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Letting Pulsars Sing: Sonification With Granular Synthesis

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An astronomy sonification project has been initiated to create sound and music from the data of pulsars in space. Pulsars are formed when some stars burn out all of their fuel and emit electromagnetic radiation, which hits earth periodically as the pulsar rotates. Each pulsar has unique characteristics. The source of the data is the online Pulsar Catalog from the Australian National Telescope Facility. The first result is a stereo fixed media composition, *From Orion to Cassiopeia*, which reveals a sweep of much of the Milky Way, displaying audio for many of the known pulsars. Galactic longitude, rotation speed, pulse width, mean flux density, age, and distance are mapped to granular synthesis parameters. Sound event duration, amplitude, amount of reverberation, grain rate, grain duration, grain frequency, and panning are controlled by the data. The piece was created with the new SGRAN2() instrument in the RTcmix music programming language.

0 INTRODUCTION

The purpose of this sonification project was to explore the potential of mapping astronomical data to sound. As a computer music composer, the author often draws on a core source sound idea such as an instrumentalist’s sound, bird sounds, or specific synthesis algorithms. An intense curiosity about outer space, and pulsars in particular, motivated investigation of pulsars and subsequent experiments in sonification for creating music. How might the characteristics of celestial objects and their forces be made audible? Can astronomical parameters be mapped in a way that seems intuitively congruent with their corresponding sound parameters? What music could be created from such sonification processes? The primary purpose of the project is artistic, to create material from this experimental process, for composing music. Can astronomical data parameter mappings generate sequences of organized sound that a listener can experience as music?

The music can become more meaningful, however, if the listener understands at least in part how the sound is revealing actual physical properties of these distant galactic objects, so a secondary purpose is elucidative. Can such an auditory realization convey information about galactic objects? Can a musical composition be experienced as a time-based aural map revealing positions and certain properties of the pulsars in the Milky Way Galaxy?

The goal was to map many of the pulsar data parameters available to granular synthesis parameters, because this technique can be used to produce a wide variety of sonic textures. These textures become perceptible auditory displays of the data, expanding the idea of what sound may be considered “musical.” While aesthetic decisions were occasionally involved, they were often made to increase the clarity of the textures. The intention was to let the pulsars “sing” their unique sounds. For this experimental approach, a new STGRAN2() granular synthesis instrument [1] in the RTcmix music programming language [2] was used.

The first result is the composition *From Orion to Cassiopeia*, a stereo audio computer music composition based on the data of pulsars. A video version was also created from photos of space. The author’s previous sonification project was based on very different data [3], so sources such as *The Sonification Handbook* [4] were consulted for insight on approaches.

The purpose of this paper is to share information about these sonification experiments and compositional processes for those who might attempt similar projects or for interested listeners. Why pulsars were chosen for the project is discussed in Sec. 1, the source data in Sec. 2, the granular synthesis techniques employed in Sec. 3, and mappings from data to sound parameters in Sec. 4. In Sec. 5, sonification examples are presented, and in Sec. 6, challenges encountered in managing the data are described. A sum-

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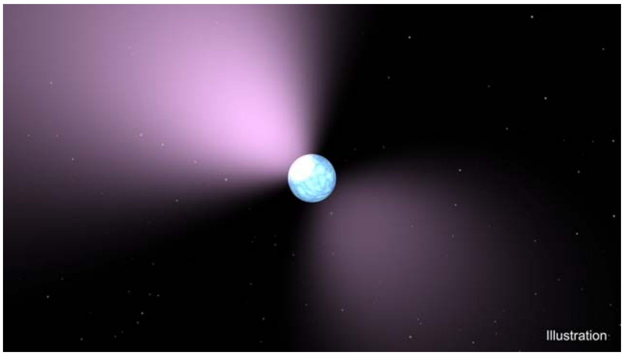

Fig. 1. Artist's conception of a pulsar. Jet Propulsion Laboratory/Caltech [6].

mary of the compositional process of the work is in SEC. 7, and conclusions are drawn in SEC. 8, with a mention of in-progress related projects.

