Astronomy for Equity, Diversity and Inclusion
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CosMonic sonification project

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Abstract. CosMonic (COSmos harMONIC) is a sonification project with three primary objectives: data analysis through sound, artistic inspiration, and educational outreach. This contribution focuses on the project's efforts in inclusive astronomy outreach, particularly within the Astroaccesible initiative, aimed at audiences including blind and partially sighted individuals, as well as a broader public seeking alternative ways to engage with astrophysics. CosMonic strives to create simple, acoustically accessible astronomical cases that are easy to understand. By using sonification to complement visual data, CosMonic pairs its audio creations with animations to offer a more holistic experience. This contribution presents several examples of these sonifications and reflects on our experiences with diverse audiences. Additionally, it offers insights on the role of sonification in inclusive and multi-cultural scientific outreach.

Keywords. Sonification, Astrophysics, Inclusive Outreach, Inclusive Cultural Aesthetics

1. Introduction

Sonification, the process of representing data through sound, has evolved significantly over the past several decades, growing from a niche research interest into a versatile tool with applications spanning science, education, and art. The origins of sonification can be traced to early experiments with auditory representations of data in fields such as seismology (Speeth 1961; Frantti & Levereault 1965) and physiology (Bernstein & Schönlein 1881; Wedensky 1900) more than a century ago. However, it was the advent of digital computing in the late 20th century that transformed sonification into a systematic and impactful methodology. The 1992 establishment of the International Community for Auditory Display (ICAD) marked a turning point, fostering the development of sonification as both a scientific discipline and an expressive medium.

At its core, sonification serves as the auditory counterpart to visualization, translating data into sounds to enhance analysis, communication, and understanding. This approach harnesses the human capacity to discern patterns and nuances in sound, often revealing insights that might be missed through visual methods alone. Beyond acting as a supplementary layer to visualization, sonification creates synergies that enhance multidimensionality in data interpretation. Importantly, it also serves as a powerful inclusive medium, offering new avenues for accessibility and outreach. For individuals with blindness or visual impairments (BVI), sonification provides a means to engage with complex datasets in research and STEM education, enabling direct access to scientific exploration. Furthermore, as an outreach tool, sonification bridges the gap between visual and non-visual modalities, fostering engagement and inclusion in scientific discovery for a broader audience.

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The field has matured through contributions from interdisciplinary research spanning psychology, computer science, music, and beyond†. Seminal works such as *The Sonification Handbook* (Hermann, Hunt, & Neuhoff 2011) and periodic reviews (e.g., Nees 2019) have outlined theoretical frameworks and practical guidelines. Despite these advances, the discipline continues to face challenges, particularly in establishing a cohesive theoretical foundation and developing standardized evaluation methods.

Auditory displays and sonification can be organized by their functions or design approaches, with flexibility to adapt as the field evolves. Key functions include alerts and notifications, which provide simple, low-information sounds to indicate events, and alarms or warnings, which emphasize urgency but often lack detailed specificity. Object and status indicators, such as earcons‡ and auditory icons§ play an integral role in our daily interactions with technology, offering information about events or actions through sound cues in devices like computers, smartphones, and appliances. Auditory menus, often speech-based, enable users to navigate hierarchical options and tasks, demonstrating the pervasive utility of auditory design in modern life.

Sonification can be understood through several conceptual frameworks (e.g., de Campo 2007), but three key techniques—audification, parameter mapping, and model-based sonification—form the foundation of classical methodologies. These approaches represent some of the most widely used methods in traditional sonification practices.

Audification, one of the oldest and most classical approaches, directly transforms periodic data waveforms into sound, making patterns immediately perceptible. This technique often involves frequency or time adjustments to render data audible. As noted earlier, it has been applied in fields such as seismology and physiology, where early experiments demonstrated its ability to translate complex data into auditory insights.

Parameter mapping sonification, one of the most established approaches, translates data dimensions into corresponding acoustic dimensions, offering a broad design space for auditory representation. While traditionally considered a standalone method, it often involves passive interaction, with listeners interpreting the data.

Model-based sonification allows interactive exploration of data through virtual models, where sound responses are driven by data and user interaction. This makes it particularly effective for high-dimensional datasets. However, most sonifications integrate multiple approaches, creating a gray area where methods overlap to produce more nuanced auditory experiences.

