CAP journal

Issue 32 | June 2023

Communicating Astronomy with the Public

SPECIAL EDITION

HIGHLIGHTS FROM CAP CONFERENCE 2022

What are CAP Conferences?

Join the international forum for astronomy communication.

The Power of Awe

How can astronomy help those with anxiety and depression?

Describe Your Universe

By making our outreach accessible, we invite a wider audience to experience the wonders of the cosmos.

www.capjournal.org

IAU

In April 2023, the IAU Office of Astronomy for Education (OAE) announced its third astrophotography contest. The OAE Astrophotography Contest aims to provide high-quality images of the night sky as open educational resources. This year's edition will feature a number of categories, including a smartphone astrophotography category sponsored by the Office for Astronomy Outreach (OAO). After the conclusion of this contest, the OAO will host a virtual exhibition and gala for all the winners and honourable mentions to share and discuss their work and their relationship with the night sky. For more information about the contest, see their website: https://astro4edu.org/oae-astrophoto-contest-2023/

IAU's Office of Astronomy for Education

Astrophotography Contest 2023

2023 Categories:

- Images of phases of Venus
- Images of day arc of the Sun and solargraphs
- Images of sunrise and sunset locations over the year
- Time lapses of rotation of Big Dipper or Southern Cross
- Images of any astronomical object taken exclusively with smartphones/mobile devices

For details, please visit: **https://astro4edu.org/oae-astrophoto-contest-2023/**

This is a joint venture with the OAE Center Italy and the IAU's Office for Astronomy Outreach

Submission deadline: 30 June 2023

Editorial

As we wrap up our celebration of dark and quiet skies, the Office for Astronomy Outreach Team wishes you countless nights unaffected by light pollution. We hope you are able to experience the awe of seeing a sky awash with stars.

This Special Edition of CAPjournal celebrates the work featured at the Communicating Astronomy with the Public Conference, which took place in September 2022. This conference turned a new page for CAP as the first hybrid conference that took place in-person in Sydney, Australia, and online.

For this edition of CAPjournal, we asked Ramasamy Venugopal and Samir Dhurde (the co-chairs of the CAP Conferences Working Group), as well as Richard Tresch Fienberg (former president of IAU Commission C2), and Oana Sandu (current president of IAU Commission C2) to give us an overview of how these conferences have evolved.

This edition, which is presented in lieu of a proceeding (though this certainly does not cover the breadth of what was discussed at CAP 2022), features four of the top talks presented at the conference.

Libraries are a place of endless imagination, including imagining yourself in a STEM career. In our first article, *Cosmic Curiosity: Why collaborating with libraries results in impactful family engagement with astronomy,* the author presents a collaborative project that aims to engage parents and carers for the benefit of child STEM identity and career development. To ensure these youngsters have a chance to fulfil their dreams of becoming aerospace engineers, astronauts, or planetary geologists, there must first be an Earth on which to study these fields. The article *Driving action on the climate crisis through Astronomers for Planet Earth and beyond* presents the international organisation, *Astronomers for Planet Earth,* which aims to encourage astronomers to critically look at our practices here on Earth while we study the cosmos above. Our next article asks how astronomy can benefit humanity outside its intellectual pursuits. *The astronomy for mental health guidelines: A living document for the community* focuses on the power that astronomy has to inspire awe, curiosity, and change mindsets. This article presents the *Astronomy for Mental Health Guidelines*, which is a collaboratively built set of recommendations to build programmes that have been shown to improve mental health and well-being. Our final article, *An accessibility case study incorporating rich visual descriptions for* Chanra's *high-energy universe*, makes the wonders of astronomy available to all through touch, sight, and sound. This article presents three case studies that highlight unique ways to bring more people into the conversation of astronomy by providing resources and pathways to engage with astronomy.

All of these articles exemplify the theme of CAP 2022: *astronomy for a better world.* We are hopeful that through these works — and the many others shared at CAP 2022 — we will discover new ways to collaborate, build bridges, and understand our Universe just a little bit better.

Lina Canas
Editor-in-Chief

Kelly Blumenthal
Managing Editor

Cover: This issue of CAPjournal celebrates a select few of the highlights from CAP Conference 2022. Though it took place in person in Sydney, Australia, people from 43 different countries tuned in to share their knowledge and learn. Though the Covid-19 pandemic was devastating for millions of people around the world, it taught us the value of connection, both personally and professionally. Hybrid meetings, like CAP 2022, afford us a bright future in which we can gather perspectives from all over the world.

Contents

Communicating Astronomy with the Public Conference 2022 – At a glance 4

IAU Selects Names for 20 Exoplanetary Systems – The NameExoWorlds global contest names the next set of exoplanets and host stars 5

Explained in 60 seconds: CAP – Communicating Astronomy with the Public Conferences 8

Cosmic curiosity: Why collaborating with libraries results in impactful family engagement with astronomy 9

Driving action on the climate crisis through *Astronomers for Planet Earth* and beyond 15

The Astronomy for Mental Health Guidelines: a live document for the community 21

An accessibility case study incorporating rich visual descriptions for *Chandra's* high-energy universe 25

Communicating Astronomy with the Public Conference 2022 – At a glance

Kelly Blumenthal
IAU Office for Astronomy Outreach
blumenthal.kelly@oao.iau.org

Ramasamy Venugopal
CAP conferences Working Group chair
rv@astro4dev.org

Richard de Grijs
LOC Chair
richard.de-grijs@mq.edu.au

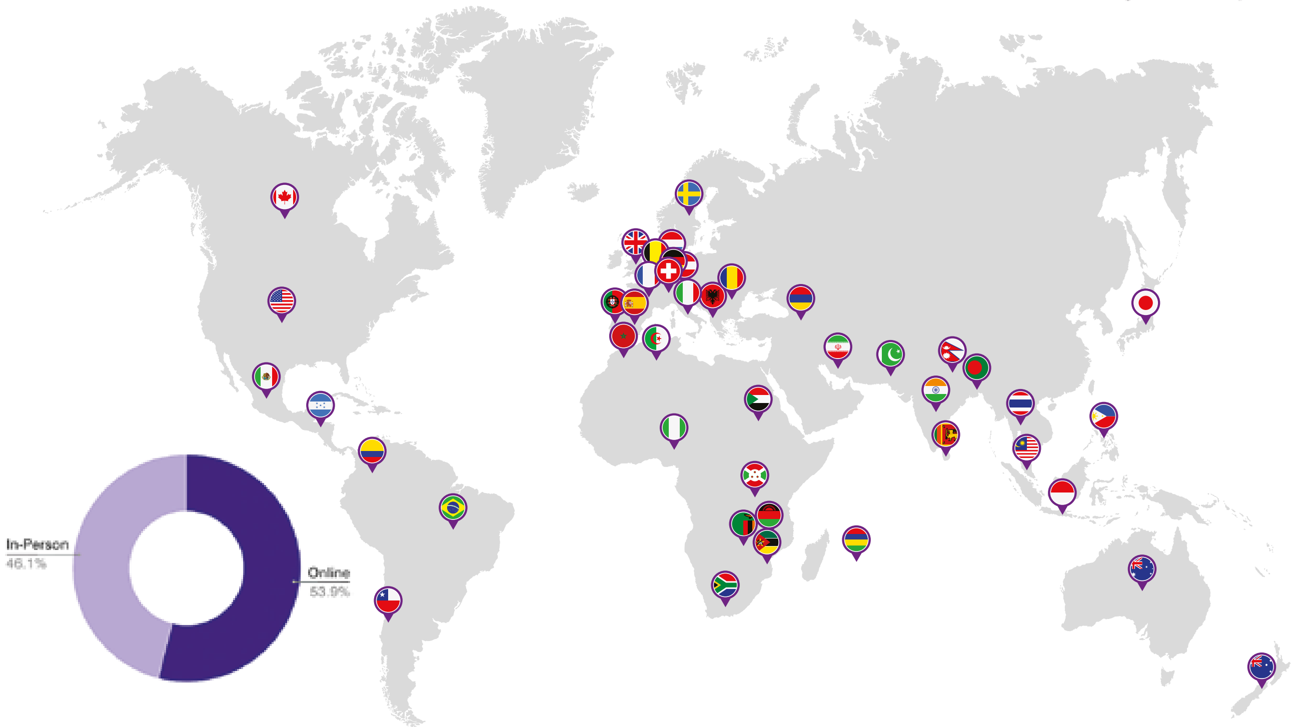
Lina Canas
IAU Office for Astronomy Outreach
lina.canas@nao.ac.jp

Samir Dhurde
CAP conferences Working Group chair
samir@iucaa.in

The world's largest conference on astronomy communication, Communicating Astronomy with the Public Conference, was held from 12-16 September 2022. This edition was held in-person at Macquarie University in Sydney, Australia and online – the conference series's first hybrid event. It was co-organised by the International Astronomical Union (IAU) Commission C2 – Communicating Astronomy with the Public (CAP) and the IAU Office for Astronomy Outreach.

The conference featured 5 keynote speakers, 30 invited talks, 92 parallel talks, two discussion panels, 13 workshops, and 48 posters, in addition to our online programme, which featured meet-ups, virtual poster sessions, a lightning poster session, and more. The participants represented 44 different countries. Of the 111 in-person and 130 online participants were professionals from science communication, informal education, planetariums and science centres, as well as professional and amateur astronomers, journalists and artists.

Throughout the five-day conference, our diverse group of both online and in-person participants gathered together to address our central theme: "Communicating Astronomy for a Better World." They addressed a wide variety of topics, from astronomy communication in planetariums to the role of astronomy in bridging cultures to current challenges in astronomy communication. We look forward to the exciting conversations you all will engage in during the next CAP Conference online and at Cité de l'espace in Toulouse, France, in June 2024. Nous espérons vous y voir [*We hope to see you there*]! For more information, see the CAP Conferences website: https://capconferences.org/



IAU Selects Names for 20 Exoplanetary Systems – The NameExoWorlds global contest names the next set of exoplanets and host stars

Lina Canas
IAU Office for Astronomy Outreach
lina.canas@nao.ac.jp

Suzana Filipeki Martins
IAU Office for Astronomy Outreach
suzana.filipeki@oao.iau.org

Gonzalo Tancredi
Departamento de Astronomía, Facultad de Ciencias, Udelar
gonzalo@fisica.edu.uy

Lars Lindberg Christensen
International Astronomical Union
lars.christensen@noirlab.edu

Eric E. Mamajek
Jet Propulsion Laboratory/California Institute of Technology
mamajek@jpl.nasa.gov

The International Astronomical Union's NameExoWorlds 2022 contest has selected 20 pairs of names for exoplanets and their host stars. The contest was organised within the framework of the celebrations of the 10th anniversary of the IAU Office for Astronomy Outreach (OAO). With 603 entries from 91 countries, the campaign attracted over 8,800 individuals working in teams, who put forward outreach initiatives that stimulated the direct participation of almost 12 million people worldwide.

The NameExoWorlds 2022 contest was set up to recognise and honour the efforts of the people who have been making it their life's work to popularise astronomy in an accessible and public-friendly way to their communities. The contest was open to anyone to form a team, implement an astronomy outreach event and propose a name for one of the 20 exoplanetary systems, each with one known exoplanet and its host star. The star and planet names were to be connected by a common theme, allowing other planets, if discovered in future, to be named following the same theme. These 20 systems were selected as they were among the first exoplanetary systems targeted for observations by JWST[1].

The contest attracted over 8800 professional and amateur astronomers, students and teachers, and astronomy enthusiasts in teams that hosted astronomy events. From intimate events for neighbours to large online lectures, the astronomy outreach events created for *NameExoWorlds 2022* showcased the diversity and creativity that is possible in astronomy outreach practices. For example, students from the JaHo School in Taipei created a participatory game that helped the public engage with the JWST[1], while students at Chittagong International School in Bangladesh created a gender-inclusive, week-long festival that included exhibitions, Q&A sessions, and film screenings.

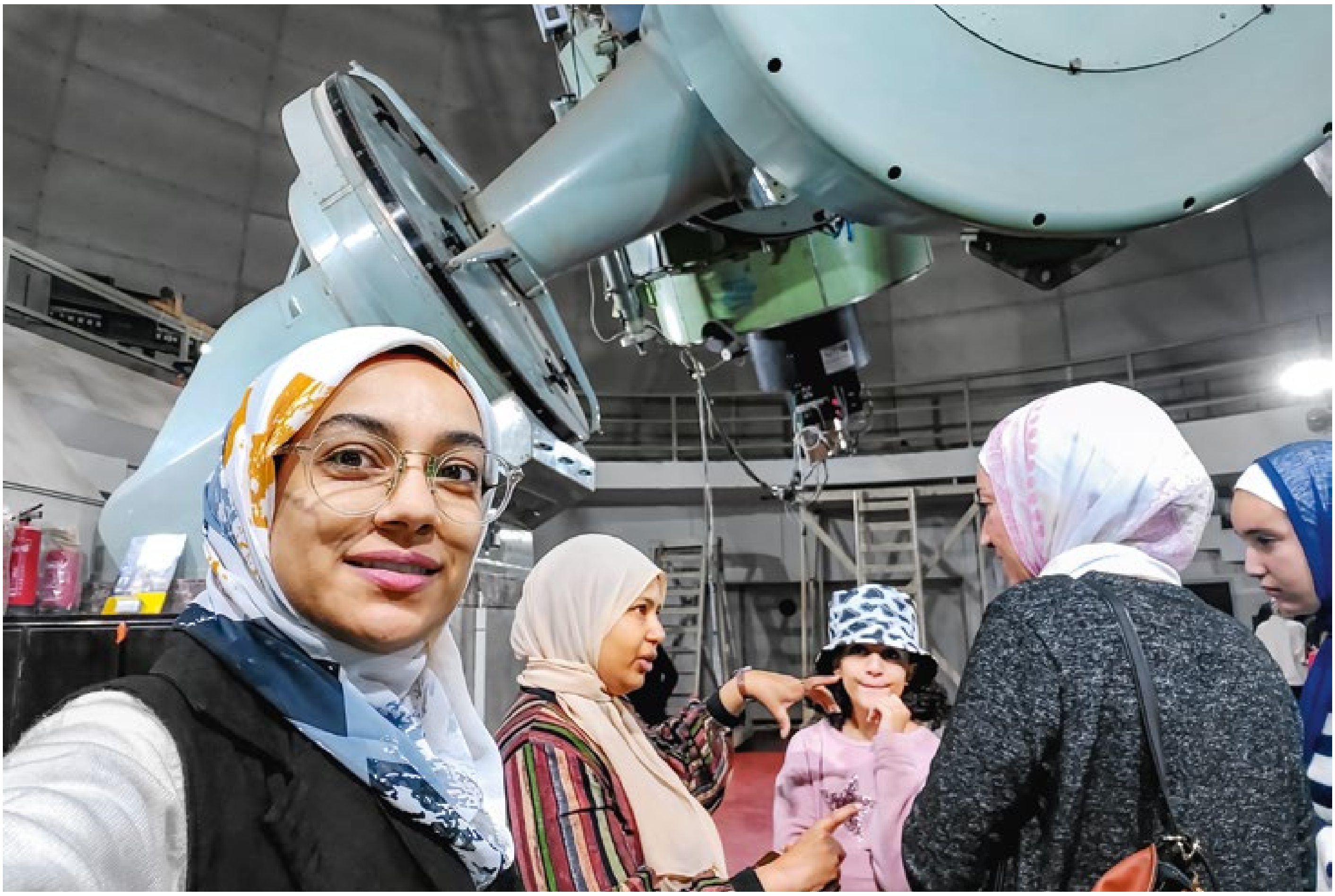
Through the *NameExoWorlds* initiatives, the IAU recognises the importance of the connections between the sky and our diverse cultures. In recognition of this link and of the UN International Year of Indigenous Languages 2019, speakers of Indigenous languages were encouraged to propose names from those languages. Seven of the selected names are of Indigenous etymology.

The newly adopted names[2] honour native fauna and flora with cultural significance, for example, **Batsũ̀** (LHS 3844) & **Kua'kua** (LHS 3844 b), from Costa Rica, are the words in Bribri Language for hummingbird and butterfly; while **Wattle** (WASP-19) & **Banksia** (WASP-19 b), and **Añañuca** (GJ 367) & **Tahay** (GJ 367 b) are names of native flora of Australia and Chile, respectively, whose characteristics allude to the properties of the celestial objects. Selected names also highlight significant geographical landmarks: **Zembra** (HATS-72) & **Zembretta** (HATS-72 b) are UNESCO biosphere reserves in Tunisia, while **Wouri** (WASP-69) is a river in Cameroon & **Makombé** (WASP-69 b) its tributary.

Some names also celebrate literary works, such as **Kosjenka** (WASP-63) & **Regoč** (WASP-63 b), which refer to the work of Croatian writer Ivana Brlić-Mažuranić, and **Filetdor** (WASP-166) & **Catalineta** (WASP-166 b) which refer to Mallorcan folktales recorded by writer Antoni Maria Alcover i Sureda. Other names celebrated folktales, mythologies and lore from around the world, including words in Maa, Cherokee, Taino, Zoque, Chinese, and Korean. The full list of selected names can be found on NameExoWorlds website[3].

