

## A SONIFICATION OF THE ZCOSMOS GALAXY DATASET

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### ABSTRACT

The sonification of scientific data is useful not only for the work of visually impaired scientists but also for having a feeling of the global behaviour of a set of data and has also an intrinsic artistic value. Here we present the sonification of the zCOSMOS spectroscopic survey aimed to study the evolution of galaxies within the last 6 billions years of the Universe’s life. The goals of such an initiative are multiple: providing a sound-based description of the dataset in order to make hidden features emerge, hybridizing science with art in a cross-domain framework, and treating scientific data as cultural heritage to be preserved and enhanced, thus breaking down the barriers between scientists and the general audience.

### RESUMEN

La sonificación de datos científicos es útil no solo para el trabajo de científicos con discapacidad visual, sino también para tener una idea del comportamiento global de un conjunto de datos y también tiene un valor artístico intrínseco. Aquí presentamos la sonificación del estudio espectroscópico zCOSMOS destinado a estudiar la evolución de las galaxias en los últimos 6 mil millones de años de vida del Universo. Los objetivos de este tipo de iniciativa son múltiples: proporcionar una descripción sólida del conjunto de datos para que surjan características ocultas, hibridar la ciencia con el arte en un marco cruzado y tratar los datos científicos como patrimonio cultural que debe preservarse y mejorarse, rompiendo así las barreras entre los científicos y el público en general.

*Key Words:* galaxies: evolution — cosmology: observations — galaxies: fundamental parameters

### 1. INTRODUCTION

*Sonification* is the transformation of data into acoustic signals, namely a way to represent data values and relations as perceivable non-verbal sounds, with the aim to facilitate their communication and interpretation (Kramer et al. 1999). Like data visualization provides meaning via images, sonification conveys meaning via sound. As discussed in Barras & Kramer (1999), non-verbal sounds can represent numerical data and provide support for information processing activities of many different kinds.

A first scenario is the possibility to receive information while keeping other sensory channels unoccupied, as required in medical environments, process monitoring, driving, etc. Common experiences in everyday life range from the sounds naturally produced by physical phenomena and automatically associated with specific events (e.g., a whistling kettle) to sound-augmented objects (e.g., a Geiger counter). This approach is explicitly used in sensory-

substitution systems, like orientation and navigation applications for blind or visually impaired people (Ahmetovic et al. 2018). Sonification techniques prove to be useful also when the data to represent are complex and have multiple dimensions to track (Bent-Tal, Daniels & Bergerl 2001). In fact, music and sound present multidimensional features (e.g., pitch, intensity, timbre, spatialization, etc.), and these dimensions can be simultaneously employed to provide understandable representations of complex phenomena. An effective design of sonification can draw, e.g., on musicality, musical acoustics, sound synthesis and human perceptual capacities (Bregman 1994). Listening to data can open new scientific frontiers, thanks to the human ability to parse sound for patterns and meaning. This approach can make non-trivial structures emerge and help to unveil hidden patterns (Cooke et al. 2017). Social processes (Lenzi & Ciuccarelli 2020), natural events (Arai 2012), and physical observations (Dubus & Bresin 2003) are only a few examples of applicability fields.

Finally, sonification can be applied to those scenarios where a set of data is only the base to build an experience with artistic goals. In this context, it is worth mentioning also the concept of *musification*, namely the representation of data through

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music. The resulting musical structures can take advantage of higher-level features, such as polyphony or harmony, in order to engage the listener. The relationships of sonification to music and sound art have been explored in Gresham (2012). After providing these definitions, we can affirm that data can be visualized by means of graphics, sonified by means of sound, and musified by means of music.

Sonifications can be enjoyed as scientific inquiries, aesthetic experiences, or both. The idea of bridging the gap between art and science in the context of scientific dissemination and “edutainment” initiatives has been explored in a number of works. Following Ballora (2014), the sonification, as opposed to visualisation, is still an under-utilised element of the “wow” factor of science.

Proposing a sonification initiative during an exhibition or another public event can also add value to the dataset itself. First, a sound-based multimedia installation can be an engaging way to make a non-expert audience enjoy scientific subjects; in this sense, the experience can be enhanced through suitable support materials (e.g., wall-mounted panels), the stimulation of other sensory channels (e.g., a video installation), and real-time interaction with the audience (e.g., through motion detectors and ambient-light sensors). Moreover, such an initiative can play a cultural role by raising scientific data and achievements to the rank of cultural heritage to be preserved and exploited. Examples are reported in Avanzo et al. (2010); Dunn & Clark (1999) and Polli (2012).

