The Sound of Light: Sonification of Atomic Emission Spectra into Musical Scales and Timbres

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Abstract. This paper presents a systematic methodology for sonifying atomic emission spectra—transforming the spectral line radiation data of chemical elements into playable musical scales and unique timbres. Wavelengths from the NIST Atomic Spectra Database are converted to frequencies via the fundamental relation $f = c/\lambda$, yielding element-specific frequency ratios. These ratios are mapped into the audible range to construct microtonal scales measured in cents, while the relative intensities of the spectral lines serve as amplitude coefficients in an additive synthesis framework to generate distinctive timbres. The two outputs—*scale* and *timbre*—are conceptually and procedurally distinct: the scale encodes the *intervallic* structure inherent in an element's spectrum, whereas the timbre encodes its *spectral envelope.* We demonstrate the complete pipeline using hydrogen as a case study and describe its implementation as a real-time digital instrument in Max/MSP. The approach establishes a reproducible, physically grounded bridge between atomic physics and musical composition, contributing to the broader field of scientific data sonification.

Keywords: sonification, atomic emission spectra, spectral lines, musical scales, timbre, additive synthesis, microtonal music

1 Introduction

Every chemical element possesses a unique set of spectral lines—discrete wavelengths of electromagnetic radiation emitted when electrons transition between energy levels. These spectral fingerprints have long served analytical chemistry and astrophysics as identifiers of elemental composition [5, 8]. In a parallel domain, music is fundamentally structured around frequency relationships: scales define the set of pitches available to a composer, while timbre—the "color" of sound—is determined by the relative amplitudes of frequency components within a tone [3].

This study asks a direct question: *can the physical frequency relationships embedded in an element's emission spectrum be translated into a coherent musical language?* We propose a sonification pipeline that performs two distinct mappings:

1. **Scale construction:** The frequency *ratios* among an element's spectral lines define a set of musical intervals, yielding an element-specific microtonal scale.
2. **Timbre construction:** The relative *intensities* of those same spectral lines serve as amplitude weights in an additive synthesis model, producing a characteristic tone color.

It is essential to distinguish these two outputs clearly. A musical scale determines *which notes* are available; timbre determines *how each note sounds*. In conventional Western music these are independent choices—a pianist and a violinist may play the same C-major scale, but their timbres differ. Our methodology preserves this independence while grounding both outputs in the same physical data source.

The practical application of this research has been showcased in the "Beyond the Light" installation, a collaborative effort with NASA and ARTECHOUSE, premiered at ARTECHOUSE New York in June 2023 and subsequently exhibited at ARTECHOUSE DC in September 2023. The installation demonstrates the practical viability of spectral-data-driven musical composition in a public context.

The remainder of this paper is organized as follows: Section 2 reviews the relevant physics, sonification literature, and music-theoretic concepts. Section 3 details the sonification pipeline. Section 4 presents results using hydrogen as a case study. Section 5 discusses implications and limitations. Section 6 concludes with directions for future work.

2 Background

2.1 Atomic Emission Spectra

When an atom absorbs energy, one or more of its electrons are excited to higher energy states. Upon returning to lower states, each electron emits a photon whose energy equals the difference between the two levels. The relationship between the photon's energy E, its frequency ν, and its wavelength λ is given by:

$$E = h\nu = \frac{hc}{\lambda}, \tag{1}$$

where h is Planck's constant ($6.626 \times 10^{-34}\,\mathrm{J\,s}$) and c is the speed of light in vacuum ($2.998 \times 10^{8}\,\mathrm{m\,s^{-1}}$). Because each element has a unique electronic structure, its emission spectrum—the collection of all such wavelengths—acts as a spectral fingerprint [5]. Figure 1 illustrates this principle for five representative elements.