Several notable exoplanets were named in this campaign. The benchmark transiting exoplanet GJ 1214 b — one of the most-studied 'sub-Neptune' planets intermediate in size between Earth and Neptune — received the name **Enaiposha**, which refers to a large body of water like a lake or sea in the Maa language of Kenya and Tanzania. Two well-studied hot-Neptune exoplanets, designated GJ 436 b and GJ 3470 b, that orbit very close to their stars, but on highly inclined orbits nearly perpendicular to their star's equator, and show observational evidence for evaporating atmospheres, were also named. GJ 436 b was named **Awohali** — Cherokee for eagle — referring to a legend in which an eagle was sent to the Sun by a warrior to deliver a prayer. GJ 3470 b was named **Phailinsiam** — Thai for blue Siamese sapphire — alluding to the blue colour of the planet inferred from the detection of Rayleigh scattering in its atmosphere. The recently discovered hot sub-Earth-sized exoplanet GJ 367 b orbits its star every eight hours, and has a density that suggests it is a very iron-rich planet like Mercury. It has been named **Tahay,** after a flower that blooms for only about eight hours every year, similar to the length of the 'year' for this ultra-short-period planet. Awohali, Phailinsiam, Tahay all orbit nearby red dwarf stars within 33 light-years of Earth.

At the core of the decision process to select these 20 names were members of the Executive Committee WG Exoplanetary System Nomenclature[4], in consultation with the discoverers of the planets, who joined for the selection of the new names from 134 national entries[5].



Students join the Kottamai Observatory staff for two open days organised in the context of NameExoWorlds 2022 on 18 and 19 November 2022, in Cairo, Egypt. Image credit: National Research Institute of Astronomy and Geophysics/ Photographer: Eman Fathy Noureddin Mohamed.

Eric Mamajek, chair of the *NameExoWorlds 2022* campaign, noted, "The thoughtful names for these recently discovered planets and their stars, show that IAU public naming campaigns can draw upon the imagination of people around the world."

Debra Elmegreen, IAU President, remarked, "Congratulations to those who proposed winning names for these exoplanetary systems, and to everyone who entered. This large engagement of school children, the public, and professional astronomers in the competition is a fitting tribute to the efforts of the IAU Office for Astronomy Outreach over the past decade. Many thanks to the Working Group on Exoplanetary System Nomenclature and the OAO for running the competition."

The text of this piece was originally published as an IAU Press Release on 7 June 2023[6].

Notes

[1] The systems selected in 2022 are of special interest, as they are among the first exoplanet targets of the JWST. This international space observatory, led by NASA with its partners, the European Space Agency and the Canadian Space Agency, saw first light in July 2022. The newly named exoplanets have been discovered via a mix of techniques, mostly the transit method, direct imaging, and radial velocity method.

[2] The winning names will not replace the scientific alphanumeric *designations*, which already exist for all exoplanets and their host stars, but they will be sanctioned as IAU-adopted *names* and will be publicised as such. Due credit will be given to the communities that proposed them. These public names may then be used freely worldwide, along with, or instead of, the original scientific designation.

[3] The NameExoWorld 2022 results can be found on the project website: https://nameexoworlds.iau.org/

[4] The Executive Committee WG Exoplanetary System Nomenclature is an IAU Working Group tasked with providing advice on guidelines for the naming of exoplanets and their host stars, as well as supporting the IAU's public naming campaigns for exoplanetary systems.

[5] The lead author of the discovery paper for the exoplanet, or a coauthor (either delegated by the first author, or selected by the panel if the first author did not respond), was invited by the panel to participate in the *NameExoWorlds 2022* campaign. They were given the choice of either providing input to the panel on the naming selection (after reviewing the leading naming proposals for that system) or participating on a team that proposed names for the system — but they could not do both. Most elected to provide input to the panel on the top proposals for a particular system from the various national campaigns.

[6] The original press release can be found on the IAU website: https://www.iau.org/news/pressreleases/detail/iau2304/

In late April of this year, a massive geomagnetic storm in the Earth's magnetosphere produced an impressive display of the Aurora Borealis close to the Arctic Circle and as far south as the border between Mexico and the United States. This image was captured during this storm from Xinjiang, China, where the storm displayed beautiful red and pink hues across the starry night sky.

Jeff Dai

Column

Explained in 60 seconds: CAP – Communicating Astronomy with the Public Conferences

Ramasamy Venugopal
CAP conferences Working Group chair
rv@astro4dev.org

Samir Dhurde
CAP conferences Working Group chair
samir@iucaa.in

Richard Tresch Fienberg
American Astronomical Society,
Past President, IAU Commission C2
rick.fienberg@aas.org

Oana Sandu
President, Commission C2,
Communicating Astronomy with the Public
osandu@partner.eso.org

The Communicating Astronomy with the Public (CAP) Conference brings together professionals from around the world to exchange ideas and practices on astronomy communication. It is organised by the CAP Conference Working Group, under IAU Commission C2, and the Office for Astronomy Outreach.

Early history — Bringing the community together

The CAP conference series traces its origin to "Communicating Astronomy," an international meeting held in February 2002 in Spain (*Instituto de Astrofisica de Canarias (IAC), 2002*). Organised chiefly by Terry Mahoney of the IAC Scientific Editorial Service, the conference attracted nearly 70 participants and addressed a variety of topics in publishing, broadcasting, education, and public outreach. Most presentations concerned academic publishing, yet among the attendees were numerous public information officers, science journalists, and others working as intermediaries between astronomers and the public. One of them, Charles Blue of the U.S. National Radio Astronomy Observatory, decided to organise a meeting for that constituency.

The "Conference on Communicating Astronomy to the Public" convened in October 2003 in Washington, D.C., and attracted nearly 250 participants (*Blue, 2010*). It led to some significant outcomes, including a draft of the Washington Charter for Communicating Astronomy *with* the Public (*Robson, 2007*), the establishment of a working group that eventually became the International Astronomical Union (IAU) Commission 55 (now C2), and a commitment to hold Communicating Astronomy with the Public (CAP) conferences every two to three years. The first one held under the auspices of the IAU was CAP 2005 at the European Southern Observatory Headquarters in Germany. CAP 2007 in Greece played a central role in planning the International Year of Astronomy 2009 (IYA2009), while CAP 2010 in South Africa focused on the outcome of the IYA2009 activities, their evaluation, and plans for future work. It was during the planning for this conference that organisers introduced key topics to unite the conference under a single theme. This structure has been adopted for all subsequent CAP conferences beginning with CAP 2011 in China.

2013-2016 — Professionalisation of the conference

In 2013, after the CAP conference in Poland, the working group implemented a survey among participants that provided the basis to set new standards for the conference: more robust evaluation of conference hosts and submissions; extended programme with workshops, networking sessions, and parallel sessions; high-level invited speakers; and increasing participant numbers. CAP 2016 saw about 250 participants, while CAP 2018 had almost 450.

2016-2018 — Sustainability and inclusion

To be more mindful of the environment, the working group introduced criteria to encourage 'green' conferencing practices. As of 2016 in Colombia, this included the use of sustainable accommodation and transportation, the elimination of single-use plastic, and the reduction of print products, as well as recycling.

Another priority was to make the conference more inclusive. The topic of Diversity, Inclusion, Equity and Empathy was added as one of the sub-themes of the conference. In addition, conference hosts were asked about practical steps to ensure inclusivity, such as the provision of daycare, a quiet room, and accessibility of venues to people with disabilities.

2021-2022 — Virtual and hybrid

After the highly successful 2018 conference in Japan (*Canas, Agata, Yamaoka, & Karino, 2019*), the CAP conference had to move online during the Covid-19 pandemic. The first virtual CAP conference attracted 1,000 participants from 87 countries, who spent, on average, 17 hours attending talks and poster sessions, participating in workshops, and networking (*CAP Conference 2021, 2021*). Due to the continued uncertainty in global travel and to accommodate participants, the 2022 conference was held in hybrid mode — in Australia and online. Future events will likely continue in this hybrid format, enabling more participants to learn from and contribute to the rich discussions.

Since 2005, nine CAP conferences have been organised with more than 10,000 participants. The conference series has provided a space for the growing, diverse, global community of astronomy communicators to meet, learn, exchange ideas, and collaborate. We are grateful to the IAU and supporters, as well as the global team of volunteers who run the conference.

References

Blue, C. (2010). 20 -Communicating astronomy to the public. In C. Blue, *Teaching and Learning Astronomy Effective Strategies for Educators Worldwide* (pp. 235 -237). Cambridge University Press. From https://www.cambridge.org/core/books/abs/teaching-and-learning-astronomy/communicating-astronomy-to-the-public/A84BD83703CEF49069401D1D738F46F8

Canas, L., Agata, H., Yamaoka, H., & Karino, S. (2019). Behind the Scenes of CAP2018 Japan: Producing the Largest Astronomy Communication Conference to Date. *CAP journal*, 07.

CAP Conference 2021. (2021). *CAP 2021 Virtual Conference*. From CAP 2021 Virtual Conference: https://www.communicatingastronomy.org/cap2021/

Instituto de Astrofisica de Canarias (IAC). (2002). *Communicating astronomy: an international conference*. From Communicating astronomy: an international conference: http://research.iac.es/proyecto/commast/

Robson, I. (2007). Communicating astronomy with the public and the Washington Charter. In A. Heck, *Organizations and Strategies in Astronomy Vol 7, Astrophysics and Space Science Library Vol 343*. Springer. https://doi.org/10.1007/978-1-4020-5301-6_26

Cosmic Curiosity: Why collaborating with libraries results in impactful family engagement with astronomy

Nuala O'Flynn
University of Hertfordshire
n.oflynn@herts.ac.uk

Keywords
Outreach, Public Engagement, Community, Children, Storytelling, Co-creation

The University of Hertfordshire Department of Physics, Astronomy and Mathematics (PAM) Outreach and Public Engagement (OPE) Team offer wide-ranging and impactful activities and events. The Team's goal is to support and maintain the science capital of young people in underserved and underrepresented communities in physics, astronomy and maths with the hopes they will one day study one of these subjects at a higher level. A young person's decision to choose to continue with the physical sciences is a complex one, but their parents or carers have a great deal of influence. However, in astronomy, we often leave parents and carers out of our outreach. Public libraries, on the other hand, often specifically target families and offer a welcoming and informal setting to learn. For example, they often run storytelling sessions for young families, though these are rarely focused on STEM (Science, Technology, Engineering and Math). Therefore, libraries promise enormous potential for STEM and astronomy outreach with young children aged 4-7 and their parents and carers. From this realisation, Cosmic Curiosity: Stories that Spark the Imagination was created in collaboration with the Hertfordshire Library Services. In this article, we will demonstrate how engaging families in libraries results in impactful and sustainable engagement.

Introduction

Cosmic Curiosity is a collaborative project between the University of Hertfordshire's Department of Physics, Astronomy and Mathematics (PAM) and Hertfordshire Libraries in the United Kingdom (UK). For this project, we collaborated with four partner libraries located in the top 20% of the Index of Mulitple Deprivation rankings in Hertfordshire (*"Index of Multiple Deprivation Herts Rank," 2019*). The IMD takes into account various factors such as income, employment, education, health, and crime rates to assess the relative deprivation of different areas.

The project was funded by a Science and Technology Facilities Council (STFC) Spark Award and targeted children aged 4-7 and their parents and carers. We ran four sessions in each library and themed each session around a career in space science (Table 1). During the sessions, one of the librarians read a story that was linked to the space career featuring diverse gender and ethnicity role models, which was followed by an astronomy activity (Figure 1) and concluded with an additional activity which participants were able to take home with them. We also purchased multiple copies of 25 STEM books for the project that were related to the careers that participants could borrow from the library and ran a STEM book loyalty card scheme so that every time a library member took out a STEM book, they received a stamp. After filling the card with four stamps, the participant received a bookmark as a reward (Figure 2). The 25 STEM books were given to a total of 11 libraries, four of which were our specific partner libraries where we ran the Cosmic Curiosity storytime sessions, three were where we just ran the STEM book loyalty card scheme, and an additional four libraries were used as a control comparison which had no specific engagement. We interacted with a total of 218 participants (including parents, carers and children). In total, 69 families gave demographic feedback in the questionnaire. Of the 69 parents and carers, 81% identified as women. Of the 77 children, 44% of them identified as girls.

With these sessions, we aimed to increase the interest of the local community in astronomy and STEM in libraries, to create a long-lasting partnership between the Department of PAM and Hertfordshire libraries, and to broaden families' awareness of the possibilities in astronomy and STEM fields.

We utilised a mixed-method approach to evaluation. For the attending families, we collected data through short questionnaires asking for feedback and demographic data. We gauged participants' opinions of scientists by drawing a scientist at the start of each session. Then, participants placed themselves on a scale of comfortability with science that we depicted with different chairs.

Session and linked career	Linked Book Title	Linked Activity	Linked at-home Activity	NUSTEM STEM Attributes (NUSTEM, 2020)
You could be an… Astronaut	Astro Girl	Astronaut Glove Box	Eating like an Astronaut	Collaborative, Communicative, Hard-working
You could be an… Aerospace Engineer	Meet the Planets	Straw Rocket	Bottle Rocket	Creative, Passionate, Tenacious
You could be an… Astronomer	Look Up	Constellation Tube	Galaxy Model	Open-minded, Self-motivated, Patient
You could be a… Planetary Geologist	Moon	Make a Moon Crater	Tracking the Moon Phases	Observant, Curious, Creative

Table 1. *Summary of Each Session*

Figure 1: *An outreach practitioner demonstrates to children how a rocket takes off before they make their own straw rocket. NUSTEM career characteristics are visible in the background. Image Credit: Hertfordshire Library Service*

The least comfortable chair was a stool, and the most comfortable chair was a large armchair. We used two snap-shot interviews, a short form of interviewing in which one or two questions are incorporated into a general conversation with participants. We used these to find out if we were meeting the needs and expectations of families. For those who returned for more than one session, we additionally asked if they carried out science activities after the sessions. We had post-session meetings and feedback forms for event facilitators that looked at ways to improve sessions and boost staff confidence in the practice of STEM delivery. We also tracked the number of participants attending and how many of our project STEM books were issued from the libraries.

It has been shown that public libraries are a successful and beneficial partner for universities (e.g., *Pekacar, 2017*) and, specifically, astronomy/STEM outreach (e.g., *Percy, 2017*). The inverse is also true: these collaborations have proven to be valuable to the library partner as it boosts their STEM offerings (e.g., *Shtivelband et al., 2017; LaConte, 2019*). However, higher education as a sector does not commonly partner with libraries. In this article, we will outline the importance and benefits of co-creating projects with libraries, why it is crucial to include parents and carers in outreach, why discussing and highlighting STEM careers is vital, and how to sustain engagement in a library setting.

Benefits of a university-library collaboration

The Department of PAM's OPE team initially reached out to Hertfordshire Libraries with the project idea of STEM/astronomy storytime sessions for families, and we found this idea aligned with many of their and our strategic aims.

Hertfordshire Libraries follow the Universal Library Offers (*Libraries Connected, 2018*), which aims to build a literate and confident society by developing and promoting creative reading activities in libraries. This project also supported the information and digital offer, ensuring local communities have access to quality information and access to creative and innovative technology. Finally, underpinning the Universal offers is "The Children's Promise", developed by The Association of Senior Children's and Education Librarians (ASCEL), which aims to ensure that children are inspired and have access to a range of inclusive and diverse books, and other information resources to support their literacy, learning, health and wellbeing, as well as imaginative cultural opportunities. Therefore, this project aligned well with some of Hertfordshire Libraries' strategic aims.

One of our strategic OPE goals in the Department of PAM is to support and maintain the science capital of people in underserved and underrepresented communities (*O'Flynn & Burningham, 2020*). Libraries are familiar and trusted learning spaces, free to all, and often located in the centre of cities and towns (e.g., *Shtivelband et al., 2017; UK Government, 2017*). Additionally, libraries also remove barriers around inconvenience and intimidation that a participant may feel in having to come onto a university campus. For this project, we collaborated with four libraries located in the top 20% of IMD rankings in Hertfordshire, with local surrounding areas of the library being mostly 20-40% (*"Index of Multiple Deprivation Herts Rank," 2019*). Therefore, partnering with libraries enabled us to meet our strategic aims and reach these target communities, with which we otherwise would not be engaging.

We also found that although libraries offer wide-ranging programmes of events that provide exciting opportunities for co-created projects, there was a gap in the libraries' offerings for STEM storytime sessions. Hertfordshire libraries have a history of running successful STEM-themed activities for the community using VR, 3-D printing and Lego. Through the existing storytime programme for families with 0-8 years old children, the libraries had an established relationship with a diverse public and offered a welcoming and informal setting to learn. However, their storytime activity sessions did not have a science focus, as staff did not feel confident running science-related activities. The University was thus able to offer its expertise and training, and the Libraries provided an engaged public and safe third space (e.g., *Elmborg, 2011*) for learning to occur. By building upon pre-existing knowledge and learning from both the University and Library and considering our strategic goals, we were able to create a mutually aligned project.

