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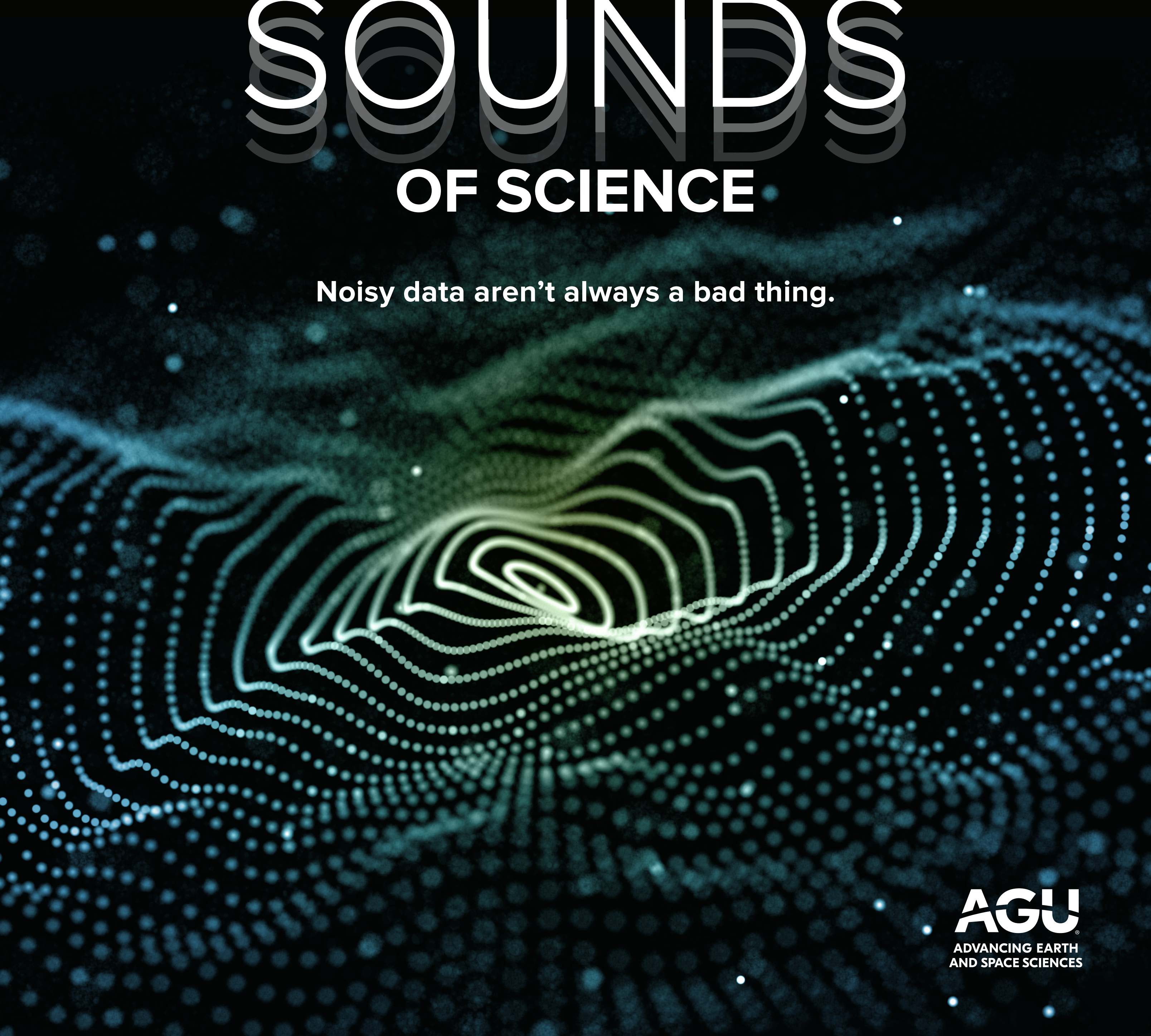
Five Remaining Martian Mysteries

Crowdsourced Science Pulls Off a Daring WWII Data Rescue

New Depths to North America's Deepest Lake

THE SOUNDS OF SCIENCE

Noisy data aren't always a bad thing.