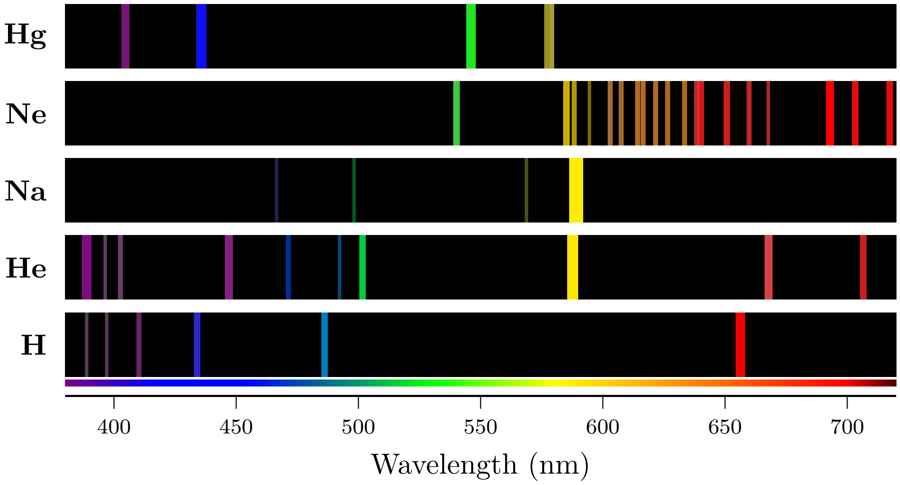

Figure 1: Visible emission spectra of five representative elements, illustrating the concept of spectral fingerprints. Each element produces a unique pattern of emission lines at wavelengths determined by its electronic structure. These distinct patterns form the basis for element-specific sonification.

2.1.1 The Hydrogen Spectrum and the Rydberg Formula

Hydrogen, the simplest atom, provides the canonical example and serves as our primary case study. The Balmer series comprises the visible emission lines corresponding to electron transitions from upper levels $n > 2$ to the $n = 2$ level. The wavelengths of these lines are described by the Rydberg formula:

$$\frac{1}{\lambda} = R_\infty \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right), \qquad n_2 > n_1, \tag{2}$$

where $R_\infty \approx 1.097 \times 10^7\,\mathrm{m}^{-1}$ is the Rydberg constant, and n_1, n_2 are the principal quantum numbers of the lower and upper energy levels, respectively. For the Balmer series, $n_1 = 2$ and $n_2 = 3, 4, 5, \ldots$, producing lines at approximately 656.3 nm (H_1, red), 486.1 nm (H_2, cyan), 434.0 nm (H_3, blue), and 410.2 nm (H_4, violet). The convergence of these lines toward the series limit ($n_2 \to \infty$) is a direct consequence of the $1/n^2$ spacing of energy levels—a pattern that, as we shall demonstrate, produces a characteristically compressed upper register when mapped to a musical scale.