A practical example of sonification in daily life is the auditory parking aid system in cars. These systems emit sounds that vary in pitch or frequency based on the vehicle's proximity to obstacles, enabling drivers to navigate tight spaces without relying solely on visual cues. Such implementations exemplify how sonification seamlessly integrates into everyday tasks to enhance safety and convenience (Lundkvist et al. 2017).

Sonification serves as a versatile tool across various disciplines, extending far beyond its common use in daily user-machine interactions. Its applications span scientific, pedagogical, and artistic domains, each with distinct objectives but often overlapping in practice. In scientific research, sonification assists in data exploration, analysis, and interpretation

† Audio alone can even serve as the primary component in creating unique acoustic ecosystems in audiogames: `https://www.audiogames.net`

‡ An example of an earcon is the three-tone chime that plays when a new message is received on a phone or the shutdown sound of an operating system. These sounds are stylized, nonliteral audio cues designed to indicate specific events, such as a system state change, without directly imitating real-world sounds. Their abstract nature and intentional design align with the definition of earcons. For further discussion, see Blattner, Sumikawa, & Greenberg (1989).

§ A trash bin sound on a computer, such as the sound of crumpling paper, represents deleting a file. This directly mimics a real-world action, making it immediately recognizable. See Gaver (1986).

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(Candey, Schertenleib & Diaz Merced 2006; Diaz Merced 2013). By converting data—whether environmental, physical, or social—into auditory form, it enables researchers to uncover patterns and anomalies that may be overlooked by visual means alone. While its use in research is still less widespread compared to other applications, this analytical approach holds significant potential to make complex datasets more accessible, facilitating new insights that can enhance understanding across various fields.

Sonification is increasingly used for pedagogical and outreach purposes. It has proven particularly effective in enhancing comprehension and engagement within STEM (Science, Technology, Engineering, and Mathematics) education. As a sensory alternative, sonification provides a unique pathway for understanding abstract concepts, especially benefiting individuals with visual impairments. Beyond accessibility, it also helps increase student engagement and deepen the learning experience, creating a multisensory approach to education that can make challenging ideas more tangible.

The third domain of sonification extends to artistic creation and public engagement. In this context, artists use sonification not only to communicate data but to evoke emotional responses and provoke reflection on important societal, environmental, or scientific issues. Sonification, as an artistic medium, transforms data into auditory experiences that invite the audience to reflect on topics such as climate change or technological advancements. Projects in this area often combine sound with visuals to engage the public and stimulate curiosity, encouraging reflection and dialogue.

While the specific goals of sonification vary across these domains, the design of the auditory experience is critical in each case. The degree of acoustic complexity and how clearly the data is represented depends on the intended audience and the objectives of the sonification. Whether the goal is to facilitate data analysis, educate, or inspire, the balance between the richness of the sound and the clarity of the data is key to ensuring effective communication.

Pioneer composers, such as Lucier in his *Music for Solo Performer* (1965; Lucier 1967; Straebel & Thoben 2014), have been at the forefront of integrating scientific data into their musical works, using it as a catalyst for creative exploration. More recent works, such as the sonification of chemical evolution through biochemical data (Everett 2013), demonstrate a direct engagement with scientific data, translating complex concepts into auditory experiences. These approaches, among others, highlight how scientific data can inspire artistic expression. While these works often prioritize the overall musical experience over the underlying data, they use the data as an exotic and inspiring element to engage the audience. However, as the data is often embedded in intricate musical arrangements, these works can be challenging to apply in outreach activities.

This gap between pure analytical sonification and artistic compositions constitutes a broad intermediary space. The CosMonic project inhabits this "transitional buffer state", where sonification serves both analytical and educational purposes while remaining accessible to the general public. In this paper, we will examine the CosMonic project and present two examples produced through this initiative. These cases illustrate how sonification can be used in outreach, bridging the gap between complex scientific data and the broader public, making abstract concepts more tangible and engaging.

2. The CosMonic Project

The COSmos harMONIC (CosMonic†) project is dedicated to exploring and transforming a wide range of data—from passenger rail traffic and weather patterns to astrophysical data—into sound, spanning analytical, educational, and artistic dimensions. Building on the principles outlined in the introduction, CosMonic strives to

† http://rgb.iaa.es/cosmonic

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harness the full potential of sonification as a multifaceted tool. It does so by considering the specific nature of the data and tailoring its presentation to suit the target audience. Whether through rigorous scientific analysis or creative artistic expression, CosMonic embraces the versatility of sonification in providing insights and fostering engagement. The project also actively seeks collaboration with other initiatives that aim to create innovative sonification resources, broadening the possibilities for this technique and offering fresh perspectives.

