COMPOSING MUSIC FROM BLACK HOLE AGN SPECTRA

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ABSTRACT

Black Hole Symphony is an audiovisual symphony touring planetariums and science centers across the US, with the goal of communicating the richness of science to a wide audience. Composed in 5 movements, the composition is derived from a single harmonic structure: a sonification of the electromagnetic emissions from a black hole's Active Galactic Nucleus (AGN). Originating from a complex 3-dimensional structure of dust and gas, these emissions span the entire electromagnetic spectrum - a range of >20 orders of magnitude or 60 octaves - and thus far exceed the frequency span of our eyes. In this paper, I will discuss my development of spectral audification methods, their application for creating the Black Hole Chord, and how this harmonic structure gives rise to the galaxy of themes and movements that make up Black Hole Symphony.

1. INTRODUCTION

Spectral audification, a term coined by James Treyford of the University of Portsmouth is an emerging field within sonification, showing promise within research fields [1], communicating data to nonscientists and to the visually impaired [2], and for humanistic explorations of science and its interconnections with the arts. Its value stems from the comparatively large harmonic range of our ears compared with that of our eyes. This can be counterintuitive. From an initial frequency span comparison, the average human eye's range of 400–790 terahertz [3, p.94] greatly exceeds that of our ears' 20-20,000 hertz [4, p.163]. However, in a universe filled with harmonically resonant systems - where resonances are accompanied by their frequency multiples in a harmonic series - the frequency span of our senses can be less important than their ability to perceive harmonic relationships originating from sound, electromagnetic or other wave phenomena. A comparison of human vision and hearing is below:

	Vision	Hearing
Frequency Range	400-790 THz	20-20,000 Hz
Frequency Span	390 THz, or 390 Hz * 10^12	19,980 Hz
Harmonics Perceptible from the Lowest Frequency	400, 800 THz (possible in some individuals with aphakia)	20, 40, 80, 160, 320, 640, 1280, 2560, 5120, 10240, 20480 Hz (possible in young children)
Harmonic Range in Octaves	≤1	≤10

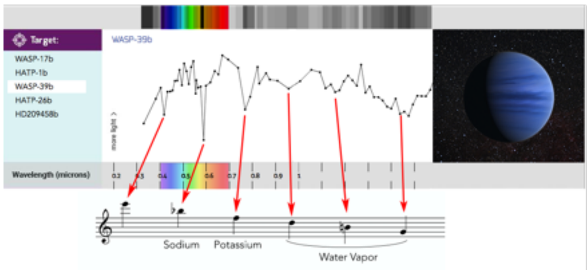
Figure 1: Human vision and hearing ranges comparison

When looking for ways to represent data sources containing harmonic resonances, it is clear that the ear's wide octave range offers a key advantage over the eye.

2. SPECTRAL AUDIFICATION DEVELOPED IN OCTAVE OF LIGHT ALBUM

In 2019-2020, I composed a series of songs for voice, violin, piano and electronics entitled Octave of Light on a theme of exoplanets, in collaboration with Roy Gould of the Center for Astrophysics | Harvard & Smithsonian. At this time of writing, 5,602 exoplanets have been discovered, 4,168 of them via the transit method of detection [5]. This method involves recording the light curve of a star over time in search of regular dimming patterns indicative of orbiting planets. The light at the moment of transit can then be broken into an electromagnetic spectrum: revealing patterns of absorption from the chemical constituents of the planet's atmosphere. As these patterns are too widely spread to be visible by the eye - even if transposed to visible range - I developed a spectral audification technique in order to reveal them to the ear.

