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A multimodal approach to data analysis in astronomy: SONOUNO applications in photometry and spectroscopy

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ABSTRACT

In the past decade, multimodal data analysis has gained importance, especially for including individuals with visual impairments in education and science dissemination. However, its application in scientific research is still limited due to a lack of conclusive evidence on its robustness and performance. Various sonification tools have been developed, including XSONIFY, STARSOUND, STRAUSS, and SONOUNO, which aim to enhance accessibility for both sighted and visually impaired users. This contribution presents SONOUNO (a data visualization and sonification tool) using data, and comparing to corresponding visuals displays, from established data bases like SDSS, ASAS-SN, and Project Clea for astronomical data. We show that SONOUNO is able to replicate the visual data displays and provide consistent auditory representations. Key features include marking absorption and emission lines (in both visual and sonification) and multicolumn sonification, which facilitates spectral comparisons through sound. This approach ensures consistency between visual and auditory data, making multimodal displays more viable for use in research, enabling greater inclusion in astronomical investigation. The study suggests that SONOUNO could be broadly adopted in scientific research and used to develop multimodal training courses and improve data analysis methods.

Key words: Multimodal Data Analysys – Sonification – SONOUNO software – User Center Design – Algorithms – Multimodal Astronomy.

1 INTRODUCTION

Human beings by nature explore the world through all their senses, however, for scientific research, education, and outreach most of the representations are visual: images, plots, and graphical representation of the data. This is the case, even in astronomy, where most of the data are outside the visible range, and, evidence is found about the benefits of auditory display as a complement to visual display (Díaz-Merced 2013).

The use of sound/audio in astronomy has existed for years; some examples are: the zCOSMOS astronomical data set sonification, where the authors describe the data set and the sonification strategy used (Bardelli et al. 2021); LightSound, an electronic device that converts light into sound, created to observe eclipses (Bieryla, Hyman & Davis 2020); a sound platform built in collaboration with the ATLAS Outreach team and a website that allows the general public to listen to experiments in real time (Cherston et al. 2016); the Quasar spectroscopy sound, a resource which proposes using sound to enhance the exploration of the intergalactic medium and the circumgalactic mediums developed by Hansen, Burchett & Forbes (2020); a project with the refunctionalization of two cosmic particle accelerators where the use of auditory display in conjunction with visual display was described, the objective was to make the discoveries more accessible, the sound was made with musical characteristics and developed specifically for this case study (Ohm et al. 2021); Quinton, McGregor & Benyon (2021) describes a sonification design for planetary orbits in asteroid belts. In the majority of cases, the mapping carried out to obtain the sonification of the data set is defined by its creator and shared as a final product.

Between all the different projects, groups, and sonification techniques, some works by visually impaired people arise. Diaz-Merced et al. (2011) describes a study of the EX Hya light curve and Solar Wind using XSONIFY. In the article, the authors describe the software as well as how to interpret the data using sonification. Moreover, Foran, Cooke & Hannam (2022) manifests how he continues working as a researcher using the software STARSOUND and VOXMAGELLAN. They explain the use of STARSOUND to sonify high-redshift galaxy data and the Deeper, Wider, Faster (DWF) program. For more complex data, for example, a scatter plot that contains galaxies dispersed in colour (one axis) and magnitude (another axis), they used VoxMagellan with a parameter sonification that represents the different parameters. These examples reinforce that sonification could be used to research and generate inclusion in the field; however, it is a challenge for the technique to be universally adopted.

Devoted to sonification in general, since its creation in 1992, the purpose of the International Conference on Auditory Display (ICAD) has been to bring together multidisciplinary experts working in the field of sonification. This conference presents a repository where there is a large number of works that Andreopoulou & Goudarzi (2021) grouped into six categories: sonification methods, sonification tools/systems, review/opinion studies, exploratory studies, perception/evaluation studies, and others. This systematic review of the

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ICAD repository highlights a high percentage of articles dedicated to sonification methods and tools, in contrast to a low percentage concerned with design methodologies, perception studies, evaluation methods, and astronomical data analysis using this technique. It is alarming that perception studies showed growth between 2005 and 2009, but decreased below 1 per cent by 2019, even when Ferguson & Brewster (2017) pointed out the importance of perception studies in auditory displays and reported some psychoacoustic parameters mentioning how people perceive the sound. These works were complemented recently by Fitzpatrick & Neff (2023), where the study of the full text of the ICAD proceeding from 2017 to 2022 was done; concluding that the keyword 'perception' presents a low rate of use: six times less than 'auditory', three times less than 'display', and two times less than 'music'.

The novelty of the technique and its low case of use inside the research field, raise concerns about whether the technique may be biased. Supper (2014) describes the difference between visual and audio displays and how both are perceived in terms of the immersive and emotional environment. Along the same lines, Neuhoff (2019) raises the challenge of sound versus visualization at a perceptual level, pointing out the high percentage of works that use the word 'music' when talking about sound for data deployment [remember the rates of Fitzpatrick & Neff (2023)]. These concerns, added to the lack of perception studies to understand if the brain perceives the same concept by sonification and visualization, complicates a broad use of sonification in scientific environments. This reinforces the need for robust software, accessible to functional diverse people, to support future perception studies.

Remarkably, a work by Tucker Brown et al. (2022) uses the software ASTRONIFY (see Section2) to study light curves. They describe the sonification process, how some sample data were made, and the process of testing with participants. The participants had no experience with sonification, and the results showed that experts perform better with plots; on the other hand, experts and non-experts present no difference using sonification. The last may reinforce the lack of training in this technique that both groups present. Now using STRAUSS (see Section2), last year Trayford et al. (2023) presented the use of spectra sonification to evaluate if participants could rate (A) variation in SNR, (B) variation in emission-line width, and (C) variation in emission-line flux ratio. Under 58 respondents, the ratings present a relevant correlation with the physical properties presented. The authors express that, given the minimal training and small sample, these are very promising results.

The last investigations focused on using sonification and testing its efficiency, emphasize the importance and needs of investigations centred on sonification as a technique that could complement the current display of astronomical data. In addition, it is important to have a tool that allows this technique to be carried out autonomously by people with and without disabilities.

This work explores the sound model of the SONOUNO software, which aims to provide an open-source platform that allows users to open different sets of data and explore them through a visual and auditory display (Casado, de la Vega & García 2024). Then, using the SONOUNO library and maintaining its accessibility features, a new update was designed to work with galaxy spectra and stellar data (light curve and spectra). This contribution demonstrates the data visualization achieved in conjunction with sonification techniques in astronomy, taking into account the availability of open data in very well-known data bases. In addition, new features such as peak detection and spectra comparison through sonification were presented. These applications in the field of astronomy aim to show the possibilities of development proposed by research in multimodal astronomy.