1 WHY PULSARS?

Pulsars are one of the more interesting and useful types of celestial objects. These extremely dense neutron stars are formed when the intense fire in a star burns up all of the fuel, ending in a supernova explosion. The rotations of pulsars can be so precise as to serve as a clock. Collisions between neutron stars have allowed scientists to observe gravitational waves. Highly magnetized neutron stars may also emit electromagnetic radiation, and as they spin around, these waves may reach earth each time the pole faces it, as in Fig. 1. Telescopes on earth detect pulses of many different frequencies and spectra, from radio waves to gamma rays, from pulsars across the galaxy and even beyond. Each pulsar has a unique set of characteristics. Because the frequency of rotation of the pulsars seemed to have an inherent connection with frequencies in sound, they seemed a good subject for sonification. After exploring the NASA website and data from various studies to find something suitable for the computer music software, the need for a pulsar map became clear, to understand the position of pulsars in space and have some way of organizing the sounds. Isaac Shivvers' online visual map [6] was an inspiration for creating a sound map of pulsars. His mention of the Australian National Telescope Facility's Pulsar Catalogue [7], [8] led the author to their data. Mark Ballora's pulsar sonification [9] and a study that described audifications with large datasets and complex noisy signals from solar wind [10] were also considered, along with Wanda L. Diaz-Merced's XSonify, for astronomy sonification [11].

Background information on pulsars necessary to understand the parameters in the database and their emissions was found in Pulsar Astronomy [12]. Resources on pulsars [13] and the Milky Way [14] were from NASA, and audio created from pulsar data was heard at the University of Manchester's site [15].

2 AUSTRALIA TELESCOPE NATIONAL FACILITY PULSAR CATALOGUE

The online Pulsar Catalogue, of the Australia Telescope National Facility, provided the data for this project. Data were available for 3,359 pulsars in version 1.69.

Data could be displayed in various formats specifying number of digits, decimals, and accuracy. Tables of chosen parameters were displayed in text format and pasted into text files for formatting. Plots were also done on the web page for pairs of items, which were helpful for understanding relationships between parameters. There were around 69 data items for each pulsar, some of which were duplications for convenience (coordinates in various systems such as Galactic or Ecliptic), or derivatives of other parameters. Some data were not available for particular pulsars, which was indicated with an asterisk.

Data initially selected for this work from the complete list of parameters for the 3,359 pulsars in the catalog included discrete values for galactic longitude, galactic latitude, rotation speed, distance, age, width of pulse at 50% of peak, and S1400, which is related to luminosity. Since the data could be ordered according to any parameter, parameters were taken from the catalog in order of galactic longitude, making it easy to structure orders of sounds according to spatial position in the galaxy.

3 GRANULAR SYNTHESIS

Granular synthesis was the main technique chosen for the current version of this sonification and a logical choice for a number of reasons. In this technique, sounds consist of many small "grains" of sound, containing bits of enveloped waveform or sampled sound. The stochastic granular synthesis instrument used generates grains according to probability distributions for four sets of parameters: grain rate, grain duration, grain frequency, and left-right grain panning. Each of these four aspects of sound is defined by four values: (1) a low value and (2) high value delimiting the range, (3) a middle point of preference or avoidance, and (4) a value that specifies the amount of preference/avoidance. Grains are synthesized according to these values, each of which can also change according to a function over the event time.

The probability distributions allowed for unique-sounding events each time an event is synthesized, because there were small variations in actual grain values. However, on separate runs, events based on the same pulsar parameters were generally quite similar. The SGRAN2() granular synthesis instrument is a new and more flexible version of older stochastic granular synthesis instruments programmed using the RTcmix music programming language. This new instrument, SGRAN2(), will be available in future distributed versions of RTcmix from the github site and is available as a separate instrument collection now.

While the term granular synthesis usually refers to short grains that often fuse into connected sounds, here also larger grains are heard as individual notes, when the pulsar rotation speed is very slow, as with some older pulsars.