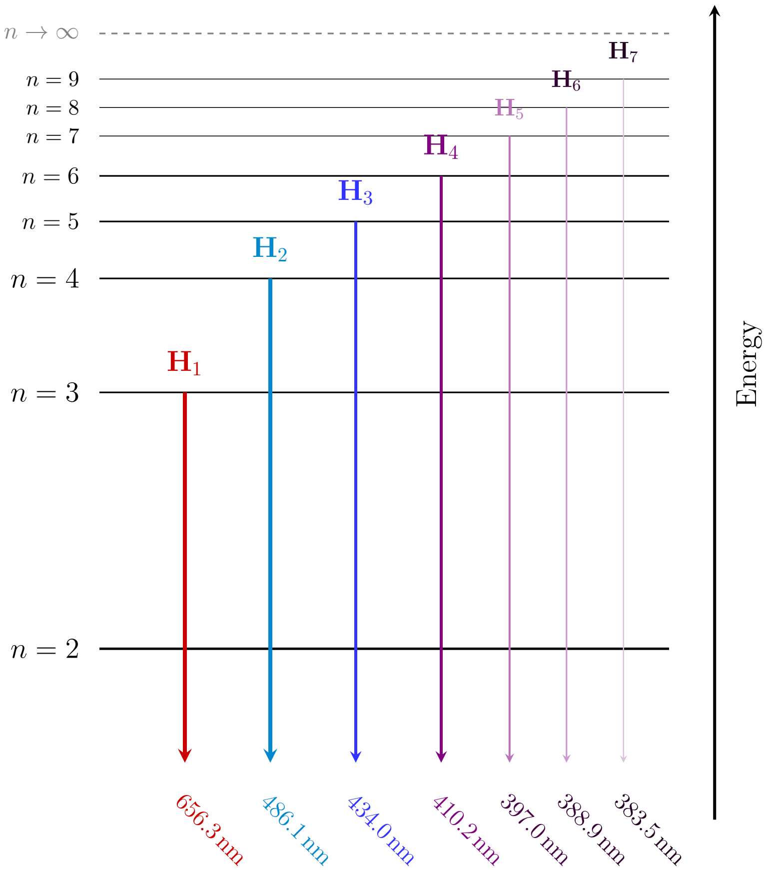

Figure 2: Energy level diagram for hydrogen showing Balmer series transitions ($n > 2 \to n = 2$). The convergence of upper levels toward the series limit produces the compressed upper register characteristic of the Hydrogen Scale (Section 4).

2.1.2 Spectral Line Data

The National Institute of Standards and Technology (NIST) maintains the Atomic Spectra Database (ASD), which catalogs observed wavelengths and relative intensities for emission lines of all elements [8]. Each entry provides a wavelength (in vacuum or air), a relative intensity value, and the associated electronic transition. These two quantities—wavelength and relative intensity—form the primary dataset for our sonification methodology. Crucially, the Rydberg formula and analogous quantum-mechanical relations for heavier elements determine the specific wavelength values, ensuring that the resulting frequency ratios are not arbitrary but reflect the fundamental electronic structure of each atom.

2.2 Data Sonification

Sonification is the systematic representation of data through non-speech audio [4]. It has been applied to domains ranging from seismology [2] to astronomical data [1]. Effective sonification strategies require a principled mapping between data dimensions and perceptual audio parameters. [7] identify key design principles: the mapping should be intuitive, the output should be perceptually distinguishable across data variations, and the sonification should serve either analytical or aesthetic goals (or both).

In this work, we adopt a *parameter mapping* strategy: wavelength ratios map to pitch intervals (scale), and intensity ratios map to partial amplitudes (timbre). This dual mapping is physically motivated—both data dimensions carry independent information about the element's electronic structure.

2.3 Musical Scales and Tuning Systems

A musical scale is an ordered set of pitches spanning an octave (a 2:1 frequency ratio). In twelve-tone equal temperament (12-TET), the octave is divided into twelve equal semitones of 100 cents each, where the cent is defined as:

$$\text{cents} = 1200 \cdot \log_2\left(\frac{f_1}{f_0}\right), \tag{3}$$

with f_0 and f_1 being two frequencies. Scales not conforming to 12-TET are termed *microtonal*. Many non-Western musical traditions employ microtonal intervals—for example, Turkish *makam* music uses intervals as small as approximately 22.6 cents (a Holdrian comma) [13]. The scales derived from atomic spectra are inherently microtonal, as the frequency ratios imposed by quantum mechanics bear no predetermined relationship to 12-TET intervals.

2.4 Timbre and Additive Synthesis

Timbre is the perceptual attribute that distinguishes two sounds of the same pitch and loudness [3, 9]. Physically, timbre is largely determined by the spectral envelope—the distribution of energy across frequency components—and by temporal characteristics such as the attack and decay profile of the sound. Figure 3 illustrates how the same fundamental pitch produces visually and aurally distinct waveforms across different instruments.

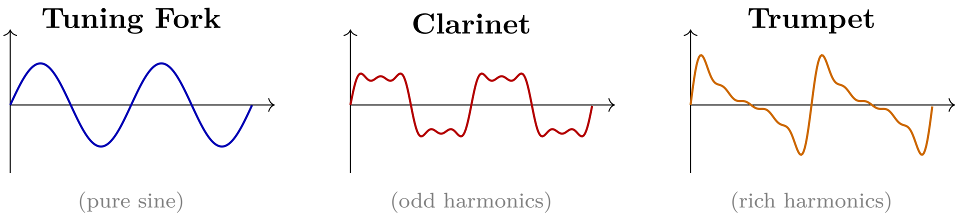

Figure 3: Stylized waveforms of three instruments playing the same pitch. A tuning fork produces a pure sinusoid; a clarinet emphasizes odd-numbered harmonics; a trumpet combines many harmonics with varying amplitudes. These differences in spectral content are what the ear perceives as timbre.