In the context of sensory substitution techniques, sonification can make scientific data accessible to specific categories of users, e.g., blind and visual impaired people, with an important impact on their education, too (Laconsay, Wedler & Tantilillo 2020; Pereira et al. 2013; Reynaga & Lopez-Suero 2020).

For the sake of completeness, it is worth underlining that the legitimacy of sonification as a scientific method of data display is being debated by scholars and experts, as discussed in Supper (2012). According to Neuhoff (2019), widespread adoption of sonification to display complex data has largely failed to materialize, and many of the challenges to successful sonification identified in the past are still persisting. Nevertheless, since the goal of the initiative described below is dissemination, even if scientifically accurate, our proposal does not fall within the scope of problematic applications.

## 2. THE ZCOSMOS SURVEY

This paper uses the information currently derived in the zCOSMOS-bright project (Lilly et al. 2007,

2009) a major spectroscopic redshift survey of the galaxies in the COSMOS field (Scoville et al. 2007) at the ESO-VLT telescopes. The final zCOSMOS-bright survey is designed to yield a spectroscopic information of 20,000 galaxies with  $IAB < 22.5$  across  $1.7 \text{ deg}^2$  of the COSMOS field with high success rate in measuring redshifts (close to 100% at  $0.5 < z < 0.8$  and 70% global) and good velocity accuracy (about  $110 \text{ km.s}^{-1}$ ).

These spectra, added to the multi-wavelength coverage of the COSMOS survey (from UV to IR), permitted to derive galaxy physical quantities. In this work we focused to

- Stellar Mass, a value describing how many stars have been formed in a galaxy and, therefore, a proxy for the galaxy history. It is the sum of masses of the alive stars in terms of the Sun mass  $M_{\odot}$ ;
- Star Formation Rate (SFR), i.e. the total mass of stars formed per year, which reflects how active is a galaxy at the moment of the observation;
- Redshift, namely the measure of the recession velocity of the galaxy as a consequence of the expansion of the Universe. Due to the Hubble’s law, the higher the redshift (measured as the shift of spectral lines toward the red part of the spectrum), the higher is the galaxy distance; The zCOSMOS-bright survey permits to explore the  $0.2 < z < 1.2$  redshift range
- Lookback Time, this is related to the galaxy redshift, because the higher is the distance of a galaxy (and its redshift) the further back in time we are looking. Knowing the age of the Universe today (13.7 billions of years), the difference between the age and the lookback time is the age of the Universe at the moment the galaxy emitted the light we observed
- Absolute magnitude MV, i.e. the absolute luminosity of the observed galaxy (related to the intrinsic luminosity) in the Visual filter. Note that due to the magnitude definition, lower values of MV imply brighter galaxies;
- Position in the sky, in terms of right ascension R.A and Declination (Dec). These are the equatorial coordinates of the galaxy.

As shown in Fig.1 with this survey we can explore only up to 6-7 billions of years ago, an epoch where the average star formation is rapidly increasing with

the lookback time. The star formation peak is expected to be around 10 billions of years ago but it has not been explored yet by massive surveys. Note that the Star Formation density increased (decreased) by about one order of magnitude with the lookback time (age of the Universe)

### 3. PREPARING THE SONIFICATION

The zCosmos survey, as the vast majority of astronomical surveys, observed objects up to a limiting apparent magnitude. This means that at lower distances one spans a large range of intrinsic luminosities (absolute magnitudes) from bright to faint objects. On the contrary at larger distances, the picked up galaxies are only the brighter ones. This introduces the wrong impression that the galaxy density as measured nearby is higher. To avoid this effect, we cut the sample to a magnitude of  $M_V < -21$  in order to have in the sample the same magnitude range between  $0 < z < 0.9$ . This reduces the number of galaxies to 8361. This cut is a compromise to balance the luminosity range, the redshift range and the number of galaxies. In this redshift range we can go to a look back time of about 6 billions of years.

