5000 EXOPLANETS: LISTEN TO THE SOUNDS OF DISCOVERY

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ABSTRACT

In March of 2022, NASA announced the discovery of the 5000th planet orbiting a star other than our sun (an exoplanet). We have created a sonification and visualization to celebrate this milestone and to communicate the exciting history of discovery to the general public. Our work provides a visceral experience of how humanity's knowledge of alien worlds has progressed. A relatively simple and straightforward sonification mapping is used to make the informational content as accessible to the general public as possible. Listeners can see and hear the timing, number, and relative orbital periods of the exoplanets that have been discovered to date. The sonification was experienced millions of times through NASA's social media channels and there are plans to update the sonification as future milestones are reached.

1. INTRODUCTION

In the past 3 decades the search for exoplanets has made dramatic progress. With the development and refinement of several techniques and the launch of dedicated space-based telescopes, the pace of discovery has increased from roughly one per year to dozens or even hundreds per month. In 2019 we converted the first 4000 exoplanet discoveries into a musical and educational experience through sonification [1]. In 2022 as the planet count approached 5000 according to NASA's Exoplanet Archive, NASA contacted us to request an updated version for the upcoming milestone [2]. We produced a new version with improved visuals which was released as the 5000th planet was announced on March 21, 2022 [3], [4], [5].

2. SCIENTIFIC BACKGROUND

Since Giordano Bruno's heretical 16th century hypothesis that stars are actually suns and may host their own planetary systems, the existence and nature of exoplanets has been one of humanity's greatest questions. Detecting a planet orbiting a star from many light years away is a formidable task since they are small and dim compared to their bright host. In many cases this requires detecting signature fluctuations that are smaller than one part in a thousand in the brightness or color of the star. After several contentious claimed detections, the first confirmed exoplanet detection occurred in 1992 when a pair of planets were found orbiting a pulsar. In 1995 the first planet found orbiting a main sequence star was discovered and since then detections have occurred with dramatically increasing frequency.

Most early detections were accomplished using the radial velocity method. In this case, slight motions of a star due to the gravitational interaction with a planet can be detected by measuring the periodic changes in spectral lines due to the Doppler effect. Beginning in 2002, planets began to be discoverable with the transit method which measures the periodic dimming of a star due to an orbiting planet passing between the star and our line of sight. More than half of all known exoplanets have been discovered with the transit method, with over 2700 planets being detected by the Kepler space telescope alone. Several other methods have also been successful such as gravitational microlensing, various types of timing variations, and direct imaging. In the case of direct imaging, the infrared light emitted by warm, massive planets with large orbits can be spatially resolved from the light of the host star to produce actual photographs and time-lapse animations of planetary systems. Currently, the TESS space telescope is monitoring the entire sky and is expected to detect more than 10 000 new planets in the coming years [6].

The number of planets discovered and their characteristics allow us to address questions with deep relevance to our understanding of Earth's place in the cosmos. *How common are planets? How many of them can support life?* We now know that on average there is at least one planet per star and about 20% of Sun-like stars host an Earth-sized planet in the habitable zone [7]. There are likely hundreds of billions of exoplanets in our galaxy alone, including 10-40 billion potentially habitable Earth-sized planets, depending on which classes of stars are considered [8]. This incredible achievement is worth celebrating, and worth sharing with the world.

3. GOALS AND AESTHETICS

The wealth of known exoplanets is commonly communicated graphically, either through scatter plots or more sophisticated visualizations [9], [10]. Some sonifications of the catalog have also been produced [11]. While engaging and informative, these typically flatten the time dimension to a static axis on a graph or do not communicate their discovery over time at all. Our goal was to create a time-based musical sonification that gives the listener a visceral experience of how our knowledge of exoplanets has progressed. In addition to communicating the pace of discovery, some general trends in the types of planets discovered and some key events should also be audible. It is intended to have artistic and pedagogical value.

Since our goal is to reach and impact the general public (largely through social media), we chose a relatively pleasing and consonant aesthetic. Matching the changing rate of detections, it transitions naturally from calm and contemplative to uplifting and driving as time unfolds.