As an example of one of its ongoing collaborations, CosMonic has been working with the Astroaccesible project† Pérez-Montero et al. (2017), an inclusive astronomy outreach initiative designed to support blind and partially sighted individuals. This collaboration, while focused on accessibility, also serves the broader public by providing an alternative format for understanding astrophysical concepts. The mission of this partnership is to create sonification-based resources that explain complex astronomical ideas in ways that are intuitive, engaging, and inclusive.

In this context, CosMonic develops custom-made sonification cases that simplify complex astrophysical phenomena, ensuring they are accessible and easy to comprehend. The aim is to produce brief sonified representations that can be used in educational activities, helping to explain or illustrate key concepts in astronomy. The philosophy behind these sonifications is captured by a metaphor: painting graphs with sounds. Just as a visual artist paints a picture with colors and shapes, sonification "paints" data with auditory representations that can reveal patterns, structures, and relationships in the data that might otherwise go unnoticed.

Sonification, as explored in this project, is not just a tool for scientific communication but also a means of enriching visual content. By codifying information through sound, CosMonic enhances the audience's experience, creating powerful synergies between auditory and visual channels. These complementary methods work together to ensure that the concepts being explained are accessible to a broad and diverse audience. The use of audiovisual content makes the project inherently inclusive, allowing people with varying abilities and backgrounds to engage with the information across different sensory dimensions.

All material produced by CosMonic is made publicly available through its dedicated YouTube channel‡. Each video begins with a short audio description, followed by a detailed explanation in the video's text description. This ensures accessibility for those who rely on auditory content and provides additional context for all viewers. The data used in these sonifications is extracted from the literature and various catalogs, with appropriate credits provided in the descriptions. To accommodate a global audience, there are two versions of each video—one with audio and text descriptions in English§ and another in Spanish¶.

In this context, rather than relying on musification or music-driven sonifications, CosMonic adopts an approach specifically tailored for the Astroaccesible initiative. The examples incorporate scientific data and plots derived from research, catering to outreach activities that range from introductory to advanced levels of complexity. The emphasis is on producing videos that seamlessly integrate into presentations and public engagement events. These sonifications are designed to enhance live storytelling, fostering a more immersive experience through group dynamics and contextual interactions.

Each video includes comprehensive explanations of the sonification process and the underlying scientific data, but their true impact is realized when presented alongside

† http://astroaccesible.iaa.es/

‡ The first videos, although produced months earlier, were uploaded in June 2019

§ English CosMonic YouTube channel: https://bit.ly/3tmXhGo

¶ Spanish CosMonic YouTube channel: https://bit.ly/3FfIbVi

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a narrative. Guided by a speaker, these auditory representations are contextualized, transforming them into cohesive and engaging tools for communication. This approach ensures that the audience not only understands the data but also connects with it on a deeper level, bridging the gap between technical information and meaningful storytelling.

This approach acknowledges a key principle: sonifications, like visual plots, require proper context to be meaningful. Just as a plot becomes more informative with labeled axes, annotations, and a descriptive caption, sonifications benefit greatly from explanations that illuminate the data and its significance. By embedding these auditory representations within a broader explanatory framework, CosMonic ensures that they not only convey information effectively but also captivate and inspire audiences.

CosMonic project is not limited to a fixed set of tools for creating its content. Instead, CosMonic adapts its approach to the specific needs of each project, selecting the most appropriate techniques for the task at hand. For the sonifications discussed here, a combination of ChucK, a powerful audio programming language (Wang, Cook, & Salazar 2015), and Python (for video creation and data preprocessing) has been employed, ensuring flexibility and precision in the creation of the final products.

2.1. *Data Sonification of an Exoplanet Transit*

This example presents the data sonification of an exoplanet transit, a technique increasingly used in astronomy for analyzing light curves. The case study focuses on the extrasolar planet HAT-P-7b (Kepler-2b), located 320 pc away and discovered in 2008 Pál et al. (2008). The light curve data for this transit was obtained from the NASA Exoplanet Archive† and includes observations contributed by both professional and amateur astronomers. In particular, the dataset used here originates from amateur observer Peter Kalajian (KP2).