Additive synthesis constructs complex tones by summing sinusoidal partials, each with a specified frequency and amplitude [11]:

$$y(t) = \sum_{k=1}^{N} A_k \sin(2\pi f_k t + \phi_k), \tag{4}$$

where A_k, f_k, and ϕ_k are the amplitude, frequency, and phase of the k-th partial, respectively. When the partial frequencies f_k are integer multiples of a fundamental frequency, the resulting sound is *harmonic* and perceived as having a clear pitch. When the ratios are non-integer, the sound is *inharmonic*—a characteristic of bells, metallophones, and, as we shall see, spectrally derived timbres.

It is critical to note that the partials used in our additive synthesis are *not* harmonics in the musical sense. The frequency ratios arise from quantum-mechanical transitions, producing inharmonic spectra that yield timbres with metallic, bell-like, or otherwise unconventional qualities. This is a fundamental distinction from conventional instrument modeling, where additive synthesis typically assumes harmonic partials [6].

3 Methodology

The sonification pipeline consists of five stages, illustrated in Figure 4.

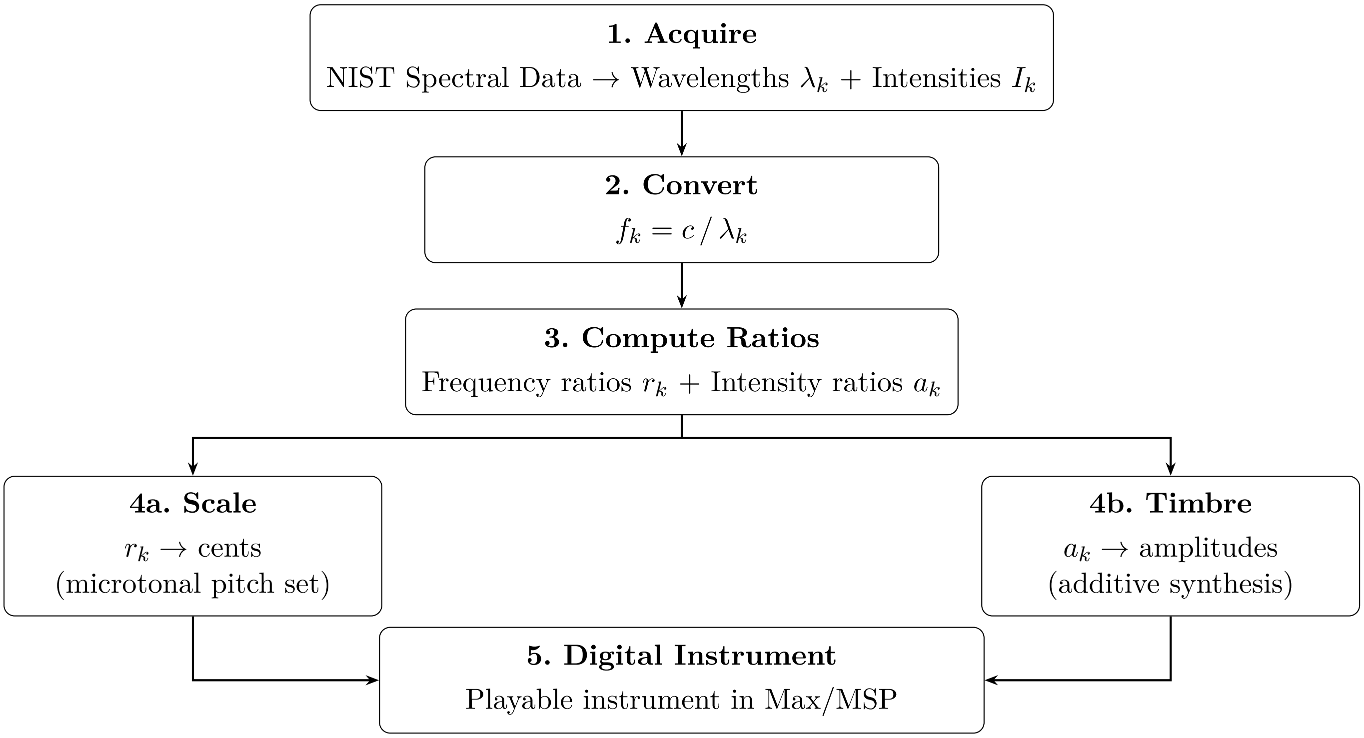

Figure 4: Schematic overview of the sonification pipeline. Spectral data branch into two independent outputs—scale and timbre—which are combined in the final instrument.

3.1 Stage 1: Data Acquisition

Spectral line data were obtained from the NIST Atomic Spectra Database [8]. For each element, we retrieved all observed emission lines within the visible spectrum (380 nm to 700 nm), recording both the wavelength λ_k (in Å, where $1\,\text{Å} = 0.1\,\text{nm}$) and the relative intensity I_k. The visible range was chosen because it provides a manageable number of lines for sonification while ensuring that the spectral data are well-characterized and experimentally reliable.

3.2 Stage 2: Wavelength-to-Frequency Conversion

Each wavelength is converted to a frequency using the fundamental relationship:

$$f_k = \frac{c}{\lambda_k}, \tag{5}$$

where $c = 2.997\,924\,58 \times 10^8\,\mathrm{m\,s^{-1}}$. Note that these are electromagnetic frequencies (on the order of 10^{14} Hz), not audible frequencies. The conversion to audible range is achieved through the ratio-based mapping described in the following stages.