Sonification can be seen as the junction point between the artistic use of science and the scientific use of art, thus combining the separate viewpoints of the artist and the scientist. Coherently, the project described in this paper has been designed and implemented by a working group made of scientists, technicians, and artists.

The software tools used in the whole process include: MATLAB for data inspection and preprocessing, Supercollider to parse the CSV exported by MATLAB and perform real-time sound synthesis, Ableton Live to record the distinct audio tracks generated by Supercollider, and, finally, Steinberg Cubase for post-production.

The proposed sonification is based upon three main layers: a) Galaxies, sonified through a dense stream of events, each modulated independently, thus generating a synthetic sound texture, b) Statistics, producing a very simple, continuously modulated, synthetic drone sound, c) outliers, causing a rare occurrence of events, each modulated independently, thus generating complex sound icons.

The distribution of Star Formation Rate values is a rapidly decreasing positive quantity with 90 % of the sample with  $SFR < 10 M_{\odot} y^{-1}$  but with outliers as big as  $600 M_{\odot} y^{-1}$ . An early idea was to consider  $\log(SFR)$ , but this would have involved an excessive flattening of the values to the higher values. We therefore decided to transform the data in a monotonic way by extracting the twelfth root of the Star

Formation Rate, namely  $SFR^{1/12}$ , which showed a more balanced distribution. In all design phases we followed the principle of *ecological metaphors*, thus trying to make the sonification coherent with users' real-world sensory and cognitive experience. This approach implies that variations of auditory dimensions are consistent with those of physical parameters; for example, position values may be mapped onto left/right sound panning. The use of ecological metaphors should improve intuitiveness and learnability.

One of the goals was to keep the technical setup required to play the sonification as simple as possible, so as to make it easily reproducible in a wide range of contexts. For this reason, the final outcome was a standard stereo file. Sound spatialization through an array of loudspeakers or a binaural approach would have extended the possibilities connected to ecological metaphors, but it would have prevented the performance in a great number of environments not adequately equipped.

#### 3.1. Setting the parameters

Each galaxy is sonified as a single and short sound event, occurring at a time which is proportional to its lookback time. When the event density is very low, single galaxies can be easily spotted and compared, while, in case of very dense and crowded sections, the overlapping of many events generates a complex texture which is more informative about the overall trend.

Each sound event is generated by 3 distinct sinusoidal oscillators, called  $O_{1-3}$ , presenting an exponential-decay envelope. Each oscillator can be controlled in terms of pitch, level, decay time, stereophonic position, and frequency modulation.  $O_1$ ,  $O_2$ , and  $O_3$  are the master, the harmonic (with 2X the pitch frequency), the sub-harmonic oscillator (0.75X) respectively. The rationale is to have a fundamental frequency generated by  $O_1$  which is louder and lasts longer than the harmonic and sub-harmonic sounds generated by  $O_{2,3}$ .

The volume is determined by the absolute magnitude  $M_V$  of the galaxy under exam by exploiting an analogy with vision: brighter galaxies are represented with louder sounds, while dim galaxies (harder to see) are represented with softer sounds (harder to hear). The resulting dynamic range is about  $-24\text{dB}$ , which is sufficient to discriminate between bright and dim galaxies without making the latter inaudible.

Since the sonification has been conceived to be reproduced through a stereophonic speakers layout, it

