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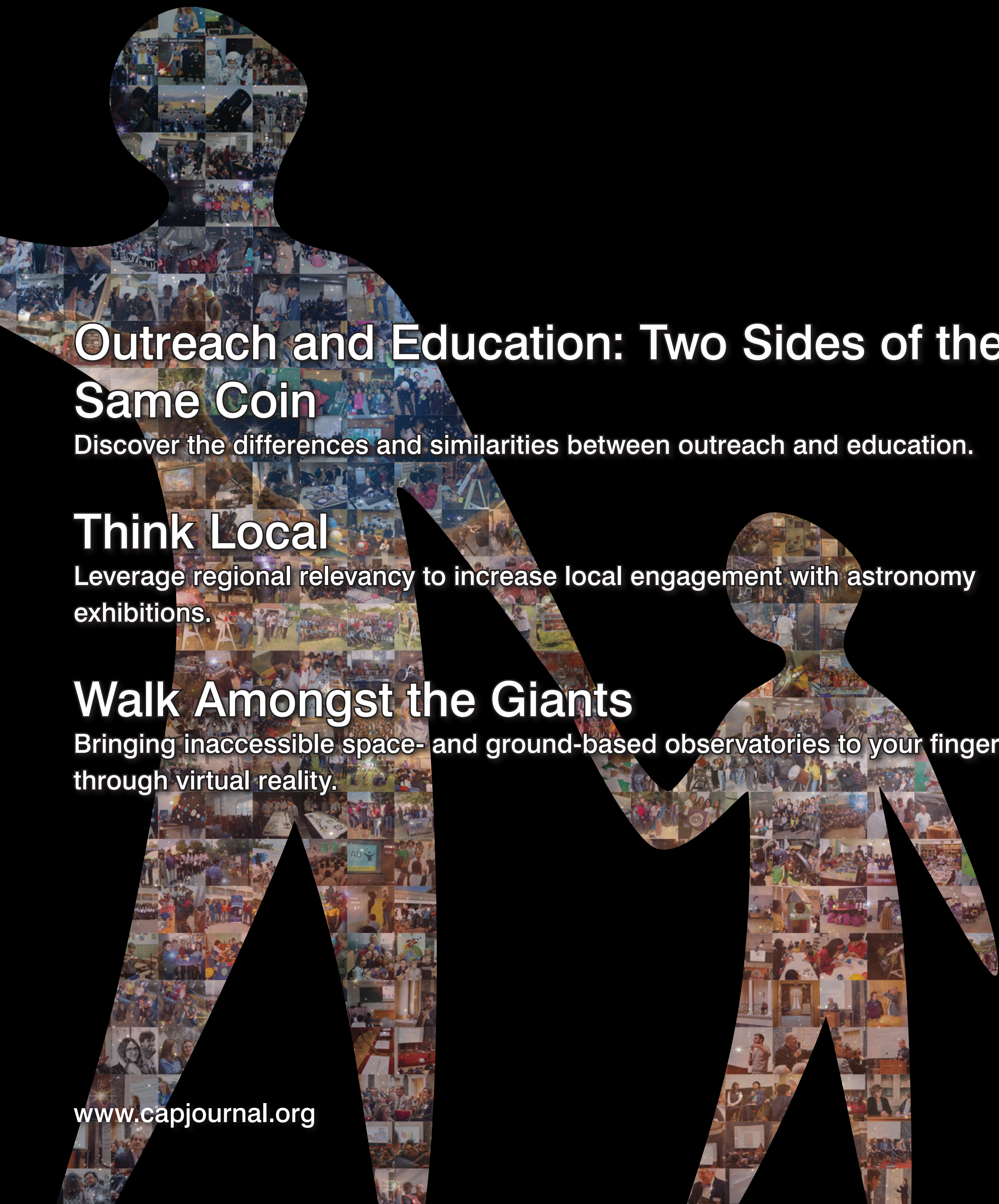
Communicating Astronomy with the Public



Outreach and Education: Two Sides of the Same Coin

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Peer into a stellar nursery at the edge of the Carina Nebula as seen through ***James Webb Space Telescope's (JWST)*** eyes. In one of ***JWST***'s First Images, we see an iconic formation of gas and dust sculpted by the radiation from nearby young massive stars. This is giving us remarkable new insights into stellar evolution. Credit: NASA, ESA, CSA, STScI

Editorial

For this CAPjournal issue, we partnered with our colleagues at the IAU Office of Astronomy for Education (OAE) and asked them to briefly review the similarities and differences between education and outreach. You will encounter one article, *astro-lab@home – Bringing Science to the Sofa*, which crosses the boundary between these two regimes. Read on to discover how they adapted school-based astronomy laboratories into outreach activities that anyone with a smartphone and some household supplies can do.

Inclusivity is at the heart of everything we do at the IAU Office for Astronomy Outreach (OAO), and two articles in this issue perfectly reflect these ideals. In *Accessibilising Astronomy: SciAccess Programmes for Disability Inclusion in STEM*, you will find a detailed description of the programmes offered by SciAccess, complete with best practices and lessons learnt for accessible activities, conferences, and programming. For an in-depth understanding of how regional relevance and a strong sense of community can impact museum goers' engagement, look no further than the article *Making Your Region the Heart of the Universe: Regional Engagement Through an Astronomy Exhibition*. Though they tackle different aspects of inclusivity, these two articles both speak to the OAO motto: Astronomy for Everyone. In all of our programmes, the OAO strives to ensure that astronomy is for everyone through access, accessibility, inclusivity, and community.

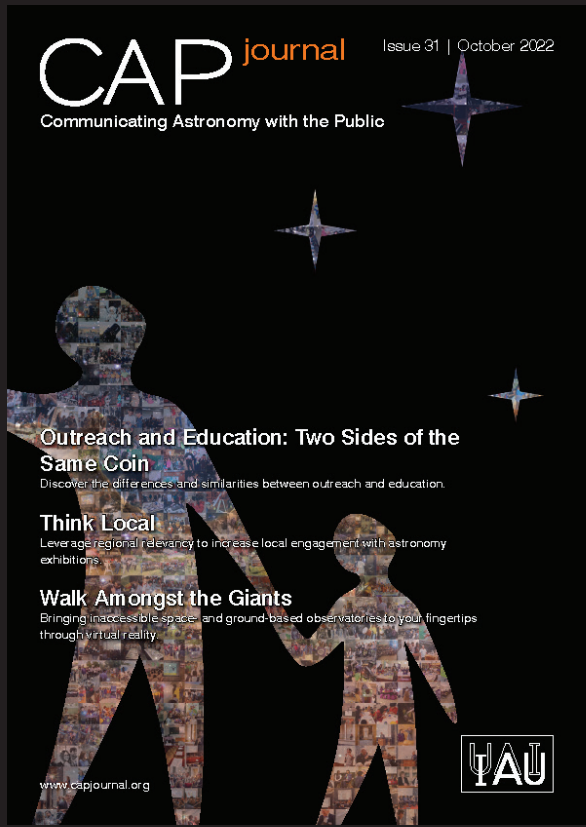
Our remaining two articles for this issue deal with space missions. In *Exploring the Frontiers of Space in 3D: Immersive Virtual Reality for Astronomy Outreach*, you will find a detailed report of one team's journey to bring a new dimension of understanding of space-based telescopes to the public through immersive virtual reality. For those readers who are interested in outreach for space missions, the article *Hayabusa2 Outreach Activities and Its Public Response* provides an in-depth narrative and important best practices.

In honour of OAO's 10th Anniversary, this edition of CAPjournal has something for everyone. We hope you find new ways to connect and collaborate with your communities through these articles and, as always, build bridges to help us make astronomy accessible for everyone.

Last but not least, we at the CAPjournal and IAU Office for Astronomy Outreach want to give a warm welcome to Kelly Blumenthal, the OAO's new Deputy Director and the new Managing Editor of the Communicating Astronomy with the Public Journal, without whom this edition of CAPjournal could not have been accomplished.

Lina Canas
Editor-in-Chief

Kelly Blumenthal
Managing Editor



Cover: This issue of the Communicating Astronomy with the Public Journal marks the 10-year anniversary of the IAU Office for Astronomy Outreach. The cover image honours our decade of dedication to bringing our motto, Astronomy for Everyone, to life. Look closely, and you will find images from across our ten years: from Telescopes for All to 100 Hours of Astronomy, and the wealth of social media photos we have shared over the years. Thank you all for an incredible decade! Looking forward, we plan to bring our communities more access to programmes and resources through exciting new international collaborations. We can't wait to share with you all that 2022-2032 has to offer.
Credit: IAU OAO, ESO/T. Preibisch

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Column

Explained in 60 Seconds: Astronomy Outreach and Education, Overlap and Differences

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Research institutes publishing press releases about their latest results, scientists sharing their passion for astrophysics on social media, amateurs welcoming the public for a stargazing night, school classes visiting a planetarium or science museum, initiatives training teachers in astronomy or developing classroom resources, colleges and universities offering astronomy courses for majors and non-majors – astronomy education and outreach comprise a broad range of activities. They also frequently go together, with numerous people active in both, but where does one end and the other begin? Let's take a closer look!

Astronomy Outreach

Astronomy outreach is communication from inside the (amateur or professional) astronomical community to audiences outside of that community, notably to the general public or specific subgroups thereof. Going by the outreach stakeholders we have met and interacted with in the field over the past twenty years, the motivations for doing outreach, which astronomy outreach shares with science outreach in general, include:

1. fostering a society that sees astronomy as a useful and important part of publicly funded activity;
2. attracting bright young adults to scientific careers in astronomy and related subjects, specifically in the case of universities;
3. bolstering the public standing of an (astronomical) institution – whether a scientific institute or an amateur astronomy club;
4. contributing to a science-literate society – more important than ever in the times of Covid-19 and the climate crisis; and
5. in particular, on the part of individual astronomers: sharing their own passion for their subject.

In the first three instances, astronomy outreach is a subset of public relations: institutions communicating in order to influence public perception.

Informal and Non-formal Education

Whenever astronomers communicate about astronomy in public, they are automatically contributing to informal education: the umbrella term for any learning that takes place outside a structured learning environment. Non-formal education, in a structured setting such as a youth club, summer camp, or community learning center, also offers opportunities for astronomy outreach.

Formal Education

Formal education is learning that takes place within the hierarchical education system that runs from primary school through secondary school to university. At the college or university level, astronomers are official actors in their institution's formal education activities. But even at the elementary or secondary-school level, astronomers can contribute to formal education in several ways: organising events that are attended by school classes, or projects in which pupils can participate; producing resources to be used by teachers, or providing teacher training workshops.

Formal education and outreach have fundamentally different goals: those active in formal education are primarily concerned with getting their students to complete, successfully, a predefined course of study. In practice, this means completing a specific curriculum, including required tests and examinations. But curricula frequently do not align with the key content that astronomy outreach is interested in communicating, and for two different reasons: In a number of countries, at least at school level, astronomy is not part of official curricula at all. Where astronomy is part of a curriculum, the focus is frequently on basic phenomena and concepts (e.g., *Office of Astronomy for Education, 2022*), while important parts of astronomy outreach are related to topics of current research at a considerable remove from the basics. Neither discrepancy means that astronomy outreach cannot play an important role in helping to enrich education – astronomy in particular is known to be particularly interesting to students (e.g., *Sjøberg & Schreiner, 2010*), and can thus provide a low-threshold entry into the world of STEM subjects (science, technology, engineering mathematics). But it does mean that people you are in contact with in the formal education sector may approach the matter from a different direction than those active in astronomy outreach – which you should take into account if you plan to work with them (e.g., *Pompea & Russo, 2021*).

From the perspective of astronomy outreach, investing effort in resources in a formal education setting can be worthwhile in particular because that setting comes with its own effective means of dissemination: produce materials that appeal to school teachers, for instance, and those teachers will then gladly assist you in bringing those materials, and your content, to a wider young audience, namely to their students.

What Does This Mean in Practise?

In practise, this means there will often be an overlap between astronomy outreach and education. When institutions or individuals think about how best to organise their education and outreach activities, other considerations – which target group the activities are meant to reach, and which formats best suit one's own strengths (e.g., *Christensen, 2010*) – will be much more important than the education-outreach divide, and rightly so. Nonetheless, it pays to keep in mind at least the fact that, when interacting with (formal) educators, their goals, wants, and needs are likely to be somewhat different from yours – and those differences should be respected.

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IAU Office for Astronomy Outreach 10th Anniversary: Astronomy for Everyone Through Access, Communication and International Cooperation

Announcement

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Building on the unprecedented momentum created by the International Year of Astronomy in 2009, the IAU Office for Astronomy Outreach (IAU OAO) was launched in 2012 as a joint venture between the IAU and the National Astronomical Observatory of Japan. Over the last decade, the IAU OAO has helped to coordinate many large-scale international projects, such as Cosmic Light (2015), NameExoWorlds (2015, 2019, and now 2022), the largest in-person CAP Conference to date in 2018, the first virtual and hybrid CAP conferences in 2021 and 2022, respectively, the IAU 100 years celebrations (2019) and the first IAU Symposium on Equity, Diversity and Inclusion (2019). The IAU OAO has accomplished all of this and more by building and relying upon an active network of experts – the IAU National Outreach Coordinators (NOCs) – as the backbone for the IAU's international outreach implementation.

In 2022, the IAU OAO celebrates its ten-year anniversary: a celebration to honour the communities that have shaped the IAU's outreach programmes into the successful initiatives we are proud to support today. This decade, we will expand our Annual Programmes, strengthen our skill-building projects with the recently formed Communicating Astronomy with the Public Trainings, build programmes that leverage astronomy to tackle issues that threaten the planet and our night skies, develop new programmes driven by the IAU Strategic Plan 2020-2030 and the emergent needs of our communities, and increase the opportunities for our NOCs to learn, share, and connect. These will all inform new online and hybrid projects, drawing from our experience of establishing effective collaborations that heavily rely on remote relationships.

In addition, as announced during the IAU General Assembly in Busan this August, the IAU has relaunched a special edition of NameExoWorlds. This international competition will bring together professional astronomers and the wider public, including teachers, students, and amateur astronomers. In this way, NameExoWorlds 2022 embodies the OAO's motto, Astronomy for Everyone, by providing all with the opportunity to name 20 of the first exoplanetary systems to be observed by *JWST*.

With international collaboration, sustainability, and the IAU Strategic Plan 2020-2030 at the strategic core of the IAU OAO, we are reshaping our actions and structures for the next decade. The IAU OAO has recently expanded to include a Director, Deputy Director, and International Outreach Officer, all of whom have a sense of shared responsibility to work with and for our communities.

We envision the IAU outreach communities as bridge-builders, facilitating access to information and reaching new partners – from professional astronomers to the general public – thus perpetuating our efforts to make astronomy accessible to everyone.

(This article was first published in IAU Catalyst #7 *on 28 September 2022)*

Figure 1. *The IAU Office for Astronomy Outreach logo and motto: Astronomy for Everyone. Credit: IAU OAO*

Announcement

Launch of NameExoWorlds 2022 Competition — IAU Global Contest to Name the Next Exoplanets and Their Host Stars

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To celebrate the 10th anniversary of its Office for Astronomy Outreach (OAO), the International Astronomical Union (IAU) is launching a contest to name 20 exoplanetary systems to be observed by *JWST*. The competition, NameExoWorlds 2022, was announced at a press conference at the XXXI IAU General Assembly, held in Busan, South Korea. The contest seeks to bring together both professional astronomers and the wider public, giving them the opportunity to name the 20 selected exoplanets along with their host stars.

Through the NameExoWorlds initiatives, the IAU and its partners[1] recognise the importance of the connections between the sky and our diverse cultures. The NameExoWorlds 2022 contest invites communities across the globe to connect their own cultures to these distant worlds. Each team can propose a name for an exoplanet and its host star from a list of confirmed objects (referred to collectively as "ExoWorlds" in this competition).

Cultures around the world have long made connections with objects in the natural world by giving them names in their native tongues. Many civilisations have developed their own stories, mythologies, and cultural contexts around specks of light in the heavens above. Through these connections, we eventually found our place among the stars. This is the story of how astronomy came to be among the earliest of the disciplines we now call science, and the beginning of humanity's eternal quest to understand the Universe around us.

When the IAU was created in 1919, one of the tasks delegated to the professional astronomers was to catalogue celestial objects and provide consistent conventions for naming them. Advances in science and technology have recently enabled us to detect a new category of celestial object, called exoplanets – planets orbiting other stars. The first exoplanets were discovered just three decades ago and over 5,000 have been identified since. Most of these planets are only referred to by their scientific designations and have no connections to our stories and cultures.

Reflecting the truly international interest in astronomy, the first NameExoWorlds competition, in 2015, named 19 ExoWorlds (14 stars and 31 exoplanets orbiting them), with over half a million votes from 182 countries and territories. In 2019, as part of the IAU's centennial celebrations, the 2019 NameExoWorlds competition offered every country the chance to name one planetary system, comprising an exoplanet and its host star. As part of this contest, 112 countries organised national campaigns that involved the direct participation of over 780,000 people worldwide.

The systems to be named by NameExoWorlds 2022 are of special interest, as they are among the first exoplanet targets of the *James Webb Space Telescope (JWST)*. This international space observatory, led by the National Aeronautics and Space Administration (NASA) with its partners, the European Space Agency (ESA) and the Canadian Space Agency (CSA), had its first light in July 2022. The exoplanets have been discovered through a mix of techniques, mostly via the transit method and direct imaging.

NameExoWorlds 2022 is a collaboration between the Executive Committee Working Group on Exoplanetary Systems Nomenclature[2] and the IAU Office for Astronomy Outreach. Anyone, including students and teachers, astronomy enthusiasts, amateur astronomers, and exoplanetary scientists may form a team and propose names for 20 exoplanetary systems, each of which consists of one known exoplanet and its host star.

Debra Elmegreen, IAU President, notes *"It is exciting to have a new NameExoWorlds competition underway to celebrate the 10th anniversary of the Office for Astronomy Outreach. Their work over the past decade has had a global impact, and*

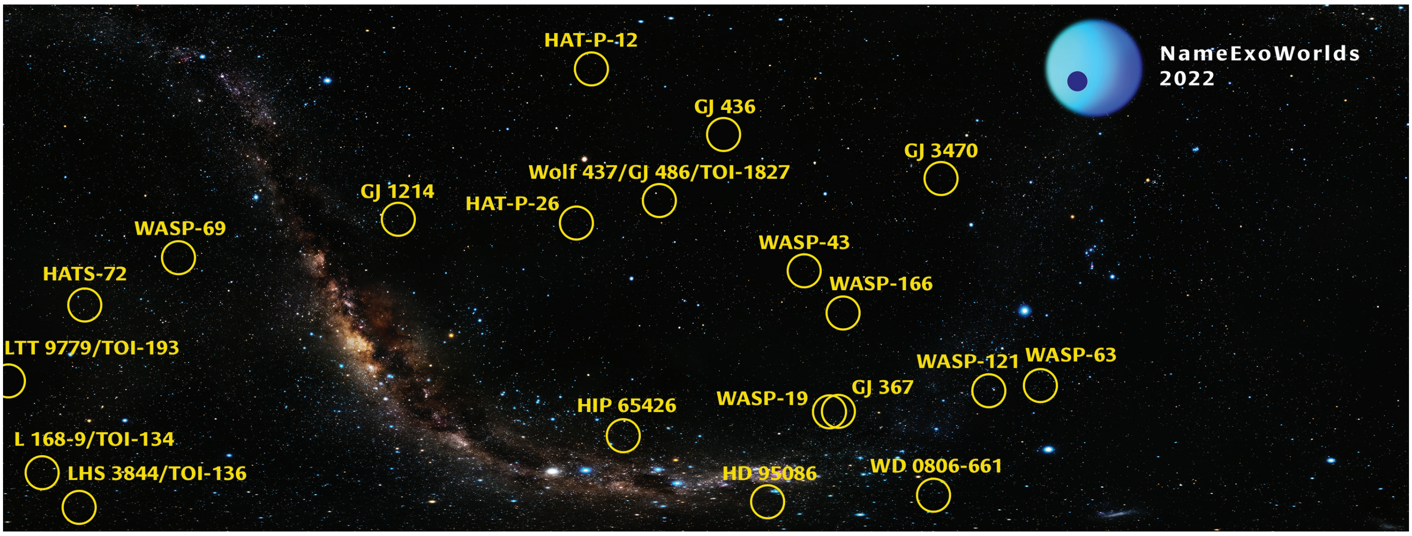

Figure 1. *The systems to be named by NameExoWorlds 2022 are among some of the first exoplanet targets of the James Webb Space Telescope. The exoplanets have been discovered through a mix of techniques, mostly via the transit method and direct imaging. Credit: IAU OAO/NARIT/M. Tangmatitham*

this competition is yet another way to bring people together through astronomy."