3.3 Stage 3: Frequency and Intensity Ratio Extraction

3.3.1 Frequency Ratios

We designate the spectral line with the lowest frequency (longest wavelength) as the fundamental reference f_1. The frequency ratio of each subsequent line is:

$$r_k = \frac{f_k}{f_1}, \qquad k = 1, 2, \ldots, N, \tag{6}$$

where $r_1 = 1$ by definition. These ratios are dimensionless and independent of the electromagnetic frequency magnitudes, capturing only the *intervallic structure* of the spectrum.

3.3.2 Intensity Ratios

Similarly, we normalize the relative intensities by the intensity of the fundamental line:

$$a_k = \frac{I_k}{I_1}, \qquad k = 1, 2, \ldots, N. \tag{7}$$

These normalized values $a_k \in (0, 1]$ serve as amplitude coefficients in the additive synthesis model.

3.4 Stage 4a: Scale Construction

The frequency ratios r_k define intervals that, when folded into a single octave (i.e., reduced by successive halving until $1 \leq r_k < 2$), form a microtonal scale. The interval of each scale degree in cents is:

$$C_k = 1200 \cdot \log_2(r'_k), \tag{8}$$

where r'_k is the octave-reduced ratio. To render the scale playable, the ratios are multiplied by a chosen root frequency. For example, setting the root to $C_2 = 65.41\,\mathrm{Hz}$ (or any preferred reference pitch) yields concrete frequencies:

$$f_k^{\text{audible}} = r'_k \times f_{\text{root}}. \tag{9}$$

Each resulting frequency can be compared to the nearest 12-TET pitch to express the deviation in cents, providing musicians with a familiar reference point.

3.5 Stage 4b: Timbre Construction via Additive Synthesis

Independently of the scale, the spectral data are used to define a timbre. Given a desired fundamental playback frequency f_0 (e.g., any note the musician plays), the synthesized waveform is:

$$y(t) = \sum_{k=1}^{N} a_k \sin(2\pi \cdot r_k \cdot f_0 \cdot t), \tag{10}$$

where r_k are the frequency ratios from Equation (6) and a_k are the intensity ratios from Equation (7). Because the ratios r_k are generally not integers, the resulting timbre is *inharmonic*, imparting a quality distinct from conventional musical instruments.