Once we established this project, the OPE team worked with the Senior Librarian for Children and Young People to write the funding bid and design the in-session and at-home activities (Table 1). We selected this based on their creative elements, age appropriateness for 4-7 year-olds and material cost, so families would be able to carry out activities on their own if they wished. In addition, together with the Early Years Librarian, we chose 25 books for the project that adequately showcased diverse role models, were age-appropriate, and accurately discussed science topics. We developed one list for children, and one list for their parents and carers. A Service Development and Project Librarian worked with us for the duration of the project's delivery and was invaluable in organising the library-specific logistics of all sessions, such as selecting appropriate event spaces and coordinating library staff.

In addition to the services and skills the library staff provided the University, we were able to share skills with the library staff. The University staff ran workshops on how to deliver and run the sessions, created training videos on how to run the activities, provided session scripts that were posted on the Hertfordshire Libraries cloud platform, and supported library staff throughout the project. Based on library staff feedback, we found that the library staff gained a breadth of skills, including presenting, communicating, managing events, and improving participants' engagement. Prior work (e.g., *Fraknoi et al., 2004*) has shown the mutual benefits of similar partnerships. In fact, two of the partner libraries will continue to run these sessions without a representative from the University, perhaps demonstrating that this programme became more sustainable as a result of skill sharing.

In addition, running outreach activities in libraries will bring new audiences with which the library and the university can engage. We found that just under 50% of participants had never been to a library event before (Figure 3), meaning that these events brought new patrons into the library. Further, we found that none of the participants had been to a University of Hertfordshire event (Figure 4). Through these events, PAM is able to interact and engage with a completely new audience.

Bringing science outreach into public libraries is also beneficial as libraries can play a major role in exposing children to books and developmental language opportunities (e.g., *Celano & Neuman, 2001*). This is crucial, as access to science requires, at least in part, familiarity with science vocabulary. Through this project we have increased the number of STEM books

Figure 2: *STEM book loyalty cards and reward bookmark.*

borrowed from our partner libraries by 1000 (Figure 5; Table 2). Table 2 compares the number of STEM books borrowed from our sequence of libraries and their STEM offerings. There was no significant increase in the number of STEM books borrowed from the libraries only with the loyalty card scheme compared to the libraries with no additional offerings. This demonstrates the impact of these specific STEM sessions on the promotion of STEM books in libraries.

Why work with children aged 4-7 and their parents and carers?

We decided to work with children of this age range as they still typically display positive attitudes about science and their science identity has not yet been solidified (e.g., *Archer et al., 2010*). In addition, in the UK, children under the age of 8 must be accompanied by a parent or carer to attend an event in a library. For this project, it was crucial to include parents and carers as they are a key influence on a child's developmental science capital (e.g., *DeWitt & Archer, 2015*). Parents' and carers' misconceptions surrounding science, scientists, and science careers, as well as their own confidence in science, can have a large impact on a child's future science aspirations. Further, it is widely recognised that parents are one of the most influential forces in a young person's career and education decision-making (e.g., *Davenport et al., 2020*). Despite all of this, very few STEM interventions include parents and carers (e.g., *Archer et al., 2021*).

In order to encourage more young people to consider science as a possible career path, universities should explicitly involve parents and carers in their science outreach. When parents and carers are engaged and have confidence in science, it contributes to their child's motivation and performance in science (e.g., *Schmidt & Shumow, 2014*). Therefore, we aimed to have a high level of parental participation in our sessions. Library staff additionally shared their past experiences that parents were typically disengaged unless they were explicitly involved in the activities. In all of our activities, we strived to invite the parents and carers into the activities. For example, during the astronaut glove box activity (Table 1), we organised the space such that the adult and child could work

Book issues at libraries offering Cosmic Curiosity sessions and loyalty card scheme (four libraries)	Book issues at libraries only offering loyalty card scheme (three libraries)	Book issues in libraries with no additional offering (four libraries)
1000	463	405

Table 2: *Comparison of the project linked STEM books issued in Hertfordshire Libraries.*

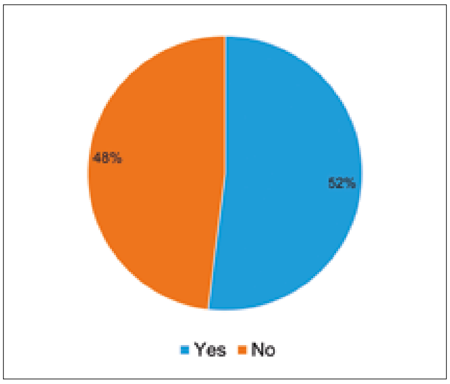


Figure 3: *Participants (n=75) were asked if they had ever been involved in an activity hosted by Hertfordshire Libraries before.*

Figure 4: *Participants (n=75) were asked if they had ever been involved in an activity hosted by the University of Hertfordshire before.*

Figure 5: *Astronomy and STEM children's books available to participants. Image Credit: Hertfordshire Library Service*

together. We ensured that the adults would be able to do all activities as well as the children. In order to increase the number of science books parents and carers took out of the library, we included a comprehensive list of adult science books on the back cover of the activity booklet that was designed for our sessions. However, we found this did not have as much impact as we anticipated, as only 2% of the total number of books taken out in relation to the project were adult books. In the future, we will need to do more to promote these books to parents and carers.

As part of our evaluation, we administered a task in which each participant produced a drawing of a scientist and later, rated their comfort level with science on a 5-point scale. We analysed these depictions to gain insight into their perceptions of scientists, which directly influenced how we ran our sessions. For example, we sought to highlight the achievements of scientists who identify as women if many drawings depicted scientists with stereotypically masculine characteristics. Similarly, if many depictions featured scientists wearing lab coats, we emphasised the diversity of science careers that are not limited to a lab setting. Additionally, this activity served as a valuable tool to engage those who arrived early to our sessions, and participants enjoyed drawing together as a family.

To understand parents' and carers' motivations for attending the session and to evaluate whether those needs were met, we conducted a snapshot interview with parents and carers. This resulted in valuable insights into the families with which we engaged. As research suggests (e.g., *Gilligan et al., 2020*), several parents expressed they felt unable to support their children's interest in space, which was initially sparked early in their education, due to their lack of knowledge of the subject. Furthermore, they struggled to find events catering to this age range. Thus, our findings reinforced that we were serving a need within the local community. We interviewed returning participants to determine their level of confidence in engaging in astronomy-related tasks with their child(ren) and whether or not they completed the at-home activities. Despite the limited number of individuals who returned for subsequent sessions, our interviews revealed that those who did were found to have gained confidence in carrying out astronomy activities with their child(ren) and took out more science-related books as a direct result of our sessions.

Why theme sessions around careers?

Research shows that career interests are relatively fluid until ages 5–6, when a child's view on what careers are appropriate for them begins to shrink (e.g., *Bian, Leslie, & Cimpian, 2017*). The factors that influence these decisions include perceived gender-appropriateness of careers, social level of careers, accessibility, and concepts of self-efficacy (e.g., *Davenport et al., 2020*). We thus decided to theme each session around a different career in space science, some of which would be familiar to participants and others that would not. We chose to use an astronaut, astronomer, aerospace engineer and a planetary geologist (Table 1).

We used The NUSTEM (Northumbria University STEM) STEM attributes (*NUSTEM, 2020*) for this project which were created by NUSTEM, a collective of STEM outreach practitioners and researchers based out of the University of Northumbria looking to increase diversity within STEM. Their research has shown that focusing on counter-stereotypical attributes such as creativity provides audiences with a new understanding of the skills needed to be a scientist and reduces children's stereotypes of science and scientists (e.g., *Davenport, 2020*). In each session, we picked three of these STEM attributes that matched the career of the session (Table 1) and highlighted these to the families by displaying them and discussing how one would use these skills in the career. Children were also congratulated for using these skills throughout the session and were recognised for their achievements on the session certificate (Figure 6). All of the skills were on the back of the bookmark linked to the STEM book loyalty card scheme so children could tick them off as they went through the activities.

By working with children around this age range and their parents and carers, there is room to challenge or prevent what may be a child's misconceptions about themselves and their ability to pursue a science career. We based the activities on careers and framed them around career characteristics, and in doing so, created a space where children and their parents and carers could authentically experience being a scientist.

How to sustain engagement in libraries

An astronomy intervention in a library setting presents an exciting opportunity to engage with parents and carers. However, free events in libraries often result in one-off engagement, which may not be as effective as a multi-intervention engagement (e.g., *Archer et al., 2021*). Though we recognised it may be difficult for participants to attend every session due to other commitments, we utilised methods that would ensure families would continue to independently engage with astronomy at home and continue coming to the library to borrow STEM books.

To encourage participants to come back, we created specific certificates and badges for each session for attendees, a tactic which proved successful in previous outreach activities we have run with children of this age group. To continue engagement with astronomy at home, we provided the resources for the participants to carry out the activity, including an activity booklet containing each of the four sessions' activities, so even if participants could only attend one session, they could do all activities at home (Figure 7). To encourage them to take out more books, the activity booklet contained a reading list for adults and children, all of which were available in the libraries. Additionally, we gave every participant a STEM book loyalty card and subsequent bookmark as a reward if they loaned four books at the session (Figure 2). We made this into a small ceremony at the end where each child would come up and collect their activity booklet, resources for the at-home activity, certificate, badge and STEM

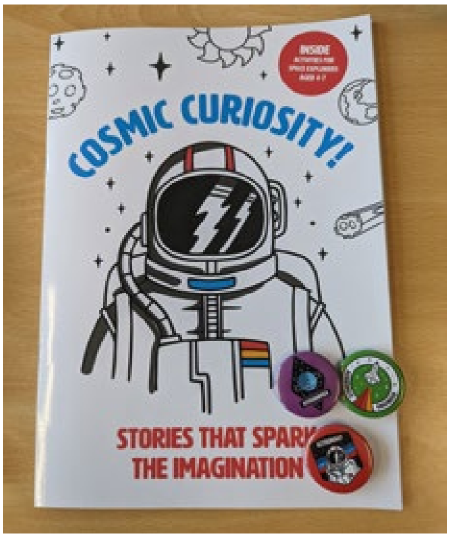


Figure 7: *Activity booklet and badges available to participants.*

book loyalty card. We congratulated them for being Aerospace Engineers (or Astronauts, Astronomers, or Planetary Scientists) and utilising the STEM attributes skills highlighted during the session. We then encouraged them to pick out as many STEM books as they liked from our display (Figure 5). We found this worked incredibly well to get every child to take out a STEM book at the end of the session. If we did not specifically highlight and direct the children to the books, they took out far fewer STEM books from the library.

We made continuous efforts to improve the quality of our sessions and enhance engagement levels by conducting post-event meetings and having all facilitator staff fill out feedback forms. These records were essential in improving future sessions and increasing participant engagement. For instance, we noticed that participants who arrived early often completed the Draw a Scientist Task before others arrived/finished and started to disengage. To address this, the library staff suggested incorporating space-themed colouring-in and word searches to keep these participants engaged. We implemented this solution across all future sessions and found that it minimised this disengagement. These insights were also valuable in identifying what worked well in events, allowing us to replicate our successes in future sessions. For example, one library facilitator noted, "The whole event was very successful. The planning was excellent because the order of activities led up to the final exciting event. The joint rocket launch was especially thrilling;

Figure 6: *Certificate available to participants for the Planetary Geologist session.*

you could feel the excitement in the room." Launching the rocket together as a full group was not originally part of the session plan, but due to its success, we decided to include it in all future Aerospace Engineer sessions.

By engaging participants in the session and providing a means of sustained engagement, we found that not only was there an increase of almost 1000 STEM books taken out from our four partner libraries (Table 2), but as previously mentioned, through snapshot interviews, we learnt that the parents and carers experienced an increase in confidence to carry out astronomy activities at home with their children.

Conclusions

Through our partnership with local libraries, we were able to reach parts of the community that are typically underserved by large academic institutions. We created the opportunity for impactful and enjoyable engagements for participants by combining literature and astronomy in a way that was comfortable and approachable. Libraries also provide a natural space to interact with families. We have found that working with families has a greater impact: not only are we shaping the scientific perceptions of the child, but the parent or carer, as well. By considering the sustainability and legacy of astronomy outreach with the participants and library staff, we have created more long-lasting engagement. Specifically, we have improved the confidence of families and library staff to carry out astronomy activities independently. We will continue working on Cosmic Curiosity with the same and new Hertfordshire libraries in the future and incorporate new outreach opportunities, such as our recently launched library exhibit on the James Webb Space Telescope.

References

Archer, L., DeWitt, J., Osborne, J., Dillon, J., Willis, B., & Wong, B. (2010). "Doing" science versus "being" a scientist: Examining 10/11-year-old schoolchildren's constructions of science through the lens of identity. Science Education, 94(4), 617–639. https://doi.org/10.1002/sce.20399

Archer, M., DeWitt, J., Davenport, C., Keenan, O., Coghill, L., Christodoulou, A., Durbin, S., Campbell, H., & Hou, L. (2021). Going beyond the one-off: How can stem engagement programmes with young people have real lasting impact? Research for All, 5(1). https://doi.org/10.14324/rfa.05.1.07

Bian, L., Leslie, S., & Cimpian, A. (2017). Gender stereotypes about intellectual ability emerge early and influence children's interests. Science, 355(6323), 389-391. https://doi.org/10.1126/science.aah6524

Celano, D., & Neuman, S. B. (2001). The role of public libraries in children's literacy development: An evaluation report. Pennsylvania Library Association. https://www.ala.org/tools/research/librariesmatter/role-public-libraries-children%E2%80%99s-literacy-development-evaluation-report.

Davenport, C. (2020). NUSTEM 6 year impact report 2014-2020. Northumbria University Newcastle. https://nustem.uk/wp/wp-content/uploads/2020/10/Impact-Report-2020-09102020.pdf.

Davenport, C., Dele-Ajayi, O., Emembolu, I., Morton, R., Padwick, A., Portas, A., Sanderson, J., Shimwell, J., Stonehouse, J., Strachan, R., Wake, L., Wells, G., & Woodward, J. (2020). A theory of change for improving children's perceptions, aspirations and uptake of stem careers. Research in Science Education, 51(4), 997–1011. https://doi.org/10.1007/s11165-019-09909-6

DeWitt, J., & Archer, L. (2015). Who aspires to a science career? A comparison of survey responses from primary and secondary school students. International Journal of Science Education, 37(13), 2170–2192. https://doi.org/10.1080/09500693.2015.1071899

Elmborg, J. K. (2011). Libraries as the Spaces Between Us: Recognizing and Valuing the Third Space. Reference & User Services Quarterly, 50(4), 338–350. http://www.jstor.org/stable/20865425

Fraknoi, A., Howson, E., Chippindale, S., & Schatz, D. (2004). Project ASTRO: A national network helping teachers & families with astronomy education. In Narasimhan, Beck-Winchatz, Hawkins & Runyon (Eds.), NASA Office of Space Science Education and Public Outreach Conference. Astronomical Society of the Pacific. https://www.researchgate.net/publication/234185697_Project_ASTRO_A_National_Network_Helping_Teachers_Families_with_Astronomy_Education

Gilligan, T., Lovett, J., McLoughlin, E., Murphy, C., Finlayson, O., Corriveau, K., & McNally, S. (2020). 'We practise every day': Parents' attitudes towards early science learning and education among a sample of urban families in Ireland. European Early Childhood Education Research Journal, 28(6), pp. 898–910. https://doi.org/10.1080/1350293x.2020.1836588.

Index of Multiple Deprivation Herts Rank (2019). Herts Insight. Retrieved from https://dashboards.instantatlas.com/viewer/report?appid=ce996db1ac514f62a00acb61e4299d54&clear=true

LaConte, K. (2019). STEAM up your library. Libraries Connected. https://www.librariesconnected.org.uk/resource/steam-your-library-guide-energizing-your-offer

Libraries Connected. (2018). Universal Library Offers. Libraries connected. Retrieved from https://www.librariesconnected.org.uk/page/universal-offers

NUSTEM. (2020, July 07). STEM Attributes. NUSTEM. Retrieved from https://nustem.uk/resource/stem-attributes/

O'Flynn, N., & Burningham, B. (2020) Outreach and public engagement in the Department of Physics, Astronomy and Maths strategy 2020-2025. University of Hertfordshire. https://www.herts.ac.uk/__data/assets/word_doc/0008/317195/PAM-OPE-Strategy-1.docx

Pekacar, K. (2017) Higher Education and Public Libraries: Partnerships Research. Arts Council England. https://www.artscouncil.org.uk/sites/default/files/download-file/Public%20Libraries%20and%20HE%20report.pdf

Percy, J. (2017). Public Libraries as Partners in Astronomy Outreach. Communicating Astronomy with the Public Journal, 22, (5–14). https://www.capjournal.org/issues/22/22_05.pdf

Schmidt, J.A., & Shumow, L. (2014). Parent engagement in science with ninth graders and with students in higher grades. The School Community Journal, 24(1).