Some previous pulsar sonifications had mapped rotation speed to frequency of tones, and these intervals seemed to have been adjusted to create a harmonic sound, not using the real relationships between rotation speeds, which were often inharmonic. With stochastic granular synthesis, it was possible to use actual rotation speeds for both the rates and frequencies in grains, producing the actual frequency relationships that emerge from the scaled data. The sonifications sometimes created dense textures mapped from faster rotations of a large number of younger pulsars, and alternatively, complex, lower-pitched polyrhythms from the sparser, older, and slower pulsar rotations.

4 PARAMETER MAPPING SONIFICATION DESIGN

The data set provided an opportunity for what Grond and Berger have described as an exploratory parameter mapping sonification design [16]. The various ranges of discrete values for each pulsar parameter demanded different types of data preparation to realize distinguishable sounds, which is described in SEC. 6. One granular synthesis event, which might contain as many as thousands of grains, was synthesized according to the parameters listed for each individual pulsar selected from the Pulsar Catalogue.

In general, one-to-one mappings between pulsar parameters and sound parameters were used, except for the dual mapping of pulsar rotation speed and of galactic longitude. Regular bursts of electromagnetic radiation can clearly be analogous with repetition of grains of sound, and this correspondence was the initial reason for choosing pulsar data for sonification. Rotation speed was consequently exactly mapped to grain rate. Since the pulsar rates are usually very regular, it was appropriate to use a non-variable grain rate by restricting the limits of the range allowed. At subaudio rates from slower, older pulsars, which can be as slow as 23 s apart, the resulting grain rate is a series of individually audible large grains, also known as boulders. At faster rotation speeds such as from the millisecond pulsars, the rate will become the frequency heard, and the frequency in the grain affects sound color more than the heard pitch.

Pulsar rotation speed was also mapped to grain frequency. The reason for the double mapping of this parameter was because pulsar rotation speeds are significant, and what distinguishes their signals from many other objects in space, which do not emit regular pulsations. While the additional mapping to grain frequency was a less obvious selection, it provided, with a logarithmic scaling function, a way to create a wide variety of sound colors in all audible registers.

Galactic longitude was mapped to event start time. The mean flux density at 1,400 MHz, which relates to luminosity, influenced event amplitude. The age of each pulsar was converted to a duration for each sound, in seconds. See Fig. 2 for mappings, with the different scaling strategies used to obtain perceptibly distinguishable output sounds.

Panning, in addition to start time, was controlled by galactic longitude. Event start times are mapped from pulsars around galactic longitude 270° and heard mostly in the right channel in the beginning of the piece, to 360°/0° mainly in the center of the two channels in the middle of the piece, and near the end of the piece from pulsars around 90° galactic longitude sounding mostly in the left channel. The variability in the stochastic parameters ensured that some grains would be present in both channels at all times during the overall sweep from right to left in the piece.

Pulsar Parameter	Unit	Sound Parameter	Unit	Scaling
Galactic Longitude	Degree	Event Start Time	Second	Linear
Age	Year	Event Duration	Second	Exponential
Distance	Kiloparsec (kpc)	Reverberation (Silververb)	% Wet (0,20,30)	Linear
S1400 (Mean Flux Density at 1400 MHz)	Millijansky (mJy)	Amplitude	Decibel (dBFS)	Logarithmic
P0 – Rotation	Second	Grain Rate	Second	None
PO – Rotation	Second	Grain Frequency	Hz	Logarithmic
Galactic Longitude	Degree	Grain Pan Prob.	0 – 1.0	Linear
W50 (Pulse Width at 50%)	Second	Grain Duration Prob.	Second	Quadratic

Fig. 2. Mappings table.

What is heard inside each grain can be a pure waveform or sampled sound, but in this piece, a triangle waveform with eight partials was used. This choice gave some richness to the sound, without being too distracting when layering was dense. The grain envelope shape was a Hanning window.