2 SONIFICATION TOOLS

Over the past 10 yr, there has been a large increase in the number of projects using sonification to represent astrophysical data. Zanella et al. (2022) showed that 98 sonification projects had been developed since 1962; many of them were discontinued, lacked documentation, or had no evidence of applications in science. The majority of sonification projects, almost 80 per cent, have been carried out between 2011 and 2021. Not all of them share the same objective: some are tools to produce sound through the command line, others have the purpose of offering the user the ability to modify the sound configurations to achieve a sound system that fits their needs, and others prioritize the development of an accessible graphical interface.

One of the tools analysed in 2017 at the beginning of the development of SONOUNO was XSONIFY. This program was taken as a reference because it presented a development framework focused on the user and inclusion. In addition, the authors had contact with one of its developers. A notable feature was that XSONIFY allowed the sonification of multiple columns, varying the instrument between each column to be sonified. Furthermore, at that time, it was one of the few open-source tools that could be used with a screen reader.

StarSound is a program that began its development at the same time as SONOUNO, contact has been maintained with its developers. Its graphical user interface (GUI) allows the configuration of the sound process in detail, similar to a sound equalizer. An accessibility feature they added was the ability to modify all parameters using a text file for people with visual disabilities. Subsequently, to provide sonification for more complex graphics and images, VOXMAGELAN was created, a software with a GUI that allows scatter plots to be imported and provides sound for the region where the pointer is located, allowing the plot to be spatially explored by sonification (Foran et al. 2022).

Concerning STRAUSS, it is a Python package, open source, and available on GitHub[1] (Trayford & Harrison 2023). It has been developed with the aim of improving the current visual display of data and accessibility. It presents the possibility of being used by people without knowledge of sound or programming, through predefined examples and using the default configurations. However, it offers documentation that allows its use at a more advanced level, allowing modification of the sound parameters. A direct application of this development is in the 'Audio Universe' project, in which they have recently published a tour of the solar system (Harrison et al. 2021).

Some other Python packages devoted to data sonification are SONI-PY[2] (Patton & Levesque 2021), ASTRONIFY[3], and SONISCOPE.[4] These three could be used in a Python environment, a tool widely used to analyse data sets. SONI-PY and ASTRONIFY were developed and used with light curves, but they are not limited to them. About SONISCOPE, its sonify regions pointed out with the mouse on a scatter plot (Enge et al. 2022). Something remarkable about ASTRONIFY is the game they offer with its documentation, it has two levels and presents different characteristics of a light curve; this is the first tool presenting something comparable with a training task.

Now migrating to developments with a graphical web interface exists: HIGHCHARTS SONIFICATION STUDIO,[5] AFTERGLOW ACCESS

[1]STRAUSS: https://github.com/james-trayford/strauss
[2]Soni-py: https://github.com/lockepatton/sonipy
[3]ASTRONIFY: https://github.com/spacetelescope/astronify
[4]SONISCOPE: https://github.com/fhstp/soniscope-jupyter
[5]HIGHCHARTS: https://sonification.highcharts.com/

(AGA),[6] and SONOUNO.[7] The first is a software developed with four objectives as a guide (Kondak et al. 2017): (1) maximize accessibility; (2) easy tool for beginners without reducing its high performance; (3) maximize portability; and (4) maximize its utility. Cantrell, Walker & Moseng (2021) describes the joint work between Highsoft and the Georgia Tech Sonification Lab to develop the tool. Notably, HIGHCHARTS SONIFICATION STUDIO is based on almost 20 yr of experience in sonification by the Georgia Tech Sonification Lab and the previous development of the Sonification Sandbox software (Davison & Walker 2007). Particularly, HIGHCHARTS SONIFICATION STUDIO has two tabs, one for the data and another that contains all the control elements over the visualization and sound.

AGA, using a different initial approach, presents as its main objective the analysis of astronomical images through sonification. The tool was developed by a multidisciplinary team (high school students, undergraduate students, astronomers, software engineers, and educational researchers, among others) and included people with and without visual disabilities. Meredith et al. (2020) describes the process carried out to achieve a user-centred tool. Some of the techniques used were role models, exercises with questions such as 'What?-If' in search of a creative flow of ideas, and direct or indirect contact through GitHub between users, designers, and developers, among others. This marks a clear and published precedent, in the field of astronomy, about the need and importance of user-centred design to create useful, usable, and efficient tools for data sonification.

As for the SONOUNO program, which is described and used in this contribution, it is a software proposed, initially, for astronomical and astrophysical data sonification, focused on the user from the beginning. It has a desktop version (currently available) with a graphical interface tested by people with and without disabilities (Casado et al. 2022a) that allows to open tables with two or more columns, display the graph, and allow sonification (Casado et al. 2024).

At the beginning of SONOUNO development, a theoretical framework focused on accessibility was developed with Dr. Díaz Merced. The analysis includes a literature review and ISO standards evaluation (Casado et al. 2022b), given as a result the graphical user interface of SONOUNO desktop and a document with accessibility recommendations.[8] Then, the prototype was tested following a focus group methodology at Southampton University with nine participants, where fifth of them were visually impaired. The results found that sonification could significantly enhance data analysis for functionally diverse researchers. They highlighted the importance of designing tools that enable autonomy and adaptability to meet diverse research objectives (Casado et al. 2022a).

In 2019, the development of a web interface (De La Vega et al. 2022a) with similar functionalities to the desktop version began. This web version follows the same principles, its accessibility with screen readers was tested and counted with several user cases. During The Audible Universe 2 workshop, this version was evaluated by experts during a sonification software evaluation task (Misdariis et al. 2023), they define SONOUNO web as: 'An online tool, or standalone user interface. Suitable for 1D data, such as light curves and spectra. Primarily for scientific analyses and education (add. accessibility focus)'. From these tests during the workshop, some problems with the SONOUNO web Graphic User Interface (GUI) arose, like a lack of functionality on the slide bar to select the minimum and maximum frequency. Then, during a degree thesis in 2023 (Olivera 2023) a user experience evaluation of the SONOUNO web was made. A Focus Group and interviews were conducted with nine participants. The principal result was a new web interface design that is being implemented.

Taking into account the programs presented, very few are focused on the user or have a graphic interface that allows controlling the sound production process and, at the same time, the visualization of data. Of those that meet this requirement and are applicable in the field of astronomy and astrophysics, only four (SONOUNO, AGA, STARSOUND/VOXMAGELAN, and XSONIFY) have included people with visual disabilities in the design. Refining the detail a little more, only one tool besides SONOUNO (AGA) has exchanged with users during its development, and it only has a web version.