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4. SONIFICATION DESIGN

The sonification is designed to be almost immediately understandable to a general audience on first listen, and hence, simplicity in design is key. The musical parameters controlled by the data were limited to timing, pitch, velocity, and spatial position. Mappings were chosen to provide an intuitive match between the meaning and psychological experience of the data.

Data Parameter	Musical Parameter	Mapping Details
Discovery Date	Timing	Linear (~0.5yr/s)
Orbital frequency ($\boldsymbol{f}$)	Pitch	Logarithmic, non-linear, note assignments (23 notes)
Number of planets in each orbital frequency bin each month ($\boldsymbol{N_f}$)	Velocity	Non-linear (45-127)
Celestial coordinates	Spatial position	Stereo (5 positions) or Altitude-Azimuth (7 regions)

Table 1: Sonification design mapping exoplanetary data to musical/auditory parameters.

4.1. Mapping Data To Time

The time data is compressed from 30 years to just over a minute. The tempo is 87.75 bpm and months of real time are mapped to 16th notes. With this choice, each year of data corresponds to 2.05s of audio time and each month lasts 0.17s. The discovery times are quantized to months because this is the native time resolution reported in the Exoplanet Archive and because the regular rhythm maintains interest by helping to build tension as the piece develops. The chosen pace is fast enough for the gaps between early discoveries to remain relatively short, but slow enough for discoveries that occur in consecutive months to still be perceived as separate transients. After the most recently discovered planet has entered and faded, a final chord including mapped notes for every planet was added. This adds musical finality to the piece and highlights the dramatic shift in our knowledge over the past 30 years.

4.2. Mapping Data To Pitch

The pitch of each note is controlled by the orbital frequency (or orbital period) of the exoplanet. Higher orbital frequencies (smaller orbital periods) are mapped to higher note frequencies. The scaling is logarithmic rather than linear so that the enormous range of orbital frequencies (spanning roughly 9 orders of magnitude) can be mapped to a comfortable region of the human hearing range. We think of this as a compressed 'Music of the Spheres' mapping as it maintains a relation between orbital and audio frequency. A logarithm is taken of the relative orbital frequency (the ratio of the orbital frequency f to the minimum orbital frequency f_{min}). The result is then squared to shift the peak of the distribution towards the middle of the mapped frequency range. Without this transformation, the vast majority of planets would be mapped to notes in the higher half of the range, limiting the ability of a listener to discriminate between planets with similar orbital frequencies and providing a less enjoyable experience. The frequency transformation used for mapping is given in (1).

$$f \rightarrow \log\left(\frac{f}{f_{min}}\right)^2 \tag{1}$$

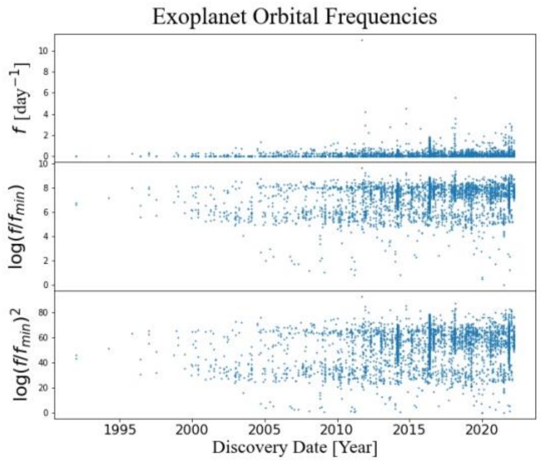

Figure 1: Actual exoplanet orbital frequencies (f) and scaled frequencies used while mapping to note pitch.