Shtivelband, A., Riendeau, L., & Jakubowski, R. (2017). Building upon the stem movement: Programming recommendations for library professionals. Children and Libraries, 15(4), pp. 23–26. https://doi.org/10.5860/cal.15.4.23

UK Government. (2017). Libraries shaping the future: Good practice toolkit. Retrieved from https://www.gov.uk/government/publications/libraries-shaping-the-future-good-practice-toolkit/libraries-shaping-the-future-good-practice-toolkit

Acknowledgements

Thank you to all of the library staff and my colleague Mily Riley. This project could not have happened without all their help and support.

Biography

Nuala O'Flynn is the Outreach and Public Engagement Manager for the University of Hertfordshire's Department of Physics Astronomy and Maths in the UK. In her role, she runs a STEM school outreach programme for children aged 7-14 from disadvantaged backgrounds and connects a variety of publics with the research coming out of her department.

Driving action on the climate crisis through *Astronomers for Planet Earth* and beyond

Adam R. H. Stevens
International Centre for Radio Astronomy Research, The University of Western Australia, Crawley, WA 6009, Australia
adam.stevens@uwa.edu.au

Vanessa A. Moss
CSIRO Space and Astronomy Marsfield, NSW 2122, Australia
vanessa.moss@csiro.au

Keywords
Accessibility, Climate Change, Communicating Astronomy with the Public Conference, Ethics, Online Engagement, Research

While an astronomer's job is typically to look *out* from Earth, the seriousness of the climate crisis has meant a shift in many astronomers' focus. Astronomers are starting to consider how our resource requirements may contribute to this crisis and how we may better conduct our research in a more environmentally sustainable fashion. *Astronomers for Planet Earth* is an international organisation (more than 1,700 members from over 70 countries as of November 2022) that seeks to answer the call for sustainability to be at the heart of astronomers' practices. In this article, we review the organisation's history, summarising the proactive, collaborative efforts and research into astronomy sustainability conducted by its members. We update the state of affairs with respect to the carbon footprint of astronomy research, noting an improvement in renewable energy powering supercomputing facilities in Australia, reducing that component of our footprint by a factor of 2–3. We discuss how, despite accelerated changes made throughout the pandemic, we still must address the format of our meetings. Using recent annual meetings of the Australian and European astronomical societies as examples, we demonstrate that the more online-focussed a meeting is, the greater its attendance *and* the lower its emissions.

Introduction

The year 2019 was memorable for many reasons. Not only was it the last year of pre-pandemic "normality", but it also saw the acceleration of the rise of astronomy sustainability. As an independent submission to the 2020 decadal survey of astronomy and astrophysics in the United States, *Williamson, Rector & Lowenthal (2019)* recommended that astronomers have "a collective impact model to better network and grow our efforts […] to address climate change" (p. 1). Similarly, in their white paper for the 2020 long-range plan for Canadian astronomy, *Matzner et al. (2019)* emphasise that "greenhouse gas emissions must be understood as significant research costs" (p. 1). Also in 2019, the Australian astronomical community conducted a mid-term review of its 2016–2025 decadal plan. Taking inspiration from the white papers of the US and Canadian communities, the first national-scale audit of the carbon footprint of astronomy was conducted as part of that review (*Stevens et al., 2020*). These papers collectively signalled the start of things to come. For example, sustainability was a focus in the 2021–2030 Strategic Plan for Astronomy in the Netherlands (*Wijers, Kuijken & Wise, 2022*).

The grass-roots organisation *Astronomers for Planet Earth* (A4E) was established in 2019 as a response by the astronomy community to the need to address the climate crisis (see overviews by *Burtscher et al., 2021; Cantalloube et al., 2021; Frost et al., 2021; White et al., 2021a*; or the independent article by *Japelj, 2021*). Two independent groups with an active interest in astronomy and sustainability came together to form A4E: one in North America (with a notable number of members from San Francisco State University) and one in Europe (with a similar-sized cluster of members from Leiden University). The organisation has since rapidly grown. With a membership base of more than 1,700 people in November 2022, we now have representation from over 70 countries (see Figure 1).

Figure 1. *Countries with members of Astronomers for Planet Earth as of November 2022. The shade of blue indicates whether the country has single-digit, tens, or hundreds of members.*

The mission statement of A4E is "To mobilise and empower the global astronomical community to take action on the climate crisis" (*Cool, 2022*). The urgency with which we must act to combat the climate crisis is clear from the latest International Panel on Climate Change assessment report (for a technical summary, see *Pörtner et al., 2022*). Physical scientists, like astronomers, hold an important position in this challenge, as we wield sufficient knowledge to understand the problem at hand, but are separated enough from its research such that when we press its importance, there cannot be claims of financial conflict of interest. A4E functions to empower astronomers with the resources necessary to engage the public on the climate crisis in their outreach. As astronomers, we can emphasise our perspective and understanding that Earth is the only place with life that we know of in the vast and ever-expanding cosmos.

This article presents an overview of how things have developed in the astronomy sustainability space over the three years since the inception of A4E. This includes the ever-increasing number of studies that have quantified the carbon emissions associated with astronomy and an outline of the efforts and recommendations of A4E members alongside other communities to help reduce these emissions. We pay particular attention to how future meetings may be conducted to better serve a sustainable future for astronomy.

The carbon emissions of astronomy

In one of the first emissions audit studies of astronomy, *Stevens et al. (2020)* considered four contributing factors to the carbon footprint of the job of an astronomer in Australia: air travel, operations of observatories, powering of supercomputing facilities, and office building electricity consumption. Based on an extrapolation from power-meter data supplied by the Pawsey Supercomputing Centre in Perth, *Stevens et al. (2020)* found supercomputing to be the single greatest source of carbon emissions, estimated at an average of 22 (confident in the range 14–28) tonnes of CO_2 emissions at ground level (tCO_2-e) per year (yr) per full-time-equivalent astronomer (FTE, including Masters and PhD students). The second biggest contributor was air travel, quoted to be 6 (5–7) tCO_2-e/yr/FTE, based on travel records from two institutes. As noted in the paper, however, this figure, based on airline quotes, did not account for non-CO_2 radiative forcing (e.g. from the production of contrails); other authors have interpreted the true value as double (i.e. 12 tCO_2-e/yr/FTE; *Jahnke et al., 2020*). Data from observatories placed a lower limit on their emissions of 4.5 tCO_2-e/yr/FTE (*Stevens et al.* accounted for most, but not all, observatories used by the Australian community) while powering offices sat at about 3 tCO_2-e/yr/FTE.

The figures quoted by *Stevens et al. (2020)* were based on data from 2018 and 2019. For most of 2020 and 2021, lockdowns, border closures, and grounded planes meant that the *air-travel* carbon footprint of Australian astronomers effectively dropped to zero. However, in 2022, work-related travel (both domestic and international) returned. While there remains to be a study that assesses whether the frequency of said travel has returned to 2019 rates, it is clear that the community has not fully embraced the opportunity to adapt to a more sustainable way of communicating and collaborating internationally, despite a broad range of emergent literature emphasising the positive benefits of doing so (e.g., *Moss et al., 2021; Sarabipour et al., 2021*).

However, the situation is not entirely bleak. Investments in renewable energy by the Australian Capital Territory government (see *Mason, 2020*) and *Swinburne University of Technology (2020)* now mean that two of the major supercomputing centres used by Australian astronomers are effectively carbon-neutral. We estimate this now places Australian astronomers' supercomputing carbon footprint at about 7 tCO_2-e/yr/FTE, a reduction of a factor of 2–3 since 2019. Air travel may have overtaken supercomputing as the largest source of Australian astronomers' emissions, emphasising how critical it is that we do not return to old flying habits. The greatest onus here is on senior staff members, as their average rate of flying exceeded postdocs by a factor of 3.8 and PhD students by a factor of 8.5, on average, prior to the Covid-19 pandemic (*Stevens et al., 2020*).

In a complementary study, *Jahnke et al. (2020)* calculated the carbon emissions of astronomers at the Max Planck Institute for Astronomy (MPIA) in Heidelberg, Germany. Compared to *Stevens et al. (2020), Jahnke et al. (2020)* found that, for the common sources of emissions considered in both studies, the job of being an astronomer was 2.7 times less carbon-intensive in Germany than in Australia. This reflects Australia's high reliance on coal burning for electricity production. Accounting for recent renewable investments in Australia suggests the difference is now closer to a factor of 1.6 (assuming the other quantities in *Stevens et al., 2020*, remain unchanged). Of course, renewable electricity bears no relevance to air-travel emissions. While air travel was evidently the greatest contributor to the average MPIA astronomer's emissions, this was 30% less than the average Australian astronomer. This could readily be explained by Australia's relative international isolation and its much lower population density, demanding longer average travel distances per trip.

Astronomers have since conducted subsequent carbon-audit studies in the Netherlands (*van der Tak et al., 2021*), France (*Martin et al., 2022*), and the United States (*Simcoe et al., 2022*). With the exception of *van der Tak et al. (2021)* — who do not consider observatories — the above studies all suggest astronomers carry a higher per-capita carbon footprint than the average citizen when controlling for location.

Individual observatories have also taken to quantifying their own operations' carbon footprint, including the Canada-France-Hawaii Telescope (*Flagey et al., 2020*) and the W. M. Keck Observatory (*McCann et al., 2022*). *The European Southern Observatory (2022)* has also calculated the emissions of ongoing operations of the entire organisation.

Many of these studies (sans *Martin et al., 2022*) have omitted at least two contributing factors of significance: (i) the emissions associated with *the construction* of observatories and (ii) the launch of space telescopes. Concerningly, *Knödlseder et al. (2022)* find that these two omissions potentially account for more than all other emissions sources of astronomers combined (though, as noted in the discussion of *Wilson (2022)*, estimating the emissions of space telescopes is challenging without raw data on the resource requirements of their construction, launch, and operation). *Knödlseder et al. (2022)* recommend that astronomers slow the construction rate of new infrastructure. Otherwise, any gains we may make through improving the sustainability of existing infrastructure will be outpaced by the additional requirements of new infrastructure.

The future of meetings

The Covid-19 pandemic forced global communication to shift online, accelerating pre-existing digital transformation trends. For astronomers and academics, this meant adapting how we run our major meetings, conferences, and workshops to work in a virtual space. Many people pointed out the opportunity this created to establish a new, permanent model for meetings that would vastly reduce carbon emissions due to a reduction in travel and increase accessibility to those without the means to travel (e.g., *Stevens et al., 2020; Moss et al., 2021*). Indeed, studies have calculated the carbon savings from online meetings (e.g., *Burtscher et al., 2020; Tao et al., 2021*), ranging from factors of tens to thousands lower than an equivalent in-person meeting.

Given that the global transition to effective online and hybrid events is ongoing, there have been many publications sharing learnings in this rapidly growing space, including the pros and cons of various meeting formats (e.g., *Moss et al., 2020; Reshef et al., 2020; Cuk et al., 2021; Moss et al., 2021; Sarabipour et al., 2021; Skiles et al., 2021; Lowell et al., 2022; Moss et al., 2022*). Alongside the positive impacts of virtual interaction on sustainability, there has also been extensive discussion on benefits in the context of accessibility and inclusivity, particularly when considering under-represented and less privileged groups in academia and our broader society (e.g., *Sarabipour, 2020; Skiles et al., 2021; Köhler et al., 2022*).

Similarly, various communities worldwide have become increasingly active in advocating for improved approaches to meeting formats. One example of this is *The Future of Meetings* (TFOM) community of practice, which formed following the 2020 same-named symposium (*Moss et al., 2020; 2021*). TFOM has grown since then from an organising committee predominantly consisting of Australian researchers to a global community actively advocating for improved widespread use of online/hybrid formats. The activities of TFOM have included providing advice and assistance to various conferences and meetings, sharing learnings in the form of publications and presentations, experimenting with new technologies in order to pioneer new approaches to online formats, and collaborating with diverse and varied groups on the theme of meetings and conferences (e.g., A4E, The University of Queensland's School of Information Technology and Electrical Engineering, SciConf historians, organisers of the 2024 International Astronomical Union (IAU) General Assembly, and Theo Murphy Initiative "Science for Public Good" workshop leads, among others). TFOM is just one example of the current global mobilisation for a better future of meetings and work, leveraging technology to improve accessibility, inclusivity, and sustainability in academia and broader society.

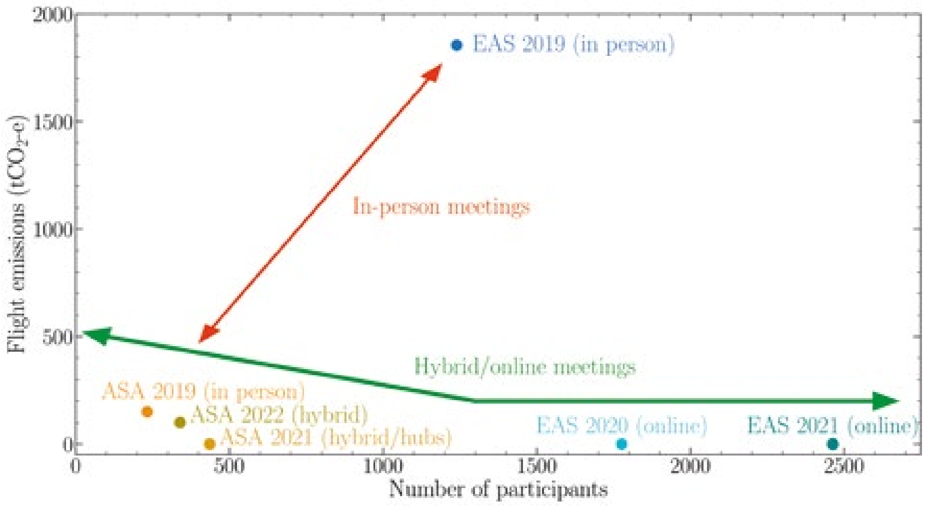


Figure 2. *How the total flight emissions of six example major astronomy meetings have compared to their total number of participants and the mode of the meeting. Classical in-person meetings should scale linearly (red arrow). By contrast, the size of an online/hybrid meeting is anti-correlated with total emissions (saturating at zero; green arrow). This suggests that not only do many participants choose not to travel when given a viable option, but the meeting becomes increasingly accessible when there is a greater online focus. EAS 2019 figures were sourced from* Burtscher et al. (2020). *ASA figures were based on a list of cities of origin of participants, using Table 1 of* Stevens et al. (2020) *to calculate emissions, applying a factor of two for non-CO_2 radiative forcing, consistent with* Barret (2020).

To demonstrate the significance of running astronomy conferences in an online/hybrid mode, we make a direct comparison between the emissions of three recent ASA (Astronomical Society of Australia) and EAS (European Astronomical Society) meetings in Figure 2. The 2020 and 2021 meetings were conducted under pandemic conditions, meaning no travel was possible. Despite this, the 2021 EAS and ASA meetings had their highest turnouts in history, with 2464 and 436 respective registrants (*European Astronomical Society, 2021; The University of Melbourne, 2021*). While the EAS meeting achieved this through a purely online meeting after a successful online model in 2020, the ASA meeting was conducted in a hybrid mode with local hubs in major cities throughout Australia for the first time. Of the 436 participants for the 2021 ASA meeting, 329 registered for their local hub, with the other 107 registered for online attendance.

One would expect the flight emissions of a purely in-person meeting to scale linearly with its number of participants (to first order). Indeed, that is consistent with a comparison of the 2019 ASA and EAS meetings. If the fraction of in-person attendees to a hybrid meeting remained constant, then we would still expect a positive correlation but with a shallower slope. Instead, we see that when major astronomy meetings are shifted to a hybrid model (ASA 2022) and then to a fully online or distributed-hub model (ASA 2021; EAS 2020; EAS 2021), the total emissions become reduced while the number of participants increases. We interpret this to mean that many attendees who would have attended an in-person meeting instead *choose* to attend online when given the option, and the number of extra people a hybrid or online meeting attracts significantly outweighs the number of people who *only* attend fully in-person meetings. Of course, to prove this statement applies generally, we should ideally have more data than are shown in Figure 2, which we defer to future work.

A4E current actions

Research

As an organisation of predominantly researchers, many A4E members actively research in the astronomy sustainability space. In September 2020, *Nature Astronomy* released a special *Climate Issue* (*Nature Astronomy, 2020*), with six articles published by A4E members on astronomy sustainability. Three of these included carbon audits, described in Section 2 (*Flagey et al., 2020; Jahnke et al., 2020; Stevens et al., 2020*), and a comparison of in-person versus virtual conferencing (*Burtscher et al., 2020*). In addition, *Portegies Zwart (2020)* discussed the carbon footprint of computation in astronomy — identified by *Stevens et al. (2020)* as one of the leading contributors to the field's overall footprint — highlighting the conflict between energy efficiency and time efficiency of some massively parallelised codes. Finally, *Cantalloube et al. (2020)* measured the potential effect of climate change on the seeing conditions at the Paranal Observatory in Chile, unsurprisingly finding that conditions were worsening.

Since then, there have been further independent studies of the effect of the changing climate at other observing sites (e.g. *Haslebacher et al., 2022; van Kooten & Izett, 2022*). The common conclusion among these works is that seeing conditions will gradually degrade, and the rate at which nights are lost due to bad weather will increase.