The duration of each grain was based on the width of the pulse at 50% of peak, if known. These values were scaled to avoid grain sizes that were too small or larger than the rotation speed. Although grains can overlap with this synthesis technique, overlapping grains contributed to a lack of clarity in the sound and were usually avoided here by keeping the rate and grain duration in balance. An effort was made to keep the grain durations shorter than the rate (the time between grain attack points), because the received bursts from pulsars are shorter than the rotation speed.

Distance of pulsars from earth was treated differently than the other parameters. For pulsar distance, there were three categories: close (0–4 kpc), medium distance (between 4 and 8 kpc), and far away (greater than 8 kpc). One stereo layer was created in a separate run of the script for each distance. Reverberation was applied in the final mix of these three layers in Logic X. The percentage of wet reverb (Silververb) was at 0% for the layers with closer pulsars, 20% for the layer with medium-distance pulsars, and 30% for the layer with far-away pulsars.

Not all data values are listed for each pulsar in the catalog. If a value was missing, default values for sound parameters were provided if possible, or the pulsar was omitted entirely from mapping.

5 SONIFICATION EXAMPLES

The first three sound examples are based on the data from four pulsars. Some of their parameters are listed in Fig. 3.

The first sound and data example has sonifications of two slow pulsars from 0° galactic longitude, named J1746-2856

```
No      Name     Gl.    Gb       P0       Dist.  Age
1  J1746-2856  0.126 -0.233   0.945224  8.149 1.2e+06
2  J1746-2850  0.134 -0.044   1.077101  5.612 1.27e+04
7  J1721-2457  0.387  6.751   0.003497  1.393 1e+10
15 J1747-2809  0.869  0.076   0.052153  8.141 5.31e+03
```

Fig. 3. Data from pulsars 1, 2, 7, and 15.

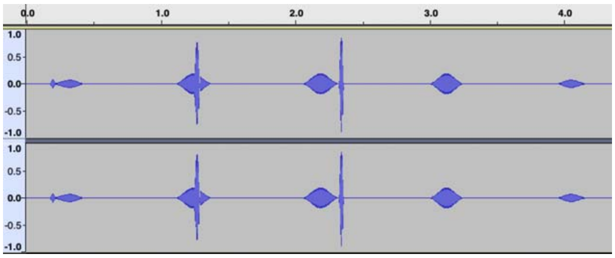

Fig. 4. Example 1: Audio stereo tracks, time in seconds across the top, vs. amplitude. Sound Example 1: https://drive.google.com/file/d/1sxjVWHxUOv1qNAYasrLWd-mjmp_wEAPr/view?usp=drive_link.

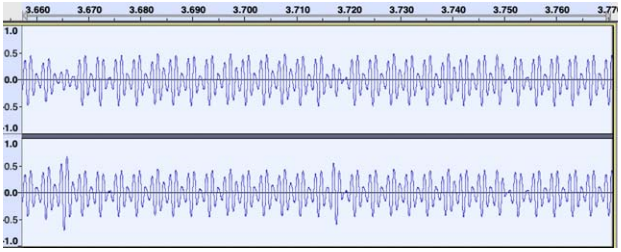

Fig. 5. Example 2: Pulsar J1721-2457 fused grains waveform, time vs. amplitude. Sound Example 2: https://drive.google.com/file/d/1lB1k2cNuR0f0B23YlUs9ptxQEGfjkwve/view?usp=drive_link.

and J1746-2850. Their slow rotation speeds are at 0.945224 and 1.077101 s, respectively.

Fig. 4 shows the amplitudes of the two sets of pulses, moving out of phase due to the slightly different rotation speeds. The first has five pulses because the age parameter was greater than the second, which has only three shorter, louder pulses.

The second sonification example in Fig. 5 of pulsar J1721-2457 is based on a very fast rotation of .003497 s, so individual grains are not heard. This zoomed-in view shows an excerpt of the waveform of the fused sound over seconds 3.66–3.77. The spectrogram of J1721-2457 in Fig. 6 shows the more complex harmonic nature of the sound.