3 SONOUNO VISUAL DEPLOYMENT AND SOUND SYNTHESIS

The SONOUNO framework was developed from the beginning to ensure simple access to information for blind and non-blind people. According to that, the deployment of all the tools is made on the same screen, without pop-up windows. The organization of the functionalities (plot, sound, mathematical, and IO functions) are located on different panels, which can be manipulated (hidden or shown) to simplify the display as the user desires. The possibility of using screen readers and shortcut keys improves access; these characteristics are tested after each update.

As the software was conceived as a tool for multimodal analysis of data, it is not only for sonification, and because of that, the graphical output was also important during the development. Indeed, the synchronization of the visual and sound display is very important, a lot of work and development was done to ensure that.

In addition, the peak detection feature is presented in this section, allowing the visualization and sonification of the positions of absorption and emission lines in absorption and emission lines of galaxy spectra. Closing this section, the use of the SONOUNO libraries in bash is presented with a focus on two scripts developed concerning this contribution.

3.1 Graphical tool

MATPLOTLIB[9] is used to produce the plots. This Python library is widely used in astronomy and other science in general. Only as a reference, Schmidt & Völschow (2021) describes the visual data analysis in their book with MATPLOTLIB. In addition, during the focus group and exchange with expert SONOUNO users, most of them expressed that they use this library for data representation. MATPLOTLIB is very versatile, allowing it to produce almost any kind of plot.

The integration of MATPLOTLIB with the graphic user interface (GUI) using WXPYTHON was relatively easy and several examples exist online. The hard part was the synchronization between the position marker on the plot and the reproduced sound for the SONOUNO. To solve that, the event function of WXPYTHON is used; this functionality is associated with a timer, something that runs automatically every predefined period. After some tests and taking into account the time of sound reproduction and GUI behaviour, the

[6] AFTERGLOW ACCESS: https://idataproject.org/resources/
[7] SONOUNO: https://dev.sonouno.org.ar/en-US/
[8] Accessibility recommendations: https://www.sonouno.org.ar/wp-content/uploads/sites/9/2021/07/Recommendations-accessible-HCI-design-2021.pdf
[9] Matplotlib: https://matplotlib.org/

minimum time to call the new event was between 50 and 100 ms (it depends on the computer's characteristics too). The consequence was that for a large amount of data, the reproduction time in the GUI was very high; for example, using equation (1) for a galaxy spectrum with around 3800 rows and a time between notes of 50 ms, the time is 3.2 min[10] (see equation 2).

$$\text{rep\_time} = \left(\frac{\text{rows} * \text{time\_between\_points}}{1000}\right) \Big/ 60 \tag{1}$$

$$\text{rep\_time} = \left(\frac{3840 * 50\,\text{ms}}{1000}\right) \Big/ 60 = 3.2\,\text{min}. \tag{2}$$

Despite the long durations of the sonifications obtained, SONOUNO prioritizes the synchronization of the plot and sound to create a multimodal display, making the reproduction note by note. The group is investigating a way to accelerate the process without compromising the synchronization using an open-source language like Python.

Another big challenge of the development was integrating around six groups of functionalities in the same GUI without pop-up windows. Casado et al. (2022a) explains the user centre design of SONOUNO and the theoretical framework used to organize the GUI. First, all the functionalities were grouped by similarity following four casual parameters defined by Casado, García & Díaz-Merced (2019). In consequence, the four groups of SONOUNO functionalities were: Data display, Data operation, Data configurations, and I/O options. With the groups, four principal panels were programmed with the possibility of showing or hiding them, as needed. The result was a clean first GUI, where only the plot and reproduction options are visible, reducing the memory overload, and better interaction with screen readers. Then, the user could open other panels from the menu bar or shortcut keys. Finally, all the functionalities are presented in the same windows, avoiding losing the keyboard focus by screen reader users.

3.2 Sonification

The sonification process is based on translating certain parameters or information into non-speech audio. This definition also includes the so-called auditory icons and earcons. For this work, only reference will be made to the conversion of information from numerical tables of two or more columns related to astronomy (particularly the spectra of galaxies and variable stars). Until now, it has been taken as a convention to relate the independent variable (which is graphed on the x-axis when performing a visualization) with the sonification time, which means that each data point is translated into sound one after the other, ordered and sequentially. The dependent variable (which is located on the y-axis when performing a visualization) is generally related to frequency, which allows increasing or decreasing changes in the data to be related to the increase or decrease of the sound frequency.

Following the described process, SONOUNO generates the waveform of the sound using the sine function or *scipy.signal* library of Python. By default, and to perform the sonifications in this work, the sine and square waveforms are used. In this sonification process, three parameters can be varied, consequently modifying the sound generated. Take in consideration that SONOUNO generates each note of the sound corresponding to each point on the data set. Particularly, the square waveform is generated using the scipy.signal library using the same parameters configuration (frequency, amplitude, and time). On the other hand, the flute waveform is generated from a sine function with the corresponding harmonics calculated from a spectral analysis of a real instrument.

The duration of each point sonification is related to the reproduction but not directly connected, to maintain the synchronicity between the plot and the sound, this duration is proportional to the minimum time between the GUI events (see Section3.1). On the other hand, variations of frequency and amplitude produce changes in the pitch and volume of the sound, respectively. SONOUNO allows one to select between these two variables to relate to the y-axis of the data plotted.

To start the sonification process, independently of the parameter adopted to sonify the y-axis, 'min-max normalization' is used following equation (3)(X refers to the array to be sonified) to bring all the values contained in the dependent column between 0 and 1. This makes it possible to map the information of the celestial object in frequency [$f = f_{\min} + (f_{\max} - f_{\min}) * X'$] or volume [$V = V_{\min} + (V_{\max} - V_{\min}) * X'$]. The link to some audio examples will be included in Section4 and could be found on the SONOUNO gallery[11] too.

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}. \tag{3}$$

It is noteworthy that the scripts presented in this contribution allow users to adjust the sonification parameters to suit their needs. Specifically, to produce the example files offered here, the following parameters were used: minimum frequency = 380 Hz; maximum frequency = 800 Hz; first waveform choice 'sine'; second waveform choice: 'square' for galaxy spectra and light curves, or 'flute' for star spectra.

3.3 Feature detection

The focus of SONOUNO is to display any data set in an effective and accessible way. However, with its use, the need to add special functionalities for data analysis has become evident, and it is part of the permanent improvement of the development. One of these new tools is the detection of peaks in the data.