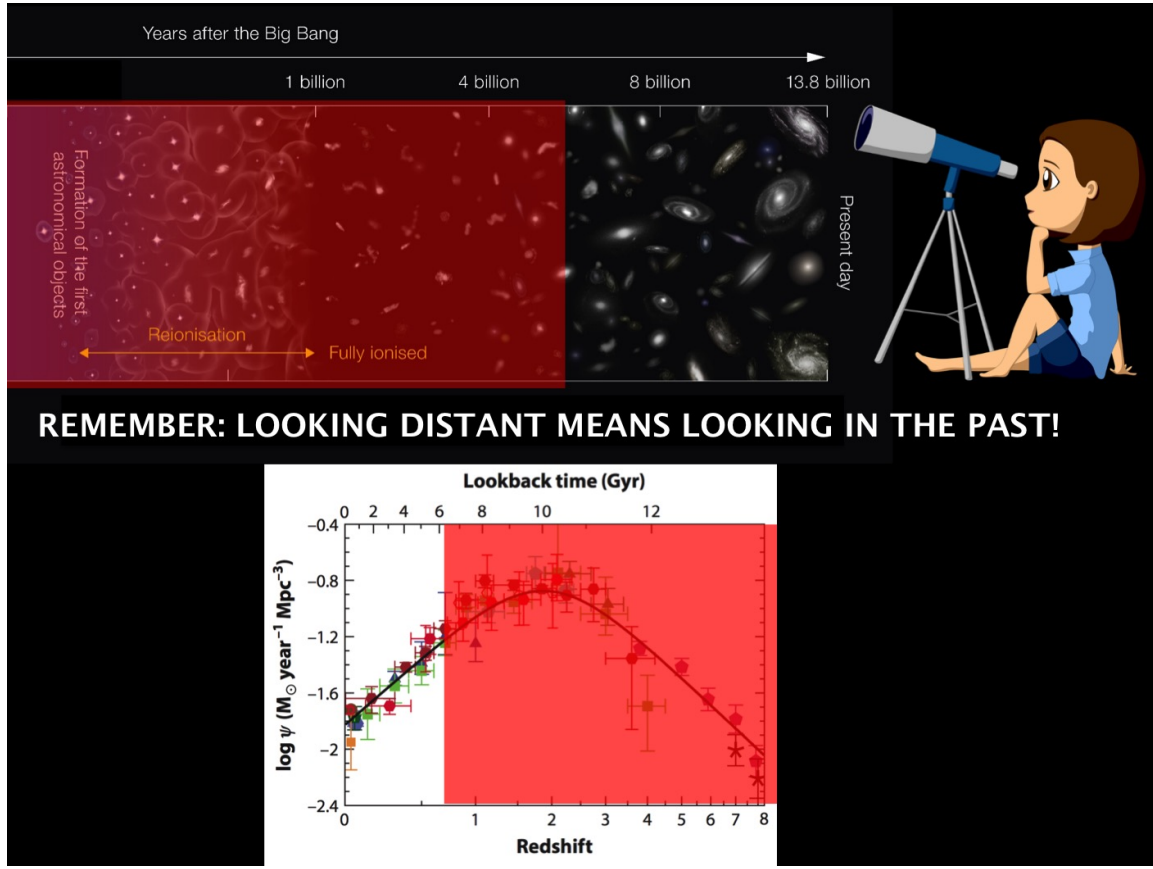


Fig. 1. Lower panel: Star Formation Density as a function of look back time (Madau & Dickinson 2014). Upper panel: a panel to show where our surveyed area is within the Cosmic History. The red area is not yet covered by massive surveys.

was natural to bind galaxy right ascension with the sound position in the stereophonic space. The resulting representation of spatial information is magnified, since original right ascension of the galaxies is included in about 1 degree of the sky, while the stereophonic field can reach 180 degrees, depending on the installation conditions. Declination could have been treated in a similar way, thanks to quadraphonic listening environments, but we decided to privilege a simpler setup.

The frequency of  $O_1$  is inversely proportional to the Stellar Mass. This binding has been chosen since lower pitches are generally associated with heavier and bigger sources, while high-pitched sounds easily recall smaller sources. In order to produce well-sounding events, many sonifications usually map values onto notes of the equal-tempered scale or consonant frequencies. Conversely, we decided to let the frequency binding be continuous; in this way, the presence of beatings as opposed to the perception of distinct sounds lets the listener clearly perceive

when two galaxies are similar (beatings) or different (distinct sounds) in terms of Stellar Mass. As an aesthetic consideration, the adoption of a musical scale would have produce a sonification more pleasant in the short term, but more boring on the long run. Another potential problem was the possibility to introduce a phenomenon of data misinterpretation in case of peculiar musical structures (e.g., consonant chords, cadences, etc.), which are strongly rooted in the tonal-harmony perception of music, but have no particular meaning in the sonification.