The third example, J1747-2809 has a rotation of around 20 times per second, heard as amplitude modulation. See Figs. 7 and 8.

Fig. 9 shows partial output from RTcmix after running a script in a Terminal window with the pulsar J1747-2809 parameters mapped to SGRAN2() parameters.

6 CHALLENGES

Challenges were related to managing the large amount of data, dealing with the extremely large or small numbers, and translating them to useful values. Data preparation in

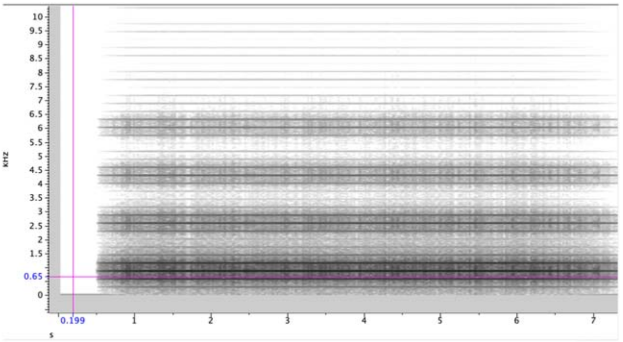

Fig. 6. Example 2: Pulsar J1721-2457 spectrogram, time vs. frequency.

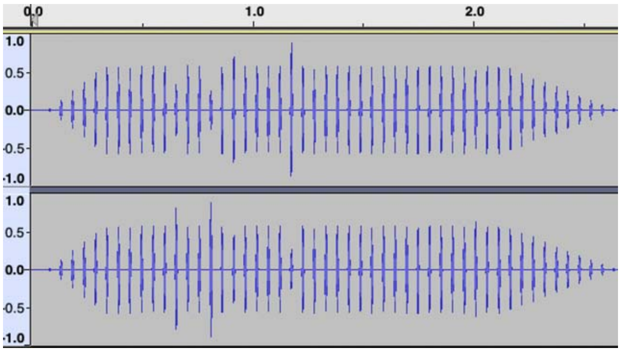

Fig. 7. Example 3: Pulsar J1749-2809, time vs. amplitude. Sound Example 3: https://drive.google.com/file/d/1SmrvCJp3oPslEMRuWKo6nNUx5-quadgT/view?usp=drive_link.

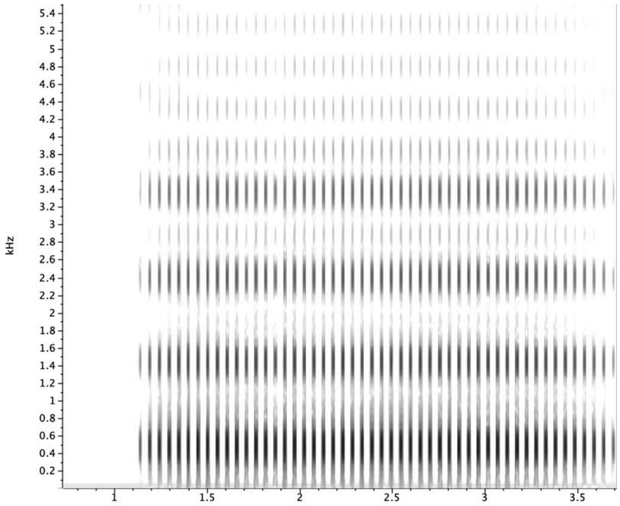

Fig. 8. Example 3: Pulsar J1749-2809 spectrogram, time vs. frequency.

```
SGRAN2: 1.1297 2.5732 PF:[0,...,0]
0.052153 0.052153 0.052153 10 0.0104306 0.0130382 0.0156459 4
479.947 479.947 479.947 1 0 0.495172 1 27
PF:\[0,...,-0.00335524] PF:[0,...,9.86957e-06]|
```

Fig. 9. Output from SGRAN2() using parameters from pulsar J1747-2809.

several cases was necessary for maximum clarity and audibility of data ranges.