The first approach to detection was implemented in the SONOUNO web interface; the two versions of the software (desktop and web) maintain the same theoretical framework and similar functions but, at the moment, do not share the same programming language (De La Vega et al. 2022b). For this, the translation of the 'peak finder' function implemented in SONOUNO web to Python was needed.

This tool receives the data table and returns an array with the positions where possible emission and/or absorption lines were detected. To search for the peaks, first, a medium line is calculated, taking all the data in the 'y' column; then, a sensitivity percentage given by the user is defined to construct a gap from the medium line, up and down; and finally, the coordinates of the maximum or minimum value found above and below this gap are stored.

The determined coordinates of the peaks are plotted in the graph together with the data. In addition, a csv file with the x-y coordinates of the peaks could be saved. This function is useful for chemical element identification (see Figs 2 and 4).

3.4 Use of the SONOUNO libraries in bash

Responding to a general request from users, a bash script was developed to improve the speed and efficiency of the data-sonification

[10] Next video shows the 3.2 minutes sonification of a galaxy spectrum: https://youtu.be/1thvhJOx4jY

[11] sonoUno gallery: https://www.sonouno.org.ar/gallery-index/

process. The first approach involved searching for all CSV or TXT files in a specific directory (with the location passed as an argument by the user) and then saving the sound and plot (if requested) relating to the first two data columns of each file, in the same folder.

The first approach shows its efficiency in producing the sonification of a lot of data sets, to then perform the analysis. The audio total time is shorter because there is no need to attend the GUI; in addition, this sonification could be accelerated externally too. Nevertheless, not all data types are equal, the general process is the same but some adjustments needed to be made between the spectrum Galaxy, the image, the phase diagram of a variable star, and spectral star classification sonification.

In this sense, three scripts were created in the framework of this contribution to process the galaxy spectrum data, the light curves, and the star spectral classification. Concerning the galaxy spectra, peak detection and multicolumn sonification were used. About the light curves, a previous script was updated to reach the same plot display on the data base and simultaneous sonification was used to represent the data from different cameras. Finally, the star spectral classification was presented using simultaneous sonification as a tool, showing the potential of this technique to compare equal or different features on the signal. In Section 4, results obtained from these scripts, with its own repositories, will be shown.

4 EXAMPLE DATA REPRESENTATIONS

The previous section details the visualization and sonification techniques employed to translate data into multimodal displays. In this section, the potentiality and results of using SONOUNO scripts with open data is presented. This software is a versatile tool, open source, developed in Python, and with a user-centred design from the beginning (Casado et al. 2024).

The primary objectives of this analysis is to demonstrate the possibilities of the data visualization in SONOUNO, in conjunction with sonification techniques in astronomy, taking into account the availability of open data in very well-known data bases such as Sloan Digital Sky Survey (SDSS)[12] for galaxies. All-Sky Automated Survey for Supernovae (ASAS-SN)[13] for variable stars, and data of spectroscopic standard stars. Our first choice was spectroscopic and photometric data because of the good SNR relationship in the features, such as emission and absorption lines, and brightness variability.

Two random examples were chosen in each case to illustrate SONOUNO's data representations and diverse features. In all the cases presented the data set used was downloaded from the data base and opened with the SONOUNO script. Therefore, any data downloaded from these data bases can be displayed with this tool. This makes the code versatile and adaptable for use with any data set downloaded, while respecting the specific data type under study.

4.1 Galaxies

The SDSS data base has an extensive number of images, spectroscopy in the visible range, and spectroscopy in the infrared, among others. These data have been obtained mainly by the project's telescope located at the Apache Point observatory, New Mexico, United States ('Sloan Foundation 2.5 m Telescope'); in the last stages, it has included the 'Irénée du Pont Telescope' located at the Atacama region in the Andes mountain range, Chile, thus obtaining images of the southern hemisphere.

[12]SDSS: https://cas.sdss.org/dr18/
[13]ASAS-SN: https://asas-sn.osu.edu/variables

Figure 1. Barred spiral galaxy image extracted from the SDSS data base.

Regarding accessibility, although the SDSS website has been improved and modified over the years, use with screen readers continues to be an issue for improvement. The interface elements in the SDSS website are better described for screen readers in the last update, however, the discourse presented by NVDA for example continues to lack order and meaning. In some cases, things are presented in reverse and there are still elements that are difficult or impossible to access with screen readers.

As for the data file, when downloading the galaxy spectrum, it contains four columns: the first corresponds to the wavelength, which will be used as the abscissa coordinate (in the case of this data the wavelength range is that of the visible spectrum); the second corresponds to the flux, which represents the amount of light that reaches the instrument at each wavelength; the third is the same flux but a smoothing filter has been applied to reduce the noise; and the fourth is the light intensity of the sky at each wavelength, it presents background information that is perceived in all observations and includes the atmospheric effect.

4.1.1 *Object SDSS J115537.98-004614.2*

The Object SDSS J115537.98-004614.2 is a barred spiral galaxy.[14] Fig. 1 shows an image of this object captured from the SDSS data base[15] that could be appreciated from the Visual Tool Navigate. Using an image sonification script developed as part of the SONOUNO project (Casado & García 2024) the image of the galaxy could be sonified.[16] The image sonification was performed taking in consideration the average brightness of each column and compared to the average of the image total brightness.

The object page on the data base contains a link to download the spectrum as CSV, which can be opened with SONOUNO to display

[14]Barred spiral galaxy database link: https://skyserver.sdss.org/dr17/VisualTools/quickobj?objId=1237674649391333465
[15]Barred spiral image: https://skyserver.sdss.org/dr17/VisualTools/navi?ra=178.908277828839&dec=-0.77061784547085&scale=0.2
[16]Barred spiral image sonification video: https://youtu.be/3CC2Jl0Vw9U