In the song Wanderers, I sonify the infrared spectrum of gas giant WASP 39-B:

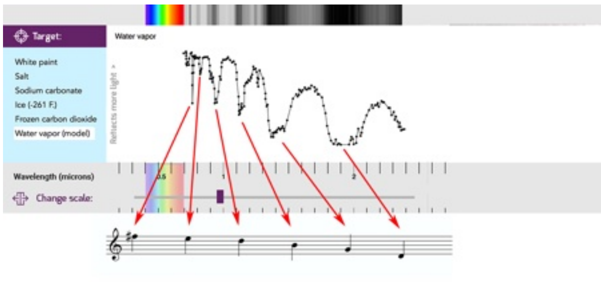


Wavelength in µm	Frequency in Hz (2.998E+14 / Wavelength)	Frequency Transposed - 40 octaves (Hz)	Note
0.4182	716881874701100	1304.000534	E4 minus 19 cents
0.5893	508739182080434	925.3911814	A#4 minus 13 cents
0.768	390364583333333	710.0690406	F4 plus 29 cents
0.93	322365591397849	586.3795948	D4 minus 3 cents
1.116	268637992831541	488.6496624	B3 minus 18 cents

1.42	211126760563380	384.0373403	G3 minus 36 cents

Figure 2: WASP 39-B absorption spectrum and sonification.

By comparing the planet's spectrum with lab spectra of pure elements and molecules from the HiTRAN database, key absorption features can be identified as originating from the presence of specific atmospheric gasses. Below is the pure water vapor spectrum in a similar range:



Wavelength in µm	Frequency in Hz (2.998E+14 / Wavelength)	Frequency Transposed - 40 octaves (Hz)	Note
0.718	417548746518106	759.5167454	F#4 plus 45 cents
0.81	370123456790123	673.2506459	E4 plus 36 cents
0.935	320641711229947	583.2438751	D4 minus 12 cents
1.13	265309734513274	482.5955957	B3 minus 40 cents
1.38	217246376811594	395.1688574	G3 plus 14 cents
1.88	159468085106383	290.070757	D3 minus 21 cents

Figure 3: Pure water vapor absorption spectrum from HiTRAN, and sonification.

The absorption features at 0.935, 1,13 and 1.38µm (shown in blue) are clearly audible in both sonic spectra. This allows an audience to hear the difference between simple and complex molecules in planetary atmospheres as a live, concert experience, interwoven into compositions that explore themes of planetary discovery and the search for life on other worlds.

3. THE BLACK HOLE CHORD: BROAD LINE SONIFICATION

Work began on Black Hole Symphony in 2019 as a collaboration between Multiverse Concert Series and a team of scientists from the Center for Astrophysics | Harvard & Smithsonian and Black Hole Initiative. Our goal with the project was to dispel the image of black holes as purely destructive entities, and replace it with the far richer picture that is unfolding to us through modern astrophysics. We now understand that black holes are creative forces shaping the evolution of stars and galaxies, and that our own Milky way could not have formed without the supermassive black hole, Sagittarius A*, at its center. This image of a 'cosmic conductor' at the heart of the galaxy was a powerful one, and naturally inviting to explorations through sound and music.

Although black holes emit no radiation from beyond their event horizons, their intense gravities trigger immense electromagnetic and gravitational emissions from their surrounding regions. This structure, close to the black hole, is called the Active Galactic Nucleus or AGN, and consists of distinct nested layers of gas and dust:

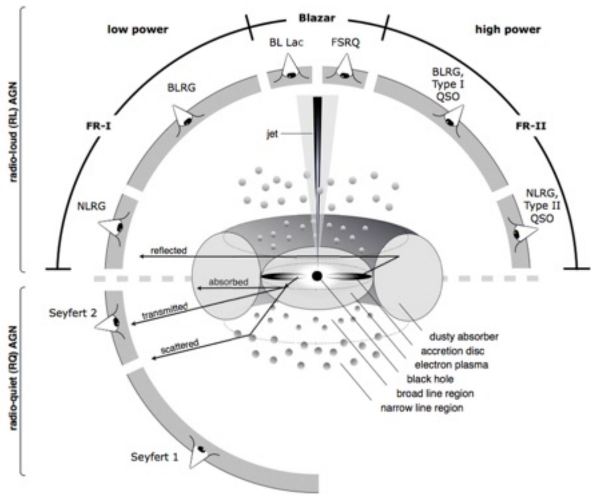


Figure 4: Beckmann, Shrader (2012) AGN unified model schematic [6]

Each of the AGN components produces their own emissions, spanning the entire electromagnetic spectrum. Unlike the absorption lines in exoplanet atmospheres, however, their features are defined by emission lines as molecules become ionized by the immense heat produced within the system.