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ADVANCING EARTH AND SPACE SCIENCES

The 21st Century's "Music of the Spheres"

Scientists and artists are giving voice to everything from planets to black holes, enriching the research experience and bringing wonders of the universe to new audiences.

By Damond Benningfield

Data sonification provides a new method to analyze and appreciate cosmic objects like the center of our galaxy, here visualized with combined data from NASA's Chandra X-ray Observatory, Hubble Space Telescope, and Spitzer Space Telescope. Credit: NASA/JPL-Caltech/ESA/CXC/STScI

The supermassive black hole at the core of NGC 1275, a galaxy in the heart of the Perseus cluster, moans like a goblin in a Halloween haunted house. The moan is produced as radiation from an accretion disk around the 800-million-solar-mass black hole pushes against gas falling into the black hole's maw. The interaction creates sound waves in the gas, producing the deepest sound ever discovered—57 octaves below middle C.

"It's hundreds of keyboards too low for us to hear," said Kimberly Kowal Arcand, a visualization scientist who works with Chandra X-Ray Observatory data at the Harvard & Smithsonian Center for Astrophysics.

The sound doesn't travel across the intergalactic void to Earth—at least not directly. Instead, astronomers see the ripples in images of the cluster's gas clouds. A team of researchers converted the light waves to sound, then pitched them into the range of human hearing. "We kept [the sound] on the low end because it wouldn't make intuitive sense to pitch it higher," said Matt Russo, a physicist at the University of Toronto who worked with Arcand and others to produce the sound.

"People say it sounds exactly like they'd expect a black hole to sound—dark, ominous, mysterious. It really touched a nerve," said Russo.

Many nerves, to be precise. The audio has been played or downloaded more than 2 billion times, and the story was featured in more than 1,200 news broadcasts, websites, magazines, and other outlets in just 1 month, Arcand said. "The reaction was just insane."

Although it is by far the most popular example, NGC 1275's black hole isn't the first astronomical "voice" to ring out across the cosmos. Scientists have enabled us to hear planets, moons, stars, supernovas, galaxies, and many other objects. Their efforts range from direct recordings of the sounds on Mars to artistic interpretations of some of the spectacular images from Chandra, James Webb, Hubble, and other space telescopes.

The sonifications—audio produced from scientific data—provide new ways for scientists to interpret massive data sets and allow blind or visually impaired (BVI) astronomers to share in research efforts more fully. "Sonification of data can…provide a complementary method for analysing observations and avoiding biases," suggested an editorial in the November 2022 issue of *Nature Astronomy.* "Our ears…can pick out weak signals against a noisy background and are sensitive to perceiving time-based changes and patterns."

A survey article in the *Nature Astronomy* issue logged almost 100 completed or ongoing sonification projects, with more in the planning stages. It is a burgeoning field, said Arcand. "There's definitely a movement toward increasing the use of sound as a tool for research or communication or art."

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Expanding Inclusivity

Chris Harrison, an astrophysicist at Newcastle University in the United Kingdom who heads a project known as Audio Universe, wrote and directed a half-hour program, "Tour of the Solar System," that combines visuals with sonifications of data about the planets and moons.

"Some of the blind audience members discussed being able to engage with astronomy for the first time, or those who lost their vision later in life [getting] back in touch with their younger joy in the subject," Harrison said.

Blind astronomers have felt that same joy after sonification tools helped them return to their research—or take it up for the first time.

"With sonification, I regained hope of being a productive member of the field I had worked so hard to be part of," said astrophysicist Wanda Díaz Merced of the European Gravitational Observatory in Cascina, Italy, during a 2016 TED Talk. Merced, who lost her vision after a prolonged illness a decade earlier, became a pioneer at sonifying data for research purposes, not just for outreach. "Today I'm able to do physics at the level of the best astronomers, using sound," she said.