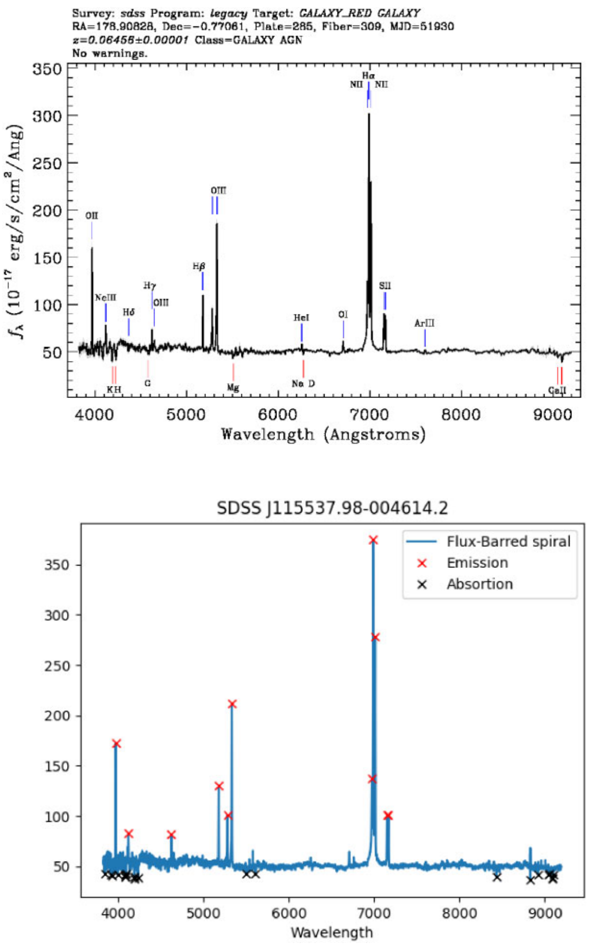

Figure 2. Barred spiral galaxy flux versus wavelength plot, top from the data base and bottom from SONOUNO, with peak detection.

Figure 3. Double nucleus galaxy image extracted from the SDSS data base.

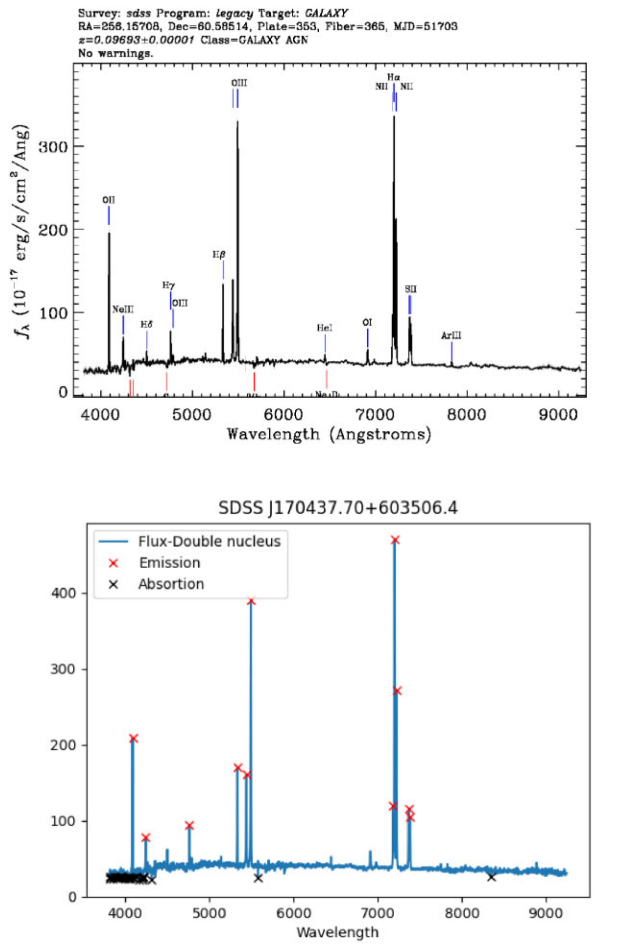

Figure 4. Double nucleus galaxy flux versus wavelength plot, top from the data base and bottom from SONOUNO, with peak detection.

the plot and sonification with the marks also sonified.[17] To be able to compare the SONOUNO display, a combination of the spectrum obtained from the data base and that plotted by SONOUNO is shown in Fig. 2. It could be appreciated that the plots exhibit the same absorption and emission lines.

4.1.2 Object SDSS J170437.70+603506.4

The Object SDSS J170437.70+603506.4 is a double nucleus galaxy.[18] Fig. 3 shows an image of this object captured from the SDSS data base.[19] Using the same image sonification script mentioned above the image sonification could be generated.[20]

Moreover, the CSV downloaded from the data base was opened in SONOUNO to produce the plot and sonification.[21] Repeatedly, to be

[17] Barred spiral galaxy spectrum sonification: https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/SDSS-J115537.98-004614.2_soundmarks.wav

[18] Double nucleus galaxy database link: https://skyserver.sdss.org/dr17/VisualTools/quickobj?objId=1237651225171197972

[19] Double nucleus image: https://skyserver.sdss.org/dr17/VisualTools/navi?ra=256.157116458609&dec=60.5851296110757&scale=0.2

[20] Double nucleus image sonification video: https://youtu.be/uDPWlBCzAXk

[21] Double nucleus galaxy spectrum sonification: https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/SDSS-J170437.70603506.4_soundmarks.wav

able to compare, Fig. 4 shows the spectrum obtained from the data base first, and then the spectrum saved from SONOUNO software. As with the previous galaxy, the plots exhibit the same absorption and emission lines.

4.1.3 *Comparison of two galaxies spectrum*

A common practice is to compare two or more spectrums between them, something that is not common to do by sonification yet. However, it is known that the human brain can distinguish between a few sounds coming from different sources at the same time, being able to discriminate between information of each one of them. Although from practice we could think that several sounds could be differentiated, it must be remembered that in this case, we are talking about the number of sounds that can be analysed simultaneously.

SONOUNO allows the generation of multicolumn sonification with a particular script (see Fig. 5), it is not integrated on the GUI yet. SONOUNO team opened a GitHub repository with this tool first approach.[22] Some modules of the SONOUNO main repository were used, these are import, export, transformation, and sound modules. So the novelty is the use of two different waveforms to sonify two curves simultaneously.

In this contribution, this tool is used to compare the spectra of the two galaxies presented above (Sections 4.1.1 and 4.1.2).[23] The waveforms used were 'sine' and 'square'; one important future work in SONOUNO is to increase the available timbres in its sound library.

Although this first approximation was achieved, it has not yet been formally presented within the SONOUNO functionalities due to two reasons: (1) to include it in the actual GUI a new design must be made to include the configuration of parameters for each of the graphs, with their consequent user testing; (2) perception and training studies must be deepened to better understand how the human ear and brain interpret this type of sound.

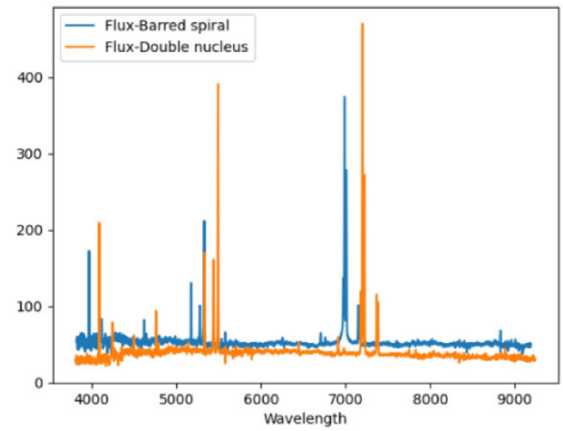

Figure 5. Image obtained from SONOUNO script with the spectrum of the two galaxies presented here in the same display.