Research into astronomy sustainability has become sufficiently prevalent that *Nature Astronomy* now keeps a library of papers it has published in the area (*Nature Astronomy, 2022*). To date, this library includes >15 publications and two editorials.

Dissemination and communication

The A4E members have been central to establishing and running astronomy sustainability events at major national and international astronomy meetings. Special sessions were arranged at the fully virtual 2020 and 2021 EAS meetings. The respective sessions on "Astronomy for Future: Development, global citizenship & climate action" and "Astronomers for Planet Earth: Forging a sustainable future" included a range of talks and panel sessions from active researchers in astronomy sustainability and eminent scientists. With 100–300 participants each, these special sessions were among the best-visited sessions of the virtual EAS meetings (each with roughly 2,000 registrants across a dozen parallel sessions on average). A special session for the 2022 EAS meeting was also arranged, but not according to the original plan, as the meeting was designed to be almost exclusively in-person, despite advice from the EAS sustainability committee to the contrary (see *Burtscher et al., 2022*). Eventually, some hybrid aspects were added to this meeting (see *Moss et al., 2022*) by popular demand.

Special town hall sessions were also organised at the 2021 and 2022 annual ASA science meetings by A4E members (in the ASA's sustainability working group) on astronomy sustainability. The 2021 meeting also included a lively presentation that featured a celebrity scientist, titled "Astronomers! Your planet needs you", which is available on YouTube (*Astronomical Society of Australia, 2021b*). Further conferences and sessions by A4E members have included the 2021 conference of the Astronomical Society of the Pacific (*Fischer et al., 2021*) and the 2022 Chilean Astronomical Society meeting (*Jaffé & Ramírez, 2022*). Overview presentations of A4E have been given at multiple meetings of the American Astronomical Society (*Sakari et al., 2020; White et al., 2021b*) and at the CAP2021 conference (*Frost et al., 2021*).

A4E also runs a webinar series on YouTube (*Astronomers for Planet Earth, n.d.*), covering a wide range of topics related to astronomy sustainability. These include question-and-answer sessions between the invited speaker and A4E members.

In 2021, A4E released an open letter (*Betancourt-Martinez et al., 2021*) to astronomy institutes worldwide, calling on them to make sustainability a priority and to specifically impose carbon-reducing policies and communicate these changes to the community and public. Over 2,800 astronomers have signed this letter from more than 80 countries, well over double A4E's membership base at its time of release, equivalent to about 20% of the member base of the International Astronomical Union (IAU; IAU membership was not a requirement of signing the letter, nor does the IAU member base account for all astronomers). Several institutes have endorsed this letter, thereby making themselves accountable for the letter's request.

Bids for sustainable events

The A4E members have bid to host some of the largest astronomy meetings around the world in sustainable and inclusive formats, i.e. with an online focus. As recent examples, we proposed to host the 2027 General Assembly of the IAU and the 2023 Annual Science Meeting of the ASA, both with an online/hybrid focus that would have minimised the need for travel. Unfortunately, similar to the 2022 EAS meeting, the decision-makers for these events have actively pursued in-person-focused events instead. This is despite official statements from both the IAU (*Lago & Christensen, 2021*) and the Astronomical Society of Australia (2021a) supporting astronomers as they address climate change. Instead, A4E opted to run its own fully virtual symposium on astronomy sustainability and the broader aspects of the organisation in the week of 28 November to 2 December 2022, attracting more than 500 registrants (*Wagner et al., 2023*).

Conclusions

The movement of astronomy sustainability continues to grow, perhaps best exemplified by the continuous growth of the currently 1700-strong volunteer organisation *Astronomers for Planet Earth* (A4E). As physical scientists, it is important that astronomers use our position to lead by example in contributing to solutions to the climate crisis and in educating the wider public on it. Within A4E, we have researched and published carbon audits of the field of astronomy, worked with communities such as *The Future of Meetings* to outline how to conduct meetings with a hybrid/online focus that both reduce emissions and increase accessibility and attendance and conducted numerous workshops on astronomy sustainability. Further information and resources about the climate crisis are available on our website[1].

Notes

[1] The Astronomers for Planet Earth website: https://astronomersforplanet.earth/

[2] PYGAL: https://www.pygal.org/en/3.0.0/index.html

[3] MATPLOTLIB: https://matplotlib.org/

References

Astronomers for Planet Earth. (n.d.). *Home* [YouTube channel]. YouTube. Retrieved November 30, 2022, from https://www.youtube.com/channel/UCEmdhU0WjlqRKsSzJf5xfow

Astronomical Society of Australia. (2021a, May 25). *ASA Statement on Sustainability*. https://asa.astronomy.org.au/asa-sustainability-statement/

Astronomical Society of Australia. (2021b, August 4). *Astronomers! Your planet needs you* [Video]. YouTube. https://www.youtube.com/watch?v=H6Kq_0l-U7c

Astronomical Society of Australia. (2022, July 1). *ASA Annual Science Meeting*. https://asa.astronomy.org.au/events/asa-asm/

Barret, D. (2020). Estimating, monitoring and minimizing the travel footprint associated with the development of the Athena X-ray Integral Field Unit. *Experimental Astronomy*, *49*(3), 183-216. https://doi.org/10.1007/s10686-020-09659-8

Betancourt-Martinez, G. et al. (2021, April 20). *Open Letter*. Astronomers for Planet Earth. https://astronomersforplanet.earth/open-letter/

Burtscher, L., Barret, D., Borkar, A. P., Grinberg, V., Jahnke, K., Kendrew, S., Maffey, G., McCaughrean, M. J. (2020). The carbon footprint of large astronomy meetings. *Nature Astronomy, 4*(9), 823-825. https://doi.org/10.1038/s41550-020-1207-z

Burtscher, L., Dalgleish, H., Barret, D., Beuchert, T., Borkar, A., Cantalloube, F., Frost, A., Grinberg, V., Hurley-Walker, N., Impellizzeri, V., Isidro, M., Jahnke, K., Willebrands, M. (2021). Forging a sustainable future for astronomy. *Nature Astronomy, 5*(9), 857-860. https://doi.org/10.1038/s41550-021-01486-x

Burtscher, L., Balaguer-Núñez, L., D'Orazi, V., Barret, D., Beuchert, T., Dil, E., Janiuk, A., Mingo, B., Poggio, E. (2022). Astronomy organizations should lead in our battle against the climate crisis. *Nature Astronomy, 6*(6), 764. https://doi.org/10.1038/s41550-022-01722-y

Cantalloube, F., Milli, J., Böhm, C., Crewell, S., Navarrete, J., Rehfeld, K., Sarazin, M., Sommani, A. (2020). The impact of climate change on astronomical observations. *Nature Astronomy, 4*(9), 826-829. https://doi.org/10.1038/s41550-020-1203-3

Cantalloube, F., Burtscher, L., et al. (2021). Astronomers for Planet Earth: forging a sustainable future. In A. Siebert, K. Baillié, E. Lagadec, N. Lagarde, J. Malzac, J.-B. Marquette, M. N'Diaye, J. Richard, O. Venot (Eds.), *SF2A-2021: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics* (pp. 310-312).

Cool, A. (2022, September 12). *Astronomers for Planet Earth: A Cosmological View on Climate* [Presentation]. Benjamin Dean Astronomy Lectures, California Academy of Sciences, San Francisco, CA, United States.

Cuk, M., Virkki, A. K., Kohout, T., Lellouch, E., Lissauer, J. J. (2021). Pathways to Sustainable Planetary Science. *Bulletin of the American Astronomical Society, 53*(4), 419. https://doi.org/10.3847/25c2cfeb.7272e5bb

European Astronomical Society. (2020, July 5). *Welcome to EAS 2020*. https://eas.unige.ch/EAS2020/

European Astronomical Society. (2021, July 16). *Welcome to EAS 2021*. https://eas.unige.ch/EAS2021/

European Southern Observatory. (2022, March 9). *Environmental sustainability at ESO*. https://www.eso.org/public/about-eso/green/

Fischer, D., Cool, A., Rector, T., Agnos, J., Sakari, C. (2021). Astronomers for Planet Earth: An International Collective Working to Address the Climate Crisis. *Astronomical Society of the Pacific Conference Series, 531,* 189.

Flagey, N., Thronas, K., Petric, A., Withington, K., Seidel, M. J. (2020). Measuring carbon emissions at the Canada-France-Hawaii Telescope. *Nature Astronomy, 4*(9), 816-818. https://doi.org/10.1038/s41550-020-1190-4

Frost, A. J., White, J. A., Dalgleish, H. S., Rector, T., Agnos, J. M., Betancourt-Martínez, J. L., Hill, C., Kayhan, C, Beuchert, T., Sankar, S., Burtscher, L. (2021). Astronomers for Planet Earth: Embracing Virtual Communication Induced by the COVID-19 Pandemic to Help Tackle the Climate Crisis. *Communicating Astronomy with the Public Journal*, *30*, 28-32. https://www.capjournal.org/issues/30/30_28.php

Haslebacher, C., Demory, M.-E., Demory, B.-O., Sarazin, M., Vidale, P. L. (2022). Impact of climate change on site characteristics of eight major astronomical observatories using high-resolution global climate projections until 2050. *Astronomy & Astrophysics, 665*, A149. https://doi.org/10.1051/0004-6361/202142493

Jaffé, Y. L., Ramírez, K. P. (2022). Chilean astronomy and climate change. *Nature Astronomy, 6*(3), 306-307. https://doi.org/10.1038/s41550-022-01637-8

Jahnke, K., Fendt, C., Fouesneau, M. Georgiev, I. Herbst, T., Kaasinen, M., Kossakowski, D., Rybizki, J., Schlecker, M., Seidel, G., Henning, T., Kreidberg, L., Rix, H.-W. (2020). An astronomical institute's perspective on meeting the challenges of the climate crisis. *Nature Astronomy, 4*(9), 812-815. https://doi.org/10.1038/s41550-020-1202-4

Japelj, J. (2021). Astronomers for Planet Earth. *Eos, 102.* https://doi.org/10.1029/2021EO160780

Köhler, J. K., Kreil, A. S., Wenger, A., Darmandieu, A., Graves, C., Haugestad, C. A. P., Holzen, V., Keller, E., Lloyd, S., Marczak, M., Međugorac, V., Rosa, C. D. (2022). The Need for Sustainability, Equity, and International Exchange: Perspectives of Early Career Environmental Psychologists on the Future of Conferences. *Frontiers in Psychology, 16*, 906108. https://doi.org/10.3389/fpsyg.2022.906108

Knödlseder, J., Brau-Nogué, S., Coriat, M., Garnier, P., Hughes, A., Martin, P., Tibaldo, L. (2022). Estimate of the carbon footprint of astronomical research infrastructures. *Nature Astronomy, 6*(3), 503-513. https://doi.org/10.1038/s41550-022-01612-3

Lago, M. T., Christensen, L. L. (2021, June 24). *IAU Statement on Climate Change*. https://www.iau.org/news/pressreleases/detail/iau2105/

Lowell, S., Downie, A., Shiels, H., Storey, K. (2022). The future of conferences. *Development, 149*(1), 200438. https://doi.org/10.1242/dev.200438

Martin, P., Brau-Nogué, S., Coriat, M., Garnier, P., Hughes, A., Knödlseder, J., Tibaldo, L. (2022). A comprehensive assessment of the carbon footprint of an astronomical institute. *Nature Astronomy*, *6*, 1219–1222. https://doi.org/10.1038/s41550-022-01771-3

Mason, B. (2020, January 1). *The ACT is now running on 100 renewable electricity*. SBS News. https://www.sbs.com.au/news/article/the-act-is-now-running-on-100-renewable-electricity/lorljlav8

Matzner, C., Cowan, N. B., Doyon, R., Hénault-Brunet, V., Lafrenière, D., Lokken, M., Martin, P. G., Morsink, S., Nomandeau, M., Ouellette, N., Rahman, M., Roediger, J., Taylor, J., Thacker, R., van Kerkwijk, M. (2019). *Astronomy in a Low-Carbon Future* [White paper]. Long-Range Plan for Canadian Astronomy 2020. https://doi.org/10.5281/zenodo.3758549

McCann, K., Nance, C., Sebastian, G., Walawender, J. (2022). A path to net-zero carbon emissions at the W. M. Keck Observatory. *Nature Astronomy, 6*(11), 1223-1227. https://doi.org/10.1038/s41550-022-01827-4

Moss, V. A., Hotan, A. W., Kobayashi, R., Rees, G. A., Siegel, C., Tremblay, C. D., Trenham, C. E., Engelke, U., Gray, A., Hurley-Walker, N., Roos, G. (2020). The Future of Meetings: Outcomes and Recommendations. *Zenodo.* https://doi.org/10.5281/zenodo.4345562

Moss, V. A., Adcock, M., Hotan, A. W., Kobayashi, R., Rees, G. A., Siégel, C., Tremblay, C. D., Trenham, C. E. (2021). Forging a path to a better normal for conferences and collaboration. *Nature Astronomy, 5*(3), 213-216. https://doi.org/10.1038/s41550-021-01325-z

Moss, V. A., Balaguer-Nuñez, L., Bolejko, K., Burtscher, L., Carr, A., Di Teodoro, E. M., Gregory, B., Hanko, E., Hill, A. S., Hughes, A., Kaper, L., Kerrison, E. F., Lockman, F. J., Lowson, N., Stevens, A. R. H. (2022). Around the hybrid conference world in the COVID-19 era. *Nature Astronomy, 6*(10), 1105-1109. https://doi.org/10.1038/s41550-022-01806-9

Nature Astronomy. (2020). The climate issue. *Nature Astronomy, 4*(9), 811. https://doi.org/10.1038/s41550-020-01216-9

Nature Astronomy. (2022, March 8). *The impact of astronomy on climate change*. https://www.nature.com/collections/fhfcdebecc

Portegies Zwart, S. (2020). The ecological impact of high-performance computing in astrophysics. *Nature Astronomy, 4*(9), 819-822. https://doi.org/10.1038/s41550-020-1208-y

Pörtner, H.-O. et al. (2022). Technical Summary. [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 37–118, https://doi.org/doi:10.1017/9781009325844.002

Reshef, O., Aharonovich, I., Armani, A. M., Gigan, S., Grange, R., Kats, M. A., Sapienza, R. (2020). How to organize an online conference. *Nature Reviews Materials, 5*(4), 253-256. https://doi.org/10.1038/s41578-020-0194-0

Sarabipour, S. (2020). Research Culture: Virtual conferences raise standards for accessibility and interactions. *eLife, 9*, e62668. https://doi.org/10.7554/eLife.62668

Sarabipour, S., Khan, A., Seah, Y. F. S., Mwakilili, A. D., Mumoki, F. N., Sáez, P. J., Schwessinger, B., Debat, H. J., Mestrovic, T. (2021). Changing scientific meetings for the better. *Nature Human Behaviour, 5*(3), 296-300. https://doi.org/10.1038/s41562-021-01067-y

Sakari, C., Agnos, J., Barranco, J., Brewer, J., Coble, K., Cool, A., Crumrine, W., Deveny, S., Fielder, J., Fischer, D., Lea, S., Marzke, R., McCarthy, C., Ware, I., White, A. (2020). Astronomers for Planet Earth: A Call to Action. *Bulletin of the American Astronomical Society, 52*(1), American Astronomical Society meeting #235, id. 282.04.

Simcoe, R. A., Paneth, T., Defandorf, J., Guenther, H. M., Shoemaker, D., Levine, A. M., Burdge, K. (2022, September 12). MIT Kavli Institute for Astrophysics and Space Research. *Carbon Footprint of the MIT Kavli Institute*. https://space.mit.edu/wp-content/uploads/2022/09/MKI_Carbon_Footprint_revA.pdf

Skiles, M., Yang, E., Reshef, O., Muñoz, D. R., Cintron, D., Lind, M. L., Rush, A., Calleja, P. P., Nerenberg, R., Armani, A., Faust, K. M., Kumar, M. (2021). Conference demographics and footprint changed by virtual platforms. *Nature Sustainability, 5*(12), 149-156. https://doi.org/10.1038/s41893-021-00823-2

Stevens, A. R. H., Bellstedt, S., Elahi, P. J., Murphy, M. T. (2020). The imperative to reduce carbon emissions in astronomy. *Nature Astronomy, 4*(9), 843-851. https://doi.org/10.1038/s41550-020-1169-1

Swinburne University of Technology. (2020, May 14). *Reducing our carbon footprint in a 100 per cent renewable electricity deal*. https://www.swinburne.edu.au/news/2020/05/reducing-our-carbon-footprint-in-a-100-per-cent-renewable-electricity-deal/

Tao, Y., Steckel, D., Klemeš, J. J., You, F. (2021). Trend towards virtual and hybrid conferences may be an effective climate change mitigation strategy. *Nature Communications, 12*(12), 7324. https://doi.org/10.1038/s41467-021-27251-2

The University of Melbourne. (2021, July 16). *ASA Annual Science Meeting 2021.* https://blogs.unimelb.edu.au/asa2021/

van der Tak, F., Burtscher, L., Portegies Zwart, S., Tabone, B., Nelemans, G., Bloemen, S., Young, A., Wijnands, R., Janssen, A., Schoenmakers, A. (2021). The carbon footprint of astronomy research in the Netherlands. *Nature Astronomy, 5*(12), 1195-1198. https://doi.org/10.1038/s41550-021-01552-4

van Kooten, M. A. M., Izett, J. G. (2022). Climate Change and Astronomy: A Look at Long-term Trends on Maunakea. *Publications of the Astronomical Society of the Pacific, 134*(1039), 095001. https://doi.org/10.1088/1538-3873/ac81ec

Wagner, S., Mingo, B., Majidi, F. Z., Gokus, A., Burtscher, L., Kayhan, C., Kobayashi, R., Mehta, P., Moss, V. A., Ossenkopf-Okada, V., Rice, K., Stevens, A. R. H., Waratkar, G., Woods., P. (2023). A more sustainable future for astronomy. *Nature Astronomy, 7*(3), in press. https://doi.org/10.1038/s41550-023-01912-2

White, J. A., Dalgleish, H., Burtscher, L., Frost, A. J., Beuchert, T. (2021a). Astronomers for Planet Earth: Engaging with the Public to Forge a Sustainable Future. *Bulletin of the American Astronomical Society, 53*(2), 0202.

