1 The Halley VLF Receiver, which recorded some of the sounds of space. (Jeff A Cohen)

Turning the sounds of space into art

Nigel P Meredith describes a project that combines plasma-wave science with music, dance, film and gaming to develop innovative outreach.

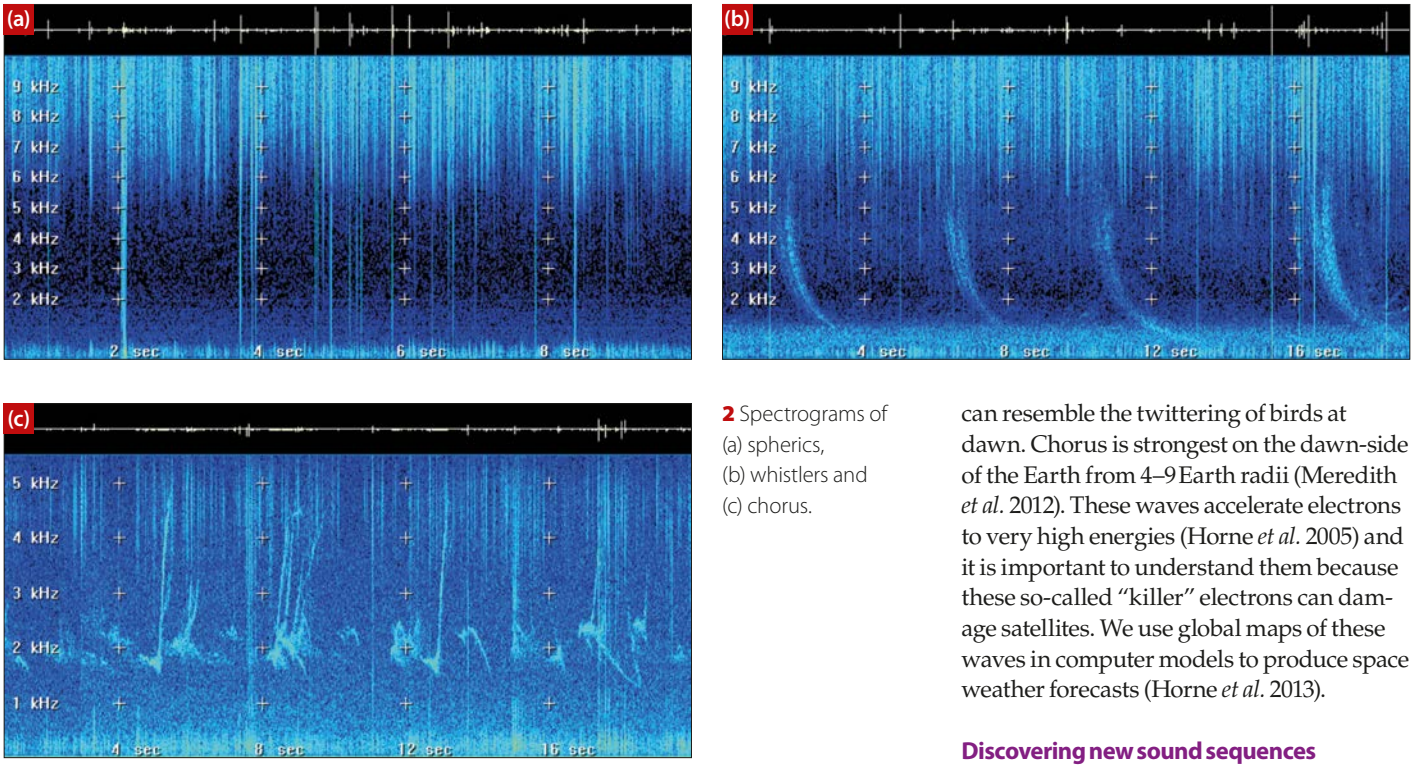
Space is a vacuum, and utterly silent. The sounds we hear are pressure waves in the atmosphere. But near-Earth space is full of a rich variety of plasma waves, many of which have frequencies in the range 20 Hz to 20 kHz, which puts them in the audio-frequency range. These electromagnetic waves cannot be heard directly, but they can be converted into audio files and played back as sound. This process reveals a series of weird and wonderful noises, known as the sounds of space, and it's a bit like entering the film set of a 1960s sci-fi movie!