The dataset consists of photometric measurements collected at regular intervals over approximately six hours. In the visual representation, the horizontal axis corresponds to time (in hours), and the vertical axis represents relative flux. For the audio sonification, the brightness values (relative flux) are encoded as frequencies, with each measurement represented by a short, discrete sound.

An animation accompanies the sonification, visually illustrating the data points as they are sonified. Each observation is initially marked in yellow for easier identification, before transitioning to blue. As the animation progresses, the individual data points are plotted alongside a continuous orange line representing the model fit, which is synchronized with the sonification.

To optimize interpretability, the six-hour observation window is compressed into a 20-second sonification. This duration balances the need for perceiving individual data points and retaining the overall "shape" of the data in auditory memory. The relative flux, which varies only slightly around a value of 1, is mapped onto a frequency range of 20880 Hz. The scatter in the relative flux due to measurement uncertainties produces a soft, fluctuating soundscape, evoking a resemblance to "droidspeak."

Beyond the raw data representation, a second sonification explores the global behavior of the transit by extracting the average trend (relative flux) from the sonified data. Instead of directly sonifying the model fit curve, this process involves applying audio processing techniques—using networks of allpass and comb delay filters controlled by a mix parameter—to smooth the scatter and emphasize the broader frequency pattern. The result is a dense, "stellar wind"-like soundscape, which abstracts the fit model from the data without visually or manually plotting it.

† https://exoplanetarchive.ipac.caltech.edu

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These two sonifications illustrate key insights: (1) audio-based approaches can replicate data visualization techniques such as fitting and smoothing, and (2) diverse soundscapes can be derived from the same dataset, depending on the method of sonification. These results demonstrate the potential of sonification not only as a tool for data analysis but also as a means of presenting scientific findings in novel and engaging formats.

2.2. *Multi-Dimensional Sonification of Stellar Evolution: Data Mapping, Metaphors, and Audience Engagement*

This example consists of a series of sonifications illustrating stellar evolution, providing an auditory representation of the Hertzsprung-Russell (HR) diagram. These sonifications depict variations in stellar luminosity and temperature throughout a star's lifetime as a function of its initial mass. The underlying data were obtained from Schaller et al. (1992). To isolate the effects of luminosity and temperature, the metallicity of all models was fixed at solar (0.02 $Z_{\odot}$). Several key stellar masses were selected to highlight the diverse evolutionary paths of stars: 1.25 $M_{\odot}$, 5 $M_{\odot}$, 20 $M_{\odot}$, 60 $M_{\odot}$, and 85 $M_{\odot}$. Each mass corresponds to a dedicated audiovisual representation.

In the visual dimension, the logarithm of temperature (inverted to align with the conventional HR diagram orientation, where temperature decreases from left to right) is plotted along the horizontal axis, while the logarithm of luminosity is represented on the vertical axis. The full evolutionary track is displayed from the beginning, with a schematic representation of a star positioned at its starting point. As the simulation progresses, the star moves along its evolutionary track. A label in the upper left corner indicates the current age in millions of years, updating dynamically as the star evolves.

In the auditory dimension, luminosity is mapped to pitch, with more luminous stars producing higher frequencies, while temperature is represented through vibrato rate—hotter stars exhibit a faster vibrato†. This mapping is intended to be intuitive, as increased temperature is often associated with heightened activity and vibrations, analogous to phenomena such as molecular motion in heated substances. Unlike the previous case, where sonifications were more discrete, this version features a continuous audio stream, ensuring a smooth progression of the stellar evolution. A bell chime, struck at regular intervals proportional to the star's lifespan, marks the passage of time. These mappings and auditory cues are briefly explained at the beginning of each video, and as in previous cases, the total duration of the sonifications is approximately 20 seconds.

For stars that end their evolution in a supernova explosion, the event is represented both visually, through an animated illustration, and aurally, using an explosion sound effect.