Star formation rate SFR is linked to the parameters of the frequency modulation of  $O_3$ . In order to give the idea of very active galaxies for high values of SFR and more relaxed galaxies for low values, we carefully tuned the sinusoidal modulator frequency  $f_m$ . This parameter runs below the audio rate (i.e.  $f_m < 20$  Hz) for low star formation rate, thus producing a tremolo-like effect, while high values for SFR produce a more distinctive and frantic modulation. For the same reason, the frequency deviation

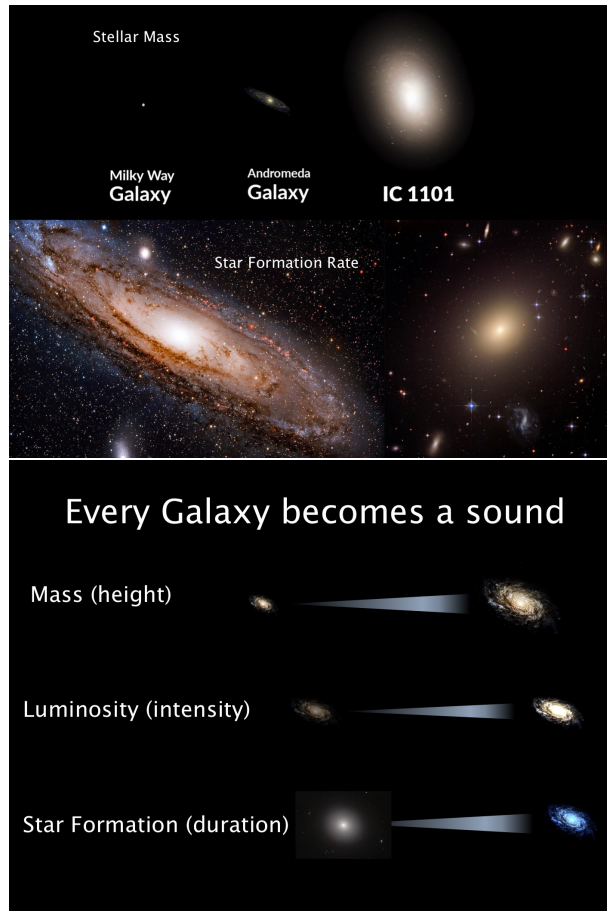


Fig. 2. Upper panel: the stellar mass is the mass of all the stars which are born in a single galaxy and is roughly correlated with its size. Lower panel: The Star Formation Rate is the mass (in stars) formed every year. An elliptical galaxy has a very low (or zero) Star Formation Rate.

$d$ , a measure of the frequency modulation amount, is modified proportionally to SFR, too.

Finally, the amplitude envelope exponentially decays with a factor proportional to SFR, so that galaxies with higher SFR present a longer tail, while lower values cause a quicker decay.

### 3.2. Statistics and outliers

Statistics include the average of Stellar Mass, SFR, and MV computed within a moving window across lookback time. These are continuous signals controlling the frequency  $f_{1-3}$  of 3 distinct resonant band-pass filters, each one filtering white noise, with different pan values. Filters frequency are set by multiplying Stellar Mass, SFR, and MV by 200, 1000, and 2000 respectively. The result is a drone sound, a non-tempered chord which is consonant only under favorable circumstances.

The quality  $Q$  of the filters is very high at the beginning of the sonification, thus producing well defined pitches; it linearly decreases in time, so as to produce band-limited noise at the end of the sonification. The idea is to suggest an increase in data variability and uncertainty of the observations as long as more distant time and space is under exam. Please note that the reciprocal of  $Q$  is the actual modulated parameters. Outliers are galaxies whose values are out of range for at least one variable<sup>5</sup> and are sonified by means of auditory icons, modulated (when possible) with the same principles of single-galaxies modulations. The icons have been carefully crafted using sound design principles coherent with other sonification-design choices. The goal is to make outliers emerge from the overall sonification, but linking their perceptibility to the frequency of their occurrence: uncommon events have to stand out with respect to more common outliers. The icon for the biggest galaxy is a low-pitched percussive sound, while smaller galaxies are associated with high-pitched bells; both approaches rely on the original binding, but provide more emphasis on their outlier nature. Such sounds are modulated in position and intensity, according to RA and MV.

Similarly, high and low SFR are represented by fast and slow pulsing rumbles, respectively. These are generated through filtered noise, and modulated in pitch, level, and position according to the original bindings, and release and non-linear distortion according to Stellar Mass and SFR respectively. Finally, very bright galaxies are represented through sound glitches, so as to suggest a saturation effect for the sensors, modulated in pitch and position only.

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<sup>5</sup>Actually, no galaxies were marked as outliers for more than one variable.

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