As a space weather research scientist at the British Antarctic Survey (BAS), I develop global models of the plasma waves in near-Earth space for input into radiation belt codes and, ultimately, to forecast space weather. Since first encountering these radio waves as sounds more than 20 years ago, the sheer variety of their diverse tones has never ceased to amaze me. I have long sought to share them with wider audiences. Now, thanks to recent collaborations with artists and audio engineers, these eerie sounds – with beguiling names like spherics, whistlers and chorus – feature in performances that fuse art and science, as well as in a world-renowned space-simulation video game.

Recording the sounds of space

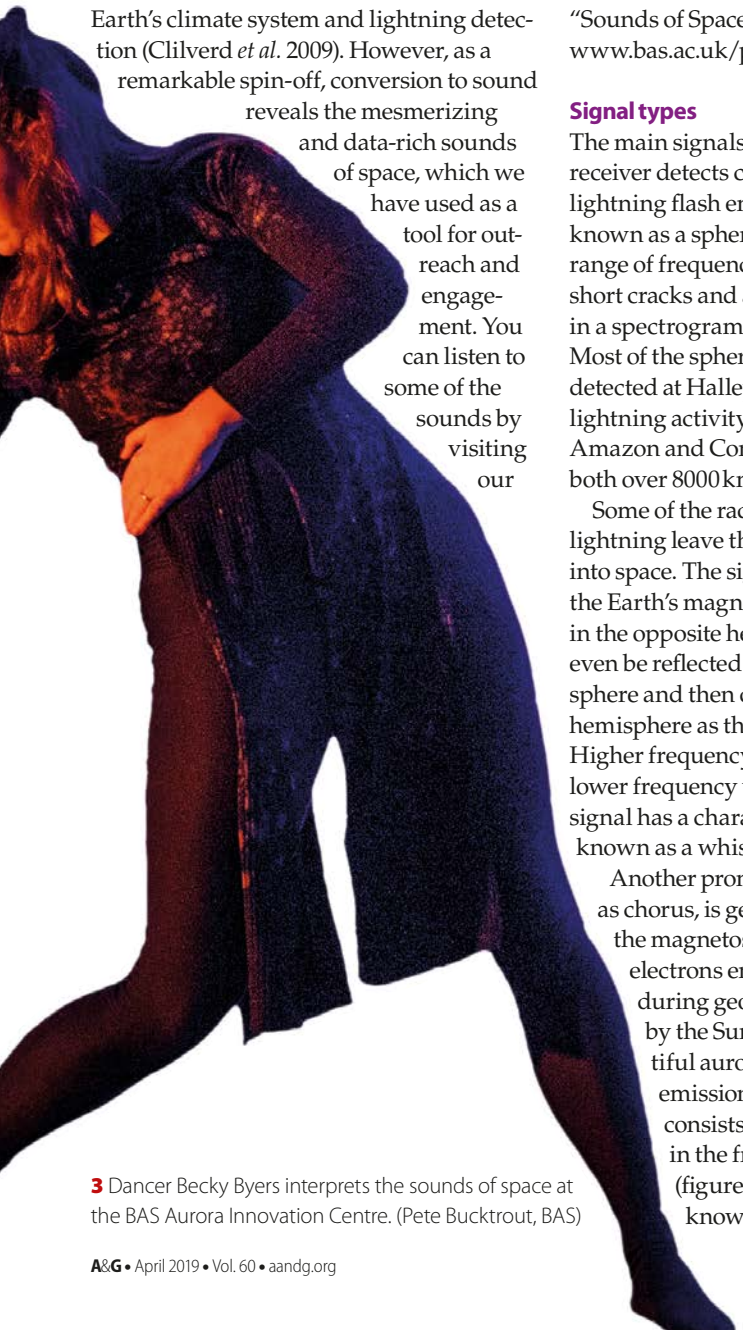
The total isolation of the Brunt Ice Shelf in Antarctica means that the Halley Research Station, operated there by BAS, is a great place to record the sounds of space. It is magnetically connected to the outer radiation belt where some of the natural radio waves are generated and is electromagnetically quiet, being so far from human society. The signals are recorded by the Halley Very Low Frequency (VLF) Receiver, which consists of a pair of orthogonal 58 m^2 single-loop antennas (figure 1), designed to detect the magnetic fluctuations of the low-frequency radio waves. The weak signals are amplified, processed electronically and subsequently digitized at 96 kHz.