The transformed frequencies were quantized and mapped linearly to notes from a dense voicing of an Emaj13 chord. The voicing contains 23 different notes and is shown in Figure 2. This can also be thought of as a superposition of a Emaj7 chord in the low register and 3 octaves of G# minor pentatonic in the higher register. A consonant harmony is chosen to avoid harsh dissonances which would be incongruous with the aesthetic goal. This particular harmony is chosen to introduce a certain amount of harmonic unpredictability (mirroring the true unpredictability) while maintaining consonance. This allows the harmonic center to shift as planets with particular ranges of periods (or different detection methods) dominate. A chord voicing was used (rather than a regular scale) because there are times when nearly every mapped note is played and sufficient space is required between low tones to keep them clear. A very large pitch range is used to approximate the enormous range of the actual orbital frequencies. Using a regular scale across the entire range would have led to a muddy and more opaque listening experience.

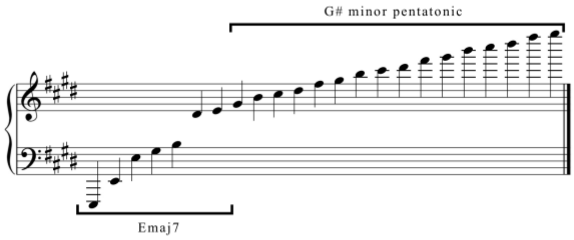

Figure 2: Chosen note set for orbital frequency mapping.

4.3. Mapping Data To Velocity

The midi velocity (a combination of volume and intensity) is controlled by the number of exoplanets detected per orbital frequency bin during each month, N_f. With this choice, a greater number of planets detected in a given month is experienced as a louder and more intense sound. In some months, many planets were discovered within the same orbital frequency bin and would be mapped to the same note (sometimes as many as 241 at once). By using N_f to control the velocity of a single note, rather than playing a note for each planet, we are able to keep the dynamic range within comfortable limits. N_f was normalized and then raised to the power of ½ to make the distribution more uniform, reducing the contrast between the average value and the greatest values. This was then mapped linearly to note velocity with a range of $v_{min} = 45$ to $v_{max} = 127$. A linear velocity boost $v_{boost} = 20$ was then applied to increase the velocity of the lower notes relative to the higher notes. This was done to create a more perceptually uniform velocity scaling across the frequency range, partially compensating for the increased sensitivity of our auditory system to higher frequencies. The mapping from N_f to midi velocity is given by

$$N_f \rightarrow v_{min} + \left(v_{max} - v_{min}\right)\left(\frac{N_f - 1}{N_{f,max} - 1}\right)^{\frac{1}{2}} + \tilde{m} v_{boost} \quad (2)$$

where

$$\tilde{m} = \frac{m_{max} - m}{m_{max} - m_{min}}. \quad (3)$$

In (2) and (3), m is the midi note number of a given note and the subscripts *max* and *min* indicate the maximum and minimum values among all data points.

4.4. Mapping Data to Spatial Position

The spatial positioning of the audio is based on the planets' position on the celestial sphere. The sonification was accompanied by two different visual animations. One shows the entire celestial sphere in galactic coordinates with an equirectangular projection. To match the visuals, the galactic longitude [-180,180] of each planet was binned and mapped to 5 different stereo positions (-90, -45, 0, 45, 90). This limited spatial resolution was deemed sufficient for our purposes as there is no spatial movement within the animation and the ability to localize individual events quickly becomes unfeasible as the number of simultaneous planet detections increases. The other animation is a 360° video that allows the user to view different directions by physically moving their smartphone or by scrolling within the video screen. For this version we placed each exoplanet's note at its correct altitude and azimuth in equatorial coordinates, matching the orientation of the video. Notes were then binned to 7 extended spatial regions (5 in the azimuthal plane, one above, and one below) and the audio was rendered as 1st order ambisonic sound. This was encoded with the 360° video so that the stereo output is responsive to the user's current field of view. A higher spatial resolution will be developed for presentation in planetarium domes or other physical installations.