4.2 Stars

4.2.1 *Variable stars phase diagram*

Variable stars have the characteristic that their brightness varies over time, which may be due to characteristics of the star (intrinsic, such as pulsating, eruptive, or cataclysmic variables) or external characteristics (extrinsic, such as eclipsing ones). In the case of this work, a Cepheid and an eclipsing binary were shown. The Cepheid is a pulsating intrinsic variable star, its period is proportional to its luminosity. The other is an eclipsing extrinsic variable star, the plane of their orbit coincides with the observation direction, so one star is observed passing in front of the other producing eclipses (the instrument observes a decrease in the amount of received light).

The 'All-Sky Automated Survey for Supernovae'[24] (ASAS-SN) data base contains information on freely accessible variable stars, where a table format file ('csv' extension) with the particular observation data of the star could be downloaded. From this data base, the following variable stars were selected to sonify with SONOUNO:

(i) Cepheid: ASASSN-V J000059.21+605732.5/CG Cas.[25]
(ii) Eclipsing Binary: ASASSN-V J003016.19-462759.5/RW Phe.[26]

One detail to keep in mind with the data obtained from the variable stars mentioned is that they do not directly have a column with the phase values, because there are different ways to obtain these phase values depending on what you want to plot. In the case of this work, equation (4) was used to calculate the phase, taking into account the epoch based on the 'Heliocentric Julian Date' indicated by the same data base ('Epoch (HJD)').

$$\phi = \frac{t - t_0}{P}. \quad (4)$$

Following equation (4), t is the time of each observation in the data file, t_0 is the start time of the observation, and P is the orbital period. Taking in consideration the parameters of each variable star selected, the phase was calculated and used to make the plots shown on Figs 6 (bottom)[27] and 7 (bottom).[28] In that figures could be observed the equivalence between the plot on the data base and that obtained from SONOUNO.

Although the calculus can be carried out externally, to later enter the table into SONOUNO and perform the sonification; here a repository with a script was presented[29] using some SONOUNO modules. This code allows loading into a variable the value of the time and period referring to the data (currently manually in the code) and then indicating by bash the directory where the file to be sonified is located. The script automatically saves the sound in that same folder with the same file name and the appendix '_sound'. Optionally, the user can indicate to save the plot when executing the code, in which case it will also save it in the same folder and with the same name by adding '_plot'. The graphics and sounds presented at the bottom in Figs 6 and 7 were obtained with the script described in this section[29].

[22]SonoUno multicolumn sonification: https://github.com/sonoUnoTeam/sonoUno-multicolumn
[23]Video with the comparison of two galaxy spectrum: https://youtu.be/Naw2q_TNcZc
[24]ASAS-SN database: https://asas-sn.osu.edu/variables
[25]Cepheid database: https://asas-sn.osu.edu/variables/753bdd73-38a7-5e43-b6c0-063292c7f28d
[26]Eclipsing Banary database: https://asas-sn.osu.edu/variables/dfa51488-c6b7-5a03-abd4-df3c28273250
[27]Cepheid sonification: https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/Cepheid_sonouno_bisound.wav
[28]Eclipsing Binary sonification: https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/eclipsante_sonouno_bisound.wav
[29]Lightcurve sonification script: https://github.com/sonoUnoTeam/ASASlightcurve

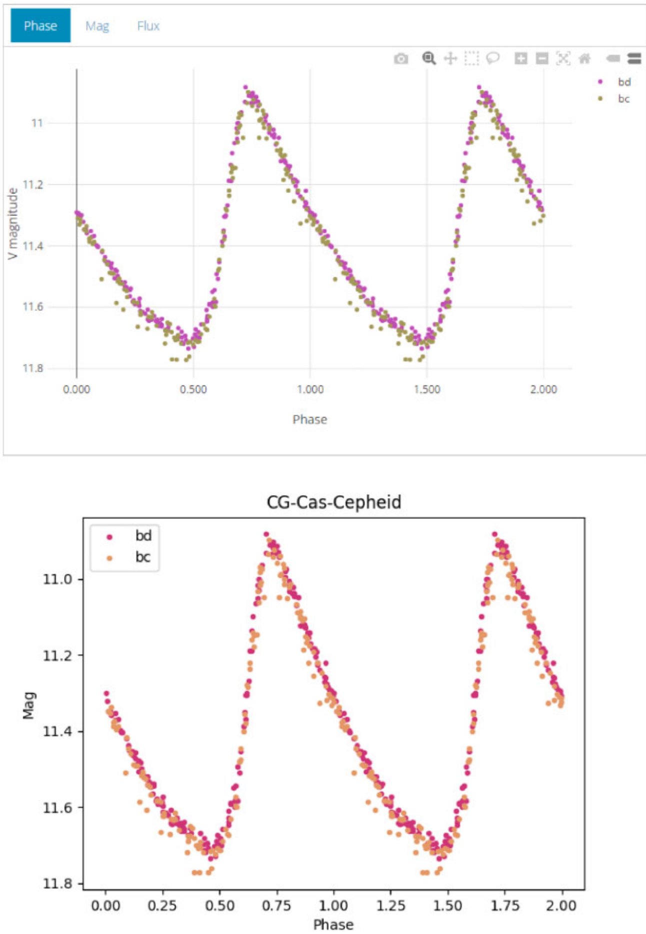

Figure 6. The phase diagram of a Cepheid extracted from the ASAS-SN data base (top). The phase diagram obtained from SONOUNO using the same data set (bottom).