This separation is a key feature of the methodology: the *scale* tells the performer which pitches to play; the *timbre* determines how each pitch sounds. Both are derived from the same spectral data, but they encode different physical dimensions—intervallic structure and spectral envelope, respectively.

3.6 Stage 5: Digital Instrument Implementation

The complete pipeline was implemented in Max/MSP, a visual programming environment widely used for real-time audio and music applications [10]. The instrument allows the user to:

- Select any chemical element from a database of pre-computed spectral data.
- Play the element's microtonal scale via MIDI input, with the additive-synthesis timbre applied in real time.
- Adjust synthesis parameters (envelope, effects) while preserving the spectrally derived scale and timbre relationships.

Figure 5 shows the instrument interface. The central panel displays the selected element, while peripheral controls provide access to FM modulation, reverb, envelope shaping, granular synthesis, and filter parameters. A real-time spectral emission display in the upper-right corner visualizes the element's spectral lines during playback.

Expander 0.00 %
Spectrum 0.00 %
Size 97
Decay Time 104
Level -inf dB
Damping 102
Diffusion 105
Amount 0.00 %
Active
Freq 0.10 Hz
Mode LP HP BP
Attack 600 ms
Decay 100 ms
Sustain 50.0 %
Release 1.00 s
Recycle 0.00 %
Reverse 50.4 %
Attack 100 %
Pos 0.94
Duration 194 ms
Rnd Dur 0.00 ms
Density 100 %
Rnd Dens 0.00 ms
Rnd Pos 0.52
Delay 75.6 ms
Rnd Delay 0.63 %
Slide 100 %
Feedback 64.6 %
Rnd Fb 92.9 %
DryWet 50.4 %
Semit 0 st
Rnd Pitch 0.00 %
Glide 0.00 %
Rnd Oct 1
Volume 1.00
Transposer 0 st
Volume 0.0 dB
Reverb -inf dB

Figure 5: The "Sound of Light" digital instrument interface in Max/MSP, shown with hydrogen selected. Left panel: synthesis and effects parameters; center: element display; right: granular synthesis controls and spectral emission indicator.

4 Results: Hydrogen as a Case Study

We demonstrate the methodology using the seven visible emission lines of hydrogen (Balmer series plus near-ultraviolet extensions). Table 1 lists the spectral data obtained from NIST ASD.

Table 1: Visible emission lines of hydrogen (Balmer series) from NIST ASD.

Line #	**Wavelength (Å)**	**Rel. Intensity**	**Transition** ($n_2 \to n_1$)
1	6562.79	6500	$3 \to 2$
2	4861.35	1500	$4 \to 2$
3	4340.47	1000	$5 \to 2$
4	4101.73	675	$6 \to 2$
5	3970.08	255	$7 \to 2$
6	3889.06	195	$8 \to 2$
7	3835.40	135	$9 \to 2$

Figure 6 provides a visual representation of these spectral lines, illustrating both their positions in the visible wavelength range and their relative intensities.

Figure 6: Visible emission lines of hydrogen (Balmer series). Line brightness and height indicate relative intensity. The clustering of lines toward shorter wavelengths (violet end) reflects the convergence of the Balmer series.

4.1 Frequency Ratios

Applying Equation (5) and then Equation (6), we obtain the frequency ratios in Table 2. These ratios are purely determined by quantum mechanics—specifically, by the energy level spacings of the hydrogen atom.

Table 2: Frequency ratios and electromagnetic frequencies for hydrogen's visible lines.

Line #	**Wavelength (Å)**	**Frequency (Hz)**	**Freq. Ratio** r_k
1	6562.79	4.568×10^{14}	1.0000
2	4861.35	6.167×10^{14}	1.3500
3	4340.47	6.907×10^{14}	1.5120
4	4101.73	7.309×10^{14}	1.6000
5	3970.08	7.551×10^{14}	1.6531
6	3889.06	7.709×10^{14}	1.6875
7	3835.40	7.816×10^{14}	1.7111

4.2 Scale Construction

Since all ratios already satisfy $1 \leq r_k < 2$, no octave folding is needed. Applying Equation (8) and mapping to a root of $C_4 = 261.63\,\text{Hz}$ (middle C), we obtain the "Hydrogen Scale" shown in Table 3.