Recompiling RTcmix to allow 4,096 array elements instead of the default 1,024 did not seem to impact performance. However, using data values in scientific notation did cause performance problems, so values for age of pulsars, for which it was not necessary to be extremely accurate, were actually scaled by converting the exponents to the number of seconds. Since each parameter exists for 3,359 pulsars, it was necessary to put each parameter into a separate array of less than 4,096 elements. Command line scripts and “awk” and “sed” were used to format the data. The sound-generating script loaded all of these arrays from different text files and accessed values by index as needed.

Scaling values proved to be a challenge, in translating pulsar characteristics to reasonable sound parameters for granular synthesis. The graduate assistant B. Kieran McAuliffe programmed Python tools for creating functions for scaling that were used for several values. Rotation speed for frequency and the S1400 luminosity data were scaled to usable ranges by adding one, applying a log to it, and applying a linear transformation with parameters calculated via linear regression. Frequencies were constrained to be between 110 and 1,000 Hz. Grain durations were scaled based on width of pulse at 50% of peak, using second-order polynomial regression. The scaling functions were run in RTcmix to convert the data to usable values.

7 FROM ORION TO CASSIOPEIA

The composition *From Orion to Cassiopeia* consists of one large sweep across the Milky Way Galaxy, with one sound for each of around 2,000 pulsars located from 220° to 360° galactic longitude and continuing from 0° to 120°. The center of the galaxy, the most densely populated area, is heard roughly in the middle of the piece. Because panning and start time depend on galactic longitude, the sense of moving slowly to the left gives the feeling of one great movement, despite minor variations, over the duration of the piece. The audio realization is in stereo fixed media: Sound Example 4, *From Orion to Cassiopeia*: https://drive.google.com/file/d/1vMfQg9sN6XT8dsxjB-0D_dNzO8ld_DME/view?usp=drive_link.

The compositional process moved from experiments to adding parameters, to adjustments to obtain clarity in relationships between layers of sound. First, many experiments with data mappings for a few parameters for small groups of pulsars were synthesized. The goal was to produce unique and at least somewhat distinguishable sounds for different types of pulsars and a mix that reflected the diversity of their characteristics. Gradually adding parameters and numbers of pulsars, the piece was synthesized and resynthesized many times, while various problems of scaling the data and many other issues, such as amplitude balance, and frequency ranges were addressed. The RTcmix script grew in complexity and included eight files of arrays for the pulsar data.

Versions of the piece with different durations were created, by changing the time scaling factor on galactic longitude. The shortest was 3 min, and the longest was around 1 h 40 min. The decision on the duration chosen was made according to desired density of sounds and the attractiveness of a compact piece that could be heard in many concert situations. Ideas for longer versions in an interactive installation format and multi-channel or headphone versions may be realized in the future.

The variety of sounds generated and the perceptibility of many aspects of the data seemed encouraging. The various grain rates and frequencies in the grains, both based on pulsar rotation speed, contribute many aurally distinguishable layers in the final mix. Slow grains at low frequencies with a pure waveform making pulsing rhythms are often heard at the same time as faster grains at higher frequencies, which are richer and perceptually fuse into a single sound. With audio-rate grains, the rate often becomes the heard frequency, and the pitch inside the grain changes the timbre of the sound.

For the most part, the parameters from the pulsar database directly resulted in the heard sound parameters. One divergence from this process was that, instead of entirely basing sound event start times on the galactic longitude of pulsars, in the middle of the piece, to avoid an unmitigated, overwhelming density of sound due to the number of pulsars near the galactic core, some moments of sparser textures are heard.

These inserted sounds are taken from a different, more stretched-out version of the piece, in which the interactions of a few sounds can be heard in more detail. This section provides an opportunity to hear individual pulsars and relationships with neighboring pulsars more clearly, which can be understood by listeners if provided with program notes or explanation. This section is analogous to a zoomed-in portion of a picture to show greater detail than is possible in a complete large image. The less-dense section functions as a fantasy and precedes a return to the original mapping of high-density sounds. At the return to the original mapping, it was interesting to notice the bursts of many younger millisecond pulsars from certain areas of the galaxy, possibly in the direction of one of the spiral arms. Example 5 contains the fantasy excerpt from 3:25, seen in Fig. 10.

