch envelope trajectory reached each envelope point. The frequency and amplitude of each grain were mapped from the frequency and amplitude of each data point. The azimuthal degree was mapped to pan position.

In one rendition, the data points for each harmonic degree were played according to radial order value. [AUDIO FILE: arcs-ascending.aif] As the azimuthal orders increased, the pan position moved back and forth between speakers as each arc sounded, which created a swirling effect as the data iterated to higher orders. In another rendition, the radial order was scrambled, so the panning appeared more randomly, for an effect more like a cloud than a swirl, with a fluttering effect.

The l-nu diagram is highly abstracted in that it does not produce a literal, photograph-like image of the sun, but plots relationships in an informative way. This is a good example of the kinds of interpretation that are essential to many visualizations, as mentioned earlier. Inasmuch as this diagram is considered a valuable component of educational presentations on this topic [10, 11], our hope is that the curving contours of the graph can be similarly compelling when heard. In addition, the sonic renderings have the advantage that information from all three axes are represented, while in the common visualization, azimuthal and radial information are not represented.

3.6. Solar Winds (the Aurora Borealis)

The sun constantly emits charged plasma—proton and electron particles that are shaken loose from the sun due to its high heat. The interaction of these plasma particles, solar winds, with the earth's magnetosphere causes the aurora borealis phenomena.

Solar wind data is available from the NASA Goddard Space Flight Center Space Physics Data Facility [26]. The datasets provide timestamped measurements of proton density and thermal speed (temperature). The sonification was created in two layers. Since the plasma is part of the sunshine and creates the glowing Northern lights, a "shiny" sound was created. Since the data also describes the density of charged particles, protons, another sound was created that was more suggestive of particles bouncing off of each other.

The shiny layer was based on grains of frequency-modulated sine tones. The grain generation rate changed proportionately to the changes in proton density values. The boundaries between the grains were blurred by duration times, a lag, and filtering, so that changes in the rate were as much timbral as rhythmic. The spectrum (carrier:modulator ratio) changed according to the changes in the thermal speed

(temperature) values, with higher temperatures increasing the sound's spectral characteristics (brightness).

For the particles layer, a percussive instrument was created that was "played" by randomly scaled impulses that were generated at an average rate that changed proportionately to the proton density values. The instrument's pitch and attack time were also mapped from proton density. The temperature values determined the volume level, as well as various filter parameters that shaped the spectrum.
[AUDIO FILE: solarwindMix.aif]

The resulting sound was a blur of shifting, shimmering frequencies. For the film, it worked well as a complement to visual material of the aurora borealis and its shifting color patterns.

3.7. Extragalactic Background Light (EBL)

EBL, the cumulative shine of all of the universe's radiating bodies [27], is believed to date back to the first stars of the universe, which began to form 400 million years after the Big Bang and reached a peak 2,400,000 years later. The background light has been accumulating as new stars came into being. The spectrum of this background radiation cannot be measured directly, but is inferred by comparing the expected appearance of distant objects (based on the appearance of similar objects that are closer) with their actual appearance. The background radiation is assumed to filter the light from that object.

The data that is available from the websites of one of its researchers [28] is a set of theoretical models. It consists of 500 datasets, each consisting of intensity values for 397 wavelengths. Unlike Fourier-based spectra, these wavelengths are not harmonically related. Instead, they are logarithmically spaced so that the ratios between successive wavelengths are equivalent—a kind of cosmic equal temperament.

The 500 datasets all reflect a different period of time. They begin 12.466 billion years ago, when the universe was 1.2 billion years old—that is, some time prior to the peak star formation period, 3 billion years after the Big Bang. The datasets reflect levels up to the present day.

The wavelength values were converted to frequencies by dividing the speed of light by wavelengths. They resulting frequencies range spanned 24.1165 Hz to 447,010.696 Hz, some 14.178 octaves.

The 14-octave frequency range was compressed by reducing the ratios between successive frequencies, so that the equal temperament was preserved, but the range spanned 5.74 octaves. This choice was arrived at by ear: with greater compression, the spectrum is squeezed spectrum, with many tones combining and beating. With less compression, the sound becomes shrill as frequencies increase. The range of 5.74 octaves seemed to lie comfortably between the extremes of too obscured and too shrill.