Table 3: The "Hydrogen Scale": microtonal pitches derived from hydrogen's Balmer series.

Freq. (Hz)	**Cents**	**Nearest 12-TET Note**	**Deviation**
261.63	0	C4	±0 ct
353.19	519.5	F4	+20 ct
395.58	715.7	G4	+16 ct
418.60	813.7	G#4	+14 ct
432.48	870.2	A4	−30 ct
441.49	905.9	A4	+6 ct
447.67	929.9	A4	+30 ct
523.25	1200	C5	±0 ct

The resulting scale is notably compressed in its upper register, with five of the seven pitches falling between approximately 700 and 930 cents. This clustering reflects the convergence of the Balmer series toward the series limit—a direct audible consequence of hydrogen's quantum structure.

4.3 Timbre Construction

Using the intensity ratios from Equation (7):

Table 4: Intensity ratios for hydrogen, used as additive synthesis amplitudes.

Line #	**Rel. Intensity**	**Amplitude a_k**
1	6500	1.0000
2	1500	0.2308
3	1000	0.1538
4	675	0.1038
5	255	0.0392
6	195	0.0300
7	135	0.0208

The timbre is dominated by the fundamental (H_1 line), with rapidly decaying upper partials. Because the partial frequencies are inharmonic (ratios such as 1.35, 1.512, etc., are not integers), the resulting sound exhibits a metallic, bell-like quality absent in conventional harmonic timbres. Figure 7 shows the resulting spectral profile as displayed in the Max/MSP instrument, alongside the corresponding visible emission spectrum of hydrogen.