A second divergence from the overall process was in the mixing. The piece was mixed in three layers, one layer for close, one for medium distance, and one for far-away pulsars with differing amounts of reverberation. To attain clarity of gesture and avoid too much density, amplitudes of the layers were intuitively sculpted by ear. While these amplitude curves may have resulted in some pulsar sounds being attenuated to nearly inaudible, the focus on certain sounds made the composition and information easier to comprehend. For example, in the beginning of the piece, rather than beginning with the full density of sound available for that longitude, only one faster higher-pitched sound, plus mostly lower-pulsing sounds from older, slower pulsars, are heard, all with some reverberation. These sounds build into denser sounds with higher-pitched, faster rates, including closer sounds with no reverb. So, one experiences the farther-away reverberated layer more clearly at first and then the more complex and complete mix.

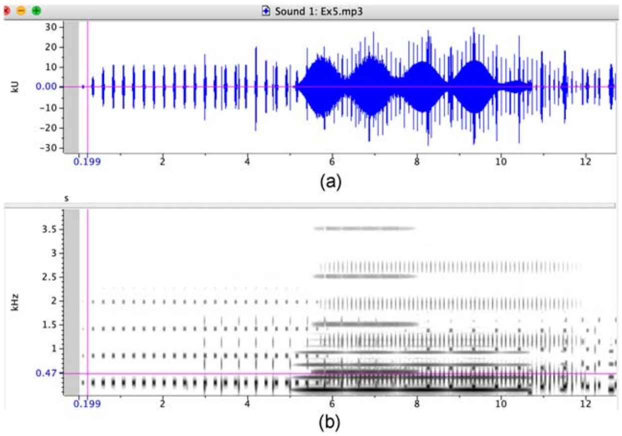

Fig. 10. Example 5: Excerpt from fantasy section at 3:25 of *From Orion to Cassiopeia*, waveform (a) and spectrogram (b). Time in seconds on the horizontal axis. Sound Example 5: https://drive.google.com/file/d/14GwP-ypJ3R366awWza7gzE_9-Qb77aOK/view?usp=drive_link.

Fig. 12. Horsehead nebula. Photo by Bill Gwynne.

Also, since pulsars of a certain distance were being emphasized at times that their layer was louder, the experience would be of hearing sounds of different distances at different times more clearly. So, in addition to hearing the pulsars in a particular direction that moves counterclockwise over the course of the piece, one is also hearing pulsars at different distances more clearly at different times. The listener hears the sweep across the galaxy as though they were moving inward and outward toward closer or farther pulsars at times. The reverberation on the farther-away layers signals distance and a deeper texture to the music, with its contrasting delay times.

The spectrogram in Fig. 11 of the entire piece shows the build from 0:00 to around 3:20, as more pulsars are heard at the middle of the galaxy; the fantasy section from around 3:25–4:35 with sparser textures; the return back to the dense layers of pulsars from the center of the galaxy; and the final thinning out as pulsars from the sweep from 0–120° galactic longitude are completed. Astrophotographer Bill Gwynne created a video for a new audio-visual version of the piece that showcases his images of space, including various nebulae and galaxies. Fig. 12 contains an image of the Horsehead Nebula from the video.

8 CONCLUSION

The dual desired outcomes were, first, to map pulsar parameters to granular synthesis parameters, creating distinguishably different types of sounds, and, second, to create an effective computer music composition that is an auditory display of pulsar data across the Milky Way. The mapping strategies used did provide great registral, rhythmic, and textural variations depending on the diversity of rotation speeds and other pulsar parameters. Also, the arrangement in space of pulsars led to musical variations in density and polyrhythms throughout the piece. While sometimes one hears conglomerates of pulsar sounds fused into a complex timbre, rather than individual sounds, the frequency relationships of these timbres are unique and indicative of