"In the last decade, the OAO has strived to build bridges between professionals, amateurs, communicators, educators, and the public. Through its collaborative nature and diverse levels of scientific engagement, NameExoWorlds is one excellent example that embodies OAO's mission of making astronomy accessible to all," adds Lina Canas, Director of the IAU Office for Astronomy Outreach.

How Can You Participate?[4]

- Create a team that brings together students and teachers, astronomy enthusiasts, amateur astronomers, and professional astronomers.[3]
- Conduct an astronomy outreach event related to exoplanets.
- Choose a system from the 20 ExoWorlds on the list.
- Propose a name for the exoplanet and its host star in your language and provide an explanation of the cultural context.
- Register your team and submit your naming proposal;

The proposals will go through a two-step process of selection. First, a national selection panel, led by the National Outreach Coordinators (NOCs)[5], will select a national candidate and two backup names. Then, a final selection committee – composed of the Working Group on Exoplanetary Systems Nomenclature and the exoplanet discoverers – will consider the candidates proposed by each country and select a name for each ExoWorld.

The names will be selected based on the description and meaning behind them, and the outreach activities held by each team. Finally, the 20 ExoWorlds will be announced, and the associated names will be recognised by the IAU as the official public names of these ExoWorlds[6].

(This article was first published as an IAU Press Release *on 8 August 2022)*

Notes

[1] The NameExoWorlds partners are the National Astronomical Observatory of Japan (NAOJ) and the National Astronomical Research Institute of Thailand (NARIT).

[2] The Executive Committee WG Exoplanetary System Nomenclature is a recently formed 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.

[3] The IAU encourages participating groups to establish collaborations and create teams composed of some combination of teachers and students, astronomy enthusiasts, amateur astronomers and exoplanetary scientists, and together brainstorm name ideas for one of the ExoWorlds (exoplanet + host star) available for naming.

[4] For more information on how to participate in NameExoWorlds 2022, please refer to our website: https://www.nameexoworlds.iau.org/

[5] The IAU National Outreach Coordinators (NOCs) will provide support to the teams, including by facilitating the connections between different groups within a team. The IAU Office for Astronomy Outreach coordinates the Meet the IAU Astronomers! Programme, which can help participating teams get in contact with professional astronomers, including exoplanetary scientists.

[6] The winning names will not replace the scientific designations that already exist for all exoplanets and their host stars, but they will be sanctioned by the IAU as the official public 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.

Hayabusa2 Outreach Activities and Its Public Response

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Keywords
science communication, strategy, social media

This report summarises the outreach activities and results related to Asteroid Explorer *Hayabusa2*, which conducted technologically challenging operations such as the release of rovers and a lander, touchdowns on the surface, and an impactor release to create an artificial crater in less than 10 months. Changes to the sequence of these operations after arriving at the target, the asteroid Ryugu, also posed a challenge for the outreach team. They had to quickly adjust the communication plan despite minimal resources. Thus, the team mapped out a strategy to share the scientific output and excitement of *Hayabusa2* with the public through the mass media. All media materials were prepared and provided under the Creative Commons Attribution 4.0. Frequent press briefings shared the mission status, operation schedule and risks, in addition to various aspects of the space mission, including engineering and scientific details. With materials provided by the outreach team, journalists and science reporters produced original content and published more than 67,000 online articles from *Hayabusa2*'s rendezvous with Ryugu to its return to Earth.

Introduction

Hayabusa2[1] is an asteroid sample-return mission operated by JAXA (Japan Aerospace Exploration Agency). Launched on 5 December 2014, it returned to Earth to deliver the material collected from its target, the asteroid Ryugu. Multiple technologically challenging operations were planned, including touchdowns, in which the spacecraft briefly landed on the surface of the asteroid to collect samples from Ryugu. The *Hayabusa2* operation team completed almost all of these operations.

The *Hayabusa2* mission was already popular when the project had the green light to proceed because of the success of its predecessor, *Hayabusa*, which overcame various issues including engine trouble and a fuel leak on return to Earth with material from the asteroid ITOKAWA. Annual JAXA surveys for Japanese citizens in 2018 - 2021 consistently show a high degree of public recognition of the *Hayabusa2* name. For example, the survey in 2019 shows more than 90% of the total 1350 questionnaire respondents knew the name of the *Hayabusa2* mission. In addition, the JAXA's advisory committee on public relations suggested to the *Hayabusa2* team and JAXA's PIOs (Public Information Officers[2]) about *Hayabusa2* outreach activities: the Near Asteroid Operation Phase, the rendezvous at and departure period from the asteroid Ryugu, and its return to Earth might appeal to those not generally interested in scientific or technological media.

Hence, the goal for our outreach activities went beyond increasing public awareness of the mission. Instead, they aimed to improve the public's understanding of the space exploration mission and the risks, challenges, values, and difficulties of space science. The outreach team had many preparation tasks to achieve these goals, including preparing the press centre operation and producing and distributing visuals. In addition, the outreach team needed to develop backup plans for contingencies. Most of these tasks had to be completed before the arrival at Ryugu, when we had enough time to develop a practical and feasible implementation plan for the communication campaign. Although scientists and engineers can be reluctant about outreach activities (e.g., *Kassab, 2019*), this was not the case with *Hayabusa2*, which made public communication a priority. They posted status updates about the mission via Twitter for more than two years before its launch and accumulated more than 20,000 followers at its lift-off (see Figure 1 for the number of the *Hayabusa2* Twitter followers). For more than two years, the *Hayabusa2* team also worked on EPO (education and public outreach) activities independent of JAXA's Public Relations Division. Therefore, the JAXA's outreach team coordinated the previous *Hayabusa2* team's outreach activities and started an outreach campaign by the time the spacecraft arrived at Ryugu.

This paper describes the strategy and implementation of the outreach activities of the *Hayabusa2* mission so far and summarises the results.

Mission Overview

Hayabusa2 is an asteroid explorer and sample-return mission. *Hayabusa2* aimed to collect a sample from the asteroid 162173 Ryugu and deliver it to Earth. Launched in December 2014, *Hayabusa2* took about three and half years to reach the target object and stayed about one-and-half years near the asteroid. Six years after its launch, *Hayabusa2* returned to Earth, having completed several missions at the asteroid Ryugu. When *Hayabusa2* reached Earth, a capsule containing a sample from Ryugu separated from the main spacecraft. Only the capsule landed on Earth. After the capsule separation, the main spacecraft continued on a fly-by orbit and headed off

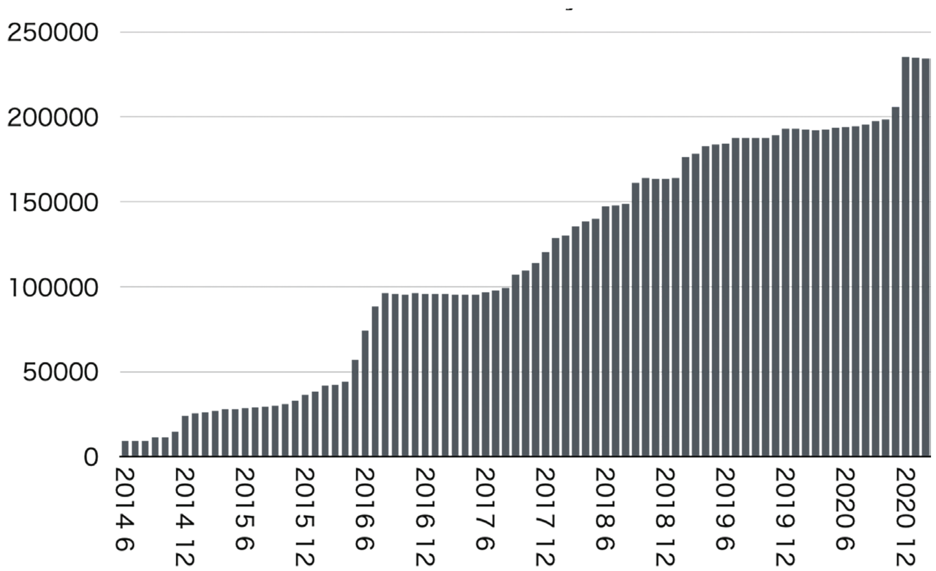

Figure 1. *The number of followers of the Hayabusa2 Official Twitter account. Credit: The author*

toward a new asteroid. Table 1 shows the timeline of several milestone events of the mission. The activities of the *Hayabusa2* mission during its near-asteroid phase (the period between arrival at Ryugu and departure from it) were described in detail in *Tsuda et al. (2020)*. This article refers to the following as critical operations: rovers/lander releases, touchdowns, and Small Carry-on Impactor operations.

To maximise its scientific output, *Hayabusa2* was equipped with multiple instruments to be released. These included the MINERVA-II1 rovers, the MASCOT Lander, a small carry-on impactor, and target markers. The surface condition of Ryugu was utterly different from that expected and was found to be unexpectedly harsh. Facing the target, the *Hayabusa2* team decided to reconsider the strategy and change the order of the critical operations. The change in the order of the critical operations resulted in the change in our implementation plan of outreach activities. For example, video clips explaining the spacecraft's movement had to pause production until the *Hayabusa2* team specified the movement of the spacecraft and the target landing sites for the MINERVA-II1 rovers and the MASCOT lander. Human resources, including interpreters, a photographer, video crew and staff operating press centres, could be allocated only after the MINERVA-II1 rovers' and the MASCOT Lander's release schedule were determined.

Outreach Strategy

Our outreach campaign aimed to raise awareness of and increase the public's interest in engineering challenges and scientific discoveries of *Hayabusa2*. Through our outreach activities, we tried to establish engagement with the public and make the public who engaged with *Hayabusa2* become its fans. *Sashi (2012)* mentioned:

> *a classic example of fans is provided by customers of professional sports teams who are loyal supporters of their teams in times of good and bad, delighted when they win, dejected when they lose, with trust and commitment characterising their enduring relationship with a team they regard as their own.*

We tried to increase the number of *Hayabusa2* fans, like the fans of professional sports teams above, who advocate the *Hayabusa2* project even when unexpected incidents happen.

A marketing funnel model (e.g., *Sellers, 2021*) suggests that only a small part of people aware of a project or mission will engage with it. Thus, we should first direct as many people as possible to the mission status, its achievements and its scientific results. Only a fraction of people aware of *Hayabusa2* will be interested in and engage with the *Hayabusa2* mission, as the marketing funnel model suggests. A comprehensive strategic approach was necessary to communicate with the broadest audience possible. An essential aspect of the communication plan was to

Date	Operation
3rd December, 2014	Lift-off
3rd December, 2015	Earth Fly-by
28th June, 2018	Arrival at Ryugu
19th - 21st September , 2018	MINERVA-II1 Rover A & B Deployment
30th September - 4th October, 2018	MASCOT Deployment
20th - 22nd February, 2019	First Touchdown (TD1)
3rd - 6th April, 2019	Small Carry-on Impactor Operation (SCI)
9th - 11th July, 2019	Second Touchdown (TD2)
13th November 2019	Departure from Ryugu
5th December, 2020	Capsule separation
6th December, 2020	Capsule landing and capsule recovery operation

Table 1. *Timeline of Hayabusa2 mission.*

offer several feasible opportunities for the public to engage with the mission.

The outreach team tried to share the process, not only the engineering achievements or scientific results. We believed that sharing the process helped gauge public interest and publicly relayed the excitement of the *Hayabusa2* team. The outreach team constructed the outreach plan based on a policy that emphasised timely disclosure of updates about the *Hayabusa2* mission to share the process of the mission and humanising shared content, implementing it as follows: promptly releasing images, sharing risks, and sharing the mission's history-making moments.

We considered that the media could efficiently disseminate updated information about the mission and its discoveries to the public because the media published coverage reached wide audiences. Our plan met a need. It was apparent that the media were keen to obtain information regarding *Hayabusa2* and its mission status since JAXA's press room was over capacity each time JAXA held a press conference about *Hayabusa2*. Thus, we positioned the media as one of our important channels to communicate with the public.

We also expected social media to be an effective tool to communicate with the people attracted by *Hayabusa2*. Studies on customer engagement (e.g., *Thackeray et al., 2008; Sashi, 2012*) suggest that social media greatly facilitates the establishment of a connection with a large number and wide variety of individuals and firms. Referring to these studies, the outreach team utilised social media to establish engagement with the public.

Prompt Image Release

The PIOs found that photographs and video clips of the *Hayabusa2* team members in the Operation Room were one of the key materials to be shared with the public. Before the rendezvous with Ryugu, domestic journalists often asked the PIOs if they could have a chance to take photos of the *Hayabusa2* team operating the spacecraft during the critical operations. The JAXA's advisory committee on public relations also recommended the PIOs make photos (and even more desireable, video clips) taken in the Operation Room available. Since the Operation Room is narrow, it did not seem realistic for media representatives to stay and take pictures. Therefore, we decided to share photos and video clips from a camera crew allocated by JAXA.

A consensus was necessary among the operation team members, PIOs, and security personnel to release Operation Room snapshots. A photographer and videographers filmed what happened in the operation room and the expressions of the team members (Figures 2 and 3). To disclose some of these images, the operation team and the PIOs agreed in advance on several points. One example was the camera angle. The PIOs were prohibited from releasing photos containing staff members who were reluctant to share their image. Photos and video clips were reviewed according to JAXA's security guidelines, and the PIOs could distribute the photos and video clips that passed the review. The situation was more complicated for images taken using scientific instruments onboard *Hayabusa2* (see *Lorenzen, 2016* for another example). We noticed a tension between those scientists who wished to keep all images from *Hayabusa2* proprietary and those who wanted to share them with the general public. These two opposing views about image release raise an essential and challenging debate in outreach. The *Hayabusa2* team took the middle ground and published quick-look and edited images. The edited images were not suitable for scientific quantitative discussion because the resolution was reduced or contrast altered for presentation purposes. Thus, more than 900 images, photographs and video clips were released and made downloadable from at least five official JAXA websites. These visuals were used in the media coverage and social media posts.

Optical Navigation Cameras revealed the first images of the asteroid's appearance and surface condition. The outreach team started releasing photos of Ryugu

Figure 2. *A video director instructs a camera operator in the Operation Room. Credit: JAXA*

Figure 3. *Cameras were installed at the corners of the Operation Room to avoid hindering the Hayabusa2 operators in their work. Credit: JAXA*

when it still looked like a speck. As the spacecraft moved nearer to the asteroid and the apparent size of Ryugu gradually increased, its shape and surface got sharper with every photograph (Figure 4). Each new image with a simple caption was shared promptly with the engaged public. The images taken using CAM-H during the touchdown operation were another example[3] of images released to the public. CAM-H is a small monitor camera, made possible by public donation, used to capture pictures. At the touchdown operation, CAM-H monitored changes in the surface before and after the touchdown. The *Hayabusa2* team arranged the data transmission sequence to download the images captured via CAM-H as early as possible. The effort helped maximise public excitement and maintain momentum when new images were released and viewed. Two hours after the touchdown, the team presented the images to the journalists at the press centre. Meanwhile, the PIOs distributed the images to the press using a cloud file-sharing service. The images were also posted on the official JAXA websites and Twitter. The *Hayabusa2* team created a time-lapse video clip from the images and released on YouTube within 12 hours. This was an excellent example of the collaboration between the public, the engineers who developed the camera, and the operations team, with their sequences of commands that enabled data transmission on such short timescales.

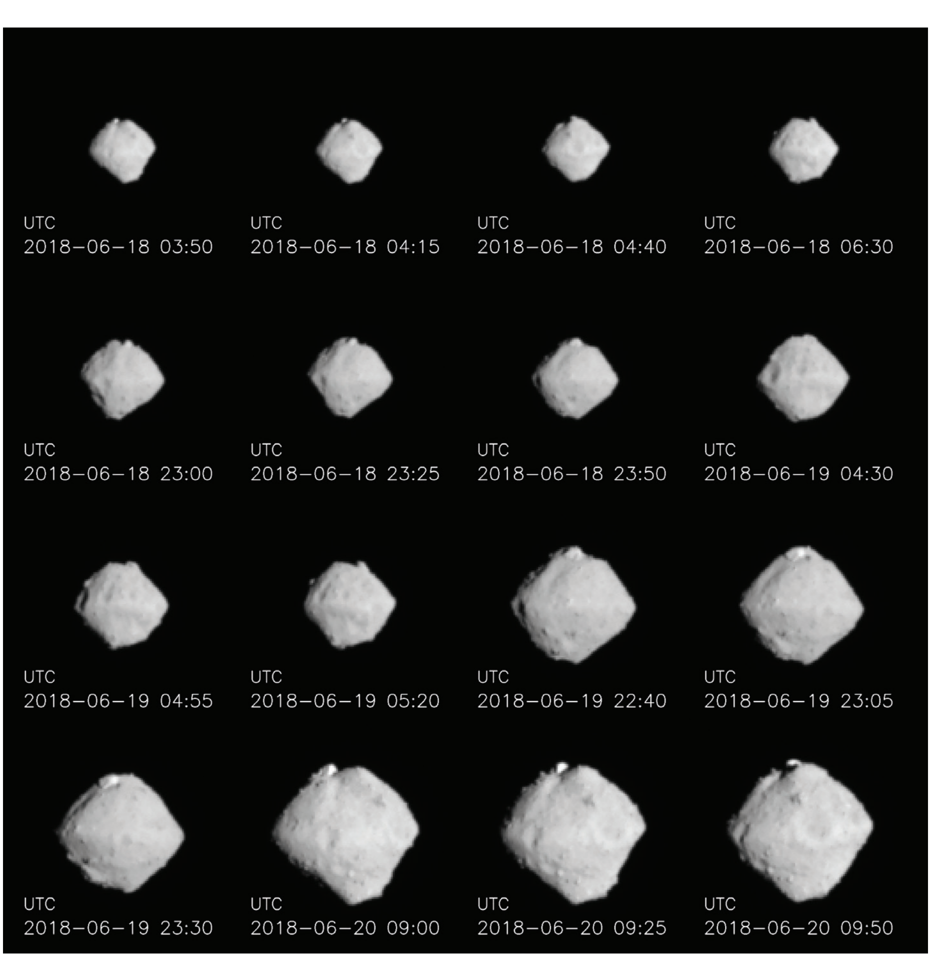

Figure 4. *The asteroid Ryugu, taken by the Optical Navigation Camera onboard Hayabusa2 while the spacecraft was approaching Ryugu. Credit: JAXA, U. Tokyo, Kouchi U., Rikkyo U., CIT, Meiji U., Aizu U., AIST*

The images and videos were made available under a Creative Commons Attribution 4.0 licence. Sharing visuals under this licence enabled the press, publishers, researchers, science communicators, and researchers to use our visuals easily without troublesome deskwork to get permission to use them. In addition, the PIOs could save time and effort in responding to inquiries about using visuals. See also *Davis & Christensen (2009)* and *Christensen (2019)* for discussions about the conveniences of introducing Creative Commons licences.

Humanising Shared Content

The excitement generated by the space programs of many nations has increased public interest in recent decades (e.g., *Bauer et al., 2016*). To enhance public awareness of the findings and achievements of space exploration, one has to create a context that the audience can relate to and make them newsworthy (e.g., *Maran et al., 2000*).