The sonification was produced by literal additive synthesis: 397 sine wave oscillators were created for each of the frequencies. The data files were read one at a time, with the corresponding volume of the oscillators updated with each set.

As the lower elements of the spectrum are at negligible intensity levels, the fundamental partial is at a volume that is often inaudible. The number of frequency components involved tends to blur the pitchiness, and instead produce an indefinite,

multiphonic shimmering curtain of sound, like a thick organ chord. It starts soft, then becomes louder and fuller-bodied as the time progresses towards the present day and the spectrum evolves. The datasets advance every 0.25 seconds, so that the shape of the background energy over 12.466 billion years is rendered in just over two minutes.
[AUDIO FILE: EBL-fund@76.439.aif].

The researchers were happy with the sound, and felt that it worked as an engagement element, as the sound adds a sense of drama that is not as readily conveyed by a sequential viewing of spectral plots.

3.8. Cosmic Microwave Background Radiation (CMB)

Cosmic Microwave Background radiation was initially an acoustic wave resulting from the Big Bang and propagating through the early plasma of the universe before its particles had spread enough for empty space to form. The microwave background energy is still present and is measurable.

Lawrence Berkeley Labs provided spectra of CMB, in which intensity is a function of wavelength (Figure 6). To create an audification, these had an inverse Fourier transform applied to them, and the results were audified. The results of two different spectra being audified were low, noisy, and rumbling, and not terribly distinguishable from each other, although they did have the makings of an interesting ambience.
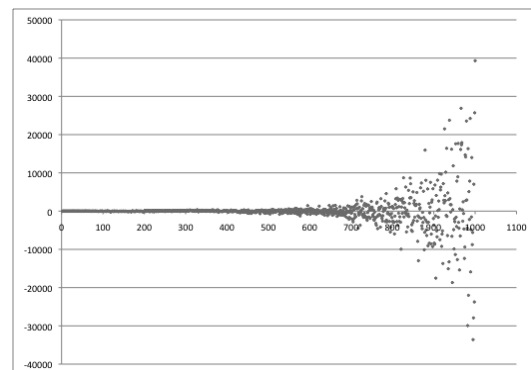

Figure 6: CMB spectrum. Source: Lawrence Berkeley Labs.

The spectra were also sonified by remapping the values for power as a function of wavelength into values for frequency as a function of time. Converting spectra to melodies has been done previously [9, 17]. It is an effective approach, since it allows untrained listeners to hear salient spectral events, such as increased power at a certain wavelength, appearing as a clear pitch sweep or jump. The gradually widening contour of the plot shown in the figure created a dramatic effect in the form of a slow swell in the sound.

There were two timbres chosen. The first was a shimmering, cymbal-like sound, with the "pitchiness" related to the mapped frequency value at the current data point. The second was a "dusty" sound, created by putting noise through a bandpass filter with center frequency at the mapped frequency value of the current data point.
[AUDIO FILE:
 cmb-data-TE-power-spec-DUR0.025-DUST+SHIMMER.aif]

4. CONCLUDING REMARKS

As the work described here is not a research project or the creation of a new tool, we have not done formal assessments of the effect of these sonifications. Hopefully, further showings of the film will be scheduled, which will allow us to gather feedback from audiences. To date, our feedback has been anecdotal, and thus this document admittedly lacks a level of rigor that typically accompanies presentations of this kind. However, the long-term goals are the same as those of the more formal research that is being presented at ICAD: the promotion of sound as an engagement and informational factor in data displays. The sonifications were chosen for their dramatic effect, yet they were also designed with the intent that they could be informative, as discussed in the descriptions of each of them in the last section.

The feedback we have had thus far has been enthusiastic. For example, a meeting several years ago with a leading climatologist colleague to discuss the possibilities of using sonifications was quite cordial, but his interest in the idea of sonification was cautious at best. Five years later, when *Rhythms of the Universe* was shown to his weekly lunch meeting of graduate students, he was quite excited about the film, and eager to have the same type of treatment done to climate-related datasets. A lively discussion followed, which produced a number of ideas as to how various climatology datasets might be sonified. These ideas led, in turn, to sonifications of Antarctic ice datasets, which were presented in an outreach event called "Polar Day" [29]. Similar excitement was generated there, and possibilities of future work are emerging.