Also in 2016, Garry Foran, an Australian scientist who had lost almost all vision, heard about Merced's work. After earning a Ph.D. in chemistry, Foran developed precision instruments for a project that used synchrotron radiation to probe the structure of matter.

He lacked the accommodations he needed to continue in chemistry, but the opportunities offered by sonification contributed to his decision to pursue a doctorate in astrophysics at Swinburne University of Technology. "I always had a lay interest in astronomy and astrophysics," Foran said. "I kept a close eye on developments in the field through podcasts and radio interviews."

Foran contacted Merced, and they collaborated on sonification projects for several years. Foran also worked with colleagues in Australia to develop StarSound, a free, downloadable tool for sonifying data.

Foran uses StarSound to analyze spectra from high-redshift galaxies, which are billions of light-years away from Earth. Using either a text-based interface or an audio mixing board, he can produce an overview of the spectrum or examine any individual data point in detail.

"I can listen to things at different rates, characterize the spectra, find features of interest, move to them, find the peaks, find the troughs," said Foran, who completed his Ph.D. in 2022. "Then I can use those results in another software package for my research or my writing."

Foran and his colleagues are working on a more powerful tool to sonify detailed images and other sophisticated data sets. But he said sonification tools need wider acceptance to become successful. "If sonification is to be sustainable and self-supporting, it needs to be more than just an accessibility tool," he said. "It needs to find a place in science's mainstream. It needs to be taught from the beginning and used as a common tool."

Eavesdropping on Mars

If you were to attend a symphony performance on Mars (assuming the thin, carbon dioxide–rich atmosphere wasn't a problem for you or the musicians), you'd notice something odd: The high notes of the piccolos and the low notes of the cellos would reach your ears at different times.

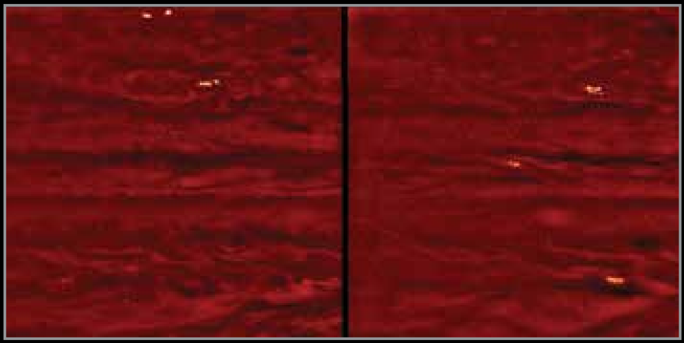
"The speed of sound on Mars is different for different frequencies. This is unheard of on Earth, literally," said Roger Craig Wiens, a planetary scientist at Purdue University and principal investigator of the Perseverance rover's SuperCam instrument suite, which includes a tiny microphone. "We scratched our heads and wondered how this [phenomenon] might work. We decided that in a carbon dioxide atmosphere, the vibration modes are different from those in the nitrogen-oxygen atmosphere on Earth."

"There's definitely a movement toward increasing the use of sound as a tool for research or communication or art."

Perseverance's microphone is a rarity: an instrument that directly records sounds in an extraterrestrial environment. The Huygens lander recorded the sounds of its descent through the cold, dense atmosphere of Saturn's giant moon Titan in 2005, but nothing from the surface. Two prior Mars missions carried microphones, but Mars Polar Lander crashed and the Phoenix lander's microphone couldn't be turned on because of an electronics glitch.

SuperCam fires laser bolts at rocks and soil, then uses a spectrometer to analyze the composition of the vaporized material. The microphone records the zaps, the sounds of which reveal the hardness of the original material, which, in turn, reveals details about its formation.