The *Hayabusa2* mission has overarching scientific themes concerning the origins of the Solar System and potentially the origin of water and life on Earth. There is also the recognition that near-Earth objects have the potential risk of colliding with Earth. While these big questions fascinated some members of the public, they may have seemed relatively distant to the rest of the population, not as pressing as the issues of everyday life. Emphasising scientists and engineers who conduct the research or exploration seems to be one key element in increasing the probability of media coverage and public awareness (e.g., *Maran et al., 2000*). The outreach team spotlighted staff members to the public and ensured their visibility by presenting *Hayabusa2* on video and during the live events. About 70 per cent of the footage released from the arrival at Ryugu to the departure contained the *Hayabusa2* team members. Scientists, operators, engineers and managers were featured intensively in JAXA internet broadcasts and videos, external TV interviews, documentaries and online channels. During interviews, tweets and press conferences, they discussed the facts and their passion for the mission.

The outreach team provided behind-the-scenes access through live-streamed events with opportunities for questions on our social media channels. The audiences were able to witness scientists and engineers nervously sitting through the nail-biting minutes when *Hayabusa2* dispatched rovers, conducted the touchdown operations and descended the Small Carry-on Impactor to create an artificial crater. Several key individuals involved in the mission, including the project and engineering managers, became the faces of *Hayabusa2*. Comments posted on our YouTube programs show[4] the public could relate to them because they showed their emotions and the human aspect of their work.

Preparing for an Off-nominal Situation

The Near Asteroid Operation Phase was full of risks and engineering challenges. When a camera on-board *Hayabusa2* captured the configuration of the Ryugu surface, the *Hayabusa2* team members found that the surface was almost entirely covered with boulders. Because of this, the team faced difficulties with the rover's safe landing and touchdown to collect samples while keeping the spacecraft in sound condition. Off-nominal events could occur during the Near Asteroid Operation Phase, and the PIOs had to prepare for them.

Decades of experience in space missions have demonstrated that unexpected events will occur during any mission. In preparation for such contingency, the PIOs regularly learn risk communication and media relations at outside experts' seminars and training. Based on our in-house experience and knowledge learnt at the seminars and training, the PIOs understood that presenting risks early helped control the public's expectations.

Because space science programs were funded by taxpayers and private donors and supported by politicians, the public's trust and credibility are vital, similarly to astronomy (*West 2011*). Building trust in risk management bodies was also a goal of recent risk communication (*Frewer 2004*). Sharing risks and benefits early and frequently with the public was essential to earn and maintain the public's trust and credibility (see *Dawson, 2006* as an example of the risk communication strategy of NASA's *New Horizon* mission).

We took many opportunities to convey the potential risks of each critical operation together with the scientific and engineering significance that *Hayabusa2* addressed. We also explained how the *Hayabusa2* team assessed risks and took measures to reduce the probability of fatal situations of the spacecraft. Describing the risks with in-depth insight was aimed at tempering public expectations. To share information about possible off-nominal situations, the team had to explain how the team analysed data, what they discussed, what problems existed, and how they tried to overcome them. In other words, the risk discussion also served to visualise the process of space exploration.

As *Höppner et al. (2010)* summarise in their report on risk communication, "transparency (includes openness, honesty and comprehensiveness) in communication appears to be the single most called for principle of good communication". In retrospect, our outreach activities, including communication to prepare for off-nominal situations, were consistent with this principle.

As mentioned above, there were many possible risks during the critical operations. Therefore, the outreach team assumed contingency, preparing for press release texts and planning operations of the press centre in emergencies.

Implementation and Results

Figure 5 shows the rough timeline of our outreach activities to prepare for the period from the rendezvous with Ryugu to the second touchdown, while Figure 1 demonstrates changes in the number of the *Hayabusa2* Twitter followers. The visibility of the mission reached a local maximum when the spacecraft launched; this was a chance to bolster awareness and engagement with the public. The next opportunity came one year after the lift-off, at the Earth fly-by. This was the start of the relatively long cruising phase.

Although the operations team had to guide the spacecraft carefully to the target, no drama occurred if there was no trouble for the spacecraft. Therefore, it was natural to assume that the public may lose interest. To avoid this and to maintain public interest, the *Hayabusa2* team held a press conference at least once every few months. Additionally, we held multiple press tours of the operations room during the cruising phase to explain the mission's progress in navigating the spacecraft to Ryugu.

Long-term engagement was key to *Hayabusa2*'s outreach activities. The *Hayabusa2* team kept updating the mission status, telling behind-the-scenes stories through the *Hayabusa2* official Twitter account and frequent (at least bi-monthly) public lectures and speeches during the cruising phase to the asteroid. The team also published manga (comic strips), which are available on the *Hayabusa2* website[3] and relayed behind-the-scenes stories, making it easier for newcomers to understand space exploration and operations.

Twitter

The outreach team focused on Twitter for two reasons: first, the *Hayabusa2* official Twitter already accumulated more than 90,000 followers when the spacecraft rendezvoused with Ryugu, and became an important tool to communicate with the public; and second, at the time, Twitter was one of one of the most influential social network platforms in Japan[4].

Figure 1 shows follower growth as a function of time on the *Hayabusa2* Twitter account. Since launching on 5 December 2014, followers gradually increased until the Earth fly-by on 5 December 2015. Followers remained steady, around 100,000, during the cruising phase and grew again before the arrival at the Ryugu. By the time the spacecraft arrived at Ryugu, Twitter was well-established as the direct channel to connect the *Hayabusa2* team and the public.

The team used Twitter to update the public on the status of *Hayabusa2* and provide schedules of outreach activities, including online and on-site public lectures. The team frequently tweeted on the mission's progress with snapshots from the Operation Room. Twitter contributed enormously to public communication during the critical operations. Some *Hayabusa2* team members concurrently contributed outreach activities and tweeted from the operation room. Thus, the tweets played an impactful role in sharing first-hand information about the mission and the operation team.

Naturally, tweets about *Hayabusa2* dramatically increased during the critical operations. Figure 6 shows the number of tweets and re-tweets about *Hayabusa2* before, during, and after the critical

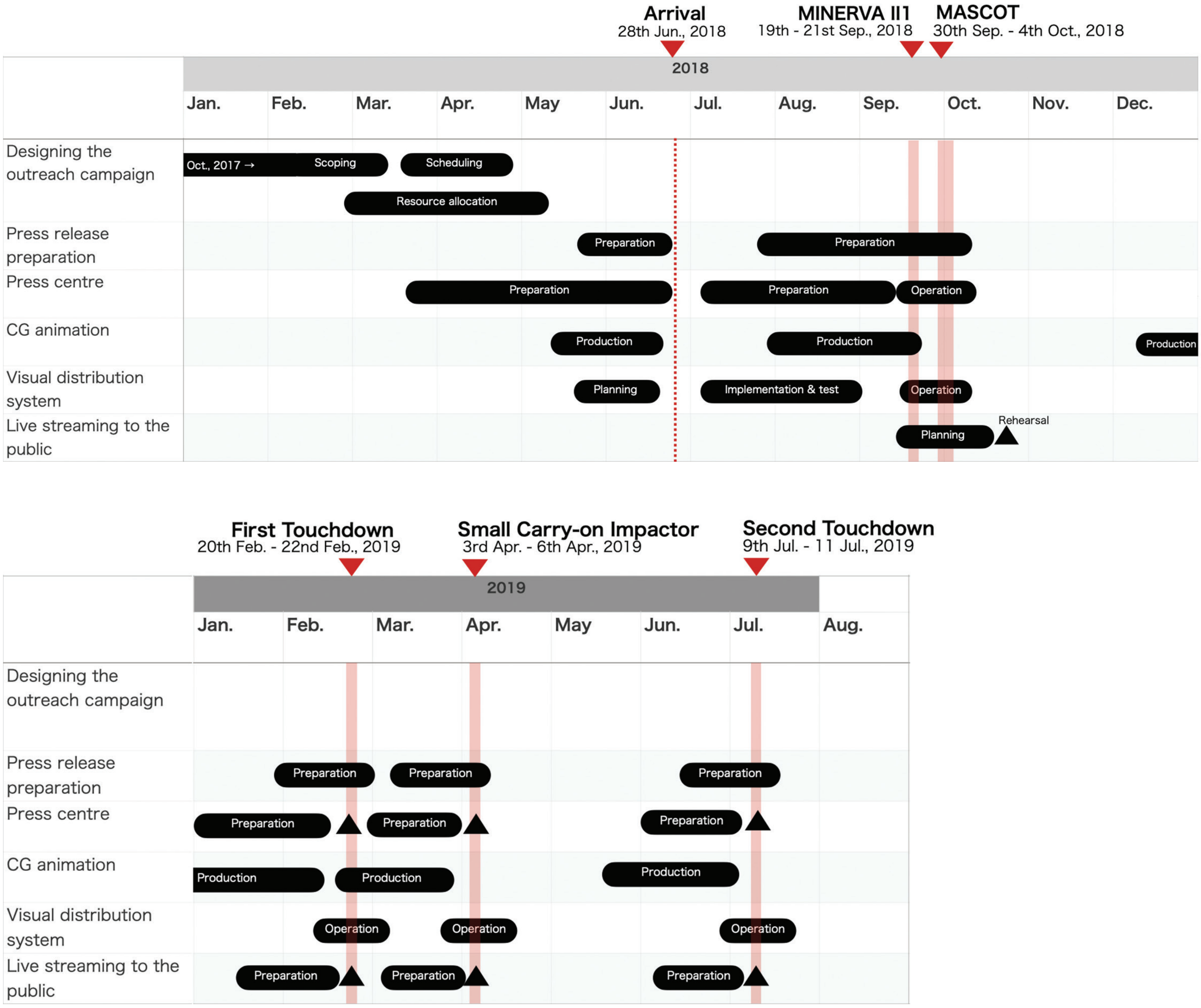

Figure 5. *The rough timeline of our outreach activities to prepare for the period from the rendezvous with Ryugu to the second touchdown. Filled in black triangles in the "Press Centre" and "Live Streaming to the Public" rows show that the PIOs were running them. A filled-black triangle with the text "Rehearsal" means this live streaming was a test run. In "Scoping", we discussed the aims of our outreach activities and decided on what we would and would not carry out. During "Scheduling", we made a task list that described how long each task would take and estimated when we would start each task. Finally, in the "Planning" category, the PIOs worked on how to implement it. We made the necessary arrangements during the "Preparation" phases. Credit: The author*

operations. The curve for each critical operation is normalised along the x-axis such that 0 represents the moment of the critical operation.

The distribution of tweets regarding the MINERVA-II1 Rovers A and B descent shows a somewhat flat distribution. The images taken by the rovers were released a couple of days after the descent and this delay contributed to the distribution's long tail. Because people saw Ryugu's surface so closely for the first time, and the photos themselves were beautiful, the pictures gained as much attention as the operation to deploy the rovers. The images taken by the two rovers are still inserted into media articles as striking examples of the mission's successful outcome (e.g., *Gibney, 2018*).

The second-largest number of tweets came with the first touchdown. Just after the spacecraft started approaching Ryugu, the team was forced to temporarily stop the operation due to some trouble. After a five-hour behind the nominal schedule, the team finally fixed the problem and resumed the operation. Seeing incredible images taken by CAM-H, people tweeted congratulations when the touchdown was completed successfully and sent voices of surprise such as "Congratulations, another historic moment by JAXA. Thank you for sharing it with the world!".

The most significant number of tweets was on *Hayabusa2*'s return to Earth. The peak corresponded to the day when it passed

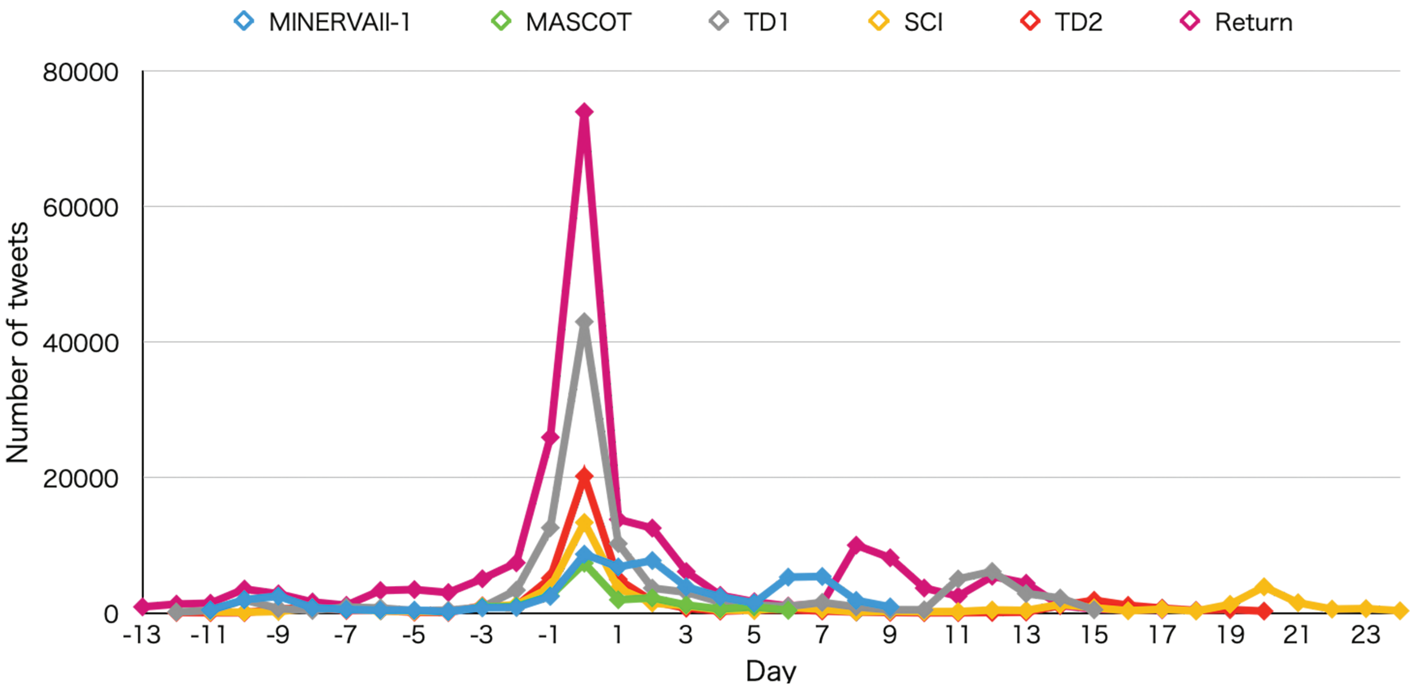

Figure 6. *Number of tweets before and after each critical operation (peaks). We adjusted the peak of the number to zero on the x-axis. We counted re-tweets but excluded SPAM tweets. Note that the number of the vertical axis refers to the sum of tweets and re-tweets. Credit: The author*

through Earth's atmosphere, streaming like a fireball, followed by the recovery operation of the landed capsule. These events happened between a Saturday and Sunday. Hence, the pinnacle is apparent in the two events. The related events occurred sequentially: the capsule's dispatch, the re-entry through the Earth's atmosphere, the capsule's landing, and its recovery. Analysing the hourly time variation of the number of tweets, we found that the number showed a peak corresponding to each event. Therefore, on a daily scale (Figure 6), the number was the summation of these tweets and became significantly high. Another peak appears almost one week after the recovery operation, which is about a press release on the confirmation of Ryugu's gas and sample collection.

The popularity of *Hayabusa2* had an unforeseen side effect. While analysing the Twitter data before and after its return to Earth, we found that many tweets were commercial. That is, we found many tweets that promoted products or services and embedded some words related to *Hayabusa2*. When these tweets are subtracted from the total number of tweets, the peak value decreases to approximately 62,000 (the original peak number was about 74,000). We speculate that these tweets used the *Hayabusa2* name to obtain higher visibility of their offering. It seems natural that people working in advertising expected *Hayabusa2* to become a buzzword and tried to use it for publicity and promotion. This behaviour may reflect the success of the outreach activities of *Hayabusa2*.

Video Footage, YouTube and Livestream

We found video to be a powerful communication tool: it helped us understand complex movement, behaviour, and changes in attitudes about the spacecraft. Through video, people can share the feelings of the scientists, engineers, and team members and sometimes feel like they are participating in the mission. Further, video is a highly sought-after product: established newspaper publishing companies need video clips for their digital newspapers, the public and media often demand ready-to-use video clips, and user-friendly videos (and images) are required by science communicators working for museums and planetariums.

In response to this, the outreach team regularly produced computer graphic video clips to explain the movement of the spacecraft during a critical operation and digested videos of compiled images recorded in the Operation Room. Video clips were posted on YouTube, and downloadable versions were made available on JAXA's website[5]. We expected a small number of video clip views because we provided the footage as raw materials to be edited by professionals such as media members or video creators. We thought the number of views for professional use footage should be smaller than that target for a broader audience. Nevertheless, the number of views of each video clip was between 10,000 to 100,000 as of June 2022. There are many video clips for the general public with less than 10,000 on JAXA's YouTube channel. Considering this, we can judge that the *Hayabusa2*-related video release went well.

As we intended, domestic media outlets actually used the videos and inserted them into their news programmes. On the basis of the rich materials shared by multiple news outlets, the press treated reports on *Hayabusa2* as feature stories rather than straight news – news that impartially

Figure 7. *Press conference of the first touchdown operation on 22nd February 2019. Credit: JAXA*

Figure 8. *Press conference of the first touchdown operation on 22nd February 2019. Credit: JAXA*

reports only essential information about a story. Without JAXA's rich content and robust information, the *Hayabusa2* mission may have been considered a simple straight news clip with a short running time. Various materials enabled the press to create original coverage. For example, some news agencies reported from the point of view of science and engineering. Others focused on the mission's teamwork and collaboration with private companies. The public could obtain a deeper and broader understanding of the mission, thanks to the outreach team's content.

Live programming[6] streamed during the first and second touchdown, the artificial crater creation operation, the capsule's release and the capsule's re-entry. The members of the *Hayabusa2* team wrote the plot for each live program together with a director from a production company which was interspersed with back-stage stories of challenge, struggle and the repeated trial of prototype, heart-warming episodes and more. These live programs helped familiarise the public with the space mission on a deeper level. Comments posted during the live streaming programmes show that the programmes earned an excellent reputation. Examples of response to the programmes can be found in the YouTube[6] comments and the live chat section. They provided the audience with a unique experience to share in the excitement and breath-taking moments with the *Hayabusa2* team members.

Conventional Media

Popular newspapers with large circulations and five nationwide television networks comprise the media landscape in Japan. Although traditional newspaper readership is falling, newspapers remain influential and an excellent channel to disseminate the mission's information (e.g., *Reuters Institute for the Study of Journalism, 2020*). Television networks are powerful delivery mechanisms for stories about *Hayabusa2*. Therefore, exclusive opportunities are availed to reporters from newspapers, news agencies and TV broadcasters. Freelance journalists were given the same opportunities because of their expertise in space science and experience reporting on space missions.

Frequent media events helped journalists to understand the mission deeply. Such media events included a monthly press conference. We also arranged a guided tour of the Operation Room and meet-and-greet events. During the Near Asteroid Operation Phase, press conferences increased in frequency to almost twice a month. These media events helped journalists get familiar with the *Hayabusa2* team and the space mission's operation. The connections the team fostered contributed to the long-term engagement with the media and *Hayabusa2*.

One such press conference occurred during the Near Asteroid Operation Phase, when its first critical operations were underway. Due to space constraints, attendance was limited to only three representatives from each media outlet; even with this restriction, more than 100 media representatives attended each press conference. Figures 7 and 8 show a presentation by representatives of the *Hayabusa2* project and a photo session at the press centre, respectively. Although these were taken on the day when *Hayabusa2* completed the first touch-down operation, the situation at the press centre was similar to other events.

During the first critical operation at the Near Asteroid Operation Phase, two small rovers called MINERVA-II1 Rovers A and B were deployed. Although the press centre opened two hours before releasing the rovers, photos and video clips from the Operation Room were distributed one day before to registered media representatives with updates on the operation status. The outreach team tweeted the atmosphere of the operation team members and status updates more frequently during this time. These tweets and email notifications enabled media representatives and the public to know the ongoing mission status from wherever they were. Meanwhile, the PIOs answered media inquiries by phone. Thus, journalists could write articles with photos and video clips even before the press centre opened. Once the press centre opened, a member of *Hayabusa2* team and specialists in space engineering gave a briefing explaining the current status of the operation, the daily schedule, and the atmosphere of the *Hayabusa2* operation team. Both the specialists and the PIOs stayed in the press centre to answer press questions whenever required.

Exclusive live video was streamed from the Operation Room to the press centre during the descent of the MINERVA-II1 rovers. We note that live streams became available to the public at the later critical operations, such as the touchdowns and the impactor operation to create an artificial crater. Photos and video clips were also provided to the media and are downloadable from JAXA's website.

Three and half hours later, after the successful deployment of the rovers, a press briefing began. The Project Manager of *Hayabusa2* and the other two specialists summarised the day's operation and provided status updates on the spacecraft and rover. A few hours after the press briefing was over, the first images arrived from the rovers. It was almost midnight in Japan. These first images (Figures 9 and 10) were released immediately and made the headlines. All the daily national newspapers and many local papers the following morning covered the rover deployment operation results. The articles included straight news reports, interviews and featured articles. Some newspapers even reported side stories about manufacturers that developed and provided parts of the MINERVA-II1 rovers.

A similar press centre operation and media communication strategy were repeated for each of the critical operations during the Near Asteroid Operation Phase (see Table 1 and Figure 5). Scientists of the *Hayabusa2* team and the PIOs answered inquiries from the media at any time when we held the press centre. In addition, we took as many questions as possible at each press conference (Figure 7). Because the PIOs received no complaints about a shortage of information or visuals, we understand that the media representatives were satisfied by the information provided by JAXA and our press centre operation. Thus, we conclude that our media communication strategy worked well.

Figure 11 shows the number of articles posted on news websites about *Hayabusa2*. We used the online news posts monitoring service by a company, Meltwater, to collect the data. In Figure 11, the peaks correspond to the critical operations. The total number of online news posts about *Hayabusa2* was the largest in Japan, but the news media in other countries, including the United States, Germany and France, also prominently featured the mission, as shown in Figure 12. These numbers would not have been possible if the articles were published only in scientific and technological media; the outreach team played a central role in publicising the mission. As a result, the *Hayabusa2* mission was a global news story with an audience of millions.

Amid the Covid-19 pandemic, the established media communication channels, such as in-person interviews and photographers surrounding the team members (Figure 8), were interrupted. The only activity media representatives could do in the press centre was to watch live streams of the operation. In particular, this impacted the press conferences when *Hayabusa2* returned to Earth. Although photos and video clips were still preferentially provided to the press, the volume of these materials decreased significantly compared with those of the critical operations during the Near Asteroid Operation Phase.

The team still tried to engage the media even during Covid-19. After the capsule's recovery, a virtual press conference was held by connecting the venue in Australia, where the capsule landed, and the venue in Japan via a network conference system. The PIOs knew the internet connection between the press centre in Australia and Japan was not fast enough to transmit video, so the press conference was originally planned to be audio-only. However, this plan was changed, and a video conference was ultimately adopted. The unavoidable result was that the speakers could not communicate well: the video transmission hampered the audio. Although the PIOs did their best to improve the communication after the first press conference, the measure was not enough. We understand that a video conference is visually attractive, but it is not very

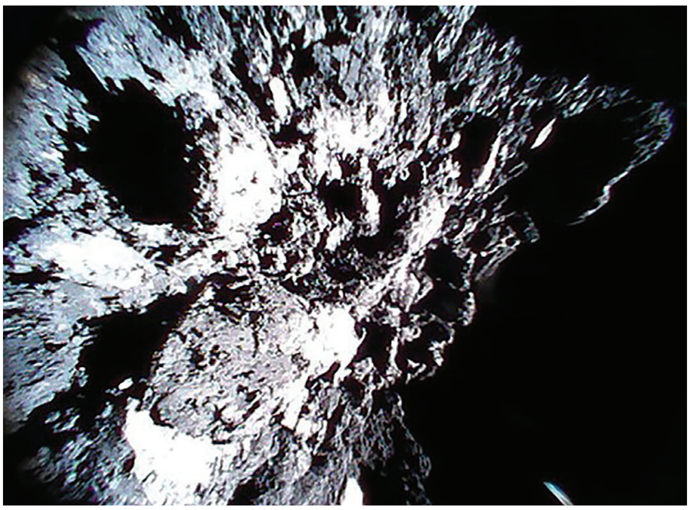

Figure 9. *Image taken by the MINERVA-II1 Rover A. The surface of Ryugu is seen in detail. Credit: JAXA*

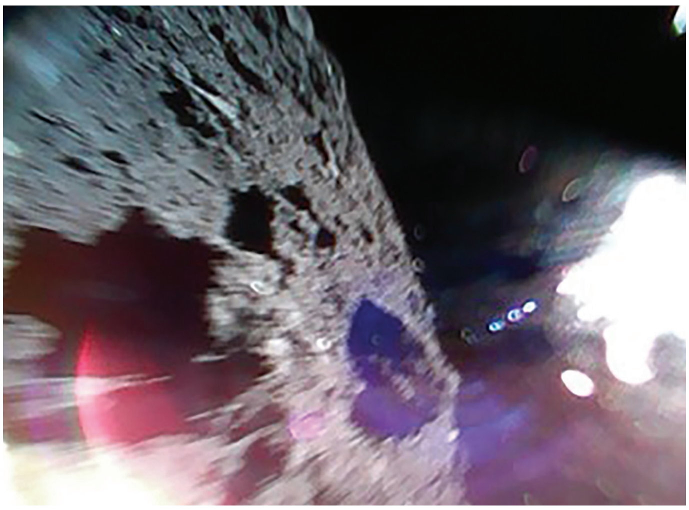

Figure 10. *Image taken by the MINERVA-II1 Rover A. Sunlight produced the white area on the right side. Rover A took this picture mid-hop. Credit: JAXA*

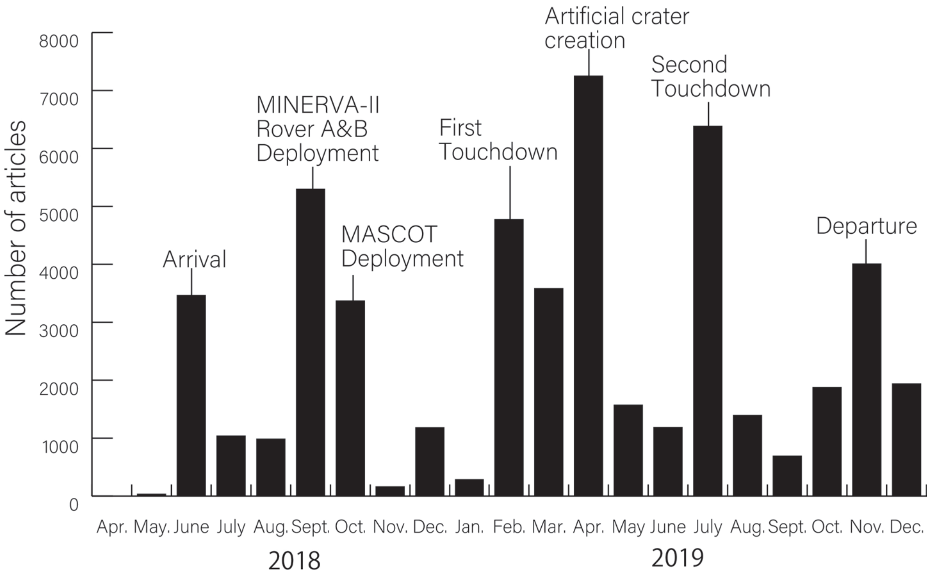

Figure 11. *The number of articles on news websites about Hayabusa2 posted each month during the Near Asteroid Operation Phase. The number includes both inside and outside Japan. The data were collected using Meltwater. Credit: The author*

meaningful if we cannot communicate. We should have considered the network's capacity from the outset.

The audience's reaction to the live stream of the virtual press conference[6] was not as positive as prior press conferences. According to comments, the audience felt a shortage of information and inadequate preparation for the press conference, in part due to the slow network connection between the press centre in Australia and Japan.

Despite this setback, there was still ample media coverage of the capsule's return to Earth. Figure 13 shows the number of news articles from two days before the capsule's release from *Hayabusa2* to two days after the capsule arrived back in Japan. The peak shows when the capsule's fireball was observed upon re-entry, and recovery. These two events occurred on the same day, and the peak in Figure 13 represents the summation of news coverage of these two events. In reviewing some of the articles, we found similar coverage. We compared the first 200 characters of each article to examine the variety and number of unique stories. This quick check revealed that the number of unique articles was almost one-third of the total. The same comparison for the news posts in Figure 11 shows that the number of unique articles was about half. Therefore, we conclude that a smaller variety of articles were published when *Hayabusa2* returned to Earth. Feature stories revealed diversity in their opening text. It seems the majority of articles about *Hayabusa2*'s return were straight news stories simply providing facts, such as the return, the capsule's re-entry and the capsule's recovery. This limited information and material resulted in similar coverage among different news agencies.

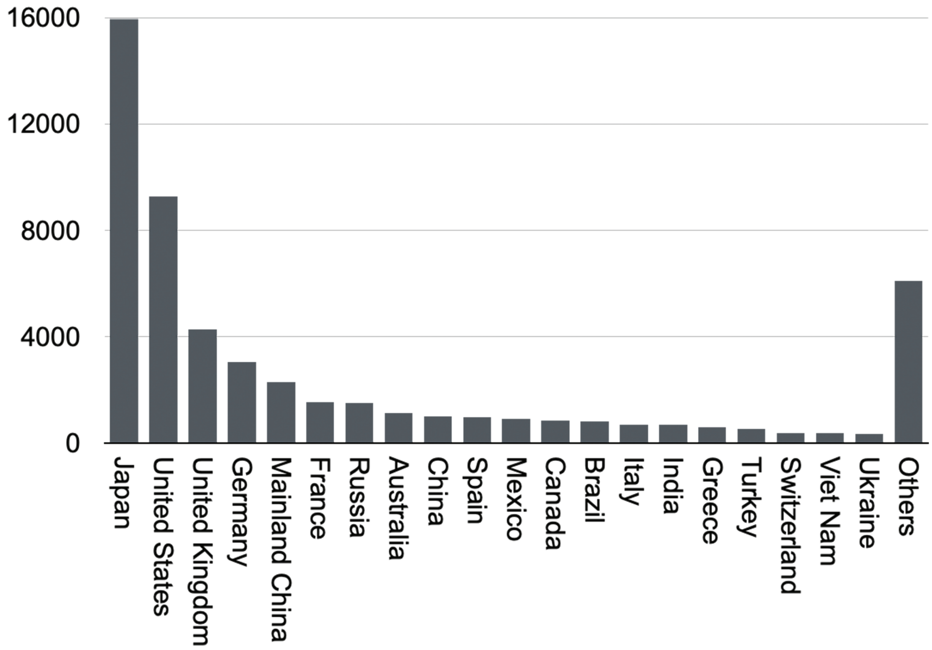

Figure 12. *The number of news articles about Hayabusa2 aggregated by country. The data source was the same time period as Figure 4. The data were collected using Meltwater. Credit: The author*

Lessons Learnt

In this section, we summarise the lessons learnt about *Hayabusa2* outreach activities.

1. *Importance of visuals' publication under open access licence*

Through the *Hayabusa2* outreach campaign, we have learnt the importance and effectiveness of material distribution under the Creative Commons Attribution 4.0. This licensing enabled the press, publishers, researchers and science communicators ease of use. Open access images and videos are essential for good communication with the public. People who wanted to use JAXA's visuals had to apply and obtain JAXA's permission until March 2018, when a new data policy on space science[7] became effective. Although the older rule was not applied to usage for news, education and research, JAXA's PIOs knew that some hesitated to use JAXA's visuals because of the rule and tended to use visuals provided by the open access licence. The PIOs often heard complaints from the media, publishers and members of JAXA's advisory committee on public relations stating the procedure to obtain permission was troublesome or time-consuming. The new data policy is compatible with Creative Commons

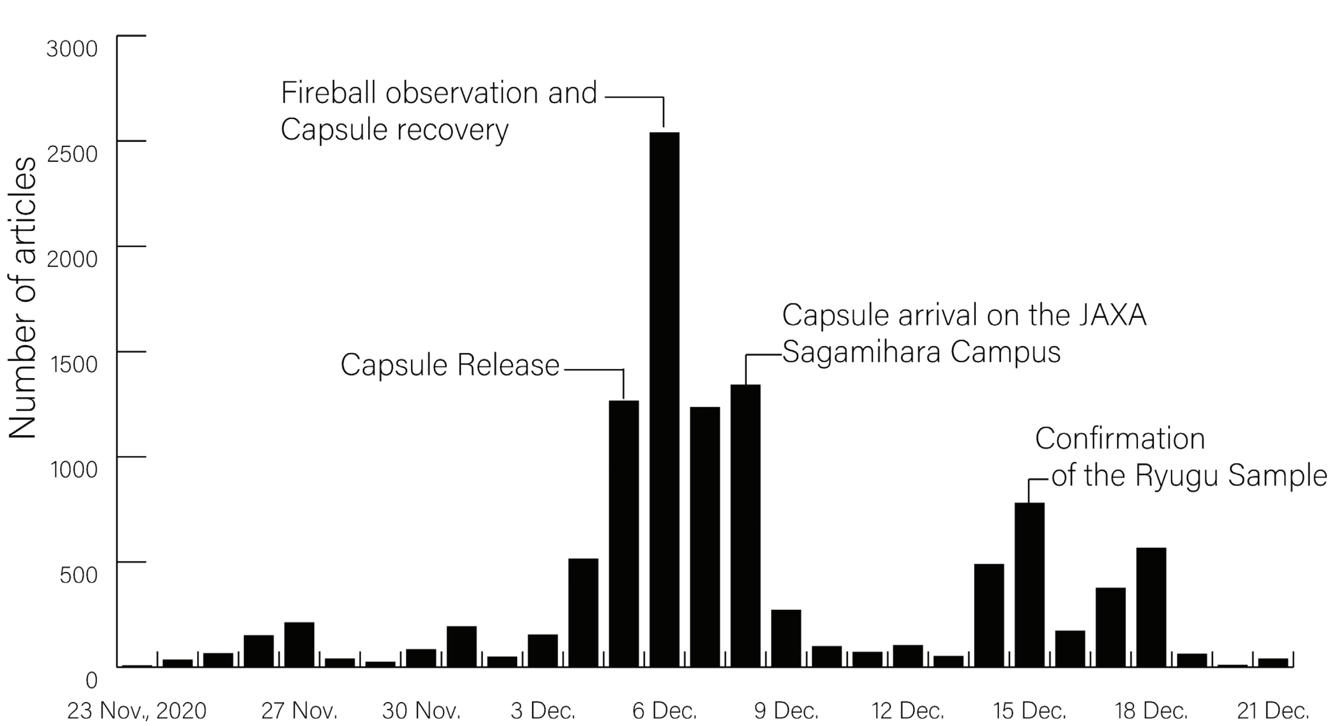

Figure 13. *The number of articles published on news websites before and after the capsule release, when Hayabusa2 returned to Earth. The data were collected using Meltwater. Credit: The author*

BY 4.0. The PIOs do not have to approve visuals' usage requests.

We also found that the demand for visual aids was higher prior to each critical operation than after: explanatory visuals should be made publicly available before events to allow maximum effectiveness.

As an example of these lessons, JAXA and NHK, Nippon Hoso Kyokai (Japan Broadcasting Corporation), worked together and created computer generated (CG) animations based on actual data from *Hayabusa2*. Unfortunately, the CGs were hardly used by the media except for NHK. The CG animations were not distributed under the Creative Commons Attribution 4.0 Licence. Aside from the fact that these animations were released two days after the touchdown operation (and as such, were likely released too late for broadcasters and news agencies), the press may have additionally perceived the permission procedure for these animations as too complex.

2. *Utilise animations, which can enhance explanation and presentation of scientific and engineering issues*

Although repeatedly emphasised, animations were an excellent tool to explain spacecraft movement. As the proverb says, a picture is worth a thousand words. With the aid of animations, scientists and the PIOs could explain complex topics such as the operational plan and the risks of critical operations more easily to the press and the public. By judging from the fact that the press inserted the animations into coverage, it seems that the press also considered that the animations helped viewers and readers to understand the contents of the coverage.

3. *It is necessary to optimise an implementation plan according to the available resources*

An outreach team should carefully confirm if a plan can be implemented, considering the available resources and the required infrastructure. As was the case for the virtual press conference, our outreach team sometimes faced high demand from managers or the public under limited resources. If the request is beyond the resources, it is wise to make compromises to optimise an implementation plan. Otherwise, the efforts of the outreach team could be wasted.

4. *Be ready for any contingency*

We took many opportunities to convey possible operations risks. The Hayabusa2 team also explained how the team assessed risks and took measures to reduce the probability of fatal situations in the spacecraft. We believe that describing the risks served to visualise space exploration. Similarly to the *Hayabusa2* team assessing the risks and taking the appropriate measures, the outreach team assumed contingencies and planned communication activities in emergencies. Fortunately, *Hayabusa2* was not exposed to a fatal situation. However, it is wise to assume and prepare for a contingency. Otherwise, we cannot handle the situation as prompt action is necessary during an emergency.

5. *Social Media is a useful tool to disseminate information and encourage the public participation*

We focused our social media efforts on Twitter. Throughout the outreach campaign, the outreach team recognised that Twitter was a handy tool to share information and the *Hayabusa2* team's excitement with the public. Twitter also contributed to humanising the *Hayabusa2* project. The *Hayabusa2* team members communicated their feelings and emotions, not only operational status, with the public via Twitter. We concentrated on Twitter because of the limitation of our resources, however employing more than one channel may have expanded the demographics of our user base.

We note that maintaining engagement is the next challenge for *Hayabusa2*'s science communicators, scientists, and engineers. After the release of the capsule from *Hayabusa2*, the number of Twitter followers began to decline on the *Hayabusa2* account.

6. *Choose carefully if exclusive treatment is offered to a specific media company*

During the Near Asteroid Operation Phase, we did not allow the media to enter the Operation Room because it was narrow with little space for cameras. As compensation, we frequently distributed video clips and snapshots taken by our contracted crew so that the media could use these as press materials.

The only exception was Japan's public broadcaster, NHK. JAXA decided on special treatment for the NHK crew. NHK was believed to produce excellent science programmes that appealed to a large segment of Japanese people. The crew was allowed to stay in the Operation Room and shoot as it produced special science programmes. Unfortunately, the special NHK programmes did not receive high ratings. The content was just a summary of previous coverage, although the video clips were exclusive to NHK. So far, there is no evidence to show NHK's special treatment had any impact on public engagement or awareness. Hence, it is wise to decide access based on a submitted proposal, not on a previous reputation.

7. *Seek as many perspectives as possible and prepare to respond to criticism and diverse concerns*

The capsule's recovery operation occurred amid the Covid-19 pandemic. Many people congratulated the success, but not all. Operators at a JAXA call centre received complaints about the capsule's recovery operation that approximately 100 staff members visited Australia by charter flights. They emphasised that taxes should be directed to supporting people who were suffering from Covid-19. Since PIOs face a front-line of critics by the public, it is wise to note that not all people favourably received the mission. Although the *Hayabusa2* project manager explained, at press conferences, why the *Hayabusa2* team conducted the capsule recovery operation then, we admit that the agency-wide messaging seemed not strong and persuasive enough. We should have kept updating responses to queries and developing talking points as people's concerns changed or new issues arose. We should also have continuously researched inquiries to JAXA and public comments posted on SNSs or other platforms. If we had made these steady efforts, we should have elicited people's specific concerns, needs and interests. Then, we could have prepared for coordinated responses to them beforehand and shared the developed responses with all of the PIOs.

Conclusions

Various outreach activities of *Hayabusa2* were executed at different levels, from research to the whole of JAXA. The steady and long-term communication efforts by the *Hayabusa2* team members achieved global attention, resulting in many followers and intense engagement with the public. Also, the volume of information shared with the media and the public garnered interest and positive emotions for this incredible mission.

However, from a coordination point of view, it would have been helpful to have more time to develop the communication campaign so we could more effectively engage with the community. We used the *Hayabusa2* mission as an opportunity to interest people in space science. Further studies are necessary to check if our outreach activities contribute to strengthening engagement with our stakeholders that leads to the long-term advocacy of space science.

At JAXA, we are constantly learning and adapting based on our experiences. In addition, we have referred to lessons learnt and experiences from other astronomy and space science projects outside JAXA, which are also valuable. We hope that the learnings described here will inform how future outreach teams engage with the public.

Notes

[1] More on *Hayabusa2*: https://www.hayabusa2.jaxa.jp/en/

[2] JAXA's PIOs are the staff that belong to JAXA's public relations section, while the *Hayabusa2* outreach team consists of a mixture of some of the *Hayabusa2* team members and JAXA's PIOs.

[3] Images can be found at https://www.hayabusa2.jaxa.jp/en/galleries/ while comic strips (only in Japanese) are available at https://www.hayabusa2.jaxa.jp/topics/kochihaya_comic/

[4] Survey Report on Information and Communication Media Usage Time and Information Behavior, National Institute of Information and Communications Policy, Ministry of Internal Affairs and Communications, https://www.soumu.go.jp/main_content/000564529.pdf

[5] Footage of *Hayabusa2*: https://isas-gallery.jp/tag/hayabusa2

[6] Archive of live programs and press conferences: https://www.youtube.com/playlist?list=PLHMAln1-d750aDmJosNXtnBcIQERQN4Sr

[7] ISAS Data Policy: https://www.isas.jaxa.jp/en/researchers/data-policy/

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Biography

Chisato Ikuta is an associate professor at the Institute of Space and Astronautical Science (ISAS) at the Japan Aerospace Exploration Agency (JAXA). She coordinated and led the public outreach campaign of the *Hayabusa2* mission in the Near Asteroid Operation Phase.

In this ***James Webb Space Telescope*** First Image, we see the Southern Ring Nebula, a planetary nebula with two stars at its centre in a close orbit. The dimmer of the two is at a later stage of evolution and periodically expels shells of gas, which get disrupted by the stars' orbit, forming the intricate nebula seen in this image. Credit: NASA, ESA, CSA, STScI

Case Study

Making Your Region the Heart of the Universe: Regional Engagement Through an Astronomy Exhibition

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Keywords
exhibition, public engagement, STEM

This article focuses on how exhibitions can be developed to help tackle regional disengagement in space sciences, and more broadly in STEM, using the Life Science Centre's *Space Zone* as a case study. We will describe techniques for creating an exhibition experience that responds to regional challenges and fosters active engagement, analyse preliminary results of a small study and discuss feedback on the exhibition.

Introduction

At the core of the diverse science communication and outreach community is our shared mission: to inspire people to engage with STEM (science, technology, engineering and mathematics), to ignite curiosity for the world around us, and to encourage a sense of inquisitive questioning. Rather than catering only for people who already show an interest in science, Life Science Centre aims to appeal to and engage with all members of our community, North East England, including those who may be more challenging to reach or who are not yet engaged in STEM.

This article describes the development process and design techniques used for the Life Science Centre's *Space Zone* to encourage engagement in space science, and more broadly in STEM, with disengaged visitors by putting the local community at the heart of the exhibition.

Life Science Centre's *Space Zone* opened to the public in 2019 and was inaugurated in 2020 by Dr Helen Sharman. It covers 750sqm and hosts 58 exhibits, taking the visitor on a journey into outer space from the heart of Newcastle-upon-Tyne, North East England. The North East is one of the most challenged regions in England in terms of material poverty and youth career aspiration. The exhibition aims to overcome these challenges and contribute to our visitors' science capital (*Archer, et al., 2015*) through space science, a popular topic in the community (Figure 1).

We will first describe techniques to design an inclusive, engaging, and empowering exhibition for local visitors. This includes theoretical and academic underpinnings of the work and also describes how *Space Zone* puts this into practice. We will then analyse a small sample of qualitative visitor feedback about the exhibition to understand its success and limitations of the results and key lessons learnt during the exhibition development process.

Background

Previous and ongoing studies help describe how socioeconomic, familial, and individual situations can predict a person's likelihood of engaging in STEM (*Grossman & Porche, 2014*). However, the science capital model has been shown to be more effective in understanding how

Figure 1. *Entrance to Space Zone. Credit: The author*

STEM engagement is ignited, shaped and maintained. *Archer et al. (2015)* wrote:

> *The concept of science capital can be imagined like a … bag, containing all the science-related knowledge, attitudes, experiences and resources that you acquire through life. It includes what science you know, how you think about science (your attitudes and dispositions), who you know (e.g., if your parents are very interested in science) and what sort of everyday engagement you have with science.* (p.2)

While personal science capital cannot, for now, be accurately quantified, the science capital framework allows us to conceptualise effective approaches to science engagement activities. That is, not only communicating science facts, but also working towards impacting attitudes and access to resources. For people with lower science capital, encouraging STEM engagement through this holistic approach in publicly accessible locations, such as science centres, is thought to contribute to broadening access and equity in science participation and pathways (*Martin et al., 2016*). In the context of exhibition development, this can involve being mindful of factors such as the inclusiveness of set design and role models, management of power structures presented through content and the curated presentation of the culture of science.

Life Science Centre (hereafter, "Life") in Newcastle-upon-Tyne, North East England, is committed to a mission of inspiring everyone in the region to explore and enjoy science and to discover its relevance to their own lives. Rather than only focusing on educating, we aim to contribute to the science capital of our target audience – young people from 6-18 years old – by creating experiences that are inclusive and empowering. As Life has a remit to serve the local community, it is essential to understand the region's specific challenges.

The population of North East England, where Newcastle-upon-Tyne is the largest city, faces many challenges. Poverty is the biggest challenge to the region, inhibiting action on other societal challenges. The North East is amongst the most deprived parts of the UK: there are 500,000 people living in poverty in the North East and, compared to the England average, Newcastle has more lone parent households, more low-income families, more children eligible for free school meals and more children with disabilities (*Office for National Statistics, 2017*). Among the multiple causes of poverty are low wages, insecure jobs, and unemployment (*Public Health England, 2018*).

The community, however, is not homogeneous. Comparing the poorest and wealthiest wards in Newcastle, there is a 10- and 12-year difference in life expectancy for men and women, respectively (*Public Health England, 2018*). This example captures the scale of inequality present in our community. However, it is not systemic barriers alone that deter the most deprived communities visiting Life Science Centre. The two most deprived areas of the region, Byker and Walker, are both situated within 5km of the Science Centre and are well connected by public transport routes. Societal and attitudinal barriers around science and culture have a much weightier influence on people's interests, access and aspiration. A report by *City and Guilds (2016)* found that young people in our region were the least confident in the country about their futures and that 42% do not expect to hold down regular employment. The Children's Commissioner found that young people growing up in the North East were concerned about their future and were unlikely to aspire to careers in STEM (*Children's Commissioner, 2018*). This was attributed to a concern about the lack of opportunities for the future and the notion that it would be more challenging to succeed in the North of England than in more affluent areas.

The *Children's Commissioner (2018)* report also pointed to career aspirations for young people as tending to be informed by friends and family rather than any knowledge of sectors of employment specifically available in the North. Most young people indicated that they had aspirations for blue-collar jobs and did not identify that broader careers were a viable choice: STEM careers, in particular, did not feature highly. The report suggested that this may be because these roles and professional fields fall outside of their immediate experience. Several young people specified that they were unconvinced that senior scientific careers would be available in their city and that they could not achieve a career in science locally. Gender bias also played a role, as young women in particular identified with gender-stereotypical career options such as caring professions (e.g., teaching, nursing, and beauty), indicating that defined roles in the North were impacting young people's perceptions and aspirations of STEM.

Despite the difficulties faced, most of the young people surveyed stated that they enjoyed living in the North, were proud of their Northern heritage, and felt a strong sense of home and regional belonging (*Children's Commissioner, 2018*). The North East region is well known across the country as a tight-knit community, brimming with local "geordie" pride (*Drape-Comyn, 2019*). Life's *Space Zone* was developed within the framework of science capital to draw on this regional pride while remaining sensitive to specific challenges faced by the region. The exhibition is organised in four immersive spaces: space technology on Earth, Mission Control, the International Space Station and our Solar System. Each zone looks at content through the prism of fulfilling jobs and local people who do them.

Framing the Local Community as the Heart of the Universe

Given Life's commitment to serving the region, it was essential to make sure the exhibition themes were of interest to the local community. Space science, as a theme, was chosen following an internal survey of our visitors, which indicated that space (as well as animals and dinosaurs) was a popular topic. The current interest would be used as a hook to spark curiosity in the exhibition and encourage visits. The challenge was to maintain engagement throughout the visit, in particular for those who were distanced from STEM, and to empower visitors by framing the local community as central to the field of space.

Essential considerations for engaging science exhibitions are often grouped into three categories: narration, participation, and interaction with others (*Hayward & Cairns, 2006*). The development of *Space Zone* aimed to make use of this understanding in order to create a meaningful narrative, design participative and interactive experiences, accommodate

Figure 2. *School children looking at the case study of Dr Ramin Lolachi, NASA planetary scientist from Consett, North East England. Credit: The author*

Figure 3. *Children using the interactive digital exhibits in Space Zone's mock-up Mission Control. Credit: The author*

different learning styles, and, in keeping with the times, create spots for photos and selfies.

The exhibition narrative is key to visitor engagement as it frames the content and the interactions with exhibits, texts, graphics, and other visitors. Other science centres and museums have created successful and engaging space exhibitions by putting the visitor at the centre of exhibition narratives. For example, *Made in Space* at the Tyco Brahe Planetarium in Copenhagen frames their exhibition narrative around the fundamental question "where do we come from?", using this as a way of talking about the origins and composition of the Universe (*Nicolaisen et al., 2021*).

Despite the demonstrated interest in space sciences, we worried that our local visitors might not feel represented in an exhibition aimed at the "universal self." We wanted to create an experience that celebrated North East England more explicitly and its current, tangible achievements. *Space Zone*'s narrative, hence, was framed, not simply around the individual, but the individual from North East England. Creating such a narrative drew on the sense of regional pride felt by our local visitors in the hope of evoking emotions of inclusion, investment and aspiration. *Space Zone*'s narrative is captured in the exhibition's introduction text, displayed at the gallery's entrance:

> *Here in the North East, stargazers love our famous dark skies. But did you know that the world relies on our dazzling space tech and engineering too?*
>
> *Explore our world-class space industry in the Space Zone. Find out about the people on a mission to tackle problems, answer questions and make life better.*
>
> *Your journey into space starts here.* (Life Science Centre, 2018)

Like all *Space Zone*'s exhibition text, this text refers to local places and landmarks as "our" in a bid to include the visitor in the narrative, putting them in an active role rather than a passive one. Further, *Space Zone*'s exhibits are inspired by contemporary science at local universities, and the case studies spotlight local researchers, experts, businesses and universities. In addition, the exhibition's voiceovers, films, and audio clips were all created with the community's help to highlight the highly recognisable local accent (Figure 2).

This is motivated by a desire to include, not alienate, our visitors, and avoid psychological disengagement, whereby visitors mentally retreat from the experience of differential treatment based on group membership (*Major & Schmader, 1998*), or do not feel part of the in-group (*Tougas & Beaton, 2008*). It has been suggested that psychological disengagement can be a defence mechanism when individuals dissociate themselves from situations in which they feel undervalued or underrepresented (*Beaton et al., 2014*).

Similarly, this is the fundamental basis for the representation of genders and ethnic origins in the examples chosen for the exhibition, even though space science and the space industry do not yet reflect societal diversity (*Pold & Ivie, 2018*). By offering a different narrative to the current perceived attitudes about space science (that meaningful careers in the space industry can only be achieved in Paris or Houston) and providing positive role models, we hoped to build confidence, aspiration, and pride in our visitors. Equally, the case studies and stories of local space scientists and experts added a more human and approachable aspect to the field, making it feel accessible.

Further, many of *Space Zone*'s exhibits were designed to highlight the space science that visitors already engage in, though perhaps unknowingly. Opening the exhibition with technology, such as GPS, and techniques, such as trial and error, that visitors use in their everyday lives, makes a subject of astronomical proportions feel more within reach and attainable. This approach builds on the idea that exhibitions have greater levels of and longer-lasting engagement when they showcase the relevance of science in everyday life (*Martin et al., 2016*) and is supported by the idea that everyday engagement in STEM is a recognised element of science capital (*DeWitt et al., 2014*).

Co-creation for Regional Relevance

In order to ensure that our design and development would indeed result in positive engagement and regional representation, *Space Zone* was created with the guidance of an advisory board of local academics and entrepreneurs. As well as assisting with fact-checking and steering, the advisory board helped us find examples of excellence in the region to spotlight in the exhibition. These interactions were also the beginning of long-lasting partnerships with local businesses and universities.

As well as experts in the field, Life also reached out to current visitors for feedback during the development process to ensure the exhibition would be relevant and engaging. In particular, the surveys and focus groups asked for visitor opinions on content, text type, and exhibition look and feel. As a direct result of these surveys, we developed *Space Zone*'s two intimate, immersive spaces, which were not part of the initial brief: Mission Control and International Space Station.

Results and Limitations

Floor staff and exhibition explainers have anecdotally reported that *Space Zone* is very well received by visitors and school groups. Visitors to the exhibition are observed interacting enthusiastically with hands-on exhibits and taking the time to read or listen to local case studies. Some have been observed expressing delight at discovering that case studies and scientists live or work very close to their neighbourhood.

Formal visitor research is essential to evaluate the success of the techniques described above and their impact on visitors. Exit surveys and interviews were prepared to understand visitor perceptions, takeaways and learning. Unfortunately, due to Covid-19, no quantitative work or summative evaluation has yet been carried out on *Space Zone*.

Before the temporary closure of Life Science Centre, we were able to complete three semi-structured, in-depth interviews with one headteacher (male), one local woman, and one mother accompanying two children under the age of 10. The interviewees were approached as they were about to leave the exhibition, and the interviewer took notes but did not record the interactions. Overall, the three people interviewed enjoyed their visit, thought that the content was interesting and educational, and appreciated the exhibition's local flavour. Some relevant comments include:

Interview 1: Local woman
- Surprised and pleased to discover the variety and number of space-related activities and opportunities in North East England.
- Happy to see people "like me" represented in the case studies of local space experts.
- Learned some unexpected facts about space.

Interview 2: Mother (with two children)
- Happy that there were opportunities in North East England for her children (and commented that this was not the case when she was young).
- Surprised at the variety of space applications currently in use on Earth.
- Felt the content was at a "good level" and could be understood by family groups.

Interview 3: Headteacher
- Especially positive about the exhibition's local connection, felt this was a powerful message for his pupils.
- Felt the case studies would provide positive role models for his pupils.
- Appreciated the exhibition's future-focused approach and felt it would inspire his pupils to aspire to future STEM roles.
- Especially liked that his pupils could see and try out STEM skills. He commented that many young people do not actually know what a scientist does and that it was important for them to see that "it is not all about white coats."

While being homogeneously positive, these interviews only represent a small sample of the 300,000 visitors that come through the doors at the Life Science Centre every year. A quantitative study with greater sample size is required to truly understand the impact of *Space Zone*.

Discussion

No single exhibition can change the world. However, our visitor feedback shows the potential for impact on our visitors' science capital through the four elements identified by the framework: knowledge of science, attitudes towards science, people in your network, and everyday engagement in science (*DeWitt et al., 2014*).

While the above results only represent three types of visitors and cannot be thought of as representing all of our visitors or the overall success of the exhibition, they do show that our aims have not gone unnoticed. All the visitors interviewed, as well as the groups they were accompanying, shared positive feedback. They had not disengaged during their visit, neither because of lack of interest nor because they felt excluded or unrepresented. This is precisely the type of effect we hoped to create, as it indicates that mindful exhibition development can positively impact visitor attitudes of science. These types of interactions may equally contribute to visitors' science capital by showing visitors that scientists are, in fact, part of their network (in this case, their community), something the *Children's Commission (2018)* report thought young people might be lacking. We hope that humanising scientists in this way will help to change the attitudes of visitors who believe that science is "not for them." Though this will require further evaluation, the headteacher's comments regarding trying out STEM skills and seeing "what scientists actually do" provides optimism that this might be the case.

Our results, though limited, also indicate that visitors have identified the core of the exhibition's narrative and its focus on North East England's contribution to space science and the space industry. The interviewees' comments show that they left the exhibition with a greater understanding of the region's rich breadth of opportunities.

We must note here the important caveat that, with the exception of school groups, many visitors to science centres and museums already have a certain level of cultural confidence and cultural capital (*Wildhagen, 2010*). However, we hope that by adding an inclusive and relevant exhibition to the cultural landscape, we contribute to changing people's attitudes to science centres and STEM.

Conclusion

This article looked at how space science could be presented in an exhibition setting to empower visitors to overcome challenges to aspirations and STEM engagement. This was achieved by responding to existing research about the community, using the science capital framework for guidance and involving the local community in reflection and decision making.

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Biography

Sarah de Launey is an exhibition developer at Life Science Centre. She is also a Pint of Science Festival coordinator and the president of La Fiole, a Paris-based association for art-science and game-science collaborations.

Galaxy interactions are an excellent laboratory for understanding star formation. That's why this image of the interacting group of galaxies called Stephan's Quintet is so breathtaking. In this ***James Webb Space Telescope*** First Image, we see in beautiful detail sweeping arms of gas and dust, knots of star formation, and a shock wave, all caused by the interaction. But don't be fooled! Although this is called a "quintet", only four of the galaxies are actually involved in the interaction. Can you guess which one is the interloper? Credit: NASA, ESA, CSA, STScI

Exploring the Frontiers of Space in 3D: Immersive Virtual Reality for Astronomy Outreach

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exhibition, virtual reality, immersive, outreach, observatory, space telescope, telescope

An immersive, virtual exhibit of large telescopes and space missions is described. The exhibit aims to overcome the difficulty members of the public have in appreciating the scale and complexity of modern astronomical research facilities. Using detailed 3D models, ground- and space-based telescopes that are impossible to visit in person can be explored by moving through a virtual space. The exhibit was created using Unreal Engine, a tool developed by Epic Games. Users wear Oculus Quest virtual reality headsets and traverse the 3D exhibit using Xbox game controllers. CAD models were gathered from open access sources and with the help of the staff of major observatories. The first version of the exhibit highlights telescopes and planetary missions with major involvement of the University of Arizona, but it can be customised to include any major telescope or space mission. Visitors can experience the 6.5-meter MMT, the twin 8.4-meter LBT, the 24.5-meter GMT, the 25-metre Very Large Array radio dish, NASA's *Hubble Space Telescope* and *James Webb Space Telescope*, the Phoenix Mars lander, and the *OSIRIS-REx* spacecraft alongside a 3D model of the asteroid Bennu. The exhibit was successfully debuted at an outreach event hosted by the University of Arizona in Washington, DC.

Introduction

The Rise of Virtual Reality

Virtual reality (VR) promises a transformative user experience, although that promise has not always been fully realised. It is a computer-generated simulation of a three-dimensional (3D) image or entire environment, in which the user can view the artificial world, move around, and interact with objects within it (*Greengard, 2019*). The modern origin of virtual reality lies in the video game industry (*Stanton, 2022*). In 1984, when Atari closed its research lab, two of its laid-off researchers, Jaron Lanier and Thomas Zimmerman, started a company called VPL Research that created several technologies that are still central to the virtual reality experience (*Lanier, 2017*). However, within a decade, the first wave of virtual reality fizzled out. The technology was cumbersome, expensive, and often failed to deliver a fully immersive experience. Headsets could lead to eye fatigue, and computers were not fast enough to render head movements in real-time, often resulting in nausea (*Kiryu & So, 2007*)

The renaissance of virtual reality started about a decade ago, in the 2010s. Well-funded start-up companies developed faster graphics, lower-cost motion tracking, and lighter screens with higher resolution that used less power (*Drummond, 2014*). Exponential increases in computational speed and power improved the user experience. Facebook bought Oculus, the maker of one of the best headsets on the market, as rated by technology websites like CNET and PC Gamer, and Google provided a virtual reality capability to the hundreds of millions of people who own Android phones (*Harris, 2020*). The first wave of applications for virtual reality in the 1980s and 1990s was confined to medical diagnostics, flight simulation, car design, and military training. The new capabilities enabled an enormous set of possibilities across scientific research, science education, and outreach. VR headsets span a wide range in quality and cost, from cardboard units for $30 to high-end devices for $800 or more (*Robertson, 2022*).

VR for Astronomy Education and Outreach

Astronomy has a strong tradition of 3D visualisation. This is not the same as virtual reality since the user does not navigate in a virtual space directly analogous to their real, physical space. However, it shares with virtual reality the characteristic of rendering data in three dimensions so that it can be explored and manipulated (*Kent, 2019*). 3D visualisation plays a valuable role in modern astronomical research, allowing researchers to extract new knowledge from complex datasets (*Hurt et al., 2019*). The data used for visualisations can be sophisticated, such as results from 3D hydrodynamic simulations (*Orlando et al., 2019*). Researchers have used Unreal Engine, the software used to create the popular video game *Fortnite*, to render an entire mock universe in real-time (*Marsden & Shankar, 2020*) and to render aspects of the entire history of the universe back to the quantum gravity era (*Hamieh, 2021*). It is noted that these applications are sophisticated visualisations, but research using VR and astronomical data has also begun to take off (*Baracaglia & Vogt, 2019; Jarrett et al., 2021*).

Once a 3D visualisation is created, it has the potential to be used for education and public outreach (*Crider, 2020*), and the use of VR headsets for education has increased rapidly in the past few years (*Cankaya, 2019*). The most capable platform for both purposes is the WorldWide Telescope, which can deliver data to museum exhibits, virtual reality headsets, and planetarium domes (*Rosenfield et al., 2018*). WorldWide Telescope incorporates many astronomy data sets; it lets users create scripted "tours," and it is open-source software with a web client. NASA provides a large, free collection of VR experiences for download. They include 360-degree videos from Mars missions and 3D models of various Solar System objects (*NASA, 2022*). A dozen virtual tours can be found on the website of the European Southern Observatory (*European Southern Observatory, 2022*). Despite this work, there have been relatively few virtual reality projects aimed at the public. Examples include interacting with a supernova remnant (*Arcand et al., 2018; Ferrand & Warren, 2018*), creating a virtual galaxy (*Borrow & Harrison, 2017*), a tour of the ALMA Observatory (*Hiramatsu et al., 2021*), and exploring the science of NASA's *James Webb Space Telescope* (*Space Telescope Science Institute, 2018*). There have been even fewer studies of the design principles that guide good virtual reality learning experiences (*Kersting et al., 2020; Kersting et al., 2021*). This is the first paper to describe a virtual reality tour of multiple major telescopes and planetary sciences space missions.

Creating the Virtual Exhibit

Software and Hardware

For this project, we selected the most popular tools for creating virtual reality experiences. In doing so, we were confident that the development experience would be as smooth as possible. On the software side, we chose Autodesk's 3ds Max – a 3D and CAD design and modelling application – and Epic Game's Unreal Engine 4.24 (UE4), and on the hardware side, we used Facebook's Oculus Quest 2 (OC2) headset.

Autodesk is the leading creator of computer-aided design (CAD) software; their most widely known title is AutoCAD. Their 3ds Max software is best-suited for rigid models like buildings and cars and is often used to create cinematic special effects. Due to Autodesk's market dominance, they have come to decide what "standards" exist in the 3d development world. As such, it is easy to use 3ds Max to create a model and any relevant animations, which can be used in Unreal Engine directly. The other software choice was easy since UE4 is a freely available state-of-the-art gaming engine used extensively for visualisations and animations in architecture, medicine, and many fields of science (*Shannon, 2017*). For hardware, the choice required more thought, as displays for virtual reality experiences are improving rapidly (*Zhan et al., 2020*). While it has been claimed that there is no substantial difference between the VR experience using an Oculus Rift headset (a more powerful device than the Oculus Quest we used) and a lower-cost smartphone headset, that only applied to the *Titans of Space* app, while the telescope exhibit described in this paper is much more demanding computationally (*Papachristos et al., 2017*)
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The OC2 is a portable, relatively lightweight, and affordable (about $300) headset capable of delivering a medium-quality VR experience (Figure 1). To provide the very highest quality experience, we would have needed an Oculus Rift or an HTC Vive headset. Both of these are higher resolution and higher framerate than the OC2, but they each require a full gaming-class computer to drive them and cost approximately twice as much as an OC2 without the computer. All VR headsets are far more affordable than a CAVE virtual reality room, which typically runs $50,000. The OC2 can deliver a novel and exciting experience to non-gamers and anybody who does not regularly play video games; gamers are highly attuned to nuances in rendering and gaming performance and will easily be able to discern quality differences between top-tier hardware and the mid-range OC2. Also, gamers tend to experience VR through a tethered headset connected to a powerful computer. In contrast, we opted for untethered headsets, with a subsequent loss in bandwidth and visual quality but much greater flexibility and convenience for multiple users. The sense of immersion does not arise from the fine details but from the fact that a 3D environment is being rendered in real-time. Developing for the OC2 is a more constrained process than developing for the Rift or Vive. Staples of modern "eye candy" such as global illumination, real-time shadows, and reflections are too much for the OC2 to handle and must be dispensed with. Also, high-resolution models cannot be used. Not only does the OC2 struggle to render so many 3D elements at once, but the entire programme – including images, sounds, models, and code – is limited in size to 2GB. However, by trimming down the complexity of 3D models, we were able to deliver a satisfying user experience with the OC2, as we discuss in the next section.

Figure 1. *Oculus Quest 2 virtual reality headset and hand controllers, used to navigate an immersive experience of large telescopes and space missions Credit: KKPCW/Wikipedia Creative Commons*

The Development Process

The first development round was bottom-up. We put our models into a world, textured and illuminated it, and then tried to run it in a VR environment. Many off-the-shelf models come with extreme detail, especially if they are based on engineering (CAD) models. Often, they include every wire, bolt, pipe, and internal structural components, such as beams and rebar. These are necessary for engineering and construction, but they are often unseen and unnecessary in a game. Despite this, the game engine must include such components in every calculation, needlessly hampering performance.

"Mesh" is the term used to describe a 3d model – every 3d model is a collection of vertices and edges which combine to create triangular surfaces. When viewed without surfaces (transparent or "wireframe"), it looks like a mesh fabric. The number of vertices (and therefore edges) defines the resolution of a mesh. More vertices yield higher resolution but also require more processing power to render correctly. Lowering the number of vertices lowers the number of real-time calculations a game engine is required to make – this is called "mesh optimisation". In the context of 3d rendering software, a true sphere technically has "infinite faces", but that is an impossible task for a computer to render. A sphere can be passably represented with a low, finite number of faces – typically 240 – without looking "low-poly" (low polygon count or jagged edged) to the user. When optimising meshes for our VR experience, we lowered the numbers of vertices in our models multiple times until they began to look low-poly, then used the previous iteration. This process enabled us to remove superfluous edges that only served to worsen the in-game experience without improving the visual quality of the model.

After many iterations of removing or mesh-optimising the components or lowering their resolution, the application functioned on the headset, but it was slow and visually unappealing. It also only worked while connected directly to the development computer (tethered), which was untenable for our needs. The major hurdle at this stage came from the fact that Oculus applications are technically just Android applications, distributed as APK files. APKs have a strict size limitation of 2GB. Importing models or meshes (3D models made of polygons) with UE4's default settings ended up being very costly, as it automatically imported textures for each model and then automatically created unnecessarily large materials for each texture. By the time we exceeded the 2GB limit, we had added less than half of the models we wanted to use. A 3D model that was very challenging to incorporate into the world and then animate was a 5-centimetre resolution model of the 500-meter diameter asteroid Bennu (Figure 2; *Bennett, 2021*).

Therefore, we started over with a top-down approach, importing bare-bones models and compiling basic shaders one at a time. A shader is extra code that can alter visuals by changing how textures and lighting are displayed. Then we built the application (compiled all the elements into an Oculus-friendly format) after each step. In this context, a shader is what defines what an object looks like in 3D space. Shaders combine colours, images, and mathematics to create a "material" or "surface" that is applied to a mesh (a 3D model). For example, shiny and matte red paint start with the same colours and images but utilise different linear algebra to create the final, different effects. Since most telescopes have the same kind of materials (white-painted steel, reflective red metal, mirrors), we were able to save significant space by creating single materials for reuse or using UE4's Material Instance object: a method for creating new materials based on existing ones, so common information is not duplicated. It takes much longer to do this as materials have to be applied to surfaces manually and individually, but in the long run, it is a more efficient process.

3ds Max was not necessarily required for this project, but we did not make all the models in-house. Despite working for a major (25%) partner on the Large Binocular Telescope, we could not obtain CAD models and had to purchase a mesh from a 3D model supplier called TurboSquid for $350. The model we bought of the LBT was so detailed it appeared to have originated directly from the internal CAD files, which meant that it included engineering information. Behind the walls were plumbing, wiring, individual bolts, and other utilities that would ultimately slow our application down significantly and take up unnecessary space. We used 3ds Max to remove those elements and keep the portions we wanted. We also purchased 3D models of the Bennu asteroid, the NASA *Hubble Space Telescope*, and an animated model of the NASA *James Webb Space Telescope* from TurboSquid. *Osiris-REx* provides a free 3D model on their website, but it is far too low-resolution to be used in our application. It looks decent from a large in-game distance, but it does not pass close inspection, instead looking like a many-metres wide ball of clay. For some other models, optimisation was required. By default, the GMT mirrors each contained 28,000 triangular faces, but the same visual effect could be achieved with 36 faces per mirror. That component-level optimisation can only be done within an application like 3ds Max (or a free alternative such as Blender).

One method for importing and texturing meshes in a game development context is to break each model into smaller components and import them individually. For instance, a radio dish telescope might have the dish, yoke, and base as separate components. This would make texturing easier – one material per model – but it would require joining them back together inside the game engine, which is time-consuming and imprecise. The best way to work with complex, textured meshes is to keep the model intact as a single mesh and apply material groups for each individual texture: mirrors as one group, reflective

Figure 2. *The near-Earth asteroid 101955 Bennu is represented in the virtual exhibit using a 3D model with 5-centimetre resolution. The OSIRIS-REx spacecraft, currently delivering a sample of the asteroid to Earth, can be seen in front of the 500-metre-diameter asteroid at the lower left. Credit: Impey/Danehy/University of Arizona*

Figure 3. *Space science research achievements of Steward Observatory and the Lunar and Planetary Lab at the University of Arizona. These items appear on a billboard at the entry point of the virtual exhibit. Credit: University of Arizona*

red metal as the next, and so on. These material groups can only be assigned in an application like 3ds Max or Blender.

Building an APK for distribution or use on an OC2 cannot be done with UE4 (or Unity) alone. An external compiler is needed. Luckily, Google freely distributes such a compiler with their Android Studio IDE. Android Studio (or just the compiler) must be installed on the build system, and UE4 must be made aware of its location on the system. Without this, even tethered development builds will not work. Oculus specifically does an excellent job of documenting this process, but despite that, it is very sensitive to even the smallest changes. We recommend that once a system is stable and functional, no updates be made to the development software. The hardware side of the project is much more straightforward. Meta's Oculus Quest 2 headsets come with controllers in the box. To test the development builds using these controllers without needing to publish to the Oculus store first, the headset had to be put into developer mode. This is as simple as creating a free developer account with Oculus and using the companion app to enable developer mode on the headset. No further modifications need to be made.

The computer that developed this project was a top-of-the-line, custom-built, gaming-class workstation, costing approximately $5,000. It contained a 24-core, 4.5 GHz AMD Ryzen Threadripper 3960X, 128GB of RAM, and an nVidia 2080 SUPER GPU. This computer was more than capable of handling the development process. Working with multiple 3D assets, high-resolution images (for textures and materials), and multiple compiles requires significant computing power. Any computer for a project like this must be considered a "gaming class" or "workstation class" to handle this workload. Compiling the code requires substantial CPU power to be accomplished in a reasonable amount of time. Developing the game requires a modern GPU and a large amount of RAM. Doing all those things at once requires more than off-the-shelf hardware.

Astronomical Facilities

The virtual reality exhibit discussed in this paper was designed to highlight astronomy and space science research at the University of Arizona (UA) for non-technical and public audiences. The research is the product of the faculty and staff in the Department of Astronomy/Steward Observatory and the Department of Space Sciences/Lunar and Planetary Laboratory. Steward Observatory is one of the largest centres for astronomical research in the world, and it makes the world's largest telescope mirrors. The Lunar and Planetary Lab was the first planetary science department in the United States, and it has contributed hardware to space missions that have visited every Solar System planet (Figure 3).

A major goal of the VR exhibit was to give non-expert visitors a sense of the scale of frontier astronomical facilities. The biggest ground-based telescopes cannot all be toured by the public or are in remote locations, and planetary probes and space telescopes are impossible to see up close. In the exhibit, visitors walk among the "giants," seeing details of the construction and watching some of them display animated motions, such as telescopes slewing. For example, *OSIRIS-REx* was launched in 2016 and is currently heading back to Earth carrying a sample of the near-Earth asteroid Bennu, with a return due in 2023 (*Lauretta et al., 2017*). Visitors see the spacecraft in front of a slowly spinning, full-scale rendering of the

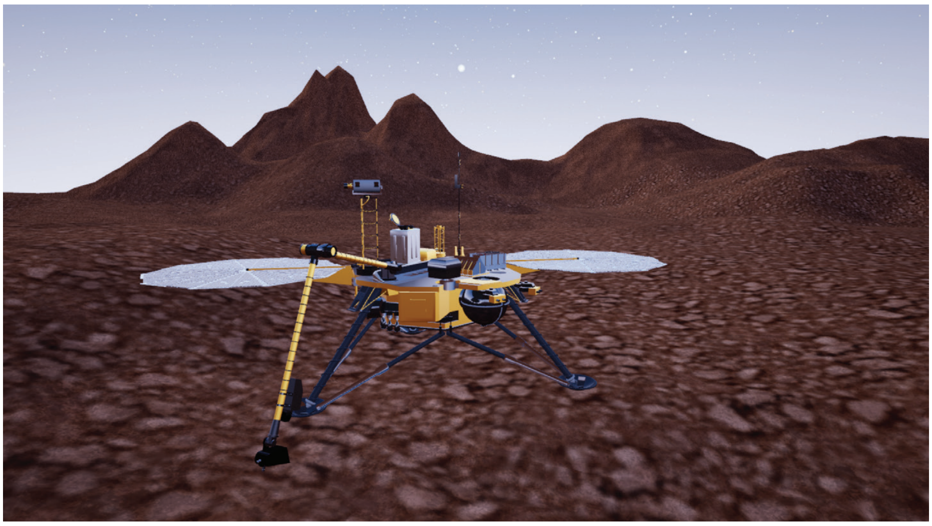

Figure 4. *A 3D model of the NASA Phoenix lander that reached Mars in 2008 and conducted experiments on the presence of water and the potential habitability of Mars. Credit: Impey/Danehy/University of Arizona*

500-metre diameter asteroid. Part of the 3D landscape is converted into a patch of Martian terrain. Here, visitors can inspect the Phoenix lander, which in 2008 studied the history of water in the Martian arctic and assessed the biological potential of the ice-soil boundary layer (*Renno et al., 2009*; Figure 4). In the sky above the Martian terrain is HiRISE, a camera attached to a satellite called the *Mars Reconnaissance Orbiter*, which has been mapping the entire planet at metre-scale resolution since 2006 (*McEwan et al., 2007*).

Optical telescopes in the exhibit are all partnerships involving the University of Arizona, where the mirrors were fabricated at the Richard F. Caris Mirror Lab (*Martin et al., 2016*). The smallest telescope on view is the 6.5-meter MMT, a joint venture of the University of Arizona and the Smithsonian Institution, located on Mount Hopkins in Southern Arizona (*Williams et al., 2016*). Nearby is the Large Binocular Telescope (LBT), which houses two 8.4-metre mirrors on a common mount, equivalent to one 11.8-metre telescope. The LBT is run by an international consortium located on Mount Graham in Southern Arizona (*Hill et al., 2014*). The largest telescope in the exhibit is still "virtual," as it is still under construction at Las Campanas Observatory in Chile. The Giant Magellan Telescope (GMT), an international consortium of thirteen leading universities and research institutions representing five countries, will have seven 8.4-metre mirrors combining to give the collecting area of a 24.5-metre telescope and a resolving power ten times greater than the *Hubble Space Telescope* (*Fanson et al., 2018*).

We additionally included a single radio telescope. The dishes used in the Event Horizon Telescope are diverse, ranging from 12 metres to 50 metres in diameter. We used a 25-metre dish from the Very Large Array (VLA) as an exemplar of radio dish design. The Event Horizon Telescope (EHT) is a global network of synchronised telescopes whose signals are combined interferometrically to make a radio image with extremely high angular resolution (*Ricarte & Dexter, 2015*). The Event Horizon Telescope made front page headlines in 2019 with the first image of the shadow created by the event horizon of a supermassive black hole (*Akiyama et al., 2019*), followed in 2022 with an image of the black hole at the centre of our galaxy (*Akiyama et al., 2022*). Animated 3D models mean the optical telescopes are shown gently slewing across the sky (Figure 5). For the LBT, lasers shine out from the telescope into the sky, part of an adaptive optics system that gives the telescope superior resolving power to the *Hubble Space Telescope* (*Rabien et al., 2010*).

Two space telescopes are suspended in the sky of the exhibit. The first is the venerable *Hubble Space Telescope (HST).* Launched in 1990, *HST* is the most productive scientific experiment in history (*Apai et al., 2010*), which is even more remarkable since it is not one of the seventy largest telescopes. The exhibit features images made with NICMOS, the near-infrared instrument on *HST* (*Schneider, 2004*). The second is NASA's *James Webb Space Telescope (JWST),* the successor to *HST* and the largest and most expensive space telescope ever built (*Kalirai, 2018*). *JWST* was launched in late 2021 and released its first science images in mid-2022 science operations (*Rigby et al. 2022*). *JWST* will be the flagship observatory for astronomy from space for the next decade (Figure 7). An animated 3D model for the *JWST* shows the 18 hexagonal gold-covered mirrors unfolding and the 15 x 20 metre,

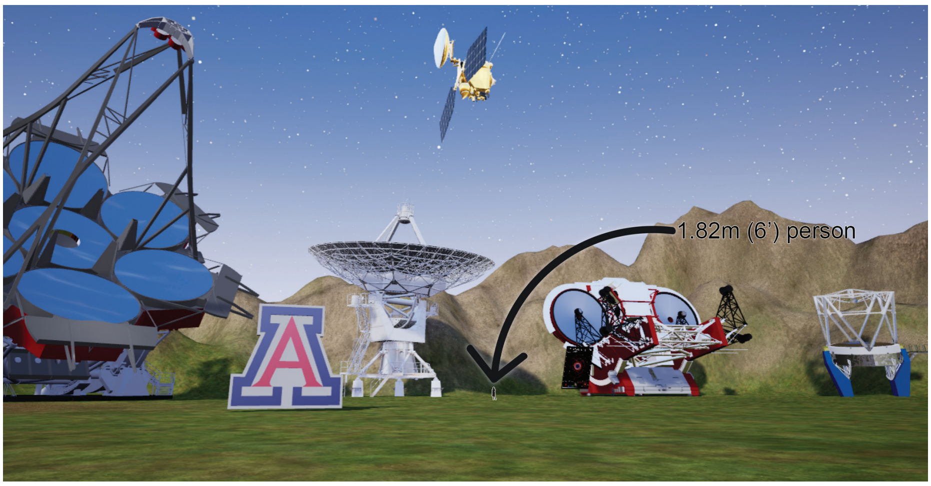

Figure 5. *Telescopes in the virtual exhibit include (from left to right) the 24.5-meter Giant Magellan Telescope, a 25-metre radio dish from the Very Large Array as a stand-in for one of the dishes of the Event Horizon Telescope, the twin 8.4-metre Large Binocular Telescope, and the 6.5-metre MMT. Credit: Impey/Danehy/University of Arizona*

tennis-court-sized solar shield unfurling, illustrating the complexity that makes the telescope such an enormous engineering challenge (*Feinberg, 2018*).

Designing the User Experience

At the project's outset, it was clear that visitors to the VR exhibit would be self-guided. This is because reactions to this type of immersive experience vary widely. The dominant factors in user satisfaction with mobile VR headsets are usability or user control, sickness, and wearability (*Choi et al., 2019*). However, there are many methods for measuring user experience, with no clear research methodology on what the best methods are in any particular application (*Weinrich, 2018*). With half a dozen headsets in operation simultaneously, the choice was between shepherding everyone through the VR experience like a tour guide or letting everyone go at their own pace. Visitors were likely to find some facilities more interesting than others, and a single pace for a tour might be too fast for some and too slow for others, leading to the decision to make the experience self-guided. The decision was validated during the inaugural event because few users needed or sought guidance.

Figure 6. *A panorama in the virtual exhibit shows most of the telescopes and space missions, with the 500-metre asteroid Bennu giving a sense of scale. Credit: Impey/Danehy/University of Arizona*

That, in turn, meant the exhibit needed signposts and some explanatory material. Users launch the app from the Oculus Quest store – a virtual-reality version of Apple's App Store or Google's Play Store, found on iPhones and Android phones, respectively – and enter the exhibit near the centre of a roughly rectangular patch of virtual land. A starry sky realistically mimicking a location above the American Southwest is rendered above them. A user-generated plugin called Data Driven Starfield is the only realistic sky that works on Oculus. In front of the user are a rotating University of Arizona logo and a large billboard with short bullet points giving the high research points at Steward Observatory and the Lunar and Planetary Lab (Figure 3). Telescopes line one side of the landscape, with a mountain range behind them. At one end of the set of telescopes, the mountains turn into foothills and a reddish Martian terrain. At the other end, they taper off to reveal the asteroid Bennu (Figure 6). Opposite the telescopes, hovering above a transparent platform so that stars can be seen above and below, are the two space telescopes (Figure 7). Since the sky we added is rendered over 360 degrees, it can be seen below the platform that holds all the telescopes. Each facility has a billboard next to it that presents a high-impact image of a science highlight with a one-sentence description, and those with a UA principal investigator have a headshot billboard located nearby.

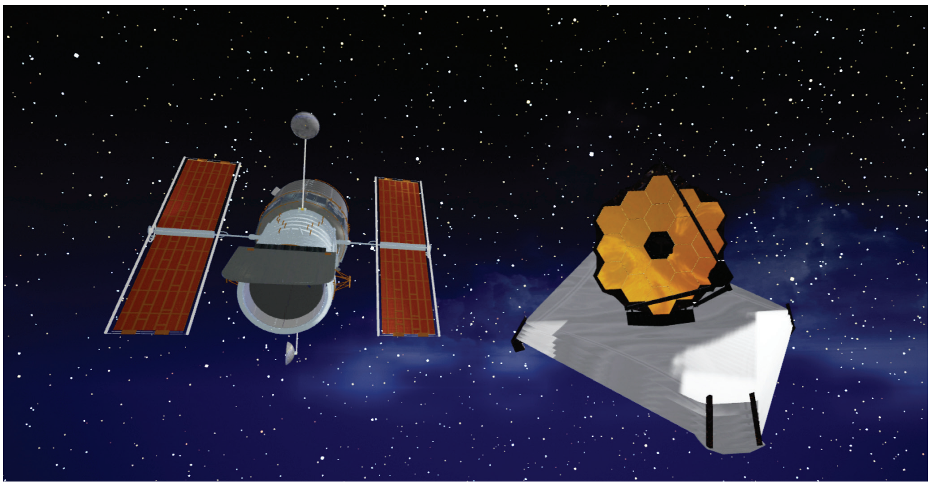

Figure 7. *Space telescopes in the virtual exhibit are the Hubble Space Telescope, launched in 1990, and the James Webb Space Telescope, launched in 2021. Credit: Impey/Danehy/University of Arizona*

Disorientation and safety issues are real possibilities with VR headsets, so visitors were seated in swivel chairs rather than standing with the freedom to move around. Navigation used a standard Xbox joystick; the side-to-side motion was possible either using the joystick or by swivelling in the chair. Normal forward motion was equivalent to a slow walking pace, with one controller button enabling a running speed to traverse the exhibit more rapidly. There was also a "jump" button which users were advised to use judiciously. It elevated them to the equivalent of sixty metres giving an aerial view of the entire exhibit. Two facilitators were at the exhibit at all times to give users guidance as needed on navigation. The final ingredient in the experience was soothing ambient music, which also helped cocoon users from background noise.

Figure 8. *Conference room at the University of Arizona Center for Outreach and Collaboration, in a real-world image, where the virtual exhibit debuted in September 2021. We set up six visitor stations. Credit: University of Arizona*

Launch and Next Steps

Development and testing of the virtual exhibit took approximately six months. It debuted in September 2021, during the opening week of the University of Arizona's Center for Outreach and Collaboration, located in Washington DC, about two blocks from the White House (*University of Arizona, 2022*). The Center aims to highlight University of Arizona research and let faculty and senior administrators connect with State and Congressional legislators, alumni, donors and potential donors, and representatives of federal funding agencies and foundations. The exhibit was given a dedicated space in the Center for 90 minutes on each of the two first evenings of the opening week (Figure 8). About 150 people were present for each of those evenings. The mix was about 1/3 university faculty, staff, and administrators, 1/3 alumni, and 1/3 members of the general public, including journalists and guests of university employees.

Due to the continuing impact of Covid-19, protocols were established to clean and sanitise the VR headsets and game controllers after each use. This was facilitated by the removable face neoprene face shields we purchased for the headsets. The view in each headset was situated at the central entry point of the exhibit to avoid users having to load the app from the Oculus store. Two staff from the Center were there to guide people into the conference room where the hardware was set up and to sanitise headsets and controllers. They also provided simple instructions on how to navigate using the game controllers. Three people acted as "experts" to answer technical questions about any of the space science facilities: the lead author of this article and the Directors of Steward Observatory and the Lunar and Planetary Lab. The second author was also available live online for troubleshooting in case of technical difficulties, however, we did not encounter any.

The dynamic nature of the opening week event, with people moving throughout the Center and not lingering anywhere long, meant it was too challenging to administer surveys or questionnaires. As a result, we only have anecdotal data to evaluate the user experience based on notes the lead author took during the event. An approximate headcount over the two evenings was sixty-five visitors. The average time spent in the exhibit was five minutes, ranging from one to fifteen minutes. People took off the headsets when they had seen enough, not because they were confused or frustrated. There were no complaints about the image quality or responsiveness of the VR. Most people could navigate the exhibit with minimal coaching; for anyone accustomed to video games, it was trivial. Only one person said they felt uncomfortable or disoriented; they removed the headset after a minute. Visitors included a number of UA officials: two members of the Board of Regents, two Vice Presidents, two Deans, and four Department Heads. Spoken comments by visitors to the lead author were overwhelmingly positive. Many affirmed the original motivation behind the VR exhibit: users gained a new sense of surprise and appreciation of the massive scale of modern telescopes. One headset and its controllers remained at the Center for use by anyone who visits the facility.

The next step for the VR exhibit is to deploy it in more controlled settings at the University of Arizona to gather data. It will be used both with student groups and members of the public. There will be installations in the lobby of Steward Observatory and the atrium of the Lunar and Planetary Lab. Discussions are underway for additional installations in the lobby of the UA Flandrau Science Center and Planetarium (*Flandrau Science Center and Planetarium, 2022*) and the visitor centre of Biosphere 2, located just outside Oracle, Arizona (*Biosphere 2, 2022*). We will administer short surveys within the virtual space to gather feedback efficiently, and software will be used to track user movements to see which facilities attract the most visits and the longest dwell times (*Kloiber et al., 2020*). We will also experiment with a VR headset driven by a powerful laptop computer, a setup that will have increased resolution and decreased latency (*Viitanen et al., 2018*). Our exhibit is freely available at the Oculus Quest app store (https://vr.as.arizona.edu/telescopes). Finally, the concept of this exhibit is adaptable. With suitable 3D models, and guidance on software, hardware, and the development process, any observatory could develop a tour of their facilities.

Conclusions

Immersive 3D virtual reality has enormous potential for science education and outreach. Frontier astronomical facilities are located in space or at remote observatories, giving the public no opportunity to appreciate their scale and complexity. We have developed a virtual exhibit using Unreal Engine and Oculus Quest headsets, untethered to any computer and getting their data from the Internet. With modestly priced hardware, it is possible to render large telescopes and space missions in detail. A single engineer built the entire project. He used his computer and a headset we purchased to create the entire experience, including 3D modelling (and optimisation), art asset creation (shaders, materials, and sounds), level creation, and build/compilation. While the exhibit described here features only facilities with the involvement of the University of Arizona, the same mechanisms could be used to give virtual tours of any observatory. Detailed CAD models must have some of their complexity stripped away to allow the exhibit to compile and give users a high-resolution and seamless experience. Initial experience with the VR exhibit at a University of Arizona outreach event showed that it met its goals of providing an appealing user experience and informing the public about space science tools and research.

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Biographies

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Alexander Danehy is a senior web developer and programmer in Steward Observatory at the University of Arizona. He got his B.Sc. in General and Applied Mathematics and Computer Science from the University of Arizona. After graduating, he worked as a Software Developer in the private sector. He has extensive experience in software development, design, and engineering, including DevOps for NASA.

astro-lab@home – Bringing Science to the Sofa

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While public interest in astronomical topics remains high, astronomy education facilities (e.g., school-labs) and outreach initiatives (e.g., observatories) have had to close (and remain closed) due to the Covid-19 pandemic. One of these facilities concerned is the astro-lab of the University of Cologne, where young learners used analogy experiments to explore how exoplanets can be discovered and analysed. Out of the desire to make the original astro-lab experiments accessible to a larger audience (e.g., students, teachers, and the general public) from a distance, the astro-lab@home idea was born. The project is based on the high accuracy of sensors built into modern smartphones, making them the ideal measuring tool for home experimentation. This article describes how everyday materials and smartphones can be used for experiments@home in the context of exoplanets.

Introduction

Student labs are very popular in Germany because they enable action-oriented, cooperative work in a laboratory environment and contribute strongly to the formation of interests in the STEM fields (science, technology, engineering, and mathematics; *Reimann et al., 2020*). One example of a student lab is the astro-lab at the University of Cologne (UoC; *Küpper & Schulz, 2017*) which focuses on detecting and analysing extrasolar planets. Such context-oriented projects, that match learners' interests, like the question of "Life in the Universe" (*Sjøberg, 2012*), have a particularly positive effect on learning success (*Harackiewicz et al., 2016*). To engage (young) learners and the general public in physics and astronomy, various experiments have been developed that focus on how exoplanets can be detected and the conditions that prevail on them, for example temperature, air pressure, atmospheric composition, albedo, and radiation, to be suitable for life (*Küpper & Schulz, 2017*).

However, when the pandemic reached Germany in spring 2020, schools shut down, and visits to the astro-lab were forbidden. Despite the restrictions, we wished to continue to inspire students, support teachers through motivating home-schooling resources and reach anyone interested in astronomy. As a result, we designed the astro-lab@home described in this article.

Astro-lab@home – bringing science to the sofa

One of the challenges of the "new normal" is to continue offering high-quality education and outreach resources independent of a specific location. This requires working with what is available, for example, the materials available at home: smartphones and everyday materials. Since modern smartphones have a variety of accurate sensors, and several studies indicate that smartphone use is ubiquitous (*Anderson & Jiang, 2018; mfps, 2019; OECD, 2020*), students factually possess "a lab in the pocket" (*Stampfer et al., 2020*). Furthermore, smartphones allow flexibility in the time and place of use, and young learners already have extensive experience with smartphones (*Anderson & Jiang, 2018*).

Based on these findings, the original astro-lab experiments (*Küpper & Schulz, 2017*), which can be performed with common lab materials and without smartphones, have been simplified and, in some cases, adapted so they can be done from home using everyday materials. In most of the following experiments, the measurement is performed with Android[1] smartphones and the free app, *phyphox* (*Stampfer et al., 2020*). Furthermore, in each experiment, the data can be exported (e.g., in CSV format) and analysed later with another program in more detail.

Below we will briefly describe each of the astro-lab@home experiments.

Discovery of Exoplanets

In the first experiment, the user rotates a "planet" (e.g., a painted styrofoam ball) around a "star" (e.g., a light bulb) and studies the light curve (illuminance as a function of time). One will notice a periodic pattern of decreasing illuminance and associate this with the shadow of the 'planet' on the sensor (primary transit; Figure 1).

The experiment uses *phyphox* as an optical stopwatch that automatically calculates the transit depth, transit duration, and the duration of a year on the "planet". Furthermore, the light curve is displayed in real-time. Thus, the user learns how

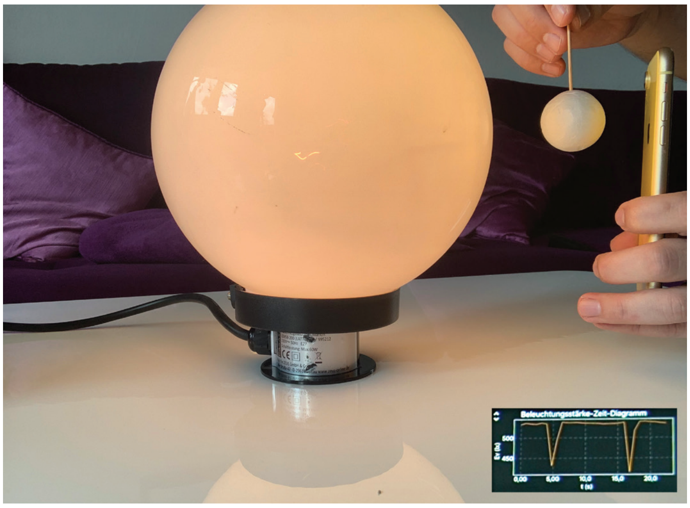

Figure 1. *Transit-Experiment@home with possible curve using a garden light, a styrofoam ball, a toothpick, and a smartphone. Credit: A. Küpper and S. J. Spicker*

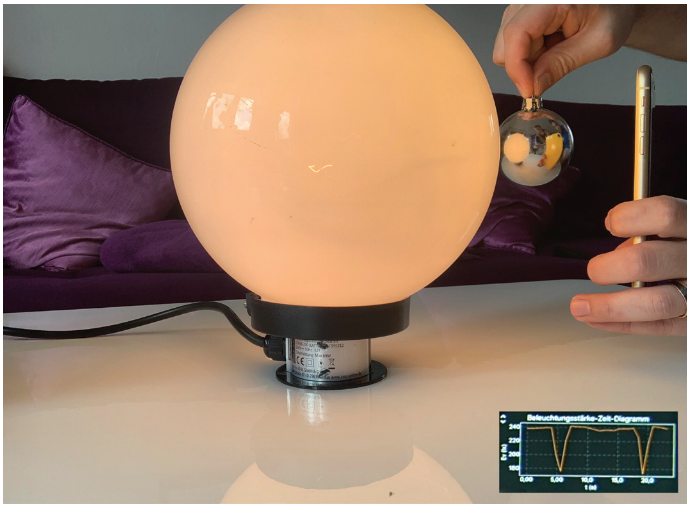

Figure 2. *Albedo-Experiment@home with possible curve using a garden light, a Christmas ornament, and a smartphone. Credit: A. Küpper and S. J. Spicker*

exoplanets can be detected via the transit method and which properties of an exoplanet can be deduced from the light curve (*Spicker & Küpper, 2022*).

Albedo of Exoplanets

By changing the "planet" to something highly reflective (e.g., Christmas ornament or a ball of aluminium foil), a secondary transit – in which reflected light from the planet is blocked when the planet orbits behind the star – can be made visible, and the albedo of exoplanets can be discussed. This way, the user can learn about reflectivity and its importance for temperature on the planet (Figure 2).

Since the changes in the light curve due to the secondary transit are much smaller than in the discovery of exoplanets experiment, it might be helpful to either zoom into the graph in *phyphox* or export the data and re-examine it in a different piece of software.

Tidal Locking

If the smartphone[2] is instead rotated around the light source and/or its own axis the user can learn about synchronous rotation and its effects on the planet's surface temperature. In the experiment, the user creates a permanent day (night) side and compares the illuminance on each side of the planet (Figure 3).

Thus, the user will learn how day and night on (exo-)planets are created and the fundamentals of tidal locking.

Analysing Exoplanets' Atmospheres

When an exoplanet is found (e.g., using the transit method), the composition of the exoplanet's atmosphere plays a decisive role in the theoretical existence of life. The app *Elements of the atmospheres of exoplanets* (*Hissel, 2020*), developed at the UoC, can be used to discuss (fictive) absorption spectra (Figure 4).

Figure 3. *Tidal Locking-Experiment@home with a garden light and a smartphone. Credit: A. Küpper and S. J. Spicker*

Figure 4. *Screenshot from the 'Elements of the atmospheres of exoplanets'-app. Credit: J.-N. Hissel*

For this purpose, "measurements" are made for the primary and secondary transits. By subtracting the light curves produced during the primary and secondary transits, the user can derive properties of the "planet's" atmosphere.

For the following experiments, additional devices are required. We used *phyphox* with an external sensor device (TI SensorTag CC2650) and a Bluetooth-low-energy mouse.

Habitable Zone

Even if an exoplanet's atmosphere seems promising, it could be that the planet is not within the star's habitable zone, which would render the planet incompatible with life. This is the topic of this experiment. The sensor is placed on the Bluetooth mouse and moved away from the radiation source (e.g., infrared lamp). Meanwhile, infrared intensity is measured as a function of distance and automatically visualised in *phyphox* (Figure 5).

Through this, the user learns about the relationship between intensity and distance: the closer the "planet" is to the "star", the higher the radiation, and vice versa. With the help of supplementary materials, which link radiation to temperature, the user thus concludes that there must be an optimal distance (or range of distances: the habitable zone) in which the temperature is optimal for life as we know it.

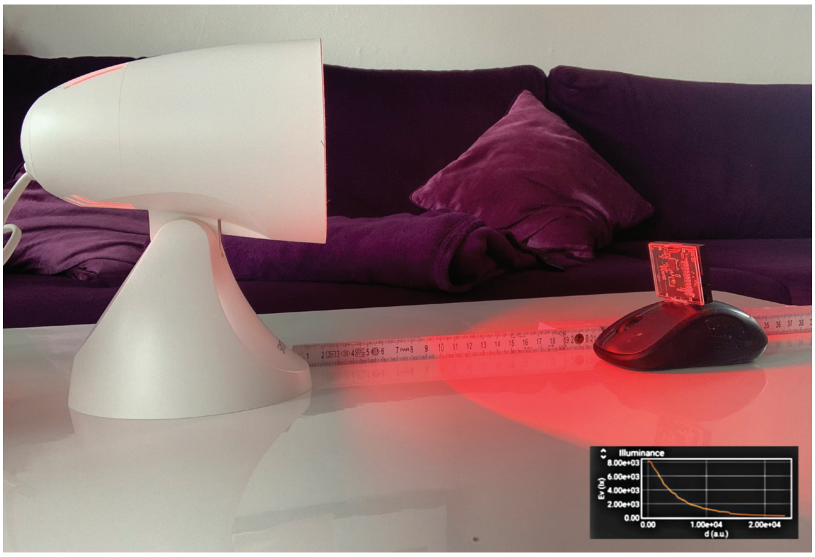

Figure 5. *Habitable Zone@home with possible curve using a Bluetooth mouse, an external sensor, and an infrared lamp. Credit: A. Küpper and S. J. Spicker*

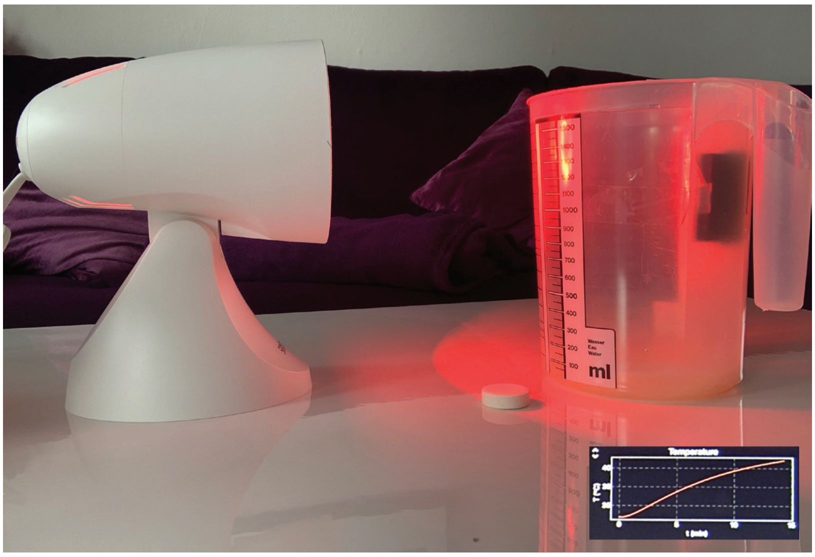

Figure 6. *Greenhouse-effect@home with possible curve using one transparent container, an infrared lamp, and one external sensor. Credit: A. Küpper and S. J. Spicker*

Greenhouse Effect and Exoplanets

As a follow-up experiment, the user uses an infrared lamp to irradiate transparent containers with different gases (e.g., air vs CO2 from a dissolved fizzy tablet) in which a temperature sensor (e.g., a SensorTag) is installed[2]. During the irradiation period, each temperature is measured over 15 minutes (Figure 6).

By comparing the measurement curves and final values, the user can discuss the greenhouse potential of the test gases and compare it qualitatively with the situation on Earth.

Building Spaceship "Prototypes"

Once a promising candidate for an exoplanet has been identified from the above attempts, the question remains: how can humanity reach that planet? An important and often unnoticed factor for human life is air pressure, and as such, the effects of air pressure on the human body are discussed in this experiment. In particular, the user learns about the importance of pressure differences by building and testing "spacecraft" prototypes (e.g., with a vacuum cleaner; Figure 7).

Meanwhile, the pressure is measured over time by the sensor in the "spaceship"[3]. The user then analyses the curve and explores the question of crew safety (*Spicker et al., 2022*).

Conclusion

By using astro-lab@home, qualitative connections in the context of extrasolar planets can be developed. Since the experiments can be performed quickly and cost-effectively with everyday materials, it is possible to experiment even in times of confinement. With the help of apps (e.g., *phyphox*, Pasco *SPARKvue*, *PocketLabs*) in the analogy or demonstration experiments, data collection and analysis are combined (*O'Brien, 2021*). In this way, the user is not overwhelmed by the need to measure and understand simultaneously. Also, advanced users can export the data to investigate in a program of choice. Furthermore, since *phyphox* now also supports Arduino, the user can build or use their own sensors. For this, the experiments must be reprogrammed to suit the respective sensor[4]. This underlines the scientific character and can be used to learn and teach basic programming or data analysis skills.

If the experiments are performed at home (instead of during science lessons at school as shown in *Spicker & Küpper, 2022*), students can either perform the experiments independently or in small groups. In both cases, the results of the experiments can be presented to the whole class at a later time. The use of technical terminology and other communication skills can be strengthened through direct video chat or presentations (*Arkorful & Abaidoo, 2014*).

Figure 7. *Testing spaceship "prototypes"@home with everyday materials, including plumbing pipes, sealable containers, cardboard, vacuum cleaner, and a smartphone. Credit: S. J. Spicker and A. Küpper*

All presented experiments on exoplanets and more (e.g., star formation) can be downloaded from our website astro-lab.app and added directly to *phyphox* using the provided QR code. For each experiment, additional information and instructional videos are also provided.

astro-lab@home and the open educational resources provided on the astro-lab.app can increase the interest in physics and physics learning not only locally at the astro-lab in Cologne itself, but worldwide, in regular classes or even from home. Since it is currently unclear to what extent there will be a return to "normal" in the foreseeable future, it is important to involve e-learning formats (*O'Brien, 2021*) like those presented above. Therefore, we invite all colleagues to participate and to (further) develop the presented materials[5].

Notes

[1] Because the light sensor is not accessible via iOS, one needs an external sensor device. The authors suggest a TI CC2650 SensorTag or similar.

[2] Can support up to two external sensors.

[3] Although the experiment can be performed with both iOS and Android devices, as each has a built-in pressure sensor, we recommend using an external sensor to avoid damage to the device.

[4] For an overview of compatible sensors, we refer to the website of the developers: phyphox.org. For Arduino use, please follow the instruction: astro-lab.app/arduino-und-phyphox

[5] If you would like to network or share your own content, please contact us directly or via the contact form on the astro-lab.app website.

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Biographies

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Alexander Küpper is a physicist currently working as a teacher at a secondary school. Before, Alexander worked as a scientist at the Institute of Physics Education at the University of Cologne. His research interests are astronomy at school (laboratories) and inclusive science education.

André Bresges is the head of the Institute of Physics Education at the University of Cologne. André does research in Teacher Education, Science Education, and Educational Technology.

Accessibilising Astronomy: SciAccess Programmes for Disability Inclusion in STEM

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SciAccess, Inc. is an international non-profit organisation dedicated to advancing disability inclusion and diversity in STEM education, outreach, and research. In this paper, the authors present an overview of accessible STEM programmes run by SciAccess, including an annual conference, an international working group, Zenith (a space science mentorship programme for blind youth), and Mission: AstroAccess (an initiative dedicated to making space exploration accessible for disabled astronauts). Recommendations for creating accessible mentorship programmes and networking events, both virtually and in-person, are detailed so that others may replicate these inclusion-focused efforts.

Introduction

In 2018, SciAccess was founded by The Ohio State University ("OSU") graduate Anna Voelker in response to an overwhelming need to address a lack of accessibility, diversity, and visibility for scientists with disabilities in STEM. It was made possible by the OSU President's Prize – a $100,000 startup grant for projects that foster social change. SciAccess began as a one-time conference dedicated to promoting disability inclusion in science, technology, engingeering, and mathematics (STEM). From there, SciAccess grew into an international initiative that has since branched off into myriad programmes working towards a more equitable future.

While it is estimated that 26% of Americans have disabilities (*NCBDDD, 2020*), people with disabilities represent only 8.3% of all workers, with an estimated 1.6% employed in science and engineering in the United States (*NCSES, 2019*). Advancement in these fields is highly influenced by networking opportunities such as conferences, internships, career fairs, virtual seminars, and social events (*Mickey, 2019*). When these opportunities are inaccessible, disabled students and professionals are denied the same experiences as their non-disabled colleagues, harming their employment prospects.

Figure 1. *Group photo from the SciAccess 2019 Conference. Credit: Heather Taylor*

Figure 2. *A map of the 54 countries represented at the SciAccess 2020 and 2021 conferences combined. Credit: Anna Voelker*

People with disabilities comprise the world's largest minority group (*DoL ODEP, n.d.*), yet they are severely underrepresented in the STEM fields. In response to these discrepancies in employment and education rates, SciAccess seeks to foster equitable STEM opportunities by providing spaces where disabled scientists, educators, students, and advocates can share their experiences with one another and with their non-disabled peers. SciAccess aims to advance the development and dissemination of best practices in accessible STEM research and education through a growing series of international programmes (Figure 1).

Overview

An overview of projects led by SciAccess, Inc. is presented below.

SciAccess 2019 Conference

On June 28 and 29, 2019, SciAccess: The Science Accessibility Conference was held at OSU. This inaugural event brought together 250 scientists, educators, students, and disability rights advocates to share best practices for STEM accessibility. The SciAccess 2019 Conference featured over 60 speakers, including keynote presentations from Dr Temple Grandin, professor of animal science and renowned autism advocate, and Anousheh Ansari, the first female private space explorer.

SciAccess 2020 Conference

On June 29, 2020, OSU hosted SciAccess 2020: The Virtual Science Accessibility Conference. With the worldwide transition to online learning and remote work during the Covid-19 pandemic, this event took place virtually and brought together speakers and attendees from around the world who share a dedication to inclusive science. The SciAccess 2020 Conference had over one thousand total registrants and 555 participants on the day of the event, with attendees joining from 46 nations and all seven continents, reaching as far as the South Pole. The conference culminated with a keynote presentation by Dr Soyeon Yi, who shared her experiences as the first and only South Korean astronaut.

SciAccess 2021 Conference. The SciAccess 2021 conference took place virtually on November 12 and 13, 2021. This event was hosted in partnership with Geneva Lake Astrophysics and STEAM (GLAS) Education, a leading non-profit in accessible education and winner of the National Federation of the Blind 2020 Bolotin Award. The SciAccess 2021 Conference brought the total number of unique countries reached by SciAccess conferences to 54 – SciAccess has participants in nearly 30% of the world's countries. SciAccess 2021 was supported by the Battelle Engineering, Technology and Human Affairs (BETHA) grant from OSU. The conference featured over 50 speakers, including keynote presentations by Dr Chris Boshuizen, Blue Origin Astronaut and Co-Founder of Planet Labs, Sirisha Bandla, Astronaut and Vice President of Government Affairs and Research Operations at Virgin Galactic, Apurva Varia, NASA Mission Director and Mission: AstroAccess Ambassador, and Dr Joshua Miele, 2021 MacArthur Fellow and Adaptive Technology Designer (Figure 2).

SciAccess Working Group

The SciAccess Working Group serves as a platform for like-minded individuals to join the SciAccess community. It is a collective of professionals that meets virtually every month to discuss the latest developments in accessible STEM. Individuals interested in joining can do so by filling out the form at go.osu.edu/wg.

SciAccess Zenith Mentorship Programme

The SciAccess Zenith Mentorship Programme ("Zenith") is a virtual mentorship programme for blind and low vision (BLV) students interested in astronomy. Established in August 2020 in partnership with OSU and the Ohio State School for the Blind, Zenith connects 8-12th grade BLV students with undergraduate and graduate student mentors at OSU. Zenith uses multi-sensory resources such as 3D-printed models of astronomical objects, provided by the nonprofit See3D, and data sonification, provided by the citizen science project Transient Zoo, to provide an accessible entry point into astronomy. For example, students learn to study supernovae light curves through sound and tactile graphs while working closely with their mentors and fellow students.

Figure 3. *Centra "Ce-Ce" Mazyck, AstroAccess Ambassador and Disabled American Veterans representative, floats in microgravity aboard the inaugural AstroAccess Zero-G mission. Credit: Zero-G / Al Powers*

Mission: AstroAccess

Mission: AstroAccess (MAA) was founded in 2021 to help build the future of accessible space exploration. This program is run in partnership with Yuri's Night/The SpaceKind Foundation and was co-founded by Anna Voelker, Executive Director of SciAccess, Inc., and George T. Whitesides, former CEO of Virgin Galactic and former NASA Chief of Staff. Through MAA, disabled scientists, engineers, veterans, students, athletes, and artists, known as "AstroAccess Ambassadors", participate in parabolic flights in partnership with the Zero Gravity Corporation ("Zero-G"). During these flights, the Ambassadors perform experiments and demonstrations in weightlessness in order to investigate accessible tools and technologies for future space vehicles and space stations. MAA aims to prove the feasibility, importance, and value of ensuring that all individuals, regardless of disability on Earth, can live, work, and thrive in space. The first MAA parabolic flight mission flew on October 17, 2021, out of Long Beach, California with twelve AstroAccess Ambassadors onboard (Figure 3). In May 2022, AstroAccess Ambassadors flew with the MIT Space Exploration Initiative and the Aurelia Institute on two additional Zero-G flights. The next AstroAccess mission will take place on November 19, 2022, in Fort Lauderdale, Florida, in order to advance research on accessibilising human space exploration. For more information, visit AstroAccess.org.

Practise Recommendations

Best Practices Recommendations for an Accessible In-Person Conference

For SciAccess 2019, the organisers employed various methods to ensure the conference's accessibility. Based on this experience and the corresponding attendee feedback, the following is recommended for in-person events:

Quiet room
A quiet room, or sensory-friendly room, provides attendees with a designated space for taking a noise-free break from socialising and conference commotion. The SciAccess 2019 quiet room included service dogs and art supplies. The benefits of sensory-friendly rooms have also recently been seen at select commuter airports (*Davis, 2019*).

Colour communication badges
Introduced by Autism Network International, colour communication badges allow conference attendees to share their communication preferences nonverbally (*ASAN, 2014*). Red, yellow, and green slips of paper are inserted into the attendees' name tags, who choose which colour they wish to display at any given time. This system allows attendees to clearly communicate their preferences on a gradient scale and eases all participants' networking anxiety. Large print and braille labels can be included on the colour badges for attendees who are blind, low vision, or colour blind.

Pronouns on name tags as the default
Displaying pronouns (e.g., he/him, they/them) on attendee name tags normalises the practice of sharing pronouns. On the SciAccess 2019 registration page, attendees were asked to specify their pronouns and were informed that this selection would be displayed on their name tag. By making pronoun sharing the default, nearly all conference attendees chose to display their pronouns on their name tags, creating a more inclusive environment. Due to the precedent set by SciAccess 2019, IAU 358 Symposium in Tokyo in November 2019 adopted this practice.

Braille and large print materials
During the registration process, attendees were asked for their accommodation requests. Specifically, braille and large print event programmes were available upon request to BLV participants.

Tactile map
The SciAccess 2019 Conference provided BLV attendees with access to a tactile map of the conference venue made using thermoform, a plastic-like paper used for tactile graphics.

Guide Volunteers
Conference volunteers were on-call at all times at the central information desk. If a BLV attendee requested assistance locating a specific room, volunteers were trained to help guide the attendee to their destination.

Sign Language Interpreting
Sign language interpreting is essential for the inclusion of Deaf attendees. If a conference has concurrent sessions, organisers should provide sign language interpreters for each Deaf attendee so that they can go to the session of their choice instead of being restricted to a single conference strand. If an event does not have the budget to facilitate this, the organisers should consider transitioning to a single-strand conference with no concurrent sessions.

CART captioning
Communication Access Real-time Translation (CART) uses a human captioner to provide a word-for-word

transcription of an event. Captioning not only benefits Deaf and hard-of-hearing attendees but also supports accessibility for second language learners (*Gernsbacher, 2015*). We suggest using human-transcribed CART captions rather than auto-generated captioning services for the best quality.

Accessible seating
In each conference room, multiple comfortable armchairs were available for individuals with chronic pain and for anyone unable to sit in a rigid chair for long periods of time. These chairs were labelled with signs requesting that attendees reserve this seating for those who need it. When implementing seating changes, it is important to ensure that armchair placement does not impede wheelchair access. For social events, it is best to avoid high-top cocktail tables. These are inaccessible for people using wheelchairs and anyone who cannot stand for long periods of time.

Slide descriptions
Train all speakers to describe their presentation slides, including verbally describing all visual content so that BLV audience members are included.

Star party accessibility
When hosting stargazing events, locate telescopes in a wheelchair-accessible area. If your observatory is not accessible, set up portable telescopes outside on the ground level, preferably along a paved area instead of in the centre of a grassy field. Table-top telescopes and binoculars can help provide more accessible stargazing options. In addition, events can use 3D models and tactile graphics of astronomical bodies to supplement the viewing experience with non-visual resources[1].

Fostering Accessibility During Online Events

As virtual events increase in popularity in the wake of Covid-19's onset, it is essential that accessibility remains at the forefront of program design. Based on the work of the virtual SciAccess 2020 and 2021 Conferences, the following is recommended for ensuring the accessibility of online programmes:

Slide descriptions
As previously mentioned, slide descriptions remain crucial for virtual programmes. In order to emphasise this during presenter trainings, tell speakers to imagine that screen-share is unavailable. What slide and image descriptions would be needed to convey information effectively without visual aids?

Pronouns
While most online events do not have name tags, organisers can still encourage attendees to share their pronouns by adding them to their Zoom profile or directly to their name on any video conferencing platform.

Increased breaks
Increase the frequency and duration of breaks in order to relieve "Zoom fatigue" (*Bailenson, 2021*).

Sign language interpreting and CART captioning
As with an in-person programme, these services are essential for the inclusion of Deaf and hard of hearing participants. Organisers using Zoom can follow these guidelines in order to successfully incorporate sign language and captioning within their virtual event: go.osu.edu/zoomaccess.

Developing an Accessible Mentorship Programme

Zenith aims to model and propagate best practices for accessible mentorship programmes. The first step in creating such a programme, or making a pre-existing programme accessible to a wider audience, is to build connections with the local community. Programmes should first and foremost be guided by the community's needs and feedback. Begin by contacting schools and organisations in your area that serve students and individuals with disabilities. Forming relationships with representatives from these institutions is the first step in identifying partners who can help design, advise, or adapt your mentorship programme to ensure it is a) accessible to underrepresented students and b) addressing the real needs of the community members it aims to serve. Organisations can also partner with local universities to recruit student mentors and seek expert guidance from faculty advisors.

Zenith holds regular guest lectures with space scientists, including BLV astronomers, allowing the students to meet role models with similar life experiences. This representation plays a critical role in each student's ability to see themselves as future successful scientists.

Each semester, students select a topic they are passionate about in the field of physics, astronomy, or aerospace and work with their mentors to develop a professional presentation on their selected subject matter. The students then present their work to family, friends, and university professors at a research symposium – the programme's culminating event. Organisations interested in furthering this work by creating their own Zenith chapter can connect with SciAccess, Inc. to receive further guidance[2].

Conclusions

These accessibility initiatives serve an essential function in connecting people who have been historically excluded from the STEM fields. In addition to fostering an exchange of ideas, resources, and best practices, they serve as eye-opening experiences for younger generations of students with disabilities facing a severe lack of representation in STEM. When the talents and perspectives of people with disabilities are neglected, science suffers. By creating accessible programmes and events, organisations can prove to students and future scientists with disabilities that not only is there space for them in STEM but a profound need. Accessibility is an active, ongoing, and intentional commitment to creating inclusive engagement opportunities on earth and beyond it.

Notes

1 Many 3D printed astronomy resources are available for free, including A Touch of the Universe: https://astrokit.uv.es/index.html

[2] SciAccess, Inc. is made possible by dedicated volunteers with a passion for disability accessibility and inclusion in STEM. Individuals interested in volunteering with SciAccess, Inc. can do so at sciaccess.org/volunteer/. For more information, visit SciAccess.org.

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Biographies

Anna Voelker is the founder and Executive Director of the SciAccess, Inc., an international non-profit dedicated to advancing disability inclusion in STEM. Anna specialises in accessible science outreach and has previously worked at the Ohio State Department of Astronomy, NASA Kennedy, NASA Goddard, Space Telescope Science Institute, International Astronomical Union's Office of Astronomy for Development, and the Aerospace Corporation.

Caitlin O'Brien is the Deputy Director of SciAccess, Inc. She is an Astrophysics & Astronomy and Physics student at The Ohio State University. In 2019, she was named an Ohio State Morrill Scholar, recognising her as a student engaged in diversity, leadership, and service. She has worked with SciAccess since Spring 2020.

Michaela Deming graduated cum laude in May 2021 from The Ohio State University with a B.S. in Astronomy & Astrophysics. She began working with the SciAccess Initiative in Summer 2020 when she helped organise the SciAccess 2020 Conference. Since then, she helped found the SciAccess Zenith Mentorship Program, serving as its first president from October 2020 to May 2021.

One of ***James Webb Space Telescope***'s First Images is of the massive galaxy cluster known as SMACS 0723. These deep observations show many newfound galaxies from early in the history of the Universe, bringing us new insights into how galaxies formed soon after the Big Bang. Credit: NASA, ESA, CSA, STScI

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