4.5. Timbre

The mapped notes were played on an electric guitar. We chose this instrument as it is familiar, has a relatively large range, and has a suitably short decay to make densely occurring transients audible. The range was extended by digitally pitch-shifting the highest and lowest notes. To further support the lowest register a synthesized electric bass was added to double the 4 lowest notes. A faint synthesized piano doubled the guitar to strengthen the note attacks without being perceived as a separate timbre. We limited ourselves to a single timbre for all exoplanets to maintain simplicity and cohesion. More information could be communicated by assigning different sounds to different planet detection methods (for example) but this would increase the cognitive load and the time needed to communicate the mapping. Low sustained notes were played on a guitar with an EBow to help ground the piece during breaks between early discoveries and to help build excitement towards the end.

5. DATA AND METHODOLOGY

The data was accessed from NASA's Exoplanet Archive and through personal communication with its administrators. This is an online archive that collates and cross-correlates astronomical information on exoplanets and their host stars based on published results. The sonification uses data of the discovery date (year and month), orbital period, and celestial coordinates of each planet and the visualization also uses the method that was used to detect the planet. Many discovery dates were ambiguous and needed to be resolved by inspection of published work. For example, some of the catalog's discovery dates do not match the date of the referenced discovery paper and others indicated when a planet was detected as a candidate rather than confirmed. Several planets do not have published values for their orbital period (mainly because this can't be determined accurately for planets discovered with certain methods). In these cases, a period is estimated by using the planet's semi-major axis and host star mass according to Kepler's 3rd law.

The data processing and implementation of the sonification design were done in python. Note times, pitches, and velocities were exported as a multi-track midi file. Stereo positioning was achieved by allocating notes to separate midi tracks and then panning each in Logic Pro.

The guitar sound was created by acoustic recording of a Fender Jazzmaster running through a Boss Reverb pedal and Fender Hot Rod Deluxe amp. A sample pack was created by recording the full attack and decay of each note on the guitar with 5 different velocities. The sounds were assigned to a sampler in Logic Pro to be triggered by midi note events. The sustained drone sound is the same guitar played by an EBow being run through a Boss Blues Driver pedal. Additional guitar chords were recorded live to accentuate key moments in 2014 and 2016 when several hundred exoplanets were announced at one time.

6. VISUALIZATIONS

Two animated videos were created to communicate the sonification mapping visually and to provide additional information. The animations show the entire celestial sphere as viewed from Earth (or very near to Earth). A digital counter indicates the year and the running total of discovered exoplanets. As each planet is discovered, a circle appears at its location on the celestial sphere. The size of the circle indicates the relative size of the planet's orbit so is also correlated with the musical pitch associated with each planet (larger orbits have smaller frequencies and hence lower pitch). The opacity of each circle oscillates with a frequency proportional to the scaled frequency in (1). The color of the circle indicates the method used to detect the planet. An expanding and fading bubble is also added to make new discoveries and their spatial clustering more noticeable and to mirror the audio decay of each note in visual form.

The equirectangular video (with stereo audio) was created in python using a catalog of visible stars and a stellar density

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image created with Gaia data to simulate the Milky Way. Running totals of the numbers of planets discovered with each method are also shown in this version. Frames were rendered in python and stitched together with ffmpeg. Layers showing the Milky Way, stars, counters, circles, and bubbles were overlaid in Final Cut Pro. A screen shot from this animation is shown in Figure 3.

The 360° version (with ambisonic audio) was created and rendered entirely with javascript using the Three.js library. It also included renderings of the Earth and Sun to highlight the fact that the number of known solar systems changed from 1 to over 5000 over the course of the video. This video could be adapted for viewing in planetarium domes or other immersive exhibits. A screen shot from this animation is shown in Figure 4.

The visuals show patterns that are not audible in the sonification. Using colors to indicate the discovery method of each planet and including a counter make it clear that the vast majority of exoplanets were discovered with the radial velocity method early on, and then by the transit method in more recent years. The most noticeable feature in the clustering of exoplanets on the sky is a very dense '+' shaped patch known as the Kepler field of view. In the Kepler telescope's first phase it remained pointed towards this patch of sky, monitoring the brightness of 150 000 stars 4 years. All of the planets discovered during this stage (including big hauls of 2014 and 2016) lie in this region, forming a mirror image of Kepler's internal CCD arrangement on the sky. After 2 reaction wheels failed in 2013 Kepler began its second stage, called K2. The telescope then surveyed isolated patches along the ecliptic. These planets appear in bursts along a sinusoidal shape in the animation. Viewers may also notice that planets discovered with microlensing are mainly in the direction of the galactic center (since it relies on a high density of stars for stellar alignments), and that directly imaged planets have large orbits.