This Hubble Space Telescope image shows the giant galaxy NGC 1275, which contains a supermassive black hole in its core. Sound waves ripple through the gas around the black hole, which researchers have pitched into the range of human hearing, creating a creepy "moaning" sound. Credit: NASA, ESA, Hubble Heritage, A. Fabian (University of Cambridge, UK)



Voyager 1 discovered lightning on Jupiter by detecting its radio waves. Later, the Galileo orbiter photographed several lightning flashes on the giant planet's moonlit nightside. Credit: NASA/JPL-Caltech

The central precincts of the Milky Way Galaxy form bright whirls, arches, and streamers in this multiwavelength image. This chaotic "downtown of the Milky Way" was sonified with piano, glockenspiels, and violins. Credit: X-ray: NASA/CXC/UMass/D. Wang et al.; Optical: NASA/ESA/STScI/D. Wang et al.; IR: NASA/JPL-Caltech/SSC/S. Stolovy

In addition, the microphone has recorded the pops and clicks of the rover itself, a dust devil sweeping across Perseverance, the sigh of gentle breezes, and the whine of the Ingenuity helicopter—a sound that brought another surprise. "We heard the helicopter from almost a football field away, but we hadn't expected to hear it at all," said Wiens. "That was a fascinating surprise—[Mars's] sounds propagate better than we expected."

Lightning Crackles from Gas Giants

No other sounds of the universe are as directly observed as those from Mars, but some are close. Through a branch of sonification known as audification, scientists can perform a nearly one-to-one conversion of data to sounds.

Some conversions are as simple as audifying the "tick, tick, tick" of dust grains hitting a spacecraft, or recording the radio crackle of lightning in a planet's atmosphere. Such recordings might need to be sped up a little to make the patterns more obvious, or pitched into the range of human hearing, but they're realistic portrayals of the actual physical events.

"If you've ever been listening to an AM radio station while you're driving at night, close to a thunderstorm, you hear a lot of crackling and popping. That's... what Cassini recorded from Saturn."

Scientists at the University of Iowa, for example, have been audifying signals from solar system explorers since the Voyager missions of the 1980s. "Fred Schaaf showed up at one of the Voyager press briefings with observations from the plasma wave experiment converted to sound," said William Kurth, an Iowa research scientist who has participated in several missions. (Schaaf is a longtime *Sky & Telescope* writer and editor.) "The data were pretty esoteric, and [Schaaf] was afraid the reporters' eyes would gloss over just looking at these 'wiggly line plots.' But people would relate to these sounds. And everything was right in the audio frequency range, so he didn't even have to change the pitch," Kurth said.

Among many other findings, the Voyager instruments revealed lightning in the roiling clouds of Jupiter. Lightning bolts produce a wide range of electromagnetic energy, from visible light to radio waves. The energy propagates freely into space, where it can be detected by spacecraft. Voyager 1 recorded signals known as whistlers—low-frequency radio waves that are characteristic of lightning on Earth—but they were subtle and could have been produced by other phenomena.

"We wanted to be darn sure we knew what we were talking about before we claimed that we found lightning at Jupiter," Kurth said. "So we listened to the sound. Based on years of experience listening to a lot of these things, those tones convinced us they really were lightning whistlers and not something else. It was another step in our verification."

Years later, the Cassini spacecraft, which orbited Saturn for 13 years, similarly revealed lightning in the ringed planet's atmosphere. "If you've ever been listening to an AM radio station while you're driving at night, close to a thunderstorm, you hear a lot of crackling and popping," said Kurth. "That's radio emissions from the lightning strokes. And that's what Cassini recorded from Saturn."

Cassini also recorded dust strikes, which sounded like a hailstorm pounding an unlucky car.

Recordings from these missions have found life far beyond scientific circles. In the 1996 movie *The Arrival*, Charlie Sheen's character discovers that aliens are about to invade Earth. "He puts together a bunch of satellite dishes to make a radio telescope, and hears a funny sound," said Kurth. "He explains to a kid that it's Voyager 2. And they used sounds it recorded at Uranus, which was a cute thing."

Another instance of science serving as artistic inspiration is composer and musician Terry Riley's Sun Rings. This performance by the Kronos Quartet and a 60-voice choir is based on Voyager's "greatest hits" and premiered at the University of Iowa in 2002.

Sun Rings gained renewed interest during the pandemic, as one critic noted that "music of the spheres may be a concept as old as human imagination, and whistlers have been rudimentarily known about for some time, but it has taken a sanguine modern shaman of the string quartet to expose their musicality."