White, J. A., Dalgleish, H., Burtscher, L., Crumrine, W., Khan, R. (2021b). Astronomers For Planet Earth: engaging with the public to forge a sustainable future. *Bulletin of the American Astronomical Society*, *53*(6), American Astronomical Society meeting #238, id. 214.06.

Wijers, R. A. M. J., Kuijken, K. H., Wise, M. W. (2022). *Strategic Plan 2021-2030 for Astronomy in the Netherlands*. https://doi.org/10.48550/arXiv.2211.04991

Williamson, K., Rector, T. A., Lowenthal, J. (2019). Embedding climate change engagement in astronomy education and research. *Bulletin of the American Astronomical Society, 51*(7), 49.

Wilson, A. R. (2022). Estimating the CO_2 intensity of the space sector. *Nature Astronomy, 6*(3), 417-418. https://doi.org/10.1038/s41550-022-01639-6

Acknowledgements

We thank all A4E members for their contributions to the organisation but in particular, the founding members and fellow members of the steering working group. We gratefully acknowledge comments on this manuscript from Leo Burtscher, Adrienne Cool, Andrea Gokus, Cenk Kayhan, Volker Ossenkopf-Okada, and Sarah Wagner.

Figures 1 and 2 in this paper were respectively prepared with the PYGAL[2] and MATPLOTLIB[3] packages for PYTHON.

Biographies

Dr Adam Stevens, originally from Aotearoa, New Zealand, is the Jim Buckee Fellow at ICRAR-UWA in Perth, Western Australia. His research usually pertains to galaxy formation models, cosmological simulations, and radio galaxy surveys. He is internationally active in astronomy sustainability, epitomised through his core involvement in *Astronomers for Planet Earth*, having presented on behalf of the organisation at CAP2022.

Dr Vanessa Moss, based in Sydney, Australia, is a senior experimental scientist with CSIRO. She is Head of Science Operations for the ASKAP radio telescope, and her research focuses on the presence of gas nearby active black holes. She is a steering-group member of A4E and leads *The Future of Meetings* community, exemplars of harnessing technology for effective distributed collaboration.

The Astronomy for Mental Health Guidelines: A live document for the community

Dominic Gregory Vertue
Office of Astronomy for Development (OAD)
mentalhealth@astro4dev.org

Sandra Benítez Herrera
European Space Agency
sandra.benitez.herrera@gmail.com

Keywords:
Collaboration, Interdisciplinary, Online Engagement, Open Source, Public Outreach, Resources

Astronomy, with its vast array of tools and resources, can greatly benefit society. One area in need of new approaches and interventions is mental health and well-being. Diminished mental health can have a profound effect on society, from financial to loss of human potential. The International Astronomical Union (IAU) Office of Astronomy for Development (OAD) is exploring how astronomy can play a role in improving mental health and well-being.

As part of its project on astronomy for mental health, the OAD is creating and publishing resources for astronomers, educators, science communicators, and others who may benefit from using astronomy in their activities. One of the key resources being developed is the Astronomy for Mental Health Guidelines. This open-access document provides practical steps, tools, resources, and examples for planning, adapting or reviewing programmes or interventions targeting mental health and well-being.

This article will provide the background and context to the problem of mental health, motivations for using astronomy such as the shortfall in global mental healthcare services, a brief summary of the Guidelines and access to the Guidelines online.

Introduction

The International Astronomical Union Office of Astronomy for Development (OAD) aims to use the resources and skills of astronomy to promote sustainable development worldwide. Astronomy is a multidisciplinary topic with strong links to culture and heritage, making it suitable for addressing a wide range of societal issues. Examples include the use of astronomy topics to improve educational outcomes and teach critical thinking and skills, such as coding (*OAD, 2023a*).

In recent years, astronomy has been used to boost tourism, especially to benefit communities in rural areas that have excellent dark skies (*OAD, 2023b*). An emerging area in astronomy for development is the use of astronomy to improve mental health outcomes (*OAD, 2022a*).

Astronomy is an exciting field that induces awe[1] and grabs attention. An astronomy-oriented activity, such as star-gazing, has the potential to change perspectives and reframe one's problems (e.g., *OAD, 2021*). It also provides opportunities to engage in a shared activity and thereby experience social integration, connectedness and belonging. It invokes curiosity and leads to new questions, interests, and ideas. Through careful design and by working in conjunction with mental health experts, it is possible to introduce an astronomy-based activity (or integrate astronomy into an existing activity) to promote mental health benefits.

As a starting point for discussion and to collect user feedback, the OAD has created the Astronomy for Mental Health Guidelines (*OAD, 2022b*). This open-access online document offers guidance for setting up astronomy-related interventions, events, or mental health and well-being activities targeted at individuals and organisations. To contextualise these guidelines, this article looks at mental health, the shortfall in global mental healthcare services, and how astronomy can be used to help. We conclude this article with a brief summary of the Guidelines.

The mental healthcare shortfall

Worldwide, nearly one billion people have mental disorders (*World Health Organization, 2022*). The Covid-19 pandemic further compounded the situation, with a 25.6% increase in reported cases of anxiety and a 27.6% increase in reported cases of depression[2] in 2020 (e.g., *Santomauro et al., 2021*).

Despite the urgency of the problem, not all people have equal access to the mental health care they might require due to the treatment gaps experienced globally (*World Health Organization, 2021*). Here, the term "treatment gap" refers to the difference between the number of people with mental health disorders and the number of individuals who can receive suitable treatment. This gap is affected by various factors such as service coverage, individual behaviours, and societal factors (e.g., *Jansen et al., 2015; Priester et al., 2016*).

Figure 1 shows the variation in service coverage for psychosis[3] and depression between high and low-income countries.

Individuals in high-income countries might have greater service coverage than low-income countries. However, service coverage does not equate to access and uptake of services, as access to mental health services is also influenced by other factors (e.g., *Rathod et al., 2017*).

Factors include the lack of official endorsement of mental health care policy, under-resourcing, a lack of awareness, stigma, and a heavy reliance on psychiatric hospitals. Despite mental health care being integrated into public health care, the focus is often on managing medication for severe disorders. In contrast, the detection and treatment of other mental disorders, such as depression and anxiety, are not given the

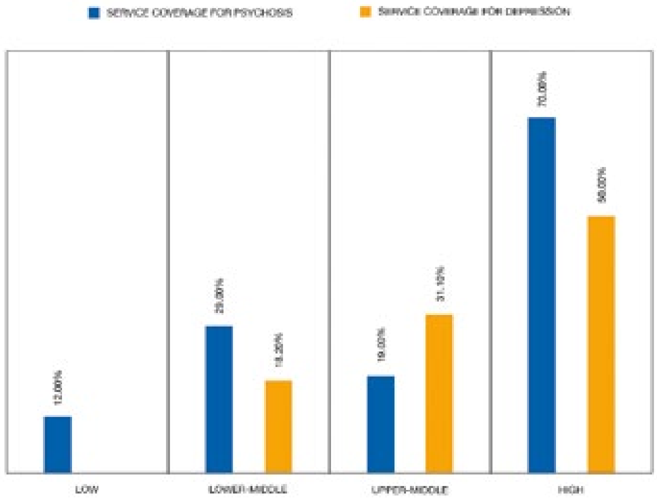


Figure 1: *Service Coverage for Psychosis and Depression (depression, n=21 countries; psychosis, n=47 countries; data from World Health Organization, 2021)*

same level of attention (e.g., *South African Department of Health, 2012*).

South Africa is a clear example: the mental health service gap is 91% despite being designated by the World Health Organization (WHO) as an upper-middle-income country. Only 1.2% of those uninsured and 7.5% of those insured who require mental health care receive some form of inpatient or outpatient care in the country (*Docrat et al., 2019; World Health Organization, 2021*).

Considering the breadth of issues that impact and surround mental health, it is clear that mental health is central to development. Proper access to mental health services allows people to realise their potential, live and work effectively, and contribute to society. Given the number of people needing mental health treatment, care, and interventions, mental health should be seen not as a healthcare issue but as a fundamental human right (e.g., *Oliveros et al., 2022*).

Astronomy and mental health

Though not a typical avenue to improve mental health and well-being, a growing body of literature supports using astronomy and nature to improve mental health (e.g., *Bell et al., 2014; Piff et al., 2015*). A review of nature-oriented mental health programmes based on horticulture and gardening showed increased positive emotions, relationships, physical activity, involvement, and feelings of inclusion within the community (*Berto, 2014*). These findings align with Kaplan's Attention Restoration Theory (ART), which posits that nature can serve as an effective "distraction" from the stress people experience (e.g., *Kaplan, 1995; Ackerman, 2018*).

Nature, whether real or virtual (e.g., potted plants, nature pictures, films, and slides), can help restore mental energy, improve mood, and provide a break to tackle challenges with renewed focus (e.g., *Berto, 2014; Ackerman, 2018*). It enables people to experience awe, which has been shown in various studies to have a positive impact on emotions and relaxation (e.g., *Berto, 2014; Piff et al., 2015*).

Awe has also been shown to promote ethical decision-making, generosity, and prosocial behaviour because it leads people to feel a sense of self-diminishment and to encounter something they perceive as superior to themselves (e.g., *Piff et al., 2015*). Through experiencing "distraction" and awe, individuals can separate themselves from their emotions or situation and experience relief from the challenges they face.

While a significant amount of research supports the benefits of spending time in nature, only a limited number of studies have explored the potential positive effects of astronomy on mental health (e.g., *Bell et al., 2014; Piff et al., 2015*). Astronomy, through activities such as stargazing, education and storytelling, allows individuals to engage with nature. In particular, in our pilot interventions, astronomy activities like stargazing were found to positively benefit mental health and empower individuals and communities affected by trauma or psychological symptoms (*OAD, 2021*).

Astronomy-based interventions equip participants with a range of mechanisms to support their mental health: learning new ideas, developing skills, strengthening cultural identity, promoting social inclusion, fostering a sense of belonging, and offering opportunities for artistic and recreational activities (*OAD, 2021*).

Through the Astronomy for Mental Health project, the OAD team is exploring ways to use astronomy as a viable and cost-effective tool for improving mental health and well-being. In doing so, the team quickly realised the need to develop and share resources and engage with the broader astronomy and mental health communities. The Astronomy for Mental Health Guidelines is an open resource to share findings, learn from other experiences, and nurture a community of practitioners who can apply astronomy to promote mental health.

The Astronomy for Mental Health Guidelines

The Astronomy for Mental Health Guidelines is a planning tool (*OAD, 2022b*). It offers a straightforward and practical approach to designing and implementing programs, interventions, and events that integrate astronomy with mental health and well-being. The document is aimed primarily at astronomers and mental health care practitioners and is based on the work and experience of the OAD team.

As illustrated in Figure 2, the Guidelines are structured in a way that helps to identify, plan, and establish these initiatives.

Initially, the Guidelines were released during the International Astronomical Union (IAU) General Assembly in August 2022. The OAD team sought input from a diverse group of people to help develop the Guidelines, including students, astronomers, psychologists, and the general public.

The document contains recommendations to plan an activity, describes how to integrate astronomy and mental health, and provides various resources such as tools, activities, and websites. It also showcases examples of pilot mental health projects that the OAD team ran in various countries. We discuss the pilot projects below.

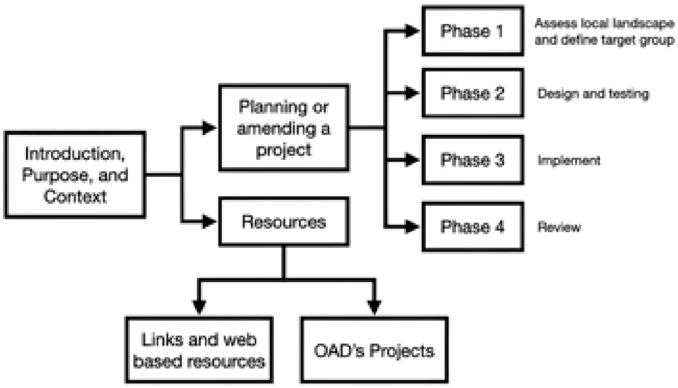


Figure 2: *Astronomy for Mental Health Guidelines Overview (OAD, 2022b).*

Activities in Armenia

In Armenia, the team organised a four-day educational project using astronomy resources for children at a local support centre.

Following an evaluation consisting of questionnaires and individual interviews, the team showed that the programme had a positive impact on the children's behaviour and mood. Notably, they saw an increase in emphasis on the value of interpersonal relationships, motivation, openness, positivity, and a change in value system[4].

Activities in Spain

The OAD team has been working with the Fundación Alicia y Guillermo, an association for senior citizens (aged 57 to 93) in Madrid, Spain, to offer astronomy talks[5].

The goal of these talks was twofold: to provide this group, who are often limited in options for activities, with access to different types of activities and to assess whether astronomy can have positive effects on their mental well-being, especially after the pandemic when this group suffered greatly from fear and isolation.

The pilot activities were held in a hybrid format: some participants physically attended the talks while others connected remotely. Evaluation questionnaires showed an increase in participants' motivation, self-esteem, community engagement, and feelings of mental activity, as summarised in Table 1.

Activities in South Africa

The OAD team hosted an astronomy and mental health workshop for the Cape Town Community Mental Health and Psychiatry Foundation (CMHPF). The CMHPF serves around 300 long-term residents, mostly suffering from schizophrenia and bipolar disorder.

Item	Average Numeric Value
Personal growth and enrichment	8.7
Improve my self-esteem thanks to the acquisition of new knowledge	7.7
Enjoy and develop a hobby that has allowed me to use my time in a positive way	8.9
Discover a new hobby	7.5
Meet other people with similar interests, expanding my social circle	6.5
Acquire knowledge that, in turn, I will be able to transmit to other people in my environment	6.9
Stay active	8.2
Feel active	8.3
Satisfaction I felt with the initiative	8.7

Table 1: *Likert scale (1 to 10, where 1 is the lowest and 10 is the highest) results in response to the question, "What do you consider that the series of talks 'Introduction to Astronomy' has provided you?". The Introduction to Astronomy talks were organised for senior citizens in Spain. Scores are averages from 22 participants, aged 57 to 93 (OAD, 2023c)..*

The goals of the workshop were to demonstrate the potential of astronomy to improve mental health and well-being, identify the needs and challenges that the OAD could help with, and improve the mental health and well-being of the participants.

We gathered feedback through qualitative face-to-face interviews[6] held after the workshops, revealing that our goals were all achieved.

Conclusion

The use of astronomy in mental health is a relatively new field, and more research is needed to establish best practices. This includes gathering more data, collaborating on the development of guidelines, testing different activities to determine their impact on mental health, and conducting both qualitative and quantitative research to better inform practice.

In order to encourage projects and research by astronomers, healthcare practitioners, and the public, the OAD has published the Astronomy for Mental Health Guidelines (*OAD, 2022b*).

As an open-source reference and toolkit, the Guidelines help ease the process of planning, running, and reviewing projects and interventions. The Astronomy for Mental Health Guidelines continues to grow and develop as the general public, astronomers, and mental healthcare practitioners contribute their personal resources and experience.