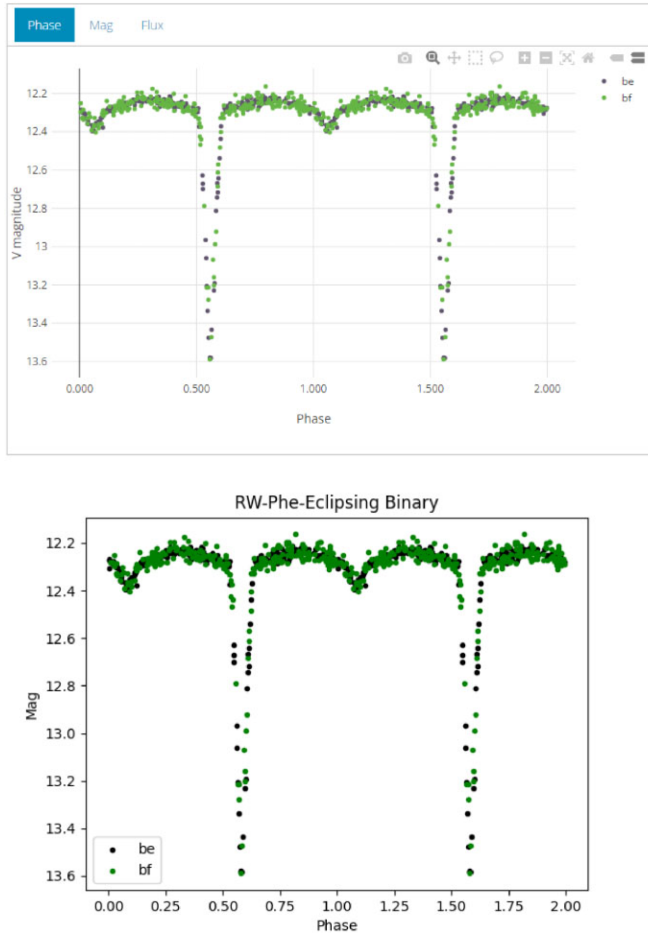

Figure 7. The phase diagram of an eclipsing binary extracted from the ASAS-SN data base (top). The phase diagram obtained from SONOUNO using the same data set (bottom).

4.2.2 Spectral classification

Spectroscopy is a powerful tool used in astrophysics. In general, the spectral classification of stars is performed by visual inspection comparing a spectrum with those corresponding with a standard star. Of course, it is possible to apply algorithms for automatic classification, which provide the results without most of the work done in the past. However, it is interesting to use the traditional methodology to explore the possibilities for classification using sound. If the stellar spectrum to classify has a good signal-to-noise ratio, and as SONOUNO can compare data from more than one column, the classification is simple, but the technique could be particularly useful if we are in the presence of a bad s/n rate, because it has been proved that in these cases, sonification can help to detect features that are not clear (Díaz-Merced 2013).

Some examples of synthetic standard stars spectra are in Fig. 8, taken from Project CLEA[30] of Gettysburg College. The plots and the sound, both produced with SONOUNO,[31] from data taken from the Atlas of Standard Stars of CLEA, are in Fig. 9. Particularly,

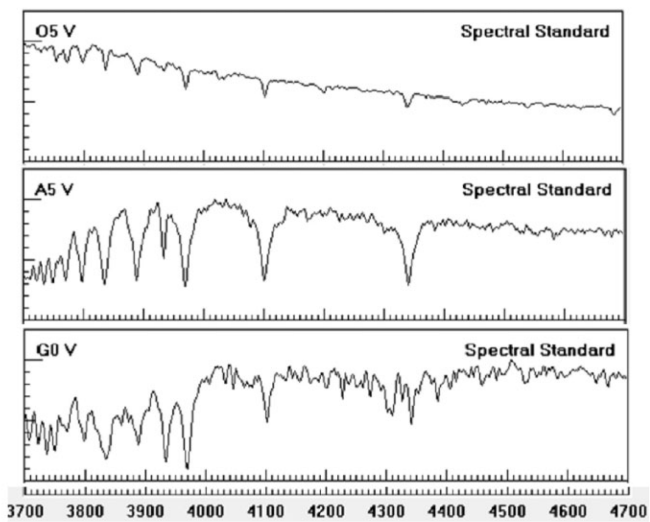

Figure 8. Standard stars spectra for O5V, A5V, and G0V types (Credit: Project CLEA).

[30]Project CLEA: http://public.gettysburg.edu/~marschal/clea/
[31]sonoUno Project CLEA repository: https://github.com/sonoUnoTeam/ProjectCLEA-starspectra

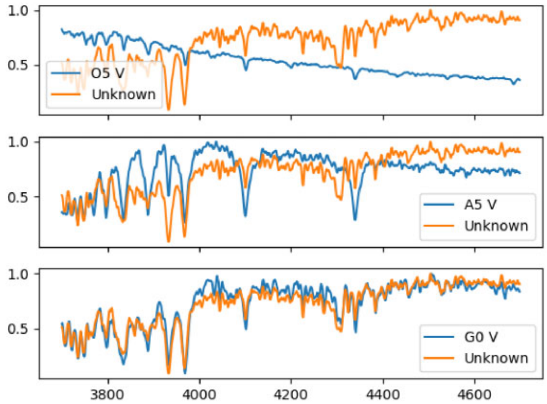

Figure 9. The blue lines sonified with 'sine' waveform represent the standard star spectra for O5V, A5V, and G0V plotted with SONOUNO, comparable with Fig. 8. The signal repeated in the three subplots was from an unknown star to be classified.

the standard data are plotted in blue lines and sonified with a 'sine' waveform.[32]

The classification of stars' spectra was performed using one sound for the standards ('sine' waveform) and another for the unknown spectra ('square' waveform). One example of the classification plot can be found in Fig. 9, then the sound of each classification were generated.[33] The work was done by trained people in stellar classification.

The bash script for spectroscopy in the multicolumn repository was used here. The algorithm receives the path with the unknown spectra and could be configured with three additional parameters: (1) Data file format: as default 'txt'; (2) Plot: a flag to save the plot or not (an example of plot in Fig. 9); (3) Display: a flag to show or not the reproduction with the plot and sonification.[34] Using the display mode OFF, the computer could work hours performing automatically all the images and sonifications to be analysed later.

5 DISCUSSION

The primary objective of this study was to compare the data visualization between SONOUNO and well-known data bases for galaxies, variable stars, and spectroscopic standard stars, with the complement of sonification. Leveraging the availability of open data in each of those data bases, SONOUNO was used to generate the plot and sonification of some galaxies' spectrum (see Section 4.1), some variable star phase diagram (see Section 4.2.1) and some star spectra (see Section 4.2.2). Remarkably, each SONOUNO script presented for each data type could open and reproduce the audiovisual material of any data set downloaded from the data base, following the README file instructions. The results show that SONOUNO achieves the same plot as the data base, accompanied by its sonification.

This application of SONOUNO revealed that it could be used to represent astronomical data in a multimodal way. Notably, for each data type, only minimal adjustments specific to the data visualization technique are needed; this ensures that the sonification and visual representation remain consistent. This is crucial for ensuring the correspondence between the two sensory modalities, which is essential for further studies on perception.

Two key features of SONOUNO presented in this contribution were the peak finder on Python and the possibility of multicolumn sonification. The absorption and emission line identification in the spectra is one of the fundamental topics in astrophysics. Sonification software does not allow these features to be marked in the data. SONOUNO introduces the innovative capability to manually or automatically mark absorption and emission lines (or other significant features in the data), sonify the marks during the data reproduction with another waveform, and save this information to a file (see Figs 2 and 4).