Outcomes like this give us an informal optimism that this work is taking us in healthy directions towards integrated learning, wherein emergent properties reveal themselves—sometimes in surprising ways—through the engagement of multiple senses.

5. ACKNOWLEDGMENTS

6. REFERENCES

[1] M. Hart, and G.S. Smoot, *Rhythms of the Universe*, a 360° Production in association with the Berkeley Center for Cosmological Physics at the Lawrence Berkeley National Laboratory, 2013. www.ustream.tv/recorded/39395730E.

[2] https://psu.box.com/ballora-icad2014-audio

[3] M. Ballora, "Sonification, Science, and Popular Music: In Search of the 'Wow,'" *Organised Sound*, vol. 19, no. 1, pp. 30-40, April, 2014.

[4] J. Godwin, *The Harmony of the Spheres: The Pythagorean Tradition in Music*. Rochester, VT: Inner Traditions, 1992.

[5] A.A. Penzias, R.W. Wilson, "A Measurement Of Excess Antenna Temperature At 4080 Mc/s." *Astrophysical Journal Letters* vol. 142, pp. 419–421, July 1965.

[6] G. Kramer, "An Introduction to Auditory Display." In *Auditory Display: Sonification, Audification, and Auditory Interfaces*, edited by G. Kramer. Reading, MA: Addison Wesley, 1994.

[7] M. Bartusiak, *Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time.* Washington, DC: Joseph Henry Press, 2000.

[8] R.L. Alexander, J. Gilbert, E., Landi, M. Simoni, T.H. Zurbuchen, D. Roberts, "Audification as a Diagnostic Tool for Exploratory Heliospheric Data Analysis." *Proceedings of the 17th International Conference of Auditory Display (ICAD 2011).*

[9] R. M. Candey, A. M. Schertenleib, W. L. Diaz Merced, W. L, "Sonification Prototype for Space Physics." Presentation at American Geophysical Union, Fall Meeting, 2005. San Francisco, CA.

[10] National Optical Astronomy Observatory, "Solar Music – Helioseismology." http://www.noao.edu/education/ighelio/solar_music.html

[11] Stanford Solar Center. http://solar-center.stanford.edu/

[12] R. McGee, "Listening to the Sound of the Universe." 2014. http://ryanmcgee.com/cmbsonification/final/

[13] L. Twyman, "Solarbeat." http://www.whitevinyldesign.com/solarbeat/

[14] J. Levin, "The sound the universe makes." TED talk, 2011. http://www.ted.com/talks/janna_levin_the_sound_the_universe_makes.html.

[15] S. A. Hughes, "Astrophysical general relativity @ MIT." http://gmunu.mit.edu/sounds/sounds.html

[16] C. Dodge, "Earth's Magnetic Field," Nonesuch Records (H-71250), 1970.

[17] M. Quinn, Design Rhythmics Sonification Research Lab. drsrl.com

[18] D. First, "The Music of the Sphere: An Investigation into Asymptotic Harmonics, Brainwave Entrainment and the Earth as a Giant Bell." *Leonardo Music Journal* vol. 13, pp. 31-37, 2003.

[19] http://arts.web.cern.ch/collide

[20] http://supercollider.sourceforge.net/

[21] http://www.jb.man.ac.uk/research/pulsar/Resources/epn/browser.html

[22] http://nssdc.gsfc.nasa.gov/planetary/

[23] K. Karplus, A. Strong, "Digital Synthesis of Plucked String and Drum Timbres." *Computer Music Journal* vol. 7, no. 2, pp. 43–55, 1983.

[24] National Science Foundation, "BICEP2 2014 Results Release." http://bicepkeck.org/. March 18, 2014.

[25] gong.nso.edu

[26] http://pwg.gsfc.nasa.gov/windnrt/archive/index.html

[27] J. Finke, S. Razzaque, and C Dermer, "Modeling the Extragalactic Background Light from Stars and Dust," *Astrophysical Journal*, vol. 712, no. 1, pp. 238-249, March 2010.

[28] http://www.phy.ohiou.edu/~finke/EBL/index.html

[29] Penn State Polar Center. Polar Day 2014. http://polar.psu.edu/news/markballora-050214.html.