The radio-wave data recorded at Halley are primarily used for investigating the science of space weather storms, understanding space weather impacts on the



2 Spectrograms of (a) spherics, (b) whistlers and (c) chorus.

Earth's climate system and lightning detection (Clilverd *et al.* 2009). However, as a remarkable spin-off, conversion to sound reveals the mesmerizing and data-rich sounds of space, which we have used as a tool for outreach and engagement. You can listen to some of the sounds by visiting our "Sounds of Space" web page (https://www.bas.ac.uk/project/sounds-of-space).



3 Dancer Becky Byers interprets the sounds of space at the BAS Aurora Innovation Centre. (Pete Bucktrout, BAS)

Signal types

The main signals a ground-based VLF receiver detects come from lightning. Each lightning flash emits a short radio pulse, known as a spheric, which covers a wide range of frequencies. These are heard as short cracks and appear as vertical lines in a spectrogram (figure 2a). Most of the spherics that are detected at Halley come from lightning activity over the Amazon and Congo basins, both over 8000 km away.

Some of the radio waves associated with lightning leave the atmosphere and leak into space. The signals may be guided by the Earth's magnetic field then received in the opposite hemisphere. They may even be reflected in the opposite hemisphere and then detected back in the same hemisphere as the original lightning strike. Higher frequency waves travel faster than lower frequency waves, so that the received signal has a characteristic descending tone, known as a whistler (figure 2b).

Another prominent signal type, known as chorus, is generated deep within the magnetosphere itself. Energetic electrons enter the magnetosphere during geomagnetic storms driven by the Sun, causing the Earth's beautiful aurora and generating chorus emissions. The most common form consists of rising and falling tones in the frequency range 1–5 kHz (figure 2c). The emissions are known as chorus because they can resemble the twittering of birds at dawn. Chorus is strongest on the dawn-side of the Earth from 4–9 Earth radii (Meredith *et al.* 2012). These waves accelerate electrons to very high energies (Horne *et al.* 2005) and it is important to understand them because these so-called "killer" electrons can damage satellites. We use global maps of these waves in computer models to produce space weather forecasts (Horne *et al.* 2013).

Discovering new sound sequences

We use the data primarily for scientific analysis. Discovering new sound sequences has its own set of challenges because the volume of data we collect is very large. To get a better understanding of the variety of the signals, I worked with five years of digital data from 2012 to 2017. During this period, 1-minute recordings were stored at 15-minute intervals – which comes to 90 minutes of audio data per day. It would take over a year and a half to listen to all these recordings, assuming a normal working day and time off at weekends! We also have periods of 24-hour coverage and archival material on digital audio tapes and reel-to-reel tapes dating back to 1971.

"Some days, space seems to be alive and breathing with the sounds"

Luckily, there are diurnal and seasonal variations in the strength and appearance of the characteristic sounds, so I could target my listening. Winter months tend to be best because the upper atmosphere is in darkness and this is better for the transmission of the signals. Chorus tends to peak around dawn and whistlers tend to peak around midnight. Conditions in near-Earth space also have to be just right; the waves travel in ducts of enhanced or depleted ionization along the magnetic field that may or may not be present on any given day. Some days there are only weak signals and other days space seems to be alive and breathing with the sounds, which can include spherics, whistlers and chorus all at the same time in a veritable symphony of space sounds.

Art–science collaboration

I began working with artist–engineer Diana Scarborough in 2016, as part of the

4 Becky Byers (left), Diana Scarborough (centre) and Kim Cunio (right) during rehearsals for the "Sounds of Space" performance at the BAS Aurora Innovation Centre. During the show, the screen on the right displayed Scarborough's animated visualizations, such as in figure 6. (Pete Bucktrout, BAS)

BAS "Data As Art" project to engage with new audiences (https://www.bas.ac.uk/project/data-as-art). One of our aims was to find novel ways of visualizing space weather data. The sounds of space from Halley formed the starting point of this collaboration and inspired Scarborough to create soundscapes by combining the incredible sounds with original visual sequences.