The promise of inspiration continues today, as the twin Voyager probes are recording the magnetic field of interstellar space and its interaction with the Sun's magnetic bubble, the heliosphere.

White Noise from a Yellow Star

Audification efforts extend far beyond the planets of our solar system, as well as straight to the star at its center.

The "boiling" motions of hot gas in the Sun's outer layers create sound waves that ripple all the way to our star's core. The waves travel differently at different depths and latitudes, so studying them—a field called helioseismology—can reveal details about conditions throughout the Sun. The ripples cause tiny changes in the Sun's brightness, so astronomers monitor those variations with Sun-watching satellites.

"There are actually millions of harmonics," said Timothy Larson, an astrophysicist who has produced audio clips of helioseismology observations for Stanford University and others. "By combining thousands and thousands of them, we can infer the pressure and density inside the Sun. We can also measure the rotation of the Sun, which is different at different latitudes and depths because it's not a solid object. This is the only way to probe the Sun's interior."

Converting the millions of "notes" that reverberate through the Sun to sound requires a bit of work, admitted Seth Shafer, a collaborator with Larson and an assistant professor of music technology at the University of Nebraska Omaha. "If you go to the raw data, [they just sound] like white noise. But by building some filters, we can narrow down the number of harmonics and actually tune in to a particular depth inside the Sun, from the surface all the way to the core."

Shafer, who produced a multimedia program, "Instrument: One Antarctic Night," based on data from telescopes at the South Pole for the Perot Museum of Nature and Science in Dallas, is developing a software tool that will allow "both scientists and creatives" to sonify any data set. "The hope is that some new discoveries will come out of these sounds," Shafer said.

"The goal is to maintain scientific accuracy while creating an aesthetic and meaningful musical representation."

A More Creative Approach

Another branch of sonification uses a more creative strategy. It produces audio from images or other complex products, a technique that often requires a musical approach to data. "The goal is to maintain scientific accuracy while creating an aesthetic and meaningful musical representation," said Domenico Vicinanza, a scientist and composer at Anglia Ruskin University in the United Kingdom, who has produced sonifications using data from the Voyager missions, the European Organization for Nuclear Research (CERN), climate-studying satellites, and other sources.

This branch of sonification features a wide range of practitioners, including scientists, musicians, visualization specialists, accessibility experts, and computer programmers—a roster of self-described computer geeks, music geeks, and sundry other geekdoms. Several have said they couldn't really decide what to be when they grew up, so they decided to do it all.

Arcand, for example, has a background in computer science and astrophysics, and was creating 3D representations of astronomical

Scientists were surprised when they could hear the Ingenuity helicopter, shown here during its 54th flight in April 2023, almost a football field away from the Perseverance rover, indicating that the Martian atmosphere is better at propagating sounds than was expected. Credit: NASA/JPL-Caltech/ASU/MSSS

Some audifications of the Pillars of Creation, seen in this composite optical and X-ray image, have created sounds of the "young stars having tantrums." Hot young stars, captured in X-rays, shine like bulbs on a strand of Christmas lights. Credit: NASA/CXC/INAF/M, Guarcello et al.; Optical: NASA/STScI

The known planets of TRAPPIST-1 line up next to their parent star in this artist's concept. A sonification uses musical notes to depict the resonances of each of the planets' orbits. Credit: NASA/JPL-Caltech/R. Hurt, T. Pyle (IPAC) objects when she discovered sonification. Shafer studied tuba and music composition in college. Russo has one degree in jazz guitar and others in astrophysics, and played with a hip-hop band that briefly signed with a record label. ("It didn't go so well," he said.)

Russo entered the field of sonification in 2017, when he was giving talks about exoplanets to elementary school students. He was trying to explain the orbits of the planets of TRAPPIST-1. "I needed a way to make that more impactful," he remembered, "and I realized [the planets'] orbital resonances could be expressed as musical rhythms and harmonies. When I showed it to the first classroom, they were yelling and clapping, so I knew I was on the right track."