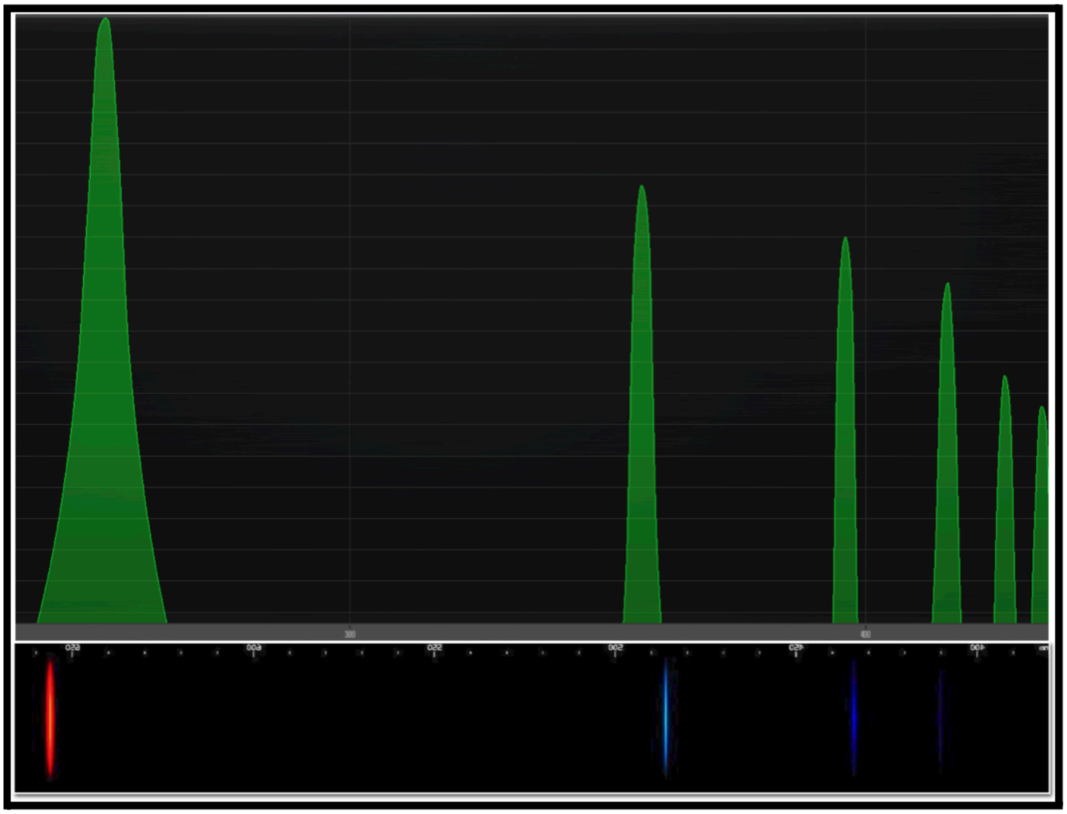

Figure 7: Spectral profile of the hydrogen timbre as rendered in the Max/MSP synthesis environment. The peak heights correspond to the amplitude coefficients a_k derived from Table 4; the horizontal axis represents the frequency ratios r_k. The lower strip shows the visible emission spectrum of hydrogen for comparison.

5 Discussion

5.1 Scale versus Timbre: A Critical Distinction

A central contribution of this work is the explicit separation of scale and timbre as independent sonification outputs. In earlier formulations, the distinction was not clearly articulated, leading to potential confusion between the two processes. We emphasize:

- **Scale** is a *pitch-domain* construct: it determines which discrete frequencies are available for melodic and harmonic composition. It is derived from frequency *ratios*.
- **Timbre** is a *spectral-envelope* construct: it determines the tonal color of each sounded pitch. It is derived from intensity *ratios* applied in additive synthesis.

An analogy may clarify: changing the scale is like choosing a different alphabet; changing the timbre is like choosing a different typeface. Both convey information, but they operate on different perceptual dimensions.

5.2 Inharmonicity and Perceptual Implications

The inharmonic nature of spectrally derived timbres has significant perceptual consequences. Research in psychoacoustics has shown that inharmonic partials weaken pitch salience and can produce sensations of "roughness" or "shimmer" [9, 12]. The degree of inharmonicity varies across elements: hydrogen's Balmer series produces relatively gentle inharmonicity (ratios near simple fractions like $4/3 \approx 1.333$ and $3/2 = 1.5$), while heavier elements with more complex spectra may yield more dissonant timbres.

5.3 Relationship to Existing Sonification Work

Prior sonification projects have mapped astronomical or physical data to sound [1, 2], but typically employ *ad hoc* mappings (e.g., brightness to pitch). Our approach is distinctive in that the mapping is *physically direct*: light frequencies become sound frequencies via a dimensionless ratio, preserving the mathematical structure of the source data. This is closer in spirit to the concept of *audification*—direct translation of a data waveform to audio—than to arbitrary parameter mapping [4].

5.4 Limitations

Several limitations should be noted:

- The restriction to the visible spectrum excludes ultraviolet and infrared lines, which could provide additional partials and scale degrees.
- Relative intensity values in the NIST database depend on experimental conditions and may not perfectly represent intrinsic transition probabilities.
- The additive synthesis model does not account for temporal evolution (attack, decay) or spectral broadening effects.
- Perceptual evaluation of the resulting scales and timbres has not yet been conducted in a controlled listening study.

6 Conclusion

We have presented a reproducible methodology for transforming atomic emission spectra into two independent musical constructs: microtonal scales and additive-synthesis timbres. By grounding both mappings in the physical properties of spectral lines—frequency ratios for scales, intensity ratios for timbres—the approach maintains a direct and transparent connection between the scientific data and the musical output. The hydrogen case study demonstrates that even the simplest atom yields a musically distinct and physically grounded result.

Future work will extend the methodology to a broader range of elements, incorporate spectral lines beyond the visible range, and conduct perceptual evaluation studies to assess the musical qualities of the resulting sounds. The integration of temporal dynamics (e.g., envelope shaping informed by transition probabilities) and the exploration of multi-element polyphonic textures are planned directions.

Acknowledgments

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