We have since teamed up with leading Australian composer Kim Cunio and professional dancer Becky Byers to develop the works into a truly multidisciplinary show. Our first show, which included a scientific presentation followed by a performance with animation, contemporary dance and soundscapes, was performed at the Cambridge Science Festival in March 2018. Following on from the success of this event, Cunio travelled from Australia to play live in our second show. This event, which was performed at the BAS Aurora Innovation Centre in November (figure 4), was streamed live on the BAS YouTube channel where it can be viewed in its entirety (https://www.youtube.com/watch?v=F35SLqBEFw8).

The science

The science presentation, which is an integral part of our "Sounds of Space" performance, takes the audience on a journey beginning at Halley, and moving out into near-Earth space, introducing chorus and whistlers recorded *in situ* by NASA's Van Allen Probes. These signals have a pure beauty because the spherics – ever-present in recordings on the ground – are absent in space. We then leave the Earth behind and travel to Jupiter to reveal similar sounds recorded by Voyager 1 deep inside the immense jovian magnetic field. We then reveal some ethereal sounds from comet 67P/Churyumov–Gerasimenko and Saturn, recorded by Rosetta and Cassini respectively, which evoke a sense of loneliness and poignancy. While these sounds were not initially produced in the audio-frequency range, they produce some amazing and rich new sound-types.

Journeying deeper into space, we present various beats from pulsars in our own galaxy, recorded by radio telescopes in the UK and Australia. These rhythms, which have periods ranging from milliseconds to seconds, are strident and unceasing – quite a contrast to the comet sounds. We then leave our galaxy far behind and introduce some oddly quixotic sounds from colliding neutron stars and merging black holes, recorded by the LIGO interferometers in America. These sounds have been produced directly from gravitational waves, ripples in the fabric of space-time, that also lie in the audio-frequency range. The chirps sound almost comical and yet they are hugely important in our understanding of some of the most violent and energetic processes in the universe. Finally, we complete our tour and return to Earth to listen to the crackles and pops of air bubbles being released from ancient Antarctic ice, which have their own other-worldly beauty – and sound remarkably like some of the space sounds.

"The raw sound is so beautifully powerful and ongoing, but at the same time lonely"

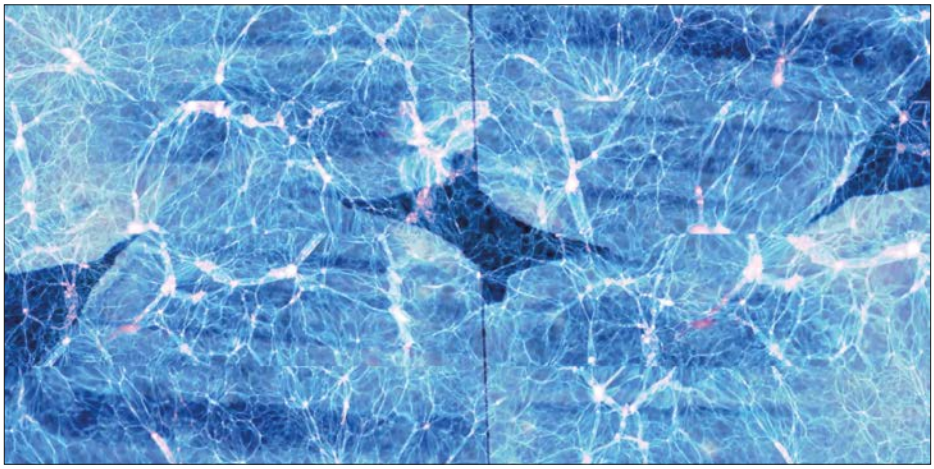
The performance

The performance at the heart of "Sounds of Space" came about from collaboration. "Hearing the sounds of space for the first time was a beautiful and moving experience," said Scarborough. "To enhance and interpret this from an artistic perspective, I wanted to lay down soundtracks where the 'data as audio' and music create animation soundtracks as a series of conceptual conversations inspired by the sound-sourced journey beyond the galaxy. This needed a talented composer and musician who is similarly inspired and this is where Kim came in. This is truly a science and sound-led performance where the visuals and dance are the rich accompaniments."

Dancer Byers provides a physical, bodily reaction, alongside the music and visual art (figure 3). She describes how internalizing the space sounds and transferring them to movement has been a playful and fun challenge: "I imagine each sound to be its own creature such as a small scuttling insect for the Antarctic ice, or a large bull-like powerhouse of energy for Saturn's radio emissions." This personalization allowed her to explore the characteristics and emotions of the sounds in order to develop movements specific to each sound and its location in space. Byers finds the comet data particularly poignant: "The raw sound is so beautifully powerful and ongoing, but at the same time lonely. It is persistent in its journey, but longing for a connection." She translates this into looped and repetitive movements in the upper body and arms, while travelling in a circle to highlight the journey and developing power of the sound. These movements are interspersed with choreography involving the whole body that yearns and draws in to the centre of the circle, highlighting the need for a connection in the orbit.