This example is particularly suited for high-level outreach and educational contexts, including advanced public audiences and undergraduate students, as it presents characteristic stellar evolution cases that could be used in a classroom setting. An additional advantage of this approach is the use of multidimensional parameter mapping to convey multiple variables simultaneously. Specifically, this case exemplifies multidimensional sonifications, integrating multiple auditory techniques: (i) multi-parameter mapping (luminosity-frequency, temperature-vibrato), (ii) auditory icons (e.g., the supernova explosion), and (iii) earcons (e.g., the time-marking bell chime). While the complexity of the auditory dimension remains moderate, testing has demonstrated its effectiveness for general audiences. Although pitch is commonly paired with timbre and loudness in multi-parameter sonifications, certain acoustic variables—such as loudness—do not always provide a sufficiently high dynamic range within a comfortable listening zone when

† Vibrato rate refers to the speed of pitch modulation, while the amplitude of the vibrato is kept constant in all cases.

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used in conjunction with pitch. In this implementation, vibrato has proven particularly effective due to its strong perceptual discriminability.

Conceptual metaphors play a significant role in shaping our understanding of scientific theories and can be leveraged to create intuitive sonifications by associating data properties with culturally familiar sound metaphors Vogt & Höldrich (2010). Typically, sonifications employ physical metaphors that maintain a direct resemblance to the physical processes they represent. In this example, beyond the vibrato-temperature mapping (which draws on the physical metaphor of molecular vibration and heat), we have also incorporated a more narrative-based approach. Specifically, as the star ages, its sound is designed to "age" as well, metaphorically "speaking" like an elderly character. The final stage of the star's life cycle is represented with an exaggerated vibrato akin to the quavering voice of an elderly person, reminiscent of how aging characters are portrayed in animated cartoons. This approach shifts from a purely physical metaphor to a more socially and emotionally resonant one. Testing across different audiences has revealed that this alternative metaphor elicits a distinct, often amused reaction from listeners. In particular, the later stages of evolution—such as those of the 20 $M_{\odot}$ case†—feature prolonged periods at lower temperatures, resulting in a slower vibrato. The contrast between the rapid vibrato of a young, hot star and the slow, sustained vibrato of an aging star often provokes smiles or even laughter from the audience when presented effectively.

3. Reflections on Sonification: Emotional Impact and Cultural Inclusivity

In the preceding sections, we have highlighted the emotional power of sonifications in conveying complex astronomical data. A key takeaway from our discussion is the significant role that the audience and environmental setup play in shaping the emotional response to these sonifications. Different soundscapes, such as the contrasting "droid-speak" and the darker "stellar wind," evoke varied emotional reactions. While the lighter, more playful soundscape is likely to resonate with younger listeners, the deeper and more intense "stellar wind" soundscape aligns more with mature or artistically inclined audiences. The venue's lighting and ambiance can enhance these responses, emphasizing the importance of considering both auditory and visual factors when designing these experiences.

Moreover, this highlights the need for a more nuanced understanding of how audiences from different backgrounds or with different levels of familiarity with complex sonic material might engage with sonifications. Just as graphs and figures in scientific papers require context and interpretation, so too do sonifications, particularly when they become more intricate. A single listening may not suffice to fully decode the information embedded in a sonification; as with visual data, repeated engagement may be necessary. This underscores the importance of providing context, detailed explanations, and the opportunity for multiple listens to ensure that complex sonifications can be properly interpreted.

As sonification continues to develop and find applications in both scientific and artistic contexts, we also observe that many of the current sonifications tend to be shaped by Western musical traditions or darker, more mysterious soundscapes. While these can be exciting and engaging, they do not necessarily reflect the wide array of cultural aesthetics and musical traditions that exist around the world. This is particularly relevant when considering the potential of sonifications in outreach and educational contexts, where inclusivity should be a key consideration. Different cultural backgrounds bring diverse approaches to rhythm, melody, and timbre, which could enhance the emotional impact and depth of sonifications, providing listeners with a broader spectrum of experiences.

† https://www.youtube.com/watch?v=77r1BquKEvQ

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Furthermore, the growing field of sonification may benefit from more formalized ear training at various educational levels. Just as visual literacy is cultivated from a young age to interpret increasingly complex data plots, auditory literacy could be developed to help individuals interpret complex sonic data more intuitively. Such training does not require formal music education, but rather a general development of skills to process and interpret auditory information, fostering a more informed and engaged audience.

In conclusion, sonification holds great promise for the future, not only as a tool for scientific analysis but also as a medium for emotional and cultural expression. The field's evolution will require us to embrace diverse cultural aesthetics and prepare future listeners through both contextual understanding and ear training. By doing so, we can unlock the full potential of sonification, creating richer, more inclusive experiences that resonate with a broader audience and deepen our understanding of the universe.

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