This spectrum from SDSS J002025.22+154054.7 [7] displays prominent emissions lines, indicating ionization in the broad line cloud region of an AGN.

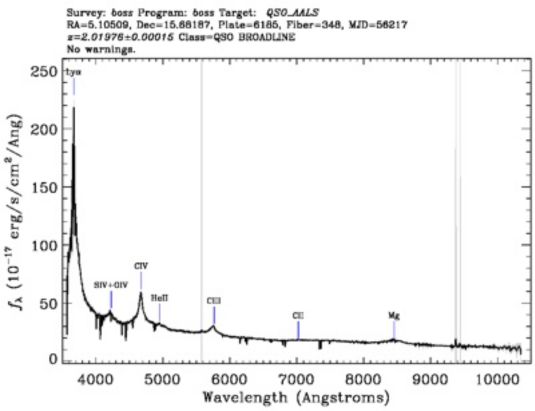


Figure 5: Broad line emission spectrum from SDSS J002025.22+154054.7 quasar.

Using the Octave of Light method, and omitting the weaker lines, these emission lines are sonified as a musical chord below:

Spectral Feature	Wavelength in µm	Frequency in Hz (2.998E+14 / Wavelength)	Frequency Transposed - 40 octaves (Hz)	Note

Lyα	0.3671	816671206755653	1485.516271	F#4 plus 6 cents
NV 1240	0.3747	800106752068321	1455.385704	F#4 minus 29 cents (rounded down)
CIV 1549	0.4678	640872167592989	1165.739682	D4 minus 13 cents
He ii 1640	0.4952	605411954765751	1101.23793	C#4 minus 12 cents
CIII] 1908	0.5762	520305449496703	946.4300992	A#3 plus 26 cents
Mg II 2799	0.8457	354499231405936	644.8303455	E3 minus 38 cents

Figure 6: Broad line emission spectrum sonification from SDSS J002025.22+154054.7 quasar.

In order to distinguish the Lyα and NV 1240 lines and still produce a chord playable by all orchestral instruments, I made the choice to round the NV 1240 down to E# (sometimes spelled as F). This broad line sonification then becomes the first building block of Black Hole Symphony, and from it I extrapolated a musical mode: a variation on a B minor scale with both perfect and augmented 4ths, and raised 7th. In turn, this mode became the Spectral Theme which begins the piece, played by solo piccolo:

Figure 7: Broad line chord, extrapolated scale, and Spectral Theme for piccolo. Audio file 2.1.

As I worked with the theme, the close proximity of the Lyα and NV 1240 lines - initially a challenge in creating the sonification - became an inspiration for melodic growth, the lower frequency NV line driving upward towards Lyα. Over time, this led to the creation of a family of melodies that leap up to an accented dissonance, then resolve to consonance on a weak beat, often in the pattern of a lower chromatic appoggiatura.

The first such example comes from the 1st Movement's Sonata Allegro theme on strings, joined by the Accretion theme. Both themes follow this melodic trajectory of rising resolution:

Figure 8: Sonata Allegro Theme

Later, the 2nd movement's Galaxy spectrum:

Figure 9: Galaxy Spectrum played by Cellos. Audio file 1.2

Later, the Heart of The Galaxy theme on trumpet follows this shape, but fails to resolve on the first attempt. Ultimately, it pulls upwards to competition of the gesture on the 2nd phrase:

Figure 9: Heart of the Galaxy Theme for Trumpet in C, Audio File 2.2.

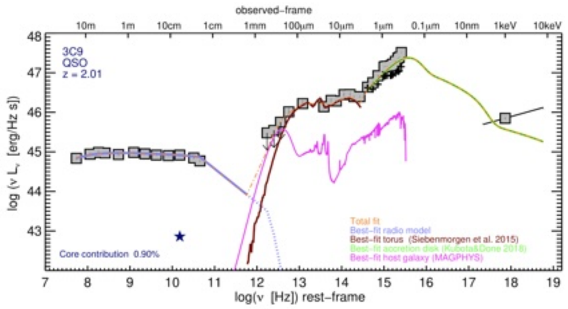
Later, this shape informs soprano motifs in the 4th and 5th Movements:

Figure 10: Soprano Themes. Audio Files 2.3, 2.4, 2.5, 2.6.