If you would like to get involved, find out more, or contribute your own experiences, reach out to the team at: mentalhealth@astro4dev.org

References

Ackerman, C. (2018, November 13). What is Kaplan's Attention Restoration Theory (ART)? Positive Psychology. https://positivepsychology.com/attention-restoration-theory/

Berto, R. (2014). The Role of Nature in Coping with Psycho-Physiological Stress: A Literature Review on Restorativeness. Behavioral Sciences, 4(4), 394–409. MDPI AG. http://dx.doi.org/10.3390/bs4040394

Docrat, S., Lund, C., & Besada, D. (2019). An Evaluation of the Health System Costs of Mental Health Services and Programmes in South Africa (Version 5). University of Cape Town. https://doi.org/10.25375/uct.9929141.v5

Bell, R., Irvine, K., Wilson, C., & Warber, S.L. (2014). Dark Nature: Exploring potential benefits of nocturnal nature-based interaction for human and environmental health. European Journal of Ecopsychology, 5. https://www.researchgate.net/publication/305041212_Dark_Nature_Exploring_potential_benefits_of_nocturnal_nature-based_interaction_for_human_and_environmental_health

Jansen, S., White, R., Hogwood, J., Jansen, A., Gishoma, D., Mukamana, D., & Richters, A. (2015). The "treatment gap" in global mental health reconsidered: Sociotherapy for collective trauma in Rwanda. European Journal of Psychotraumatology, 6. https://doi.org/10.3402/ejpt.v6.28706

Kaplan, S. (1995). The Restorative Benefits of Nature: Towards an Integrative Framework. Journal of Environmental Psychology, 16.

Office of Astronomy for Development. (2021). Astronomy for Mental Health - IAU Office of Astronomy for Development. IAU Office of Astronomy for Development. https://www.astro4dev.org/flagship-themes/celebrating-our-common-humanity-astronomy/astronomy-mental-health/

Office of Astronomy for Development. (2022a, October 26). About the IAU OAD. IAU Office of Astronomy for Development. https://www.astro4dev.org/

Office of Astronomy for Development. (2022b, November 21). Astronomy for mental health guidelines. IAU Office of Astronomy for Development. https://www.astro4dev.org/astronomy-for-mental-health-guidelines/

Office of Astronomy for Development. (2023a, April 26). Code learning with astronomical ideas Archives - IAU Office of Astronomy for Development. IAU Office of Astronomy for Development. https://www.astro4dev.org/category/code-learning-with-astronomical-ideas/

Office of Astronomy for Development. (2023b). Flagship 1: Astrostays - IAU Office of Astronomy for Development. IAU Office of Astronomy for Development. https://www.astro4dev.org/flagship-themes/sustainable-local-socio-economic-development-through-astronomy/flagship-1-astrostays/

Office of Astronomy for Development. (2023c, March 2). OAD Project Resources. IAU Office of Astronomy for Development. https://www.astro4dev.org/resources/oad-project-resources/

Oliveros, B., Agulló-Tomás, E., & Márquez-álvarez, L. (2022). Risk and protective factors of mental health conditions: Impact of employment, deprivation and social relationships. International Journal of Environmental Research and Public Health, 19(11). https://doi.org/10.3390/ijerph19116781

Piff, P. K., Dietze, P., Feinberg, M., Stancato, D. M., & Keltner, D. (2015). Awe, the small self, and prosocial behavior. Journal of Personality and Social Psychology, 108(6), 883–899. https://doi.org/10.1037/pspi0000018

Priester, M. A., Browne, T., Iachini, A., Clone, S., DeHart, D., & Seay, K. D. (2016). Treatment Access Barriers and Disparities Among Individuals with Co-Occurring Mental Health and Substance Use Disorders: An Integrative Literature Review. Journal of Substance Abuse Treatment, 61, 47–59. https://doi.org/10.1016/j.jsat.2015.09.006

Rathod, S., Pinninti, N., Irfan, M., Gorczynski, P., Rathod, P., Gega, L., & Naeem, F. (2017). Mental Health Service Provision in Low- and Middle-Income Countries. Health Services Insights, 10. https://doi.org/10.1177/1178632917694350

Santomauro, D. F., Mantilla Herrera, A. M., Shadid, J., Zheng, P., Ashbaugh, C., Pigott, D. M., Abbafati, C., Adolph, C., Amlag, J. O., Aravkin, A. Y., Bang-Jensen, B. L., Bertolacci, G. J., Bloom, S. S., Castellano, R., et al. (2021). Global prevalence and burden of depressive and anxiety disorders in 204 countries and territories in 2020 due to the COVID-19 pandemic. The Lancet, 398(10312), 1700–1712. https://doi.org/10.1016/S0140-6736(21)02143-7

South African Department of Health. (2012). National Mental Health Policy Framework and Strategic Plan 2013-2020. South African Department of Health. www.safmh.org/wp-content/uploads/2020/09/National-Mental-Health-Policy-Framework-2013-2020.pdf

World Health Organization. (2021). Mental Health Atlas 2020. World Health Organization. https://www.who.int/publications/i/item/9789240036703

World Health Organization. (2022). World mental health report: transforming mental health for all. World Health Organization. https://www.who.int/publications/i/item/9789240049338

Notes

[1] Awe: Refers to a feeling of admiration or wonder that is often triggered by experiences or phenomena that are vast in scope or grand in scale and which may challenge an individual's current perspectives or understanding.

[2] Depression: Depression is a common mental health disorder that causes persistent feelings of sadness and loss of interest in activities. It can also cause physical symptoms such as fatigue, changes in appetite and sleep patterns, and difficulty concentrating.

[3] Psychosis: A condition affecting how one processes information, resulting in a disconnect from reality. This can result in a person seeing, hearing, or believing things that are not real. Psychosis is a symptom that can be triggered by a mental illness. There are two major forms of psychosis, namely Schizophrenia and Schizoaffective disorder.

[4] Quantifying a change in value system involves assessing and measuring subjective beliefs and attitudes. We gathered this data with the assistance of a psychologist using questionnaires, surveys, and interviews. It is important to note that quantifying a change in value system is not an exact science, and different methods may produce different results. There is also a fair degree of bias present in quantifying a change in value systems.

[5] Astronomy talks: We delivered four talks on the topics: "A Voyage Through the Cosmos", "Exploring the Solar System with ESA missions", "Impacts and How to Avoid Them", and "The Red Planet".

[6] Interviews: The qualitative face-to-face interviews were held after the workshop with randomly selected participants. The interview posed a series of open-ended questions: (1) "Having been to the workshop, how do you think astronomy can be used to improve the mental health and well-being of the patients you work with?"; (2) "What challenges do you see in implementing [x](the participant's recommendation from question 1)?"; (3) "How can the OAD assist you in overcoming these challenges?".

Acknowledgements

The OAD team for their support and input into the submission. Special thanks to Armine Patanayan, Kevin Govender, Vanessa McBride, and Ramasamy Venugopal.

Biographies

Dominic Vertue joined the OAD in June 2022. Dominic has a master's in medical social work and several years of experience in public health and community-based programs to empower vulnerable groups. Within the OAD, Dominic forms part of the Astronomy for Mental Health Flagship, exploring the role astronomy can play in mental well-being.

Sandra Benítez holds a PhD in astrophysics and a specialisation in Science communication. She was an OAD remote fellow from August 2021 to August 2022, working within the Astronomy for Mental Health project.

An accessibility case study incorporating rich visual descriptions for *Chandra's* high-energy universe

Kimberly Arcand
Center for Astrophysics | Harvard & Smithsonian
kkowal@cfa.harvard.edu

Megan Watzke
Center for Astrophysics | Harvard & Smithsonian
mwatzke@cfa.harvard.edu

J.J. Hunt
Consultant
jj@jjhunt.com

Christine Malec
Consultant
christine.malec@gmail.com

Keywords
Accessibility, Visualisation

The nature and complexity of various kinds of astronomical data visualisations can be challenging to communicate with non-experts. The obstacles can become even larger for people who are blind, low vision or learn best via non-visual methods since much of the messaging in astronomical communication hinges on the visual imagery created from these data. In consultation with members from blind and low-vision communities, we present an overview of the 3D print and sonification projects and an in-depth discussion of the visual description project at NASA's *Chandra X-ray Observatory*. We offer a case study of how the 3D prints, sonifications, and visual descriptions are currently being used for mission and programme communications. We focus on how we integrate verbal explanations of the scientific phenomena along with descriptions of what the visual viewer sees in the presented imagery, sonification or 3D model to create a more accessible, cohesive package. We suggest that this process of creating content for blind or low-vision audiences can be scaffolded and applied to other types of astronomy content and a wide range of science communication.

Introduction

The *Chandra* 3D modelling and printing, sonification, and visual description programme is a set of accessible digital projects created to help communicate with communities, particularly those who are blind, have low vision, or have different learning needs. These programmes connect our target communities with the science of NASA's *Chandra X-ray Observatory* and other astronomical missions. The 3D modelling and printing project was launched about a decade ago (Arcand et al., 2019), the sonification project was launched in 2020[1], and the visual description project was launched in 2021[2]. Many of the results communicated with the public from *Chandra* science involve other telescopes that are capable of detecting light across the electromagnetic spectrum and even multi-messenger astronomy. As a result, these accessible projects also typically cover science results and images from other missions, telescopes, and instruments beyond *Chandra*.

The 3D printing project began in 2009 with the first 3D data model released of the supernova remnant Cassiopeia A (*Chandra X-ray Observatory*). By combining X-ray data from *Chandra* with infrared data from another orbiting NASA observatory, the *Spitzer Space Telescope*, and visible light from telescopes on the ground, we created the first 3D reconstruction of a supernova remnant. That 3D model was eventually improved with input from students at the National Federation of the Blind (*Arcand et al., 2019*) before being printed as a 3D print. Since then, we have added other objects, ranging from galaxies to interacting stars, to this growing 3D print collection[3].

Sonification was the next phase of our accessibility programme. Generally, sonification uses non-speech audio to provide information to listeners (*Kramer et al., 2010*). This project uses sonification to translate astrophysical data into sound, bringing cosmic objects and environments observed by *Chandra* and other telescopes to listeners by creating soundscapes of the image, spectrum, or other data. The sonifications are provided as audio-only files and in video/audio compilations. We have had a very positive response to these sonifications in blind and low-vision communities (*Arcand et al., in preparation*) as well as traditional popular and social media. For the former, workshops, talks and a research survey have been completed with the community. The workshops in particular provided time for feedback from blind and low vision community members which was positive overall. And the research survey showed high engagement and learning with the sonifications (*Arcand et al., in preparation*). In the press, recent *Chandra* sonifications of the black hole in the Perseus galaxy cluster in May 2022 led to huge spikes in our Chandra.si.edu web traffic (e.g.,15,240,111 hits in May compared to an average of about 8-10,000,000 in more typical months) and social platforms (e.g., 19,000,000 views of the Perseus sonification on Twitter (5/2022 -12/2022) compared to fewer than 1,000,000 views for most *Chandra* videos similarly shared on the platform.), as well as articles in the *New York Times* (*Overbye, 2022; Engle, 2022*) and other major outlets such as National Public Radio (*Simon, 2022*) and *Popular Science* (*Woodall, 2022*).

The visual description project creates detailed verbal descriptions of *Chandra* and multiwavelength data, which primarily take the form of 2D images, timelapse movies or sonifications, and illustrations as needed. Visual descriptions, also sometimes referred to as alternative (or "alt") text, are text-based assets that provide written information to accompany an image to describe it for a user who cannot see it (*Mack, 2021*). Working with experts in visual descriptions, including an expert who is blind, we developed rich text descriptions of the images created from astronomical data that are released simultaneously with the traditional package of press release text and images. These rich visual descriptions differ from typical image captions in that they provide extended detail of what is shown, are written in a style more suitable to listening rather than reading (e.g., shorter sentences and the frequent use of proper names), and with commonplace analogies when possible. The visual description information is created as text[4] and recorded in audio[5] format, and published as alternative texts in both web and social media platforms (shortened to the appropriate character length as needed for the latter). In response to user feedback, we now also package audio recordings of the rich texts into an XML podcast feed[6].

Visual description techniques

How can we best describe images or videos of cosmic objects constructed from light mostly invisible to the human eye to people who are blind or have low-vision? Some of the common reference points frequently used in traditional caption writing can be of low value to those who have not been able to experience certain phenomena firsthand.

We have, therefore, developed three main strategies to create visual descriptions of complex astronomical objects. The first is to weave the scientific meaning throughout the text, instead of simply describing the image or video only as it appears. Our blind and visually impaired (BVI) testers reported that this method enhanced understanding of both the visual structure and the scientific significance behind it when we integrated these information tracks.

The second strategy is adapting the writing style. Quite frequently, captions for astronomical images can include longer sentences that contain a good deal of information. While this can be effective for some sighted users, it can be challenging for someone receiving the information audibly. Our solution has been to provide shorter sentences with multiple commas that allow for natural pauses in the description. We also use proper nouns more frequently than in other settings. For example, replacing "it" with "the black hole" in a sentence may seem like a trivial change, but it can help anchor a BVI user in following along with the discourse. These changes can also have a secondary benefit by boosting the search engine optimisation (SEO) results for websites (*Ltd, Innovation Visual, n.d.*). These user-tested techniques have also been informing how other *Chandra* captions or descriptions for non-experts are written to improve accessibility and inclusion generally, with similar incorporation of more proper nouns, fewer complex structures, and so on.

Our third strategy has been to insert this process of creating descriptions into the pre-existing pipeline of communications products we produce for every publicly released result. Rather than having a separate process, we have made it an adaptation of text already being written and vetted. This is important for missions and telescopes with more limited staff and resources. By adapting existing reviewed text rather than creating it from scratch, we have been able to absorb this project into the workload without significant additional time allocations from staff. Of course, adding rich descriptions is extra work and must be considered by those who would like to implement this step in their communications. Ideally, organisations should identify staff or contractors who can write, or learn to write, in this specific style and members of the blind or low vision community who can collaborate to help adapt and verify the meaning-making of the product.

In our pilot programme we have found that using the regular caption or release text as a starting point does not require an exorbitant amount of additional research. In other words, we can improve access for an underserved community by re-writing and adapting what is already being prepared. We purport that any effort in this area is an important step in better serving these audiences that have long been overlooked by astronomical communication.

Case study examples

The following examples demonstrate elements of the accessibility scaffolding: 3D printing, sonifications, and visual descriptions. By offering such products, we hope to provide users with a suite of options that they can select based on their interests, needs and abilities. Indeed, as there is no "one size fits all" mode of accessible science communication, we work directly with members of different communities to develop, refine, and innovate to help meet the needs of multiple non-expert audiences.

Videos provide content across time, so often, there is more involved in providing such descriptions than a still image alone requires. However, it is also possible that an image can be particularly complex or nuanced and need more text to assist users in understanding the content.

***Eta Carinae 3D model (video)*[7]**

3D Print:
https://chandra.si.edu/deadstar/eta.html

Sonification:
https://chandra.si.edu/sound/index.html#etacar

Visual Description
(*Chandra X-ray Observatory, 2022a*):

Today's release features a visualisation of a massive star, Eta Carinae, which expelled about 10% of its mass in an event known as the Great Eruption observed in the 1840s. This eruption created a small nebula around the star, the Homunculus Nebula. Images taken in different wavelengths of light by the *Hubble Space Telescope*, *Chandra X-ray Observatory*, and *Spitzer Space Telescope* have helped visualisation specialists create a digital 3D model that can be rotated 360 degrees. This visualisation is presented in a short video that shows the digital model being constructed layer by layer.

The video begins with static images of each layer: Visible, Ultraviolet, Hydrogen, and X-ray, as well as an image combining all of the above wavelengths. When frozen in time, the Great Eruption resembles a peanut in the shell. The bulbous, knobby shapes at either end represent the erupting nebula, while the star itself occupies the tapered space between them.

In the 2D image and 3D model of the Great Eruption in visible light, Eta Carinae is presented in mottled and veiny browns and tans. This 3D rendering is the base image onto which subsequent layers are added. As the model rotates, cloudy columns shooting out of the glowing core become evident.

As the 3D model continues to rotate, bright blue ultraviolet light is added to the visualisation. This light blankets the peanut shape in a soft neon blue cloud. Thin shafts of blue light burst from the core, extending beyond the cloudy brown columns.