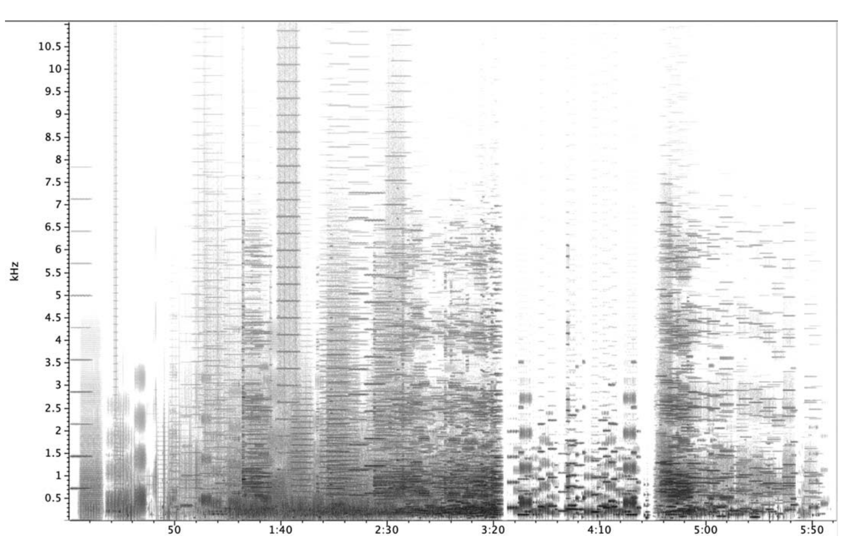

Fig. 11. Spectrogram of *From Orion to Cassiopeia*, time vs. frequency.

the density and speed of the younger pulsars in some areas of space. The author was initially concerned that the very dense textures created from so many pulsars clustered around the galactic core would be unbearably dissonant but found instead that the ear can discern differences in textures from moment to moment that make listening interesting.

The limitations of the current sonification method include that (1) only six data parameters for each pulsar are mapped, (2) various parameters must be scaled in different ways to accommodate the range of data values or be provided with defaults if values for a pulsar are missing, and (3) creating each large data array was time-consuming. While the methods used could be adapted for different data sets, this has not been tested.

From Orion to Cassiopeia was heard in a video version of the concert at the International Conference for Auditory Display in Norrköping, Sweden, in June 2023, on the author's faculty recital at the College-Conservatory of Music, University of Cincinnati, in September 2023, and at a concert at the Universidad Nacional Autónoma de México at Morelia in November 2023. At all three of these concerts, the author received enthusiastic comments from listeners, who had questions about the techniques.

Plans for many related future projects include a multichannel fixed media composition, interactive installation, and virtual reality environment. The interactive applications will be navigable by the user to explore the pulsars by moving around the galaxy with a controller. Rather than simply sweeping through the galaxy in one direction, more compositions could be created by choosing pulsars from different locations or choosing data parameters by type of pulsar or other selection processes. Expanding the number of data parameters would increase the possibilities for control of sound either using more granular synthesis parameters or additional processing. Also, the somewhat arbitrary decision to synthesize sound with a triangle wave with eight partials could be switched to other waveforms, use of sampled sounds, or even processing of a live sound such as from an instrument.

Experiments with an interactive MaxMSP patch are ongoing (using the rtcmix∼ plugin), which responds to user input to select pulsars and plays sound displaying the above and additional pulsar parameters not used in the original composition, including galactic latitude, pulsar types such as anomalous X-ray pulsars or high energy pulsars, various binary configurations, spin down, and glitch information. This work will result in an interactive application, Sonic Pulsings.

9 ACKNOWLEDGMENT

Graduate student Kieran McAuliffe created an amazing new version of the granular synthesis instrument SGRAN2() used here and programmed scaling functions. Doug Scott provided information on using large data arrays and functions in the RTcmix music programming language. Spectrograms were generated in Raven [17] and waveform displays in Audacity [18]. Bill Gwynne created a video for the multimedia version of the piece from his photos of space.

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