4. THE COMPLETE BLACK HOLE CHORD: BROADBAND SPECTRUM SONIFICATION

Although the broad line sonification spans visible and infrared frequencies wider than the eye could perceive (the ratio from lowest to highest frequency is 1:2.3), it still only represents a narrow portion of the full electromagnetic spectrum, which can span 20 orders of magnitude or more. In musical terms, this is ≥60 octaves. Even with the wide frequency response of the ear, a 1:1 aural mapping of the entire spectrum is not possible, and therefore a scaling method had to be developed which encompassed the entire electromagnetic range, yet still revealed fine-grain details.

In collaboration with Mojegan Azadi of the CFA, I developed a broadband spectrum sonification method based on her simulations separating the emissions of individual components of the AGN [8]. In order to compress the emissions into audible range, every power of ten is compressed into one musical octave, i.e. log10 becomes log2.



AGN Component	Freq. Log10 converted to Log2 Hz	Freq. in Hz	Shifted down 6 Octaves (/ 64) Hz	Equal Temperament	Orchestration
Radio Jet Synchrotron Emissions	2^10 and lower - 2^12.5	0 - 5793	0 - 91	(lowest) - F#2	Filtered Noise, Double Basses
Host Galaxy	2^11.5 - 2^13, peaking at 2^12.5	28963 - 8192, peaking at 5793	45 -128, peaking at 91	F#1 - B2, peaking at F#2	Cellos
Dust Torus, silicate grains	Peaking at 2^13.9	15287	239	A#3	Cor Anglais
Dust Torus, black body radiation	Broadband peak at 2^14.3	20171	315	D#4	French Horns
Sub X-Ray Region of Accretion Disk	2^14.6- 2^15.5	24834 - 46341	388 - 724	G4-F#5	Flutes and Oboes (nested sonification)
Fe-K 'Iron' Line X-Ray features of Accretion Disk	2^17 - 2^18	131072 - 262144	2048 - 4096	C7-C8	Electric Guitar, Piccolo, Violin Harmonics Glissandi
Relativistic Jet Gamma Emissions	2^19-2^24	524228 - 16777216	8191 - 262144	C9 and upwards	Filtered Noise and Tremolo Violins

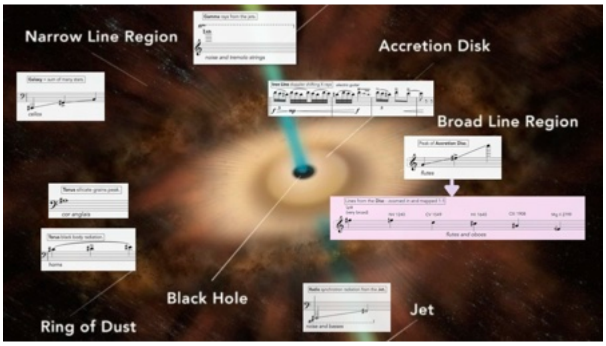


Figure 11: Simulated Spectral Energy Distribution of an AGN, Azadi et al 2023, Black Hole Chord sonification table, and visual-spatial guide.

In order to depict the varying natures of each of these components - some broadband, some narrow, many with important peak locations - I made a series of harmonic and orchestrational decisions in order to assemble the final chord. Beginning in the mid range: the Torus region has two important areas - the silicate grains (narrow lines) and black body radiation (broader). To show the broadness of the black body area, I surrounded the central D#4 with whole steps on either side. These are played by horns, and the grains by cor anglais. Together, these pitches became the Torus theme on solo horn:

Figure 12: Torus Theme, later extrapolated into a larger passage. Audio file 2.1.

To outline the broad range of emissions generated by the host galaxy from its stars and hydrogen clouds, I chose a solo cello. Its melody traces the harmonic region, emphasizing the central F#2 and upper limit B2 (see Figure 9).