In the second show, Cunio accompanied the soundscapes with improvisations on a keyboard and on a replica of an ancient instrument called a psaltery. On one of the pieces, his son Samarai accompanied the soundscape from pulsars and colliding neutron stars with energetic tabla

5 The Elite Dangerous game. (Frontier Developments)



6 Still from one of the short films to be screened at the Venice Biennale. (Diana Scarborough)

drumming. "Some of the sounds that we are working on are really musical so it is quite easy for me to notate them," said Cunio. "I then compose a short score. From there I can improvise over that, moving in and out of the original material."

Space acoustic ecology

In a separate project, we plan to release time-lapse audio and full-day recordings from the VLF Receiver at Halley as the first part of a "space acoustic ecology" project, exploring how these data, in audible form, can inspire others. We envisage that the Halley Research Station will act as an artist with the Australian National University Music Press and release *A Day in the Life of Halley*, making the recordings available for musicians and artists to take forward in separate projects with a view to producing exciting new music and art.

As part of this venture, Cunio has already combined some of his unique piano music with a day of time-lapse audio from Halley. The new work, *Aurora Musicalis*, comprises 13 individual pieces, combining piano music with VLF recordings from different times of the day. Each piece is named according to the mood of the music and the time the VLF signals were recorded. For example, *Late Night Jazz* includes spherics and whistlers recorded at 2.05 a.m., while *A Hymn for the Exploding Evening Sky* includes spherics and chorus from 7.05 p.m. It is both fascinating and awe-inspiring to listen to the amazing sounds of space accompanied by piano music; the complete work reveals the diurnal variations of the audio-frequency signals.

"It is awe-inspiring to listen to the sounds of space accompanied by piano music"

Space-simulation video game

By chance, an audio engineer from the company Frontier Developments happened to be in the audience at one of our events at BAS in March 2017. His interest led to a partnership to incorporate the sounds from Halley into the space-simulation video game Elite Dangerous (figure 5).

For this project, I provided the Elite Dangerous team with more than 200 one-minute audio files from Halley, including many different varieties of whistlers and chorus. The information made quite an impression on Joe Hogan, lead audio designer for Elite Dangerous: "My mind was a little blown when I first listened to the sounds. I had no idea that solar wind and atmospheric phenomena could cause such a complex and evolving soundscape with so many shifting components," he said. "It sounds like a living ecosystem, wild and unpredictable. Some sound like animals in the jungle, some sound like random radio static, and some contain dreamlike tones. It's all quite raw, but there is a beauty and mystery there."

Elite Dangerous features a full-size galaxy with billions of unexplored star systems. Hogan worked with the VLF recordings from Halley and used audio techniques to separate out different characteristic sounds which were then incorporated into the new exploration gameplay. Players can now detect the radio emissions from distant planets in order to locate and identify them. Each sound represents a specific planetary property, much as they do in real life. Commenting on the new feature, Hogan said: "We wanted the player to feel like a scientist making new discoveries, like they are tuning an old analogue radio, focusing in on signals from planets, stars and more, to locate objects to visit. The fact that the BAS sounds are literally radio signals makes this a perfect match, both scientifically and aesthetically."

What next?

We are really pleased with the reception of this art–science collaboration so far. We plan more shows for 2019 and look forward to seeing what comes out of the space acoustic ecology project. We are also delighted to announce that eight one-minute short films, based on the animations, music and space sounds from our show, have recently been accepted as part of a film installation at the Venice Biennale, a world-class international art exhibition. They will be screened from 8 May to 4 June at the historic Palazzo Pesaro Papafava, as part of "Alive in the Universe", an art-film project that explores the emotional understanding of the universe through arts and ideas. This is a very exciting development and demonstrates the potential for art–science collaborations at the highest echelons of the art world (figure 6). ●

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MORE INFORMATION

Diana Scarborough http://dianascarborough.co.uk
Kim Cunio https://researchers.anu.edu.au/researchers/cunio-ke

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