TRAPPIST-1, a star with seven known planets (some of which might lie inside the star's habitable zone), isn't the first system to have its planets' orbits converted to music, according to Vicinanza. He told the 2023 SXSW EDU Conference & Festival attendees that in the early 1600s, Johannes Kepler produced a piano piece depicting the orbits of the planets of the solar system to help explain his discovery that the planets follow elliptical paths. "He was using music as a powerful storytelling language," Vicinanza said.

Outreach is the main focus of most of these types of sonification efforts, with a special emphasis on serving the blind and visually impaired.

"I spent the first decade-plus of my career finding ways to visualize the high-energy universe," said Arcand. "Chandra reveals exploding stars, colliding galaxies, planetary nebulae, blazars, quasars—all sorts of cool things. It's in the kind of light that's invisible to human eyes, so I was mapping those photons to pixels. I love that, but it was missing a large chunk of the population—people who couldn't process data the way I can."

Arcand teamed with Russo and his colleagues ("they adopted me into the band"), and they've collaborated many times since. They've produced more than 2 dozen sonifications for Chandra, using images that combine Chandra's X-ray observations with visible, infrared, and other wavelengths from the Hubble, James Webb, and Spitzer space telescopes. "We opened up Chandra's data vaults for this," Arcand said.

"We're looking for images with some dramatic structure or maybe an interesting texture," said Russo. "We can't communicate everything, so we focus on the most interesting aspects. We have to make an artistic choice of which parts to highlight.... We have to inject some musicality. That turns it more into an art form than a scientific translation."

"We took a more symphonic approach.... Science directs the sound, but it's all about marrying the data in a way that's pleasant to listen to."

Marrying Glockenspiels and Black Holes

Sonifications represent different visual features as different notes played on different instruments. Some sonifications pan across the image, whereas others radiate outward from a central point, or scan like a radar beam.

To sonify the inner few hundred light-years of the Milky Way Galaxy, for example, Arcand and Russo have music pan from left to right, passing across gas clouds, star clusters, and the Milky Way's central supermassive black hole, Sagittarius A*. The music swells as it scans denser regions, and reaches its crescendo at the black hole.

"This is a very dense region—the 'downtown' of the Milky Way," said Arcand. "It's like being in Times Square, with a lot of noise, crowds, energy. We wanted to showcase that frenetic activity, especially as you get closer to Sagittarius A*. We took a more symphonic approach, with soft piano to represent the infrared, a glockenspiel to represent bips and boops in the X-ray, and violins for the arches and strings. Science directs the sound, but it's all about marrying the data in a way that's pleasant to listen to."

For the Pillars of Creation, a star-forming region made famous by a Hubble image, the scientists had the music scan from bottom to top. "We have tall pillars of gas and dust where baby stars are forming," Arcand said. "We have young stars that are having tantrums. It's kind of an eerie sound—more synthesized. Hearing the sounds with those interacting pieces really helps tell the story in such a neat way."

Voices from Beyond

We can expect to hear many more voices from beyond in the years ahead.

A "huge number" of sonification projects are in the works, said Russo, especially with the 25th anniversary of Chandra's launch in 2024. Several sonification practitioners are developing software to allow scientists to convert their own data sets to audio. Engineers are developing a microphone for Dragonfly, a helicopter that will buzz through the atmosphere of Titan in the next decade. The Iowa scientists are audifying observations from the current Juno mission at Jupiter, and plan to do the same with Europa Clipper data when the spacecraft reaches the Jovian system, as early as 2030.

"I would argue we are still in the early days [of sonification] and the potential has yet to be unleashed," said Harrison. "Sonification will help astronomers to gain initial insights more efficiently from the ever increasing, complex, large data sets. It may lead to new insights, too, because we will be exploring the data in completely new ways."

"The benefits for accessibility and making more immersive and engaging educational resources are more obvious," Harrison continued. "I expect to see more people being able to engage with science, from education through to professional scientists, as sonification becomes a more mainstream approach to data representation."

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Read the article at Eos.org