For the broad line region, a mapping problem arose in that its salient features - the emission lines - were too narrowly distributed in the log2 scale to be either audible or playable. The solution was to employ a "nested sonification", positioning the 1:1 mapped sonification of the broad line region on top of the larger log2 sonification in the appropriate octave. This allows the detailed emission lines to shine through in the same sonic space as the AGN's full emissions: spanning from infrared to gamma rays.

An important region of the AGN's emissions to astrophysicists is the X-Ray band, which originates from the iconic accretion disk. Its iron content emits a spectral feature called the Fe-K or iron line, which displays a characteristic doppler shift. This twin-peaked spectral feature can be analyzed to reveal the the black hole's precise spin:

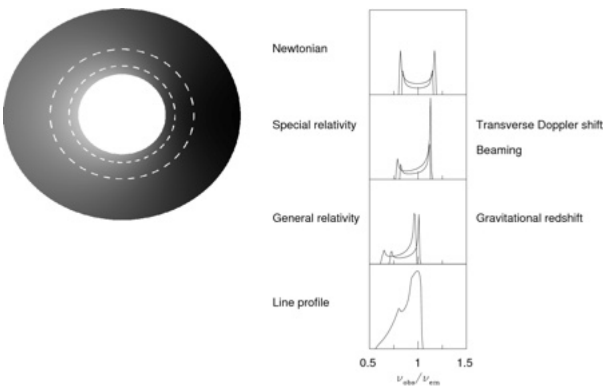


Figure 13, "Broad Iron Lines in Active Galactic Nuclei." Fabian, Andrew C., Kazushi Iwasawa, Christopher S. Reynolds and Andrew J. Young (2000). [9]

Doppler shifts are also a common feature of sound and music, and I employ two methods to evoke the spectral oscillations of the iron line - and therefore rotation of the black hole - in the sonification. The first: a written out 3-semitone oscillation for guitar and piccolo, played in inversely mirrored intervals:

Figure 14, Iron Line Doppler, Audio File 1.2.

Combined with this, I apply a 1-second modulated chorus effect to the violin harmonics playing the central pitch of C#, rising and falling 1 half step at either extreme.

With this last component in place, the complete Black Hole Chord is shown below, arranged for piano (minus the filtered noise at the radio and gamma extremes):

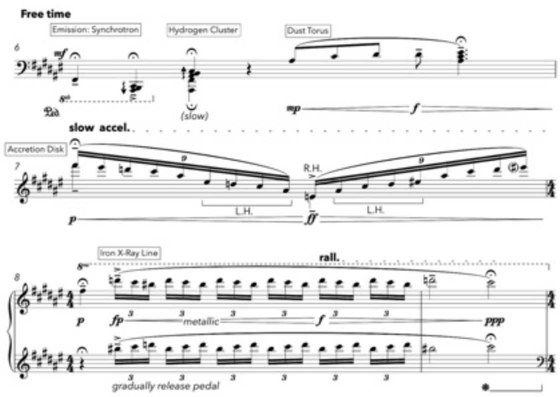


Figure 15, Black Hole Chord arranged for piano.

5. CONCLUSIONS AND FUTURE DIRECTIONS

Spectral audification continues to show promise for researchers, science communicators and artists alike. As I continue to compose science symphony projects and train students in the techniques of sonification, I look to develop these methods further and connect with other sonification practitioners to extend the techniques to new areas of data communication. Mars Symphony, premiering in summer 2024, employs the same method to sonify a spectrum of the Martian atmosphere captured by the JWST. In it, water vapor absorption lines are present - and are thus sonified as the same pitches heard in Octave of Light. As we create more science symphony projects, our audiences will experience an expanding library of molecular spectra woven through a variety of compositions on different topics. As these projects continue to tour, a vital undertaking is to survey audience members on the communication efficacy of sonifications like the Black Hole Chord, and its ability to relay the intricacies of the underlying science to different age groups. This will doubtless reveal strong and weak points in a method in a systematic manner, allowing for further improved iterations. Ultimately, we plan to pair these science symphony projects with lesson plans for school ages groups, and further education materials for adult audiences. By providing unique musical encounters with astrophysics, we aspire to spark further engagement and deep learning in audience members who might not otherwise have engaged with science.

6. REFERENCES

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