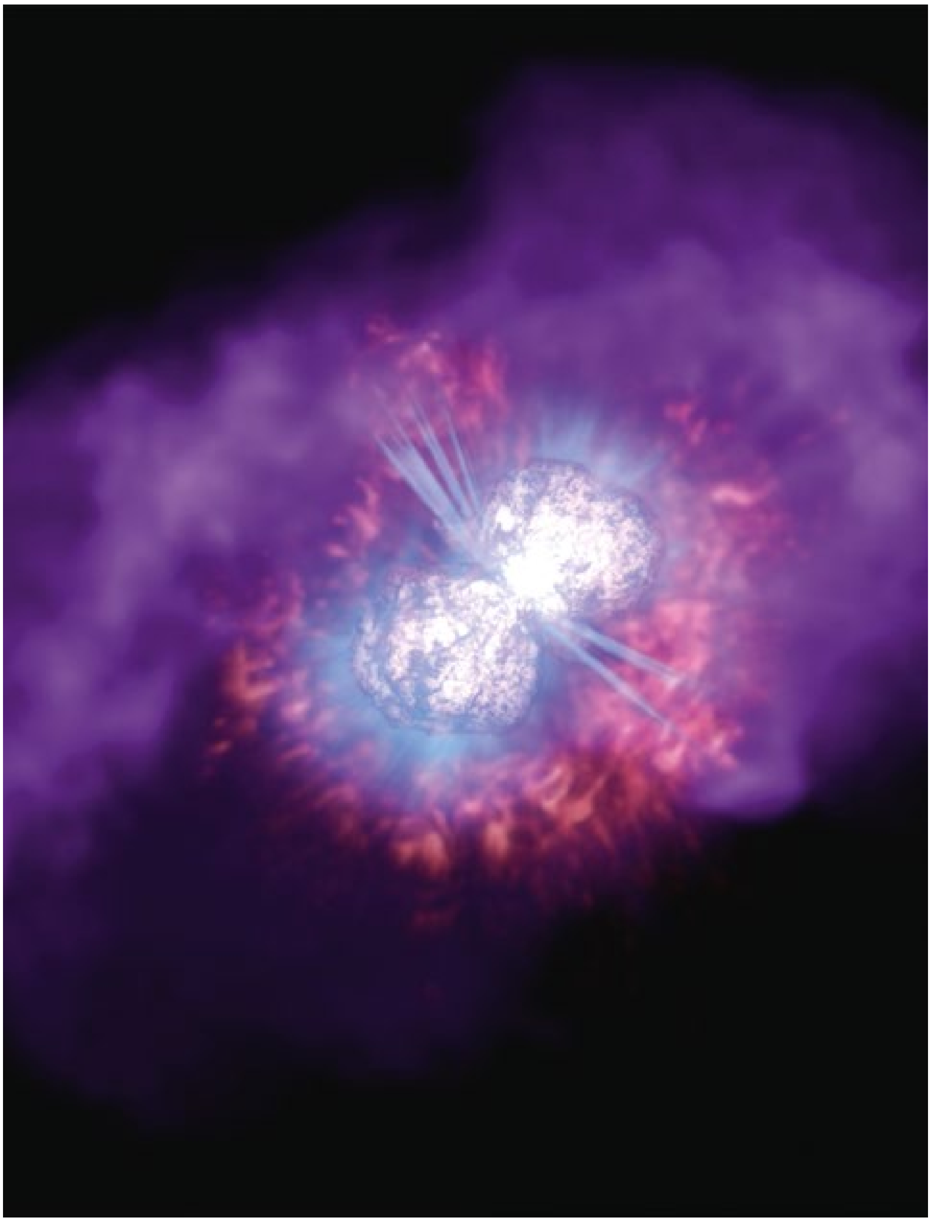


***Figure 1** A 3D visualisation of a massive star, Eta Carinae, which expelled about 10% of its mass in an event known as the Great Eruption observed in the 1840s. Image Credit: J. Olmsted, D. Player, L. Hustak, A. Pagan, J. DePasquale, G. Bacon, F. Summers (STScI), R. Hurt (Caltech/IPAC), NASA, ESA*

Next, the emission from hydrogen atoms is added to the still-rotating model. This resembles a translucent ball of red flames encircling the peanut shape and the blue ultraviolet light. Inside the cloud, the visual layer appears to glow.

Finally, an irregular cloud of purple X-ray light surrounds the red hydrogen emission. This cloud appears soft in texture and is longer than it is wide, similar in shape to the glowing eruption at its core.

Cat's Eye Nebula (sonification)[8]

3D Print:
https://chandra.si.edu/tactile/3d_printing.html

Sonification:
https://chandra.si.edu/sound/index.html#ngc6543

Visual Description
(*Chandra X-ray Observatory, 2021*):

> The Cat's Eye video features a static image of an ethereal shape surrounded by concentric circles. The shape is the Cat's Eye nebula, a huge cloud of gas and dust blown off of a dying star. The concentric circles are bubbles expelled by the star over time. The dust cloud resembles a translucent pastry pulled to golden yellow points near our upper right and lower left, with a blob of bright purple jelly inside the bulbous pale blue core. The jelly-like centre represents X-ray data from Chandra.
>
> The outer cloud and translucent circles represent visible light data from the Hubble Space Telescope. As the video unfolds, a white line emanating from the centre of the nebula scans the image in a circle, like the second hand on a clock, or the radial arm on a radar screen. The more of the nebula that's in its path, the richer the accompanying sound. Light that is farther from the core has a higher pitch than light that is close to the core. X-rays are represented by a harsher sound, while visible light data sound smoother. The concentric circles create a constant hum interrupted by a few sounds from spokes in the data. Additional videos feature Cat's Eye images and audio from separated X-ray and optical data sets.

Figure 2 *When a star like the Sun begins to run out of helium to burn, it will blow off huge clouds of gas and dust. These outbursts can form spectacular structures like the one seen in the Cat's Eye nebula. Image Credit: X-ray: NASA/CXC/RIT/J.Kastner et al.; Optical: NASA/STScI; Sonification: NASA/CXC/SAO/K.Arcand, SYSTEM Sounds (M. Russo, A. Santaguida)*

Cassiopeia A (image)[9]

Related 3D Print:
https://chandra.si.edu/tactile/3d_printing.html

Related Sonification:
https://chandra.si.edu/sound/index.html#casa

Visual Description
(*Chandra X-ray Observatory, 2022b*):

This image resembles a disk of electric blue light, purple clouds, glowing white fog, and red and yellow flames, dotted with glowing orange specks. This is Cassiopeia A, a supernova remnant. Here, elements of the exploded star are cast into space. The red and yellow flames are silicon and sulfur. The light purple within the cloud is iron, and the blast wave is blue. All were observed by the *Chandra X-ray Observatory*. The electric blue-purple light, which appears in ripples throughout the disk and around the outer rim, is radio data from the National Science Foundation's Very Large Array. This also shows the blast wave from the explosion. A layer from the *Hubble Space Telescope* adds orange to the flames and the glowing specks.

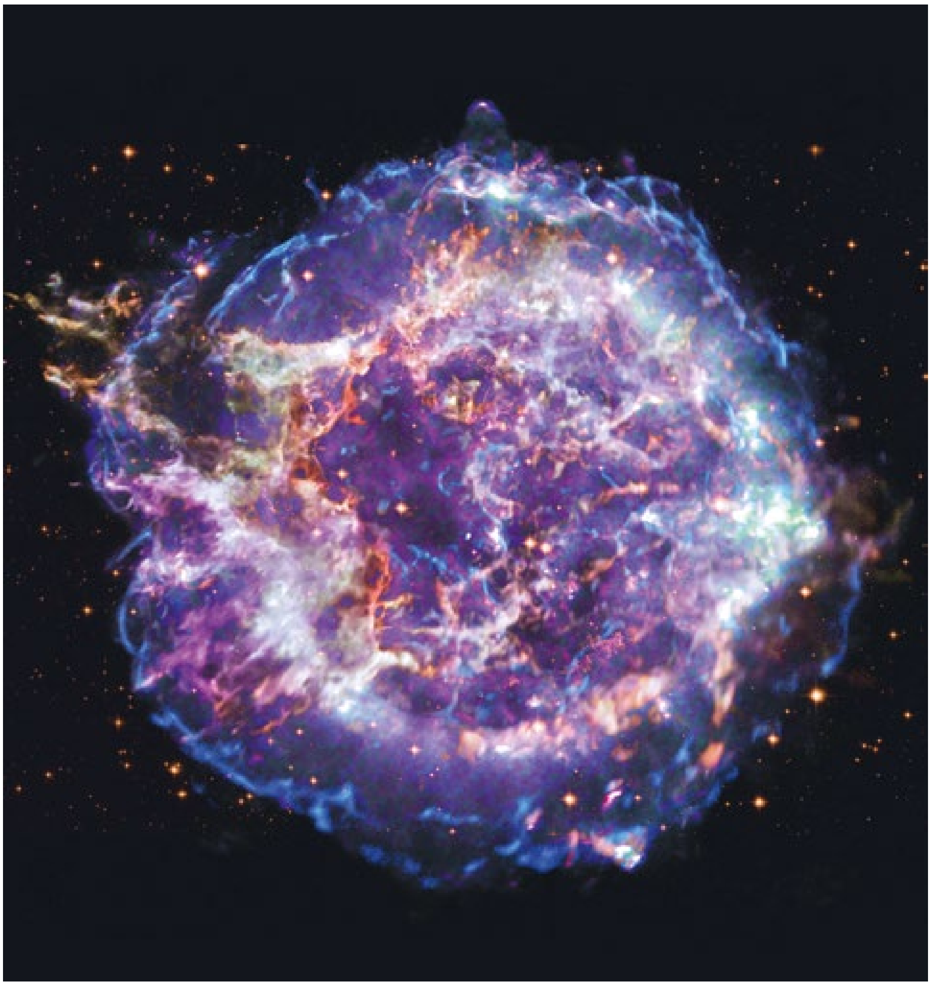


Figure 3 *Cassiopeia A is a supernova remnant observed by the Chandra X-ray Observatory. The X-ray image has been combined with radio data from the National Science Foundation's Very Large Array and optical information from the Hubble Space Telescope. Image Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/VLA*

Discussion

Since the *Chandra* Communications group began implementing these accessibility programs, we have continued to survey the results among the audiences we are trying to reach. We have presented the projects at numerous events, from webinars and workshops to radio shows and podcasts, particularly for participants who are blind or low vision, with highly positive feedback. As we learn more about the needs and wants of these communities, we will adapt further to refine our best practices. We intend to submit a paper on the sonification project's quantitative data and conduct a more formal qualitative and quantitative user study on the visual descriptions programme soon. Moreover, we have shared what we have learned so far with other NASA missions, other groups at the Center for Astrophysics | Harvard & Smithsonian, as well as with other professional astronomy and science communications organisations, and have developed a "master class" workshop to help other groups apply these techniques for their own programs. This type of program is a small but important step towards being more responsive to and inclusive of what have traditionally been underserved audiences in astrophysics.

Notes

1 *Chandra* X-ray Center, Sonification page: https://chandra.si.edu/sound

2 *Chandra* X-ray Center Visual description page: https://chandra.si.edu/tactile/visual.html

3 *Chandra* X-ray Center, 3D print page: https://chandra.si.edu/3dprint

4 *Chandra* X-ray Center, Text example: https://chandra.si.edu/photo/2021/kpd0005/kpd0005_description.txt

5 *Chandra* X-ray Center, Audio example: https://chandra.si.edu/photo/2021/kpd0005/kpd0005_description_audio.mp3

6 *Chandra* X-ray Center, URL for XML feed: https://chandra.si.edu/resources/podcasts/description_audio.xml

7 *Chandra* X-ray Center, Eta Carinae 3D model page: https://chandra.harvard.edu/photo/2022/etacar/

8 *Chandra* X-ray Center, website for example sonification: https://chandra.si.edu/photo/2021/sonify3/

9 *Chandra* X-ray Center, website for example sonification: https://chandra.si.edu/photo/2021/v404cyg/

10 NASA's Universe of Learning -Accessible Resources: https://www.universe-of-learning.org/resources/projects/accessible-learning-resources

Acknowledgements

These three scaffolded projects were created by collaborations and teams consisting of Dr Kimberly Arcand, Dr Peter Edmonds, Megan Watzke, April Jubett, Nance Wolk, Kristin DiVona, Kayren Phillips, Khajag Mgrdichian, and Kelly Williamson of *Chandra*, Universe of Learning team members, as well as sonification experts Dr Matt Russo and Andrew Santaguida of System Sounds, and visual description consultants J.J. Hunt and Christine Malec as well as other volunteers for testing.

The materials were developed with funding from NASA under contract NAS8-03060 for the *Chandra* X-ray Center (CXC). NASA's Marshall Space Flight Center manages the *Chandra* program. The Smithsonian Astrophysical Observatory's *Chandra* X-ray Center controls science from Cambridge, Massachusetts and flight operations from Burlington, Massachusetts. The 3D printing and sonification projects have also been included as part of NASA's Universe of Learning program[10]. Additional funding for that comes from NASA's Universe of Learning under award #NNX16AC65A with Caltech/IPAC, JPL, and the Smithsonian Astrophysical Observatory.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Arcand, K.K., Jubett, A., Watzke, M., Price, S., Williamson, K. T. S., & Edmonds, P. (2019). Touching the stars: Improving NASA 3D printed data sets with blind and visually impaired audiences. Journal of Science Communication, 18(4). https://doi.org/10.22323/2.18040201

Chandra X-ray Observatory (2009, January 6). *Cassiopeia A: 3-D Model: A Star From the Inside Out*. https://chandra.harvard.edu/photo/2009/casa2/

Chandra X-ray Observatory (2021, March 24). *Data Sonification: Stellar, Galactic, and Black Hole.* https://chandra.harvard.edu/photo/2021/sonify3/sonify3_description.txt

Chandra X-ray Observatory (2022a, January 25). *Eta Carinae: Visualization Explores A Massive Star's Great Eruption*. https://chandra.harvard.edu/photo/2022/etacar/etacar_description.txt

Chandra X-ray Observatory (2022b, February 2). *An Expanse of Light*. https://chandra.si.edu/photo/2022/archives/archives_description.txt

Engle, J. (2022, May 16). *Lesson of the day: 'hear the weird sounds of a black hole singing'.* The New York Times. https://www.nytimes.com/2022/05/16/learning/lesson-plans/lesson-of-the-day-hear-the-weird-sounds-of-a-black-hole-singing.html

Kramer, G., Walker, B., Bonebright, T., Cook, P., Flowers, J. H. (2010). Sonification Report: Status of the Field and Research Agenda. Faculty Publications, Department of Psychology. 444. http://digitalcommons.unl.edu/psychfacpub/444

Ltd, Innovation Visual (n.d.). The importance of understanding a user's intent for better SeoInnovation Visual Ltd. The Importance of Understanding a User's Intent for Better SEO. https://www.innovationvisual.com/knowledge/the-importance-of-understanding-a-users-intent-for-better-seo

Mack, K. Cutrell, E., Lee, B. Ringel Morris, M. (2021) Designing Tools for High-Quality Alt Text Authoring. The 23rd International ACM SIGACCESS Conference on Computers and Accessibility, Article No.: 23 Pages 1–14 https://doi.org/10.1145/3441852.3471207

NASA's *Chandra* [@ChandraXRay]. (2022, May 4). *New sonifications of well-known black holes have been released for #BlackHoleWeek! The Perseus galaxy cluster — famous for sound waves detected.* [Tweet]. Twitter. https://twitter.com/chandraxray/status/1521861464151117825

NASA [@NASA]. (2022, May 5). *If a black hole erupts in space and no one is around to observe it, does it make a sound.* [Tweet]. Twitter. https://twitter.com/NASA/status/1522287741312114689

NASA (Exoplanets) [@NASAExoplanets]. (2022, August 21). *The misconception that there is no sound in space originates because most space is a ~vacuum, providing no way for.* [Tweet]. Twitter. https://twitter.com/NASAExoplanets/status/1561442514078314496

Overbye, D. (2022, May 7). *Hear the weird sounds of a black hole singing.* The New York Times. https://www.nytimes.com/2022/05/07/science/space/astronomy-black-hole-sound.html

Simon, S. (2022, May 28). *What does a black hole sound like? NASA has an answer.* NPR. https://www.npr.org/transcripts/1101763397

Woodall, T. (2022, May 20). *NASA recorded a Black Hole's song, and you can listen to it.* Popular Science. https://www.popsci.com/space/black-hole-sound-space-sonification/

Biographies

Kimberly Arcand is an expert in astronomy visualization and has been a pioneer in 3D imaging, printing, and extended reality applications with high-energy astrophysics data.

Megan Watzke is the press officer for the Chandra X-ray Observatory at the Center for Astrophysics | Harvard & Smithsonian.

J.J. Hunt is an innovative Audio Describer and storyteller who co-founded with Malec the podcast Talk Description to Me.

Christine Malec is an arts consultant, sonification consultant and member of the blind community. She's been a lifelong space enthusiast and advocate of accessible astronomy.

In late 2022, the Office of Astronomy for Education (OAE) National Astronomy Education Coordinator Team for Serbia launched the first national smartphone astrophotography contest, *Take a Photo of the Night Sky*, for primary and secondary school students. A total of 1400 students and more than 200 teachers participated in this contest, resulting in three winners, one of which is featured here. The image shown here, entitled “The starry sky above the Old Cemetary (memorial park) in Vlasotince,” won second place in the competition and was captured by a group of 8th-grade students and their teacher. For more information about their competition, see this website: https://sites.google.com/view/uslikajnocnonebo/

Elementary school “Siniša Janić”, Vlasotince students Nina Antić, Jana Gorunović, Isidora Ilić, Sofija Stojanović, and their teacher, Tatjana Mihajlović

Colophon

Address
CAPjournal,
IAU Office for Astronomy Outreach,
C/O National Astronomical Observatory of Japan
2-21-1 Osawa, Mitaka, Tokyo, 181-8588
Japan

E-mail
capjournal@oao.iau.org

Website
www.capjournal.org

ISSNs
1996-5621 (Print) | 1996-563X (Web)

CAP journal

Communicating Astronomy with the Public

Submission

We are keen to encourage readers to submit their own articles, reviews, and other content.

Submissions should be sent to the Editor:
capjournal@oao.iau.org

www.capjournal.org
Online issues
Free subscriptions
Article submission

Publishers

Sponsors

Collaboration