The equirectangular animation includes several improvements over the version produced in 2019 for the first 4000 exoplanets. In the earlier version, the equirectangular animation was created by exporting frames from the 360° rendering. This led to noticeable distortion near the top and bottom of the frame (the North and South ecliptic poles.) Since the 360° version is in ecliptic coordinates, the ecliptic appeared horizontal while the Milky Way appeared as a sinusoidal shape. This had some educational benefits as many commentors on social media inquired about why the Milky Way appeared distorted. Nevertheless, we decided to create and present the equirectangular version of *5000 Exoplanets* in galactic coordinates. This avoided the polar distortion and allowed the Milky Way to appear horizontal and more similar to our view of it in the night sky.

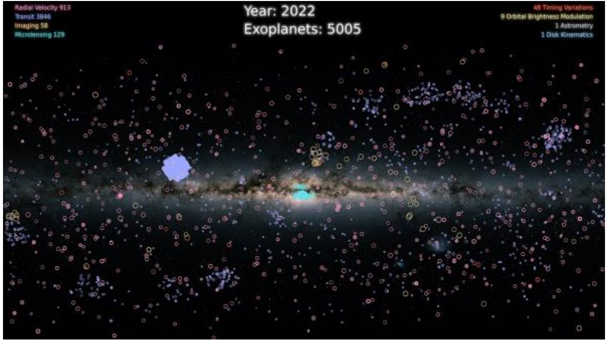

Figure 3: Screen shot from the equirectangular animation of *5000 Exoplanets*.

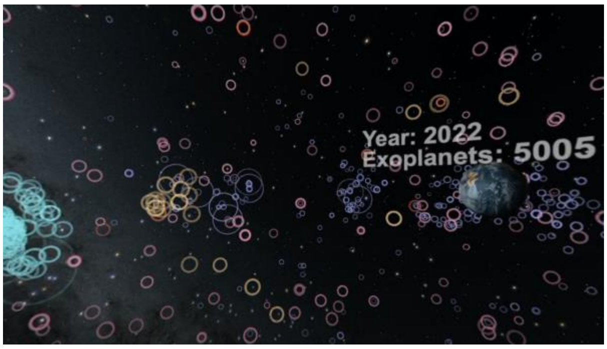

Figure 4: Screen shot from the 360° animation of *5000 Exoplanets*.

7. USER RESPONSE

Both sonification videos were posted by NASA on March 21, 2022 along with a written feature. Within the first month of release, the equirectangular version has been watched 144 thousand times on NASA's Youtube channel, 473 thousand times through NASA's Twitter account, and over 2 million times through NASA's Instagram channel. Some of the top-rated comments on Instagram were *"Stunningly beautiful 😍🙌"*, *"that is so amazing… it sounds so calming"*, *"This actually goes hard"*, and *"Music of the spheres 2022 edition!"* [12]. These comments indicate that listeners experienced it as both calming and exciting, as awe-inspiring, and even picked up on the connection to ancient ideas of musica universalis. The video was also featured by several online media outlets [13], [14], [15], [16], [17], [18].

The 360° version was viewed over 54 thousand times in its first month on Youtube. Sighted users appear to prefer the equirectangular version, possibly because it is more visually stimulating and allows them to see the appearance of every single planet. However, based on informal feedback, blind users seem to prefer the 360° version as it provides a more dynamic and interactive listening experience. We plan to update the sonification and animations as more planets are discovered so that it can act as a living record of our current progress. An orchestrated version to be performed by the New Bedford Symphony Orchestra is also in development.

8. ACKNOWLEDGMENT

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