Regarding multicolumn sonification (used for galaxy and star spectra), the adoption of two distinguishable timbres proves to be an effective approach for comparing two spectra through sound. The added value of SONOUNO in this context is that it allows users to perform the entire process within the same script, generating the multicolumn sonification sound file directly. This means there is no need to sonify each data set separately with different timbres and then merge or play them simultaneously.

Additionally, the sonification is generated point by point using the same graphed data, without any additional handling or modification. This ensures that the sonification faithfully represents the graphed scientific data, resulting in a reliable multimodal reproduction of open-access scientific data.

These findings have significant implications for the field of astronomy, particularly in making data analysis more accessible to researchers with visual impairments. The adoption of sonification techniques could lead to more inclusive and diverse research practices.

However, beyond demonstrating that the technique is reliable and versatile, it is necessary for it to be adopted in scientific environments as a complement to visualization. During a focus group published in Casado et al. (2022a), conducted in the United Kingdom in 2019, participants including both sighted and visually impaired individuals, astronomers and non-astronomers, used SONOUNO to open and sonify galaxy spectra. One participant expressed concern about how scientific findings could be exchanged and discussed between a researcher using visualization and another using sonification. Although it is not yet certain that this is possible with current techniques, the use of multimodal displays in research, ensuring that both modalities represent the same patterns and numerical data, brings us closer to this goal.

The findings in this contribution also aim to demonstrate that the use of sonification as a complement to visualization is not merely for outreach purposes but is a technique with significant potential to enrich current displays of astronomical data by improving their accessibility. In this regard, there are already works such as Tucker Brown et al. (2022) and Trayford et al. (2023) that investigate the use of sonification for scientific research with astronomical data. Both works shows promising results, testing sonification with non-trained people. In addition, Fovino, Zanella & Grassi (2024) examined the effectiveness of sonification using light curves. They provide a detailed description of the sonification parameters chosen for the study. Concluding that visual representation generally remains more effective, considering individuals without training in sonification.

Recently, Bertaina Lucero et al. (2024) explored the development of an online platform for sonification training. Building on this, a

[32]The sound of each spectrum: O5V https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/starO5.wav; A5V https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/starA5.wav; and G0V https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/starG0.wav

[33]Spectra star classification through sonification: O5-unknown https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/starO5-unknown.wav; A5-unknown https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/starA5-unknown.wav; and G0-unknown https://www.sonouno.org.ar/wp-content/uploads/sites/9/2024/07/starG0-unknown.wav

[34]Spectra star classification video: https://youtu.be/JT6gG-MTqo4

potential future implication of our current work could be the creation of a repository of multimodal files specifically designed for training in multimodal astronomical data analysis and perception studies.

6 CONCLUSIONS

From the results obtained in this work and the methods described to produce the displays (visual and auditory), we could conclude that this technique exhibits the patterns and changes in data reliably and faithfully represents the information.

In Section 4.1 image sonification was used with a barred spiral and a double nucleus galaxies. Even when the technique is very basic, the increase in light can be perceived through sound. Further, the spectrum obtained from the CSV in SONOUNO GUI (Figs 2 and 4) is equivalent to that downloaded from the data base. The detection of peaks, permits the identification of chemical elements in a similar way than using other standard astronomical software, but in a multimodal framework. Besides, the multicolumn sonification was used between these galaxy spectra, with noticeable differences in sound.

Remarkably, the previous reference of multicolumn sonification was by XSONIFY; this software permits to open a multicolumn set of data and perform the sonification of at least three plots, but the graphs are individual, one under the other. We demonstrate the power of SONOUNO's ability to visualize and sonify multiple column data for comparing galaxy spectra and for aiding spectral classification of stars.

As in the standard stellar classification technique, the comparison of known and unknown spectra was shown in a visual mode and as a complement, the data sonification was performed; the links to the audios comparing each standard star in conjunction with the unknown data set are presented in Section 4.2.2 (Fig. 9). It could be appreciated that the sonification reflects the same as the plot; if there is coincidence, the two sounds fit; and in the case of difference in the spectrum, the two sounds are chaotic. Something that enriches the technique is the possibility of hearing the sound and visualizing the plot at the same time. This novel approach allows us to compare data sets by plot and sound, using the skill of the human ear.

All the scripts presented here utilize three core modules of the SONOUNO desktop software: data import, data transformation, and the sound module. Future work is needed to enhance the SONOUNO graphical user interface, maintaining its user-centred and accessibility-focused approach, to effectively display the multimodal presentations discussed here.

Furthermore, a multimodal display allows researchers to continue working with the visual display they use daily, with the added benefit of sonification. In addition, the techniques used ensure the reliability that the data have been processed in the same way for both displays. This enables on one side the comparison between the actual display and sonification, opening the discussion to its reliability; and on the other, the start of training a new technique. In this sense, future work could be a course where the sonification technique is explained using the audiovisual material shown in this contribution. Collaboratively, some sonification training and perception evaluation could be done.

Although internal tests have been carried out with specialists, it is necessary to perform a broader study, following the example of recent ones developed by Trayford et al. (2023) and Tucker Brown et al. (2022); the evidence highlights good results after user testing with sonification without a lot of training, given the novelty of the method. Again without training, Fovino et al. (2024) conclude that visual representation is more effective but they do not rule out that sonification could be used. More studies should be done to improve understanding of multisensory perception, the use of more than one sense to study the unknown should improve perception and reduce single-sense overload. To be able to measure perception in this sense, sonification training has to be done to level the path between the visual and sonification techniques.

The dual-purpose birth of sonification in astronomy should not be lost, this is accessibility and features detection under multimodal approach. Even when sonification is here to make sense of nature through a new sense, like hearing, it brings accessibility and the possibility to make discoveries in science to people who are excluded nowadays.

DATA AVAILABILITY

SONOUNO desktop version is an open-source development and can be used freely: the code, installation, and user manuals are available on Github: https://github.com/sonoUnoTeam/sonoUno-desktop. Also, the four scripts presented here are available on its own repositories, depending on the data type: for galaxy spectra https://github.com/sonoUnoTeam/SDSSspectra, for light curves https://github.com/sonoUnoTeam/ASASlightcurve, and for star classification https://github.com/sonoUnoTeam/ProjectCLEA-starspectra.

All the data from different sources used in this work are available in their own data bases. The new plots and data sonification made with SONOUNO, can be recovered from the SONOUNO website (https://reinforce.sonouno.org.ar/).

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