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Communicating Astronomy with the Public

SPECIAL EDITION
CELEBRATING 100 YEARS OF THE PLANETARIUM

The Stars Were Just the Beginning
Join IPS representatives in a celebration of the planetarium.

The Power of Storytelling
Explore how storytelling can improve your astronomy communication practice.

Accessibility Under the Dome
Break barriers and build bridges to make astronomy more accessible to everyone.

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The Communicating Astronomy with the Public (CAP) Conference is the only large-scale international conference for astronomy communication. The next CAP conference will be held in hybrid mode from 24 – 28 June, 2024, in-person at Cité de l'espace, Toulouse, France and online. The conference will feature participant-led sessions in their state-of-the-art planetarium. For more information, see our website: www.cap2024conference.org

Pierre Carton/Cité de l'espace

Editorial

In 1923, the first planetarium projector, the Zeiss Model 1, was unveiled in Jena, Germany. Two years later, and almost 350 kilometres away, the first planetarium opened to the public in Munich. From 2023 to 2025, the world will celebrate the Centennial of the Planetarium, bookended by these two momentous occasions.

In our opening article, *The stars were just the beginning*, a team of representatives from the International Planetarium Society, including the current president, Michael McConville, take us on a tour of planetarium history, spanning one hundred years of technological innovation and creative ingenuity. They remind us that although planetariums were first imagined as a “window into the Universe”, the stars were truly just the beginning.

In this issue of the Communicating Astronomy with the Public Journal, we present works from under the dome. In our first article, *Evaluation and insights from a sonification-based planetarium show intended for improving inclusivity,* the authors discuss a tested way to make the planetarium accessible to more diverse audiences. No matter the audiencce, every good planetarium show has a story to tell. In *A guide to communicating astronomy with storytelling in planetariums,* we get a beginner’s guide to writing engaging stories for the planetarium and beyond. Of course, through their storytelling, planetariums convey an incredible amount of valuable information. The article, *Digital planetariums as new tools for conceptual change,* describes how the “allocentric” perspective afforded by planetariums can help learners confront their misconceptions. In Portugal, one planetarium has worked to bridge astronomy education and communication. The article, *Science communication through astronomy education: The creation, implementation, and assessment of Porto Planetarium’s science education strategy,* delivers the important lessons from this case study. One way to engage learners with the planetarium is by directly involving them in its construction. In *Build your own cardboard planetarium: A DIY experience for students,* the authors describe a design for a do-it-yourself cardboard planetarium. Mobile planetariums have become increasingly popular in their ability to bring the planetarium experience to wider and larger audiences. We are excited to share the insights of an expert team in *The NOVA Mobile Planetarium: Ten best practices for planetarium projects based on an astronomy education success story.* The article, *The UNAM/AMT Mobile Planetarium: Lessons learnt on how to run a student-driven mobile planetarium project in Africa,* relays a case study based on the NOVA Mobile Planetarium Project in a unique outreach setting. In our final article, *Empirical study on the digital planetarium system for measuring visual perception of the night sky: Analysis of impact from light pollution and astrotourism,* the authors take a slightly different spin on planetariums. Using the planetarium as a tool, the authors investigate how light pollution and astrotourism experiences can impact perceptions of the true dark sky.

Planetariums are often described as dark sky oases – a space to experience an authentically dark sky in a world whose sky is ever brightening. The articles presented here span the depth and breadth of creative uses for the planetarium. We hope that these works inspire you to engage with your local planetarium and rediscover the awe of the night sky.

As a note to our readers and potential authors: all articles in this issue follow our new guidelines for submission. As with Issues 31 and 32, each article has been reviewed by a member of our Editorial Board and an external Peer Reviewer. We welcome submissions on a rolling basis, and invite everyone to learn about our new Submission Guidelines on our website, www.capjournal.org.

Kelly Blumenthal
Editor-in-Chief and Managing Editor

Cover: This edition of CAPjournal celebrates the one hundred years of the planetarium. In 1923, the Zeiss Model (pictured here in the foreground) was unveiled in Jena, Germany, and two years later, the first planetarium opened its doors to the public in Munich. Since then, we have seen incredible advancements in planetarium technology. The background image is from the state-of-the-art planetarium, the 4D2U (Four-Dimensional Digital Universe) Dome Theater at the National Astronomical Observatory of Japan. Institutions like 4D2U demonstrate the power of planetariums to not only bring astronomy to a wide audience, but also to visualise astronomical data. The background of our front cover is a still image from a show on the formation of dark matter haloes across the history of the Universe using a simulation performed by the NAOJ’s supercomputer “ATERUI”.

Image Credit:
Foreground Image: ZEISS Archive
Background Image: Formation and Evolution of Dark Matter Halos (II. Formation of the Large-Scale Structure of the Universe) ver.2; Simulation: Tomoaki Ishiyama; Visualization: Hirotaka Nakayama; 4D2U Project.

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Thousands of planetariums around the world help to engage with public audiences each day and serve as essential science gateways. Starting in October 2023 and lasting through May 2025, the international planetarium community will celebrate its first Centennial and look forward to the next one hundred years of dome-based education and entertainment. While technology has changed dramatically in the past century, the core mission of the planetarium has not changed: to provide a window into the Universe and to tell the stories that gift us all with a better understanding of our place in the Cosmos.

Introduction

Today, we have more than 4,000 planetariums all over the world, varying in size from small family businesses to large institutions with dozens of employees. These planetariums run with simple fisheye projectors, built by local enterprises or using the most modern technology, with multiple projectors that provide the highest resolution images and are immersed in a fabulous sound system, all assembled together and controlled by a number of computers. Fixed or mobile, planetariums fascinate more than 140 million people yearly, from the youngest child hungry for science news to seniors excited to share stories about the sky.

The story we tell today was built over a century, and, of course, it has evolved over the years. Not only has technology changed, but our knowledge about the Universe and society has changed itself, pulling planetariums to new heights. All of these changes have drawn the skills of a professional called a planetarian. We can think of a planetarium as a body made of a dome and seats, the main computers acting as the brain, connected to lighting and sound systems, all of which is, in turn, and connected to the heart – the projection system. In this complex system, the planetarian could be the soul.

The essentials of being a “planetarian”

For a long time, during the epoch of optical mechanical systems, the planetarian was behind the control system, pushing buttons connected to complex electronic devices. The planetarian should know much more than astronomy; In the early days, one could expect abilities in optics and electronics. Today, in the computer era, the planetarian is expected to program a show in a planetarium system and update the system right after new discoveries.

In any epoch, a planetarian communicates astronomical content. From small domes to giant complex systems, each planetarium has a professional who knows how to operate the projector, speak with the public and understands astronomy. The planetarian is expected to transform stories, with all their complexities, into understandable content for young children and senior visitors, alike. The planetarian is a little bit of an actor, and, in many cases, the planetarian is also the director. Some planetariums are small family businesses, and one person plays the roles of the planetarium director, the planetarian, the cleaner, the electrician, the ticket taker and much more.

There are university planetariums where professors and technicians run the planetarium as directors and planetarians. There are city or state public planetariums with teachers or specially hired people working in the planetarium. Finally, there are private planetariums in small or big cities with dozens or even one hundred employees.

In this scenario, planetarian skills include the ability to mount a telescope outside for open-air activities, launch a water rocket and carry heavy equipment. Another challenge to each planetarium director is to select new planetarians and train new staff. As the planetarian can be thought of as the soul of a planetarium, an excellent presenter or operator will certainly excite your audience and help them fall in love with science and astronomy.

Planetariums today

During the past one hundred years, our society has developed new concerns, and planetariums have acquired new responsibilities. Today, we face climate change, and this has been introduced into many planetarium shows, looking straight to Earth or through the observation of the climates of Venus and Mars. In addition, planetariums are walking into a more inclusive world. Today, we find examples of shows specially designed for people on the autism spectrum, wheelchair-friendly places and shows for the deaf and hard of hearing and those with blindness and low vision.

At the same time, the planetarium industry consists of manufacturers, show producers, planetarium staff, and millions of people in the audience. A relatively low-cost mobile planetarium can cost around 20,000 USD, while the most advanced equipment can cost up to 10 million USD, independent of the infrastructure (the building). We estimate that more than 4,000 planetariums, tens of planetarium producers and scores of show producers can be responsible for about

3 billion USD per year and tens of thousands of direct jobs.

Planetarium associations flourish in this huge planetarium world, including the International Planetarium Society (IPS), founded in 1970. Over 500 people and institutions from 50 countries are affiliated with the IPS, a global association of planetarium professionals with the mission to provide the planetarium community professional development, science literacy and arts and humanities awareness, innovative ideas, and partnerships to enhance the world's appreciation and understanding of our Universe.

The values of IPS also reflect the understanding of the place that planetariums hold in the arenas of science communication and public outreach: science as a way to understand the world; inclusivity of and respect for cultures; sharing knowledge; openness to discovery and new ideas; service excellence; and leadership in our field.[1]

In addition to the meetings organised every two years, IPS promotes cultural exchange by offering opportunities for planetarians to visit planetariums in other countries. The organisation also helps to facilitate sharing planetarium content and resources with its affiliates, and each quarter publishes *Planetarian*, the official journal of IPS. Perhaps most importantly, IPS facilitates ongoing community professional development with special committees, such as the Education Committee, the Equity, Diversity and Inclusion Committee, and the Mobile Planetariums Committee.

The present planetarium world has become something far different from what Oscar von Muller, the founder of the Deutsches Museum in Munich, imagined when he ordered an instrument that could reproduce the night sky.

A brief history of the planetarium

ZEISS designer Walther Bauersfeld accepted the task of transforming von Muller's vision into reality and was responsible for developing the projector that gave its first light on 21 October 1923. Later, the Model I projector, as it was called, was installed in the Deutsches Museum and opened to the public on 7 May 1925. For this reason, from October 2023 to May 2025, the planetarium community invites the whole world to celebrate the invention that brought the heavens down to Earth.

Though the Model I projector was designed to reproduce the northern hemisphere sky, later planetarium projectors were developed to reproduce the whole sky. Planetariums started to spread all over Europe, and the first planetarium inaugurated outside Europe was the Adler Planetarium in Chicago, USA, in 1930. New planetariums were installed around the world while other companies started to develop their own projectors.

The modern planetarium not only illustrates the entire Universe, but it also allows the presentation of diverse topics including science, culture and art. Image Credit: Cosm

As humankind started to reach further into the heavens and learn more and more about the Universe with space exploration and huge telescopes, the planetarium industry was pushed to new developments. First, new types of auxiliary projectors were developed and later, following the technological innovations, planetariums went through a great revolution, going from opto-mechanical apparatuses to digital systems. This revolution took nearly 30 years, culminating in the development of completely digital fulldome systems and shows by the 1990s.

Today, planetarium domes can be as large as 35 meters in diameter, working with a complex computer system to control 20 computers with a 10K video resolution, a 48-channel sound system and ambient light systems. Not only are planetariums able to reproduce the night sky, but they can drive the audience on a voyage through the Solar System, the Milky Way, and beyond. Planetariums can land you on a recently discovered exoplanet, follow the launch of the most advanced mission, and rescue you from a black hole.

Conclusion

The planetarium audience can fly even further when they look inward toward a world that needs so much attention: a world facing climate change, wars, racism, xenophobia, and extreme poverty. Today's planetariums are spread all over the world, not only sharing the mysteries of the cosmos but helping society to face its worst fears. What's next for another century of history? Perhaps higher resolution images, OLED screens instead of a projector, augmented reality or a holographic planetarium? Will planetariums become islands or roots that spread, scatter and are the fountains of knowledge in our society? We invite you to find out for yourself and discover one of the more than 4,000 planetariums spread around the world.

Notes

[1] International Planetarium Society "About Us": https://www.ips-planetarium.org/page/about_us

Biography

Björn Voss is the director of Planetarium Hamburg in Germany and serves as the coordinator of the Centennial of the Planetarium Celebrations for the International Planetarium Society.

Guilherme Marranghello is a professor of Physics and director of the planetarium at the Federal University of Pampa in Brazil and serves as the vice-coordinator of the Centennial of the Planetarium Celebrations for the International Planetarium Society.

Michael McConville is the President of the International Planetarium Society, the founder of the *Dome Dialogues* online planetarium community, and the Director of Customer Outreach for the planetarium company Cosm.

Evaluation and insights from a sonification-based planetarium show intended for improving inclusivity

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Audio Universe: Tour of the Solar System is an audio-visual show for planetariums and flatscreen viewing. It is designed in collaboration with members of the blind and vision impaired (BVI) community, BVI specialist teachers and their pupils. It aims to be suitable for audiences with all sight levels by representing key concepts through sound and using a carefully constructed narration. We present results from 291 audience evaluations from online viewers and audience members of several planetarium showings in the UK and Italy. We find a strong appreciation from BVI and non-BVI audiences, with ~90% scoring 4 or 5 (out of 5) for both how useful and enjoyable the sounds are. We also present results from surveying planetariums and communication leaders known to have downloaded the show. We find international success for special events, for BVI audiences and for those with other special educational needs and disabilities (SEND; including sensory needs and learning difficulties). Feedback suggests this is due to its multi-sensory, clearly narrated, and low sensory load (calm) production. However, we also describe limitations identified during this evaluation exercise, including the show's limited incorporation into regular (non-special) planetarium programmes. This highlights an ongoing challenge of creating a fully inclusive planetarium experience.

Introduction

Astronomy communication is blessed with inspiring images. This is highlighted by the recent flurry of images from the *James Webb Space Telescope*, which have reached top media forums internationally. Furthermore, computer simulations have produced animations and images popular for public communications, including visualisations of "invisible" phenomena, such as dark matter. This all lends itself to producing visually captivating planetarium shows, combining observational data, simulated data and artistic impressions. However, this visually-focused approach naturally excludes audiences who are blind or vision impaired (BVI) and, more generally, those who prefer non-visual communication.

Innovative approaches are needed to make astronomy communication and research more BVI accessible (e.g., *Pérez-Montero, 2019; Noel-Storr & Willebrands, 2022; Foran, Cooke & Hannam, 2022*). Multi-sensory approaches to astronomy communication open a route to be more inclusive and to make the content more engaging for everyone. Encouragingly, in recent years, there has been an increase in astronomy communication projects which focus on tactile resources (e.g., *Bonne et al., 2018; Paredes-Sabando & Fuentes-Muñoz, 2021; Arcand & Watzke, 2022*) and/or audible resources (e.g., *Quinton et al. 2016; Tomlinson et al., 2017; Bieryla et al., 2020; Elmquist et al., 2021; García-Benito & Pérez-Montero, 2022; Bardelli et al., 2022*). Turning astronomical data into sound, a process called "sonification", has seen a particular boost in popularity over recent years for applications in astronomy research and communication (see review in *Zanella et al., 2022*).

Whilst encouraging, there are some limitations in preventing wider adoption of the developed multi-sensory and BVI-accessible astronomy communication resources and methods. For example: (1) many have been developed for a small number of one-time events run by the developers, without the resources widely shared; (2) they require tactile or other specific physical resources which can be difficult to manufacture or are too time-consuming or costly to produce for large audiences; and (3) they require a live presenter who would need to be trained and comfortable in delivering the specialist resources. Therefore, we identified a need for a pre-rendered BVI-accessible astronomy show that is easy to disseminate internationally and requires little-to-no effort for planetarium presenters or other astronomy communicators to use. To this aim, we created, as part of our broader Audio Universe project[1], the BVI-accessible show, *Audio Universe: Tour of the Solar System*. In this article, we discuss the evaluation results and lessons learnt since the show's launch in December 2021.

Design and creation of the show

The design process for *Audio Universe: Tour of the Solar System* and a description of the methods used are reported in *Harrison et al. (2022)*. However, in this section, we briefly summarise the design process and methods used to help put our new evaluation results into context.

Our target audience was primary school children (aged 7-11 years); therefore, we included educational content about the Solar System. Our goal was to create a show that planetariums and wider astronomy communicators could use to attract school groups whilst also appealing to general family audiences, irrespective of the level of vision of the visitors (from fully sighted to fully blind). We produced a full-dome and flat-screen version, a surround sound, and a stereo soundtrack.

Our design focus was on the soundtrack, which was to be understandable without the associated visuals. During design and development, we worked collaboratively with focus groups, including members of the BVI community and teachers of BVI pupils and young people, as well as the BVI pupils themselves. We also worked with a music composer and a creative writer (see *Harrison et al., 2022*).

The theme for the show is a tour aboard a special spacecraft, which is fitted with a "sonification machine". This machine turns light into sound, and at each location on the journey around the Solar System, the objects are represented with sounds. For example, the planets are represented by different musical instruments, with pitches chosen to correspond to their mass. In a show segment, the surround sound helps create the impression that the planets can be heard orbiting around the audience. The sounds were produced using actual data and the STRAUSS code[2], also used in astronomy research (e.g., *Tucker-Brown et al., 2022; Trayford et al., 2023a,b*). The work with the focus groups was crucial. For example, we learnt the importance of slow-paced and extremely descriptive narration (but avoiding too much reliance on visual metaphors) and giving advance warning of what was coming next. In contrast to traditional show production, we completed the soundtrack first. The visuals were added later by a professional planetarium producer.

Audio Universe: Tour of the Solar System was released in December 2021 in English, Italian and Spanish (a version in German is now available). The narration is performed by the "spaceship's captain" and an expert blind astronomer. The latter is real-life Australian-French blind astronomer Dr Nic Bonne in the English version. A voice actor plays this character in the Italian and German versions. In the Spanish version, the real-life Spanish blind Astronomer Dr Enrique Pérez-Montero is used instead (played by a voice actor). These characters provide role models for BVI people watching the show.

Dissemination, reach and evaluation approach

A series of premier events across the UK and Italy were planned to coincide with the International Day of Disabled Persons in December 2021. Simultaneously, we released the show for free download, in both full-dome and flatscreen format, and uploaded it to YouTube[3].

Dissemination and usage information

Downloading the show for anything other than personal use comes with the request to complete a Google Form to collate basic information about the proposed use, contact details, and an agreement to record information about the show's use on a best-effort basis. Although this is stated as compulsory on the download page[3], it was impossible to require the completion of the form to initiate the download. Indeed, internet searches have revealed that the show has been used by institutes that did not complete the form.

As of 15 February 2023, 51 institutions completed the form, and a further eight institutions were identified as having used the show due to email contacts or internet searches by the authors. These institutions cover 16 countries, including 46 fixed planetariums, 11 travelling science communicators (mostly those using portable planetariums), one cinema, and one school. We followed up with these 59 institutes by sending emails from 15 – 28 February 2023. We asked each of these institutes how they had used the show or planned to use it in the future. We received responses from 35. We discuss the qualitative feedback received from planetarium and communication leaders below.

Based on combined YouTube viewing statistics obtained on 24 April 2023, the

Box 1: Audience feedback form questions in full.

Part 1: Demographic Questions.

(1) Where did you see the show?

(2) What is your age bracket?
[options: <7, 7-10,11-14,15-18, >18, Prefer not to say]

(3) What is your gender
[options: Female, Male, Non binary, Prefer not to stay]

(4) Do you identify as someone who is blind or vision impaired?
[options: Yes, No, Prefer not to say]

(5) Do you identify as any of the following?
  a. Parent/carer of somebody who is blind or vision impaired
  b. Involved in the education or welfare of people who are blind or vision impaired (except parent/carer)
  c. Teacher
  d. Working/worked in a job related to science, technology, engineering or mathematics (STEM)
  e. Involved in science communication/education (other than teachers)

Part 2: Feedback Questions.

(1) After watching Audio Universe: Tour of the Solar System, do you want to find out more about science?
[options: Yes, No, Don't know]

(2) After watching Audio Universe: Tour of the Solar System, how much do you think that studying or working in astronomy is accessible for people who are blind or vision impaired?
[options: "I am now more sure that astronomy is accessible for people who are blind or vision impaired"; "I am now less sure that astronomy is accessible for people who are blind or vision impaired"; "My opinion is unchanged"; "Don't know"]

(3) On a scale of 1 to 5, how much did you enjoy having the objects in space represented by sound?
[1 = did not enjoy; 5 = very much enjoyed]

(4) On a scale of 1 to 5, how useful did you find it to have the objects in space represented by sounds to understand the show?
[1 = not at all useful; 5 = very useful]

(5) On a scale of 1 to 5, overall, how would you rate Audio Universe: Tour of the Solar System?
[1 = poor; 5 = excellent]

(6) Please provide any other comments here.

show had 4987 views across the various channels it has been uploaded[3].

Audience evaluations

We produced audience feedback forms on paper and online in both English and Italian. We focussed our evaluation efforts on the UK and Italy because these are the countries of the team running these evaluations (i.e. the authors of this article). However, our YouTube channel also advertised an online form for completion[3].

The evaluation form questions are provided in full in Box 1, including demographic and feedback questions. The feedback questions focus on the perception of BVI accessibility, whether or not the audience enjoyed the show and their opinions of how useful the sound representations were.

Self-identify as	Per cent	Age	Per cent	Gender	Per cent
BVI	25%	< 7	2%	Female	56%
BVI parent/carer or involved in BVI education/welfare (combined)	22%	7-10	7%	Male	42%
STEM-related job or involved in science education/ communication (combined)	25%	11-14	7%	Non Binary	0.3%
Teacher	14%	15-18	3%	Prefer not to say	1.4%
		>18	78%		
		Prefer not to say	3%		

Table 1: *Demographic summary of the audience members who filled in the evaluation forms.*

Results and discussion

Here, we discuss the feedback received between December 2021 and February 2023 from people who watched the show and institutes that downloaded the show.

Audience feedback

We received 291 completed audience evaluation forms. Live audience members were asked to complete paper forms after watching the show. These were handed out by those running the events. BVI audience members who were unable to complete the form themselves were directed to the online version of the form, or their answers were transcribed by an assistant. Online viewers could complete the form if they followed a link in the YouTube video description.

The majority (253) of those who completed the forms saw the show in planetariums or other venues (204 in Italy, 47 in the UK, and two in the USA), and the remainder (38) viewed the show online. A summary of the demographics of those who completed the survey is presented in Table 1. We particularly note the high fraction (relative to the general population) of those who self-declared as BVI (25%) and those involved in the care, education or welfare of BVI individuals (22%). For example, from a study in 2015, 0.49% and 2.95% of the world population are blind or have moderate to severe visual impairment, respectively (*Bourne et al., 2017; Ackland et al., 2017*). Another important part of the demographics is that the majority (78%) are older than 18. In a future publication, we will provide the results of a separate, dedicated evaluation exercise of school children who experienced the show in addition to other multisensory activities in educational settings.

We found a very high overall rating from audience members of *Audio Universe: Tour of the Solar System*, with an average score of 4.48+/-0.04 out of 5 (uncertainty is the standard error on the mean), with 91% giving a score of 4 or 5. The overall positive perception of the sound-based aspects of the show is also clear, with 90% scoring a 4 or 5 for how enjoyable they found the sounds (average score 4.50+/-0.05) and 87% scoring a 4 or 5 for how useful they found the sounds (average score 4.45+/-0.05). Furthermore, 74% responded that they were now more convinced that astronomy is accessible to people who are BVI after watching the show, and 82% responded “Yes” to wanting to find out more about science after watching the show.

In Table 2, we report the results for questions 2, 3 and 4 of the feedback questions across different demographic groups. These are the most interesting questions for the present study: to understand the audience’s opinions on the novel use of sound in this show and their perception of BVI accessibility. Overall, we found little variation in the feedback responses from the different demographic groups. We take this as a positive outcome: this show was perceived as enjoyable and interesting and promoted accessibility for all audiences. However, we highlight some particular results in Figures 1 and 2 and the following text.

Figure 1 (left panel) shows that children are more likely than adults to be more convinced that astronomy is accessible for people who are BVI after watching the show: specifically, 81^{+5}_{-6}% for children compared to 71^{+3}_{-3}% for adults (where ranges indicate 68.3% Wilson binomial confidence intervals). It is also worth highlighting that 76^{+5}_{-6}% of audience members involved in the education/welfare of BVI people were more convinced about BVI accessibility in astronomy after the show. It is a positive outcome that such a high fraction of those involved in caring for BVI people are now more positive about accessibility in astronomy after the show.

Figure 1 (right panel) shows that BVI and non-BVI audiences show a similar fraction of answering positively to this same question about accessibility (72^{+5}_{-6}% and 75^{+3}_{-3}%, respectively). We take this as a positive sign that this show and similar efforts can have a positive impact on perceptions of accessibility for all audience members. Indeed, across most questions, the BVI and non-BVI audience members scored very similarly (Table 2). However, for the question “How useful did you find it to have the objects in space represented by sounds to understand the show?”, there is a marginal difference, highlighted in Figure 2. The “very useful” option was selected by 73^{+5}_{-5}% of the BVI audience and 61^{+3}_{-3}% of the non-BVI audience. It may be unsurprising that the sounds are relatively

	Adults	Children	BVI	Non-BVI	BVI carers/ welfare	Science related job / coms.	Teachers	Other
After *Audio Universe: Tour of the Solar System*, how much do you think that studying or working in astronomy is accessible for people who are blind or vision impaired?								
More	71^{+3}_{-3}	81^{+5}_{-6}	72^{+5}_{-6}	75^{+3}_{-3}	76^{+5}_{-6}	74^{+5}_{-5}	66^{+7}_{-8}	75^{+3}_{-4}
Less	4^{+1}_{-1}	2^{+3}_{-1}	3^{+3}_{-1}	3^{+1}_{-1}	0^{+2}_{-0}	5^{+3}_{-2}	0^{+2}_{-0}	4^{+2}_{-1}
Same	10^{+2}_{-2}	6^{+4}_{-2}	11^{+4}_{-3}	8^{+2}_{-2}	11^{+5}_{-3}	7^{+4}_{-2}	20^{+7}_{-5}	8^{+3}_{-2}
Don't know	15^{+3}_{-2}	11^{+5}_{-4}	15^{+5}_{-4}	13^{+3}_{-2}	13^{+5}_{-4}	14^{+4}_{-3}	15^{+6}_{-5}	13^{+3}_{-3}
How much did you enjoy having the objects in space represented by sound?								
1	2^{+1}_{-1}	2^{+3}_{-1}	3^{+3}_{-1}	$1.4^{+1.1}_{-0.6}$	0^{+2}_{-0}	0^{+1}_{-0}	2^{+2}_{-4}	3^{+1}_{-2}
2	$0.9^{+0.9}_{-0.4}$	0^{+2}_{-0}	0^{+1}_{-0}	$1.4^{+1.1}_{-0.6}$	0^{+1}_{-0}	0^{+1}_{-0}	0^{+2}_{-0}	2^{+2}_{-1}
3	8^{+2}_{-2}	6^{+4}_{-2}	8^{+4}_{-3}	7^{+2}_{-2}	10^{+4}_{-3}	7^{+4}_{-2}	10^{+6}_{-4}	6^{+2}_{-2}
4	24^{+3}_{-3}	33^{+7}_{-6}	26^{+5}_{-5}	25^{+3}_{-3}	29^{+6}_{-5}	23^{+5}_{-5}	20^{+5}_{-7}	28^{+4}_{-4}
5	66^{+3}_{-3}	59^{+6}_{-7}	64^{+5}_{-6}	65^{+3}_{-3}	62^{+6}_{-6}	70^{+5}_{-6}	68^{+7}_{-8}	61^{+4}_{-4}
How useful did you find it having the objects in space represented by sounds to understand the show?								
1	3^{+1}_{-1}	0^{+2}_{-0}	3^{+3}_{-1}	$1.9^{+1.2}_{-0.7}$	2^{+2}_{-1}	1^{+2}_{-1}	5^{+5}_{-2}	2^{+2}_{-1}
2	$1.3^{+1.0}_{-0.6}$	2^{+3}_{-1}	$1.4^{+2.1}_{-0.8}$	$1.9^{+1.2}_{-0.7}$	0^{+2}_{-0}	$1.4^{+2.1}_{-0.8}$	0^{+2}_{-0}	3^{+2}_{-1}
3	10^{+2}_{-2}	9^{+5}_{-3}	8^{+4}_{-3}	10^{+2}_{-2}	8^{+4}_{-3}	11^{+4}_{-3}	5^{+5}_{-2}	9^{+3}_{-2}
4	23^{+3}_{-3}	24^{+6}_{-5}	15^{+5}_{-4}	25^{+3}_{-3}	29^{+6}_{-5}	24^{+5}_{-5}	20^{+7}_{-5}	22^{+4}_{-3}
5	63^{+3}_{-3}	65^{+6}_{-7}	73^{+5}_{-5}	61^{+3}_{-3}	62^{+6}_{-6}	62^{+5}_{-6}	71^{+7}_{-8}	63^{+4}_{-4}

Table 2*:* *Results of the audience feedback questions 2, 3 and 4 split into various demographic groups. Numbers are percentages, and the upper/lower bounds indicate 68.3% Wilson score binomial confidence intervals. The final category, "Other", includes all people who did not identify themselves in any category of question (5) of the demographic questions (see Box 1).*

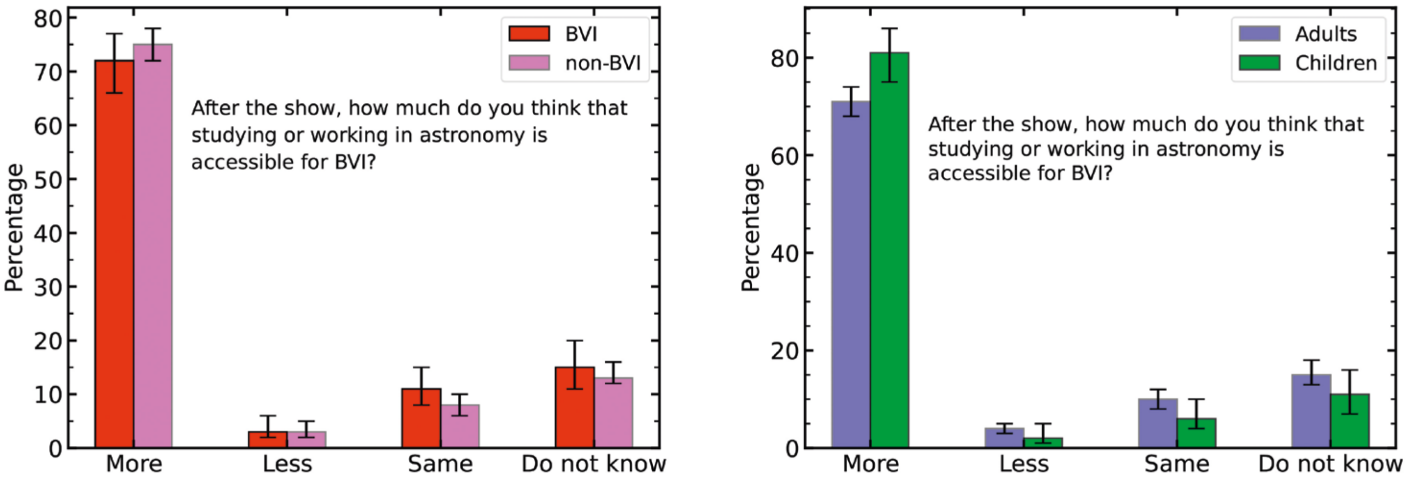

Figure 1: *Distribution of answers to the question, After watching Audio Universe: Tour of the Solar System, how much do you think that studying or working in astronomy is accessible for people who are blind or vision impaired? Left panel: answers of adults (blue histogram) compared to children (< 18 years old; green histogram). Right panel: answers of BVI (red filled histogram) compared to non-BVI (magenta histogram) audience. The error bars indicate 68.3% Wilson score binomial confidence intervals.*

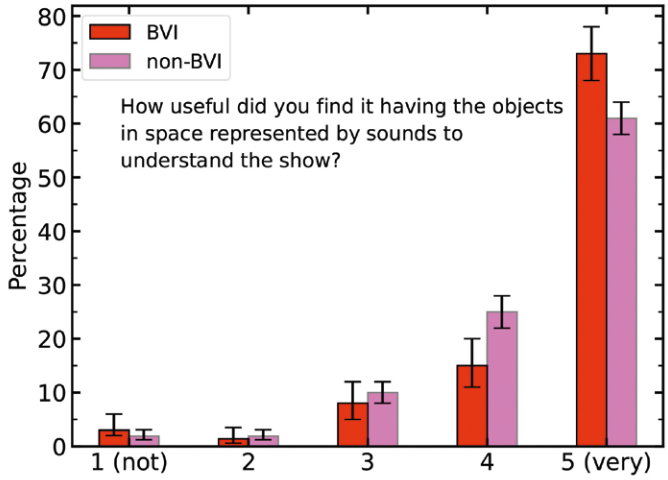

Figure 2: *Distribution of answers to the question: How useful did you find it to have the objects in space represented by sounds to understand the show? A comparison of the answers from BVI (red histogram) and non-BVI (magenta histogram) audience members. The error bars indicate 68.3% Wilson score binomial confidence intervals.*

more useful for the BVI audiences; however, it is interesting to note that significantly more than half of the non-BVI audience also answered "very useful" to this question. We believe that this emphasises the benefits of creating multi-sensory, accessible shows for all audiences and that considering such endeavours should not just be limited to BVI audiences.

The final part of the evaluation form asked for "any other comments". "Sound" was the most mentioned word in this feedback, with many positive descriptive words to describe the sounds and show overall, including "beautiful", "interesting", and "amazing". Most of the more critical comments were about sound balance ("too loud", "not enough bass", etc.). However, as the specifics of these issues were inconsistent, they were likely related to the specific venues in which they heard the show. Nonetheless, this highlights how important the balance in the soundtrack is and that guidance could be provided to support venues for fine-tuning their sound system for sound-based shows. Another comment, which appeared a few times, was the perceived difficulty in audibly distinguishing the different planet sounds when they were heard together. Although this did not come up during the focus group testing phase (*Harrison et al., 2022*), further experimentation with different sounds and wider testing could help assess the audience's ability to distinguish between multiple sounds heard simultaneously in future shows.

The importance of the soundtrack and the show's overall accessibility to BVI audience members is exemplified by the qualitative feedback from members or carers of the BVI groups. One online viewer who lost their sight as a child said:

> *Had the best and greatest accessible experience of my entire life. The sounds gave me goosebumps.*

A live BVI audience member in Italy said:

> *I am blind from birth and however much I have always tried to imagine how the space that surrounds us was made, only now thanks to you, I was able to get a clear idea of what is around us… and it's beautiful!*

A live BVI audience member in the UK said:

> *Before I went I thought planets, stars and space were all for sighted people but when I went there [the show] proved me wrong. And I then thought, oh wow anything is accessible and it was really good. Because usually when you go to a planetarium or something like that it is often very visual and I'm like 'what is going on?*

Planetarium and Communication Leaders' Feedback

Of the 35 institutions (predominantly planetariums) which responded to our enquiries, 26 have already used the show, and nine have not yet presented the show. However, most of these nine anticipated using the show in the future for specifically planned events or when a version of the show can be produced in the local language. Some of those who did not use the show discussed concerns with the directional language (pertaining to the use of "left" and "right") because their planetariums have circular seating, which can lead to the audiences having different perspectives. This has been noted as something that can be improved or avoided in future productions. One other planetarium stated that they did not intend to use the show because they were not sure how to market the show's title and content for their planetarium.

There are common themes in how the show is being used internationally. The show is predominantly used for specific events for BVI and other SEND audiences. The feedback has been extremely positive for being able to use the show for these groups, with gratitude for providing this resource for free. Although the original primary focus was on BVI audiences, the anecdotal feedback (including some comments in the evaluation forms) we have received highlights that other SEND audiences have also benefited. This includes those with sensory needs and learning difficulties. This appears to be due to the multi-sensory, calm nature and clear narration of the show. For example, one planetarium leader said:

> *I have used it on three separate occasions already. Two of them were visits to SEND schools, where I discovered, through trial and error, that the show is calm enough not to cause sensory overload, while also being multi-sensory (sight and sound matching up well), which is something SEND schools in particular appreciate a lot. The last time I used the show…was for two SEND classes within a traditional school: I presented the show to the teachers as one of the options in our repertoire, and the calm aspect of it appealed to them greatly.*

Despite the positive feedback and high uptake of the show for specially planned BVI and other SEND events, we are only aware of two planetariums that have incorporated this show into their regular programs of public events for all audiences (e.g., a daily, weekly or monthly regular planetarium program). The reasons provided for this include more minor and easily addressable comments (for future shows); for example, the show is more than 30 minutes, which is not suitable for the timetabling approach in some planetariums. More broadly, a few planetarium directors felt the show was not suitable for their usual family audiences because of its slow pace compared to other family shows. There also appears to be some perception that this show is exclusively suitable for BVI and SEND audiences. As far as we know, this is based on the opinion of the planetarium leaders rather than directly surveying their own audiences. At face value, this appears to be in contrast with our audience evaluations, for which there was a high level of enjoyment of the show and appreciation of the sounds across all demographic groups.

As of this writing, we have not achieved one of our objectives, as most planetariums do not schedule this show into their regular programming. We aimed to create a show that was considered fully inclusive and suitable for all audiences (irrespective of level of vision). Whereas, with only a couple of exceptions, the current status is that it is being used (albeit successfully) exclusively for BVI and SEND audiences.

Conclusions

We have presented our evaluation of the show *Audio Universe: Tour of the Solar System*. Overall, these results suggest that all audiences, irrespective of their level of vision, found the novel sound-based approach useful and enjoyable. Furthermore, it has had a positive impact on their perception of BVI-accessibility in astronomy. We have had the unanticipated outcome that the show has benefited wider SEND audiences. Therefore, we feel encouraged that further shows taking a similar approach to *Audio Universe: Tour of the Solar System* will benefit inclusivity and accessibility in planetariums and other astronomy communication settings. The qualitative feedback we have received will help fine-tune future shows.

We note that our results are biased towards Italian and UK audiences, and other studies would be required to understand the best approaches to using sounds elsewhere. Importantly, we cannot necessarily extrapolate these conclusions to the perceptions of audiences with particularly different musical cultures due to the predominantly Western musical choices made during this show's creation (e.g., *McDermott et al., 2016, García-Benito & Pérez-Montero, 2022*).

Our results from surveying planetarium directors are mostly encouraging, with an international reach and positive outcomes for special events for BVI and other SEND groups. Future work may break down the analysis further into different types, or levels, of vision impairment and other specific subsets of educational needs and disabilities of the audience members.

We found that most planetariums are not using this show for their general programmes, which means that the show is not always being used for fully inclusive events. Future accessible show development should consider how to overcome this limitation by working directly with planetarium directors and their audiences. This may involve some changes to the approach of the show's content, design and style. However, it may also involve changes to how the show is marketed, including how the benefits and enjoyment for all audiences are demonstrated to planetarium directors.

We now encourage show developers to explore using our STRAUSS code[2] to develop their own sonifications. The code is released on GitHub with some example scripts used to create the sonifications for *Audio Universe: Tour of the Solar System*.

Notes

[1] Audio Universe website: www.audiouniverse.org

[2] STRAUSS code: https://github.com/james-trayford/strauss

[3] Locations the show can be downloaded or viewed online: (1) European Southern Observatory's (ESO's) archive full-dome version (https://www.eso.org/public/videos/au-totss-fulldome/): (2) ESO's archive flat-screen version (https://www.eso.org/public/videos/au-totss/); (3) Audio Universe project's YouTube channel (https://www.youtube.com/@audiouniverse8137).

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Biography

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A guide to communicating astronomy with storytelling in planetariums

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Keywords
Storytelling, Professional Development, Outreach, Public Engagement, Public Outreach, Science Communication

Because storytelling is a powerful communication tool, many advocate for its use for communicating science. However, astronomical storytelling is not so straightforward for those starting out in the planetarium field who might not know how to create a story from scratch. In this article, I will review the evidence for the effectiveness of storytelling, how stories have been defined in media, and the various types of storytelling frameworks that have been advocated for use in communicating science. I show how the And-But-Therefore (ABT) framework can describe most types of stories, including fulldome videos, and can be used to create compelling content for planetarium presentations. I give example story outlines and present a general guide on converting any science account into the ABT story form.

Introduction

Even with increasingly sophisticated visuals, planetariums could not have remained popular since their inception without compelling programming to draw in an audience. It is commonly agreed by planetarians that to be successful, shows must have good stories to go along with the visuals. To support story creation within the industry, workshops and articles have appeared to describe best practices for script writing and show creation (e.g., *Spitz, 1960; Chamberlain, 1972a, 1972b, 1972c; Siemasko, 1986; Biddy, 1986; Meader, 1993; Lavoie, 2000*). From 1978 to 1994, a dedicated column appeared in *Planetarian*, the International Planetarium Society's (IPS) quarterly journal, which showcased notable scripts and featured contributed columns with advice on storytelling and writing. Best practices from dozens of planetarium professionals over the years were compiled into collections of tips on storytelling and scriptwriting, with the last update appearing in 2005 (*Tidey, 2005*). As fulldome video has become more common in the last two decades, articles describing cinematic best practices for presentations in digital domes have also appeared (e.g., *Yu et al., 2016, 2017; Wyatt, 2019; Daut, 2020*).

Yet despite this wealth of resources, there is little for the novice planetarian at the beginning of their career to learn how to construct a story or even to discover what defines a story. The work cited above provides a vast compendium of advice for crafting scripts, how to marry visuals with narration, and the unique cinematic aspects of fulldome video. However, although these authors encourage storytelling, the details of what makes a story a story at its basic level are sparse. *Chamberlain (1972a)* simply explains that stories must have three parts: an introduction to capture the audience's attention, the body containing the main programme, and an ending so compelling that it makes the audience want to return. *Lavoie (2000)* advocates six-part scripts based on his experience in film production. Although missing in the planetarium literature, the definition of story and descriptions of its structure abound in books and articles about storytelling in film, TV, and literary fiction (e.g., *McKee, 1997; Brody, 2018*). Although digital planetariums are a new medium that communicate in ways that are different from its sister media like film or virtual reality (e.g., *Yu, 2005; Daut, 2020*), the same story fundamentals apply to them as to forms of media that have existed for much longer. This paper attempts to synthesise the consensus about story structure by exploring the extensive literature on story science to create story creation guidelines for those with little practical experience in storytelling. As we will see, this toolkit for science storytelling is beneficial for those starting out in planetariums and anyone interested in using storytelling for their science communication practice.

Storytelling is a universal property of all human cultures (e.g., *Brown, 1991*). It organises our personal experiences and is pervasive in our lives (*Gottschall, 2012*). Narrative allows people to communicate their experiences with one another and subsequently alter each other's beliefs and behaviours (e.g., *Scalise Sugiyama, 2005; Avraamidou & Osborne, 2009*). Storytelling may have evolved as a cognitive tool to simulate the types of problems humans encounter (e.g., *Scalise Sugiyama, 2005; Gottschall, 2012*). Modern-day hunter-gatherers, the closest analogues we have to how our early ancestors lived, can spend up to 80% of their time around campfires telling stories (*Wiessner, 2014*). Good stories engage and help develop the imagination and capture attention by making the audience anxious to hear what comes next and how the story ends (Hadzigeorgiou, 2016). Stories are convincing because they portray information in the context of human experience, showing that transformational change is possible and motivating us to act (*Erickson & Ward, 2015*).

Research suggests that the effectiveness of narratives is due to their built-in cause-and-effect structure (*Dahlstrom, 2010; Graesser et al., 2002*), which makes them easier to read and more memorable than other forms of information delivery (*Zabrucky & Moore, 1999*). Facts inserted at causal locations in a story, where earlier and later events in the plot are linked as cause and effect, are more easily recalled than those inserted elsewhere (*Dahlstrom, 2010*). Powerful stories can create similar emotions and reactions in different audiences (*Immordino-Yang, 2011*) by engaging the same parts of the brain of the storyteller and the listener (*Hasson et al., 2008; Stephens et al., 2010*).

As tension increases during a story's dramatic arc, neurochemicals tracing empathy and attention also increase in parallel in the audience (*Barraza et al., 2015*). Stories maintain their grip because this tension makes us want to learn what happens next (*Zak, 2014*).

Audiences also find messages in narrative form more credible. Listeners identify and empathise with characters in the narrative, which weakens prior beliefs held by the audience that are counter to the story's message (*Dal Cin et al., 2004; Green, 2006; Kelly et al., 2014*). Stories that feature a heroic protagonist can be more effective for teaching science concepts than information in a traditional, expository form (*Hadzigeorgiou et al., 2012*). Both facts and misinformation from fictional narratives are so easily incorporated into people's knowledge about the world that readers of stories may believe they knew this information (and misinformation) before being exposed to the story (*Marsh et al., 2003*). Narratives that transport the audience into the world created in the story can change beliefs and motivate action (*Green & Brock, 2000*). The supporting research suggests that "people are 'wired' to be especially sensitive to information in narrative format" (*Green & Brock, 2003*). As a result, both scientists (e.g., *Krzywinski & Cairo, 2013; Dahlstrom, 2014; Enfield, 2018; Joubert et al., 2019*) and science communication advocates (e.g., *DeWitt, 2013; Barker, 2019; Foot, 2019; ElShafie, 2018*) have called for scientists to use storytelling to communicate more effectively with the public.

Early astronomical knowledge was likely transmitted via storytelling (e.g., *Hamacher, 2022*). Stories are used in many traditions to teach how to navigate by the stars (e.g., *Aveni, 1993*). They also help people learn to link seasonal changes to changes in the sky (e.g., *Krupp, 1983; Barber & Barber, 2004*). Before written records and calendars, people used the first heliacal rising or setting of a star or an asterism, or the orientation of an asterism relative to the horizon to mark the appearance of environmental phenomena crucial for survival, such as the start or end of rainy seasons, the migration of animals, and the appearance of flowers and other changes in plants. Storytelling was used to transmit knowledge about which asterisms to use, how to identify them, and how their positions, rising and setting times change during the year. Because oral traditions long predate writing, we can infer that humans in cultures worldwide learned basic astronomy through story for millennia.

Yet, despite the interest of the public, it is difficult for most people today to connect with modern astronomy. The concepts are remote and can seem irrelevant to people's everyday lives compared to other fields of science that involve medical discoveries or environmental pollution (*Storksdieck et al., 2002*; also see Figure 7.3 in *NSB, 2018*). Many topics involve abstract and non-intuitive phenomena with which the public has no personal experience. Finding ways to make astronomical content more appealing, such as through storytelling, would help improve teaching, public outreach, and public perception.

Some of the recommendations for effective stories can be easily adopted. For instance, the intrinsic awe of many astronomical phenomena visualised in a planetarium makes constructing stories about the cosmos easier, satisfying recommendations that a story must emotionally connect with an audience (*Martinez-Conde & Macknik, 2017*). However, other story elements are harder to adopt, such as requiring that a story have human protagonists who move the action forward (e.g., *Norris et al., 2005; Avraamidou & Osborne, 2009; Dahlstrom & Ho, 2012; Klassen & Froese Klassen, 2014; ElShafie, 2018*). In a story about their own personal research work, a scientist can easily recall their setbacks and successes and use them in the narrative. However, this approach becomes more difficult when trying to portray work that is not our own. As astronomy communicators and educators, we are familiar with the struggles of a small number of well-known historical figures, such as Galileo. However, we are not aware of the discovery process for most historical and even recent astronomical research, and it can take considerable time and effort to construct a science story using a historical approach (*Klassen & Froese Klassen, 2014*).

In the following sections, I will review the recommendations that have been made for science storytelling. Because the And-But-Therefore (ABT) framework seems to be the most adaptable for many different types of narratives (*Olson, 2015*), I will describe how it can describe planetarium programs, including fulldome films, and how to use it to create astronomy stories with and without human characters. I introduce a classification scheme for different types of astronomical narratives and include example outlines of such stories. I conclude with storytelling guidelines that can be used to generate a narrative outline for any science topic in and outside the planetarium dome.

The Nature of Narrative Stories

A pioneer in analysing story structure is *Gustav Freytag*, who, in 1863, used a five-act structure to describe narrative arcs in tragic theatre *(1900)*. The "Introduction" sets up the story and launches the plot. In the "Rising Movement" (commonly referred to as "Rising Action"), the story becomes more complicated as it moves toward the "Climax". The Climax, located near the middle of the narrative, is an inflexion point where the protagonist's fortune changes. In tragedies, the protagonist begins their long descent to mirror their ascendance in the first half of the narrative, whereas, in comedies, the fortunes of the protagonist begin to improve after having suffered earlier defeats. This reversal of fortune occurs during the fourth "Falling Action" act. The final act is the resolution, where we see characters die in a tragedy or go on to live happily ever after in a comedy. Although often called the "denouement" because the different story threads are resolved, Freytag called this the "Catastrophe" as he was primarily interested in tragedies.

There have been attempts to show how scientific narratives correspond to Freytag's structure (e.g., *Lavoie, 2000; ElShafie, 2018; Härmä et al., 2021; Meuschke et al., 2022*). Although it can be useful in organising our thinking about the presentation of scientific research, a five-act structure is unwieldy. Because it originated from scrutiny of tragedies, Freytag's framework is not widely used in modern analyses of popular media. Freytag's Climax does not resemble the commonly accepted definition of climax as a culminating event occurring near the end of a story. Thus, when Freytag's story structure is adopted, its definitions have often been misinterpreted or altered, with terminology—like "denouement"—added that Freytag did not use (*Bunting, 2021*).

More relevant to us is the three-act structure, which is most commonly used today to describe stories in popular media. The idea of stories having three parts dates back to

Aristotle, who simply contended that dramas must have a beginning, a middle, and an end (*1995*). Although the details of modern narrative structure depend on the author describing them (e.g., *McKee, 1997; Snyder, 2005; Vogler, 2007; Coyne, 2015; Bennett, 2020*), most three-act descriptions involve a setup introducing the characters and their world, using an inciting incident to set off the plot, a second act where tensions build over time as the protagonist has both successes and setbacks and a final third act where the tension reaches a climax. The story ends with a resolution after the protagonist has a final triumph or failure.

I will next explore two different types of story structure that have been advocated, one grounded in a three-part story structure and the other focused on character-driven plots.

And-But-Therefore Storytelling

The And-But-Therefore framework was first described by *Randy Olson*, who left his tenured professorship in marine biology to attend film school to learn storytelling, become a filmmaker, and be a better science communicator (*2009*). Based on his experience studying film entertainment, Olson argued that science communication must incorporate elements of narrative storytelling to compete with more dominant forms of media that are better at grabbing public attention (*Olson, 2019; 2020*). He notes that those from scientific backgrounds often give talks that present one fact after another. He calls this the And-And-And approach (*2009; 2015*) because each factual statement is effectively separated by the word "and." AAA can work in small doses and is usually compelling for those in the "in-group" already interested in the topic. However, if it is the only type of delivery, it is unlikely to captivate the members of the far larger "out-group" who have little initial interest (*Olson, 2015*). Without context to make someone care about the topic, an AAA approach cannot force them to invest in the story.

However, if a narrative is instead cast into a traditional story form, the audience is more likely to be interested in what is being communicated and desire to learn more (*Olson, 2009*). As an alternative to the AAA framework, Olson promotes And-But-Therefore (ABT), which he synthesised from the three-part structure commonly used to describe how popular stories work in film, TV, and other mass entertainment (*Olson*, *2015*; *2019*). ABT is similar to the principles used by the creators of *South Park* (*MVTU, 2011*) and adopted by Pixar for their films (*McDonald, 2005; Bennett, 2020*).

The ABT elements correspond to the three main components of any story (*Olson*, *2019*): agreement, contradiction, and consequence. ABT can describe plots of popular films, where characters and environments are set up in the "And" introduction, a conflict is introduced in the "But" section, and characters have to resolve this conflict in the "Therefore" segment. Because it was derived from investigations of popular film, ABT can be used to describe the structures of many, if not most, fulldome planetarium films. Films that follow a character on a quest to solve a problem almost always follow a three-act or ABT-like structure. The plot of *321 Liftoff!* (*2022; dir. M. Živocký*), a kids' film filled with charismatic computer-generated characters can be described as:

> Elon the Hamster has a dream of flying, **AND** the contraptions that he builds always fail. **BUT**, one day, the alien Eight-of-Twelve lands in his junkyard after falling from her spaceship in orbit around Earth. **THEREFORE**, Elon becomes committed to figuring out how to get Eight back to her companions.

There is obviously more to the film than described in this brief outline. The characters' attempts to travel by balloon, aircraft, and rocket are all necessary to deliver the science points and make the film fun to watch. However, they are in service to a plot, which is fundamentally ABT when stripped down to its core.

Science documentary films are filled with fact-filled segments, each of which is typically in AAA form. But again, there is usually an underlying structure that is in ABT to which the AAA portions are attached. *Incoming!* (*2016; dir. R. Wyatt*) is populated with descriptions and visualisations of recent scientific discoveries about asteroids and comets. But if it had to be summarised in a few sentences, ABT provides a model for how:

> Earth and life on it have long been shaped by impactors arriving from space. **BUT**, there is a limit to what we can learn with our ground-based tools. **THEREFORE**, we have sent spacecraft out to explore these Solar System bodies to discover their deep connections with our planet.

In a similar vein, *Dawn of the Space Age* (*2005; dir. R. Sip*) consists of multiple short chapters illustrating the history of spaceflight. Each segment delivers multiple facts in AAA style. Yet, they are in service to a story that is at heart ABT:

> Humans have long dreamed of going into space. **BUT** they did not have this ability for much of their history. **THEREFORE**, humanity had to wait until technology caught up with this desire in the 20th century when nations first competed and later collaborated to reach different space milestones.

ABT is universal enough to describe the structure of other narrative media, such as fairy tales, poems, songs, and corporate logos (*Olson, 2019; 2020*). When applied to nonfiction, ABT can be considered a setup, problem, and solution. In a science story's "And" section, the storyteller gives introductory facts and basic information on which everyone can agree. The second part introduces tension with the "But" statements. These contradict the facts presented in the "And" section, with the conflict stimulating the audience's interest. In the final "Therefore" portion, new answers are given, the conflict is resolved, and the story is concluded. The "But" and "Therefore" sections mirror the cause-and-effect framework that explain why stories have such power to grab and hold audiences (*Dahlstrom, 2010*).

Instead of focusing on the overall narrative arcs in films, let us look next at examples of how we can reorganise astronomy topics into variations of ABT.

Astronomy ABT Basic Examples

Below are examples of outlines that explain three different astronomical concepts through ABT:

> **Heliocentric Solar System**
> Educated people thought Earth was at the centre of the Universe **AND** that the Heavens were perfect, **AND** celestial bodies moved along circular paths around Earth. **BUT**, with better observations,

a model that accurately showed the motions of planets became more and more complicated. **THEREFORE,** Copernicus proposed a simplified Sun-centred Universe.

What Are Stars Made Up Of?

Stars are distant suns **AND** spectra can be taken of their atmospheres to sample their chemical makeup. **BUT** there was no consensus on what led a star to have the spectral lines that it showed. **THEREFORE,** an approach that combined gas physics with astronomy was needed. Cecilia Payne-Gaposhkin applied the new understanding of how hot gases emit and absorb light to the atmospheres of stars to show that stars consist mostly of hydrogen and helium.

Discovery of Black Holes

Most stars are in binary systems **AND** they can be observed via their distinct spectra even when the two stars are so close that we cannot see them separately in the sky. **BUT**, there are some binary pairs where one of the stars appears to be invisible or missing! **THEREFORE,** black holes were proposed as a solution to this mystery.

In these examples, the storyteller needs to know how successive observations and interpretations causally lead to a better understanding of a topic. The questions raised in the "But" section perplex scientists, creating tension in the story. This tension is not resolved until the "Therefore" section when new data or explanations are brought in to clear up the conflict. The added tension helps keep the audience's attention: after the problem is introduced, they want to see how it is resolved.

Misconceptions-Based ABT Stories

The "Misconception-Based" ABT story has as its theoretical underpinning constructivism: the educational theory that purports that we all hold mental models about how the world works around us, informed by prior experience and teachings, but frequently at odds with scientific thinking (e.g., *Brewer, 2008*). Newly acquired scientific information does not immediately overturn prior misconceptions. However, it can lead to synthetic models that combine the old with the new (*Vosniadou & Brewer, 1994*), with the transformation of synthetic to scientific models taking place slowly over time. To speed up this process, contradictory information can be introduced that adds doubt in the mind of the learner and helps to promote conceptual change (*Bakas & Mikropoulos, 2003*).

In the following ABT story outline, we start with commonly held incorrect notions by the public about the cause of the seasons (*Atwood & Atwood, 1996; Zeilik et al., 1999*). The "But" section introduces contradictory information to create doubts about prior mental models. This contradiction is resolved in the final "Therefore" section, where the scientifically correct description is presented as an alternative. To develop this type of ABT story, the storyteller must be familiar with common misconceptions and the information needed to address them.

Seasons

Over the course of a year, we experience the seasonal cycle with changes in temperature and the amount of daylight. **AND** if you ask someone, they will attribute the seasons to Earth moving in an elliptical orbit so that it is closer to the Sun in the summer. **AND** some people think seasons have to do with the tilt of the Earth, putting a part of its surface closer to the Sun.

BUT the Earth is actually closest to the Sun in early January, when it is northern winter. The seasons are also simultaneously different for people in the two hemispheres. Finally, the distance between the Sun and Earth is so vast that Earth's tilt negligibly alters the distance to the Sun at different latitudes.

THEREFORE, the reason for the seasons is not different distances to the Sun, but the Earth's tilt changing how high the Sun is in the sky during the day, and the length of the day.

Character-Driven ABT Stories

Most stories told in human history have involved human characters or non-human characters with recognisably human traits. The audience can connect with them, understand their goals and motivations, and empathise with their very human struggles. The drama comes in seeing the problems they face during their journey of discovery, with missteps and triumphs along the way, and witnessing how they ultimately succeed. For planetarium stories centred on scientists (who could be depicted by actors, animated via computer graphics, or whose story is just narrated by a live presenter), dramatic tension can come from any stage in the scientific process. Many planetarium shows employ non-scientist characters who are stand-ins for the audience. They may have questions they cannot immediately answer and must go on a journey or accomplish tasks to understand the science the show is trying to convey. By depicting the struggles of scientists or fictional characters in the narrative, the audience can be transported into the character's shoes and empathise with them in their trials.

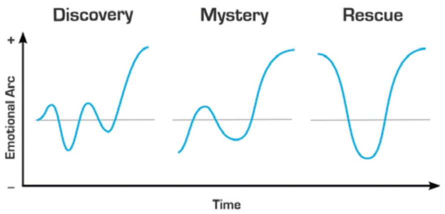

Figure 1: *The three types of narrative arcs for science stories with human protagonists from Green, Grorud-Colvert, & Mannix (2018).*

Green, Grorud-Colvert, & Mannix (2018) describe three scenarios for character-driven science stories: the Discovery, Rescue, and Mystery plots (Figure 1). Each journey's emotional highs and lows can be plotted across time as story shapes, with the final discovery representing an emotional high at the end. The Discovery story shows the protagonist overcoming adversity as they conduct experiments or make field observations, analyse their data, and move closer to the discovery. In the Mystery story, the main protagonist starts at a low point with a mystery or puzzle that must be solved. Like journalistic depictions of scientific discovery that take the form of a detective story, the scientist gathers new facts to eliminate alternative hypotheses to uncover the mystery (*Curtis, 1994*). Finally, in the Rescue plot, scientific results are viewed as solutions to challenges faced by individuals or society, where they begin at a high point and suffer loss, which is reversed only by a new scientific discovery.

I propose a new story category in addition to the normal Discovery. Much astronomical knowledge is based on the accumulation of work by multiple figures, creating a broad historical sweep of discoveries. This "Extended Discovery" involves multiple personalities working over a span of time. The drama comes from humanity's collective efforts to better understand nature. Within the larger narrative are multiple embedded ABT arcs, each of which can be a self-contained story. The following expands on the Copernican example from the start of this section.

Heliocentrism and Motions of the Planets
Classical thinkers once believed that the Earth was made of imperfect elements **AND** the heavens were perfect. Observations showed that the Sun, Moon, and planets appear to travel around the Earth.

BUT with more detailed observations, models that could accurately depict the observed motions became increasingly complicated. Also, new telescopic observations showed that not everything orbited the Earth, and the Heavens were not perfect.

THEREFORE, Nicolaus Copernicus proposed that not everything travelled around the Earth, but instead, moved around the Sun.

The Copernican model was successful in explaining some phenomena.

BUT it still relied on circular orbital motions, which meant epicycles were still required.

THEREFORE, nearly a century later, and based on careful observations of planetary motions, Johannes Kepler proposed elliptical orbits, with the planets moving faster when closer to the Sun and slower when further away.

In a science Mystery, the storyteller must understand the discovery process enough to show how the researchers worked past red herrings and other obstacles to get to their discovery. While this following example is part of a larger cosmology Discovery story, the narrative elements from first-person accounts (*Bernstein, 1984*) can be made to fit a Mystery ABT story:

Cosmic Microwave Background
Arno Penzias and Robert Wilson were trying to use a radio telescope to measure radiation from the Milky Way. **AND** in order to do that, they had to characterise any noise that could muddle their observations.

BUT there was leftover static detected even after accounting for all possible sources of noise.

THEREFORE, after eliminating other explanations, Penzias and Wilson recognised the "noise" they observed was really relic radiation from the Big Bang.

It is rare that a space science discovery is in the form of a "Rescue Story" since these revelations rarely save an individual or society. Here is one example that does have consequence:

Near Earth Objects
The main asteroid belt lies between Mars and Jupiter. **AND** since their formation, major and minor planets have continued to placidly orbit around the Sun.

BUT evidence has grown that larger planets can change the trajectories of smaller bodies. Geologists realised that impacts have altered the history of life on Earth. We now acknowledge that asteroids and comets can be hazards to human civilisation.

THEREFORE, astronomers and planetary scientists developed space- and ground-based surveys to find all objects that had the potential to collide with Earth. **THEREFORE,** plans were developed to test out new technologies to deflect objects.

Guidelines for Non-Character Driven ABT Story

Based on these examples, it becomes clear that we can generate non-character-driven astronomy stories by answering the following questions:

- **AND:** What are the basic background facts that an audience needs to know?
- **BUT:** What are the unresolved questions? What new information contradicts the basic facts?
- **THEREFORE:** What are the new observations, discoveries, or thinking that is needed to address the unresolved questions or contradictions?

Using these simple questions, we can construct ABT story outlines out of nearly any astronomical or planetary science topic, even when we are not entirely aware of the historical circumstances surrounding the discovery or the personalities involved. Below are some outlines for a range of topics.

Wet Mars
Mars is a dry desert world **AND** there is no liquid water on its surface today. **BUT** spacecraft images show surface features that look like channels and deltas carved by water. **THEREFORE,** we speculate that Mars must have been warmer and wetter in the past, and it has since lost most of its water.

End of low-mass stars
Stars generate energy in their cores via fusion **AND** this outgoing energy balances the mass of the star pressing inwards. **BUT** what happens at the end of a low-mass star's life when its fuel starts to run out? **THEREFORE**, we need to look at the physics of the stellar interior when the stellar core runs out of hydrogen fuel in order to understand how a star evolves at the end of its life.

Exoplanet discoveries
We suspect that our Solar System isn't unique in the Universe **AND** we expect planets to be found in orbits around other stars. **BUT** observing planets directly is very difficult because of how much brighter stars are than their planets. **THEREFORE,** we need new techniques for finding planets, such as measuring radial velocities or observing transits.

The radial velocity method requires careful measurements of stellar velocity changes from an orbiting planet. **BUT** this stellar motion was too small to measure with spectrometers at the time. **THEREFORE,** new spectrographic techniques were needed to make detections.

Once we have identified a question that a discovery answers, we have all the elements needed to generate an ABT story. We can, therefore, create ABT stories not only about venerable topics but also about the numerous discoveries that are announced in press releases or press conferences each year.

The last example for exoplanet discoveries also shows how the ABT method can be recursive: the follow-up about the limitations of the radial velocity method is also in ABT.

The embedded nesting of ABT in a story ensures that audience interest is maintained at multiple levels in the narrative (*Olson, 2020*).

We close by showing how a documentary-style fulldome film can also contain multiple layers of ABT. The overall story arc of *We Are Astronomers* (*2016; dir. M. Crow*) can be summarised as:

> Humans have long tried to make sense of an awe-inspiring Universe. **BUT** their understanding was limited. **THEREFORE,** they had to invent new tools and instruments to allow them to know the nature of the Universe, with the added benefit of bringing diverse groups to work together.

Instead of presenting the multiple astronomical topics it covers using only AAA, the film approaches some with ABT, such as the section on the *James Webb Space Telescope*:

> Astronomers built many telescopes to observe the cosmos. **BUT** ground-based observatories couldn't explore all parts of the electromagnetic spectrum. **THEREFORE,** astronomers launched telescopes into space.

The climactic story of the Large Hadron Collider is also set up as ABT:

> Telescopes have imaged further and further back in time. **BUT** there is a limit to how close to the Big Bang astronomers can probe. **THEREFORE,** we had to turn to particle physics to provide answers regular telescopes could not.

Other chapters of the film are done as pure AAA, such as a fact-filled review of spectroscopy. However, with a slight change of the script, the film's account of Galaxy Zoo could have turned this information-loaded AAA segment into ABT as well:

> Astronomers are acquiring more and more telescope data. **BUT** this data is often more than the professionals can analyse. **THEREFORE,** new crowd-sourced projects have been created, allowing enthusiastic amateurs (who outnumber the professional astronomers) to be involved.

Concluding Thoughts

After showing that stories are a useful way to communicate science, I have presented different examples of And-But-Therefore in the narrative arcs of fulldome films and in individual astronomy topics that can contribute to segments of a dome film or presentation. I have followed that with a description of how any science story can be recast into ABT. Nevertheless, this approach requires a different mindset and the exercise of different skills for those (including the author) who have spent most of their careers delivering information in the And-And-And style. With planetarium visualisation software, it is easy to create tours of the Universe (*Emmart, 2005*) filled with AAA content, with the presenter reciting a handful of facts at each stop before flying off to the next destination. This approach has visual appeal, as the audience can fly through space and see diverse phenomena. However, storytelling research suggests that the audience could get more out of the narrative if there were an ABT wrapper around all of the AAA components.

From my experience, creating presentations using the ABT approach is difficult at first, and practice is needed to make this process easier. Therefore, I encourage readers interested in a story-focused approach to practise constructing ABT stories themselves. Using this framework and other recommendations for creating compelling narratives (e.g., *Schimel, 2012; Corner, Shaw, & Clarke, 2018; Olson, 2020*), practitioners can improve their planetarium presentations and enhance their communications for any audience.

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Biography

At the Denver Museum of Nature & Science, **Ka Chun Yu** has written planetarium visualisation software, helped produce movies for the digital dome, created Earth systems planetarium shows, and researched how digital planetariums can be used to teach astronomy. He participates in extensive education and public outreach and advises on science content in permanent and temporary museum exhibits.

Digital planetariums as new tools for conceptual change

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Keywords
Astronomy Education, Digital, Immersive, Planetarium, Research, Virtual Reality

Misconceptions in astronomy arise because of our unique, geocentric perspective on the night sky and astronomical phenomena. However, astronomy is quintessentially a "spatial" science, and three-dimensional visualisation is necessary for understanding most of its core concepts. Since the traditional optomechanical planetarium offers the same geocentric point of view on the sky, it might generate similar misconceptions in visitors. The new digital planetarium, which projects on the dome a realistic and accurate rendition of the cosmos in 3D, allows us to break free from 2D representations and transforms the planetarium theatre into a virtual spacecraft, affording different perspectives on astronomical phenomena. This new planetarium thus becomes an extraordinary tool to foster conceptual change in visitors. Recent research in astronomy education about using the digital planetarium to teach basic astronomy concepts, like the diurnal cycle, phases of the Moon, and seasons, has shown the advantages of this new tool, compared with 2D visuals and traditional classroom instruction. More research needs to be done to better understand how to use the digital planetarium in communicating astronomy with the public, especially to present concepts with a strong spatial component, but the future is promising!

Introduction

In astronomy, many of our misconceptions arise from our inability to see astronomical systems from another point of view than the Earth-centred perspective. But astronomy is first and foremost a "spatial" science, not only because astronomical objects exist and move in three-dimensional space, but also because understanding basic astronomical concepts, like the diurnal cycle of day and night, phases of the Moon, eclipses, the Earth's seasons, or the apparent motion of planets across the sky, all require an ability to move from one frame of reference to another (*Heywood et al., 2013; NRC, 2012; Plummer & Maynard, 2014; Subramaniam & Padalkar, 2009*). Specifically, one must be able to shift between the view from the Earth's surface (i.e., the geocentric point of view) and the view from space (i.e., the "allocentric" point of view, from the Greek *allo*, meaning different; see *Chastenay, 2016*). In fact, as *Sadler (1992)* pointed out, "without the ability to imagine what objects look like from different perspectives, students will find many astronomical concepts virtually impossible to learn" (p. 103).

The origins of misconceptions in astronomy

From a very young age, people build personal explanations about the workings of the world around them. Still, most of these personal theories differ from those accepted by the scientific community (*Driver, 1981*). These misconceptions (or alternative conceptions, naïve conceptions) often represent the results of simple heuristics applied to events in everyday life. For example, to explain the diurnal movement of the sky above their heads, younger children will often say that the Sun, Moon and stars revolve around the Earth each day, as is evident to an Earth-based observer oblivious to the rotation of our planet. Phases of the Moon are often naïvely explained as the shadow of the Earth hiding a greater or lesser portion of our satellite, a clear reference to the formation of shadows that we experience every day. Many adults still think that seasons are due to the changing distance between the Earth and the Sun, an explanation linked to our experience of warming up next to a fire. Over the years, science education research has found that these misconceptions are highly resistant to change and often remain intact at the end of the educational process (e.g., *Strike & Posner, 1992*). At the heart of this resistance to change is a form of "cognitive economy" – a preference for a personal explanation that has already proven useful in day-to-day life (*Campanario, 2002*).

Where do these astronomical misconceptions come from? For most of them, it is the fact that our view of the sky is exclusively geocentric. From the unique and limited perspective of Earth's surface, we try to make sense of the functioning of the heavens and the nature and movements of celestial bodies. Indeed, apart from a few lucky astronauts, who has ever had the chance to see with their own eyes the spherical shape of the rotating Earth, the same planet which appears resolutely flat and fixed when observed at ground level? How can we expect someone to understand the mechanism of lunar phases if they cannot imagine the spherical Moon revolving around the Earth, with the sunlit hemisphere appearing to us at different angles? How can we hope that people will abandon the frequent misconception of the seasons caused by the changing Earth-Sun distance in favour of the scientific explanation involving the tilt of our planet's axis of rotation if they cannot see the Earth from space revolving around its star?

Optomechanical versus digital planetariums

The traditional optomechanical star projector, which has been the staple of planetariums for most of their 100-year history, renders an exquisitely accurate impression of the night sky and its apparent movements, as can be seen from any position on the surface of the Earth. But the star theatres equipped with such an instrument are limited to presenting a geocentric point of view on the cosmos, the same perspective that gives rise to most misconceptions discussed above. As the Scottish philosopher David Hume wrote in 1739, “the same cause always produces the same effect” (p. 173). As the traditional, geocentric planetarium cannot show a different perspective on the cosmos, it offers visitors the same experience of the night sky, which is at the root of most misconceptions in astronomy.

Fortunately, new digital tools for projecting computer-generated images on the planetarium dome offer an allocentric view of the Universe for the first time by breaking the two-dimensional, flat screen into the third dimension and allowing visitors to experience the cosmos in 3D. With the video revolution sweeping the planetarium world, we see more and more arrays of high-definition video and laser projectors replacing or supplementing traditional optomechanical devices. These new digital tools project onto the hemispheric dome realistic synthetic images generated by increasingly powerful computers and ultra-fast graphics cards. Together, they allow real-time navigation in a virtual 3D space containing all the astronomical information that can be fed into the system, including solar system ephemeris and surface maps, stars and galaxies catalogues with accurate 3D positions in space, and three-dimensional models of astronomical objects, like the Orion nebula and the Milky Way. More than just a technological revolution, this shift from optomechanical to digital is rich in possibilities for combating misconceptions in astronomy. We propose that an allocentric view of astronomical systems, made possible by digital planetariums, is a powerful tool for conceptual change in astronomy.

Conceptual change in a digital planetarium

If our unique, geocentric point of view on the sky is at the origin of most misconceptions in astronomy, how can we foster conceptual change in favour of scientific knowledge? Several studies in science education have already shown that the use of concrete models can foster conceptual change (e.g., *Jonassen, 2008*), for example, by providing a different point of view on larger astronomical systems (e.g., *Kavanagh et al., 2005*; see also the extensive work done on modelling in astronomy by Kathy Cabe Trundle and her team). This approach has its limits, though, as the highly abstract nature of a model to represent a larger entity can be conceptually difficult for younger children to comprehend and can even be the source of new misconceptions. This is where the digital planetarium can play a leading role in astronomy communication and education by presenting a spatial, allocentric point of view in a realistic and credible immersive virtual environment. By taking in the previously inaccessible allocentric perspective, the visitor is allowed to experience how the Universe really works, an experience that can have a profound effect on misconceptions. Even more than the ongoing digital revolution in the world of planetariums, this technology-enabled allocentric view represents perhaps the greatest paradigm shift the star theatre has seen since the invention of the Zeiss projector in the early 1920s.

A little more than a decade ago, the U.S. National Research Council assumed that since astronomy “requires learners to imagine a three-dimensional dynamic universe of galaxies and orbiting planets by looking up at a flat sky, it would be reasonable to assume that spatial thinking is an active area of inquiry in astronomy education research” (*NRC, 2012, p. 112*). Indeed, many science education researchers have begun to explore the promises of this new technology to teach astronomy as a spatial science, and the results are encouraging. For instance, a team led by Ka Chun Yu at the Denver Museum of Nature & Science (United States) has extensively studied the educational impact of the allocentric point of view provided by the digital planetarium on undergraduates enrolled in a university astronomy course. The team has compared traditional instruction in the classroom, 2D projection on a flat screen and 3D visualisation in a digital planetarium to teach seasons, planetary orbits, Moon concepts and the scale of the solar system, among others, and each time found a significant advantage for the digital planetarium instruction (*Yu & Sahami, 2007; Yu et al., 2015; 2016; Yu et al., 2017*). Their results suggest that in a digital planetarium, “students do not have to expend cognitive resources to mentally model the [astronomical system under study]; they can experience it directly via the immersive virtual environment” (*Yu et al., 2015, p. 43*).

In another study conducted at the Planétarium de Montréal (Canada), *Chastenay (2016)* found that students aged 10-14 years old had a better understanding of the lunar phases after a one-hour session under the dome of a portable digital planetarium, where they were able to view the Sun-Earth-Moon system from different perspectives, using the metaphor of the digital planetarium as a virtual spacecraft (see Figure 1). *A.Bélanger et al. (2018)* developed a digital planetarium show to teach lunar phases to school groups. This research identified what elements of an allocentric digital full-dome planetarium session were conducive to a better understanding of lunar phases by students 10-12 years old. It turns out that the spacecraft metaphor and visual and audio cues were important to help students make sense of the simulation and know “where they were in space in relation to Earth”. Future research should continue to identify other psychological and educational aspects of the digital planetarium experience that favours understanding astronomical phenomena, not just in the solar system, but toward stars and galaxies as well.

Summary: Communicating astronomy from an allocentric perspective

Digital planetariums are only a few decades old and are evolving rapidly with technological advances in high-definition computer graphics and projection systems. Also, the breadth of the Universe that can now be experienced in these virtual environments is expanding with every new database and catalogue that can be imported into the simulation, like the latest release from *Gaia* (see *Gaia Collaboration et al., 2023*). With this information, one can navigate effortlessly in a 3D Universe similar to the real thing, for example, by leaving the solar system and the Galaxy to experience the Milky Way from intergalactic space. The educational potential of these new tools is just beginning to be explored. But if the studies reported above are indicative of what can be done with digital planetariums, venues that will use this new digital technology alongside immersive graphics that present an allocentric point of view of

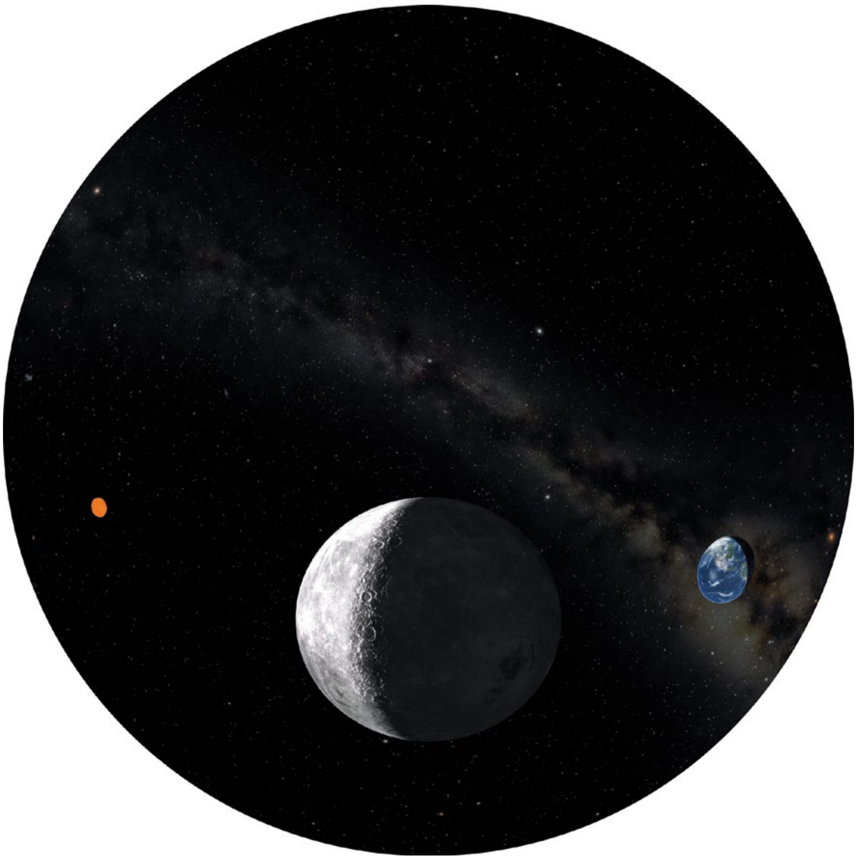

Figure 1: *This fisheye image shows an allocentric view of the Sun, Moon and Earth from a point outside the Moon's orbit. This image fills the spectators' field of view when projected on the planetarium dome via video projectors. Image Credit: Planétarium de Montréal/Espace pour la vie*

astronomical systems will have a sizeable impact on viewers' conceptions of the Universe.

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Biography

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Science communication through astronomy education: The creation, implementation, and assessment of Porto Planetarium's science education strategy

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Keywords
Planetarium, Astronomy Education, Science Communication, Public Engagement

The Porto Planetarium – Ciência Viva Center (PP-CCV) is under the scientific and operational management of the Center for Astronomy/Astrophysics Research of the University of Porto, which also hosts the Institute of Astrophysics and Space Sciences (IA), the largest astronomy research unit in Portugal. This article presents the conception, development, implementation and evaluation of PP-CCV's ongoing science education strategy, built upon two main pillars: Science Communication and Science Education. Those self-sustained pillars are interconnected, leveraging each other in a truly synergistic process. The assessment of the science education strategy was carried out through a questionnaire, participant observations and interviews. These results revealed how we can effectively connect science education and science communication using outreach structures already established in research units. However, those institutions must understand the school curricula and get to know the teacher's ecosystem. That will be the foundation for us to build upon and to move from what students should know – the prescribed curriculum – to what is scientifically relevant for them to know – the most up-to-date foundations of scientific knowledge and process. With that, we can start from science education to reach science communication by framing the curricula with the most up-to-date scientific knowledge and processes.

The context

A bit of history

Founded in 1989, the Center for Astronomy/Astrophysics Research of the University of Porto (CIAAUP) is a private, non-profit association recognised as of public utility, which has three main areas of intervention in the field of astronomy: research in astrophysics, space science, and science education and communication research, education support at all levels, from kindergarten to PhD, and public outreach.

CIAAUP was one of the first research centres in Portugal to have an outreach team to increase the general public's scientific literacy. Outreach activities began in 1990 with a portable planetarium that visits schools – an activity that continues today. So far, internal reports have indicated that more than 250,000 school children had their first contact with basic astronomy concepts inside our inflatable dome.

The experience gained in the portable planetarium was invaluable for starting outreach activities in the Porto Planetarium – Ciência Viva Center (PP-CCV). In 1998, the PP-CCV, operated and managed by CIAAUP, opened its doors to the public. Its mission is to promote active citizenship based on scientific knowledge, promote scientific culture, and challenge the public to share and discuss novel experiences. We want to inspire and mobilise people through science. PP-CCV has an annual average turnout (pre and post-pandemic) of about 38000 visitors.

CIAAUP shares with PP-CCV an Administration and Services Unit and its Outreach Unit staff: the Executive Director (also Science Communication Group coordinator at the Instituto de Astrofísica e Ciências, or IA), three science communicators, two designers, and two active school teachers. In addition to its regular science communication activities (e.g., planetarium shows, telescope observation nights and hands-on activities), PP-CCV produces fulldome shows, exhibitions (many linked to IA's scientific outputs), art shows (see Figure 1), supports national education programmes (e.g., the science clubs school network and the science school network) and promotes research in science communication and education (e.g., *Reis, 2021; Costa et al., 2023*; or compiled at CoAstro website[1]).

Astronomy education in the Portuguese compulsory schooling

Since 2009, school attendance in Portugal has been compulsory between the ages of 5 and 18 (1st to 12th grade). Within this framework, education is universal and free of charge, which is a key aspect of

Figure 1: *NOOITO: example of a concert held inside PP-CCV´s dome. Image Credit: PLANETÁRIO DO PORTO CCV*

democratising access to science (e.g., *Costa et al., 2022a*). For some children and teenagers, it may be the only opportunity to be engaged with astronomy; this is particularly important as awareness is a precondition of interest and enjoyment of science (e.g., *Price & Lee, 2013; Oliveira & Carvalho, 2015*). Further, *Dang & Russo (2015)* demonstrate that astronomy interest is shaped at an early age. Thus, it is necessary to expose school children to astronomy content and processes early on within the Portuguese national curriculum, not only for astronomy education but also for the future of national astronomy research.

Costa et al. (2022a) investigated the compulsory education syllabi in Portugal from the 1990s alongside visitors' experiences at PP-CCV. They found that astronomy has gradually disappeared as new curricula have been developed. For example, in the latest Portuguese major curriculum changes, astronomy content is explicit in very few school years and a sparse number of subjects. When astronomy content is included, it is sporadic and superficial, with limited astronomy themes, some of which are considered by research as less relevant. The 7th grade is the only exception in this scenario: students have one theme about the "Solar System & Universe". This becomes more relevant by realising that the most recent curriculum changes are the national benchmarks for external assessment – the national exams – implying that these essential learnings are the only content covered in Portuguese classrooms. As astronomy education in schools decreases, the number of school visitors to the Planetarium also decreases (*Costa et al., 2022a*). The authors found that even after it was demonstrated that astronomy functions as a gateway science for education in STEM fields and social sciences alike (e.g., *Salimpour et al., 2020*), there was still a decline in astronomy education in Portuguese schools.

Costa et al. (2022a) also pointed out that most teachers who attended training courses at PP-CCV had no prior training nor a particular interest in astronomy, so they do not spontaneously engage with in-service training in this field, and avoid teaching astronomy contents of their syllabus.

Science communication through astronomy education at the PP-CCV

Aware of the context described above, in an ongoing process since 2016, PP-CCV conceived, developed, implemented, and evaluated a new science education strategy. In response to the changing landscape of the Portuguese curriculum, PP-CCV designed a science communication strategy through astronomy education to address the decline in school visits. To do so, PP-CCV established two main pillars: the PP-CCV Educational Programme and the PP-CCV In-service Teachers Training Plan.

In parallel, PP-CCV maintains its daily programming for other types of audiences. Therefore, PP-CCV has planetarium shows, hands-on laboratories, observations with small telescopes (Figure 2), talks, exhibitions, workshops (on topics such as

Figure 2: *A public night sky telescope observation at PP-CCV. Image Credit: PLANETÁRIO DO PORTO CCV*

robotics and astronomy), and special events, both in-person and online.

However, the focus of this present work is the strategy implemented with schools, their students, and teachers. That strategy allows for all the activities to be done in PP-CCV´s facilities or at schools (both in-person or online; see Figure 3).

PP-CCV educational programme

Outlining an educational programme that would make informal education in Astronomy at the PP-CCV more efficient began by analysing all of PP-CCV´s resources. Since 2016, these resources have been cross-checked with the curricular programmes, guidelines, and targets for compulsory schooling, from pre-school to secondary school. Based on this analysis, we have continuously outlined didactic sequences based on the most up-to-date scientific knowledge and processes: we address the curricular standards using Contemporary science as a starting point.

PP-CCV has an educational programme with 45 different didactic sequences, covering all years of mandatory schooling from 19 different disciplinary curricular fields. Teachers can also make a disciplinary, multidisciplinary, or interdisciplinary visit[2].

One complete didactic sequence for visitors at PP-CCV typically consists of two major activities: full dome shows (Figure 4) and hands-on laboratories (Figure 5). The full dome shows have two distinct parts: a recorded part that includes a short film, a feature film and a live presentation, during which visitors are taken on a trip through the Universe, fostering interaction between the planetarian and the audience.

Typically, each session has two distinct parts: a recorded short film and a main movie, followed by a live presentation that encourages interactions between our astronomers and the audience.

Figure 3: *The "Astroteca": driving astronomy to schools. Image Credit: PLANETÁRIO DO PORTO CCV*

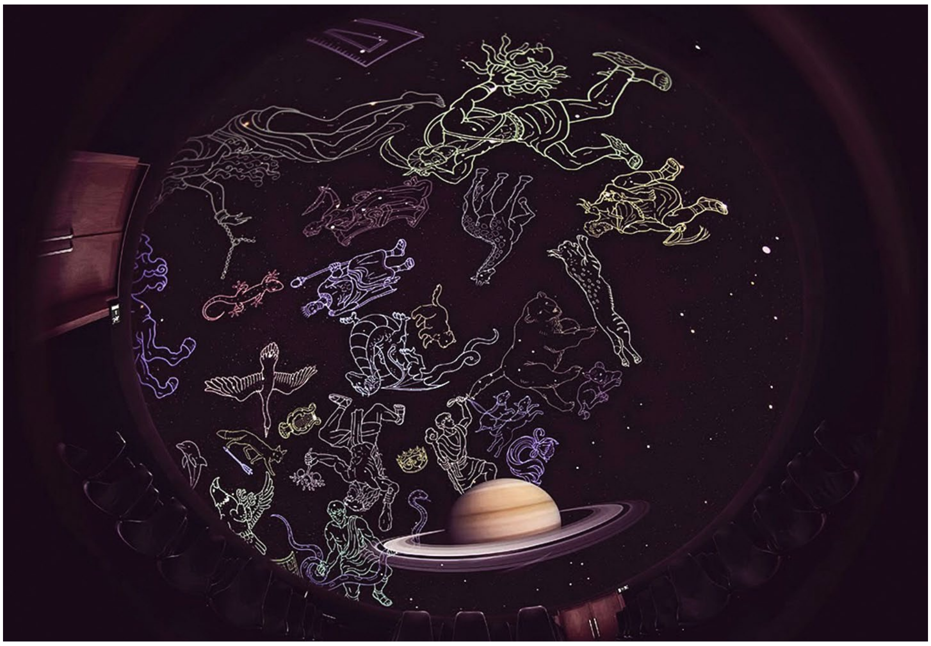

Figure 4: *A PP-CCV fulldome show. Image Credit: PLANETÁRIO DO PORTO CCV*

The visit follows the rationale proposed by Orion (1993) and, therefore, includes pre- and post-visit tasks with teachers and students.

As part of the pre-visit tasks, a new booking protocol was introduced that involves analysing all bookings in detail to ensure that all activities are age-appropriate and meet the teachers' objectives for the visit. At this stage, we analyse, with teachers, the details of the visiting groups: size, age, guidance by the teachers, and orientation of the group (science or not, focused on reaching higher education or going towards a profession, and so on). In fact, teachers co-create with the astronomers, and all of the students work with PP-CCV. This pre-visit work also resulted in creating detailed weekly work schedule maps for the facilitators, including all activities. Post-visit tasks include gathering follow-up information from the visiting teachers with a system we created that produces an attendance certificate and allows teachers to evaluate the work of the PP-CCV: this is

Figure 5: *Students during one of PP-CCV´s hands-on laboratories. Image Credit: PLANETÁRIO DO PORTO CCV*

one of the post-visit tasks. That feedback reshapes PP-CCV activity in a truly co-creative process.

PP-CCV In-service Teachers Training Plan

In-service teacher training is mandatory for career progression. Building on that and upon the in-service training limitation in Portugal, PP-CCV started their training plan in 2016. In it, PP-CCV offers the expected basic knowledge but adds an "attitude towards science" dimension, which guides this action. In PP-CCV's training plan, we still give teachers the necessary knowledge in astronomy but also change how they view science, its nature and how it is built – its epistemological component.

To that process, two key steps were crucial: creating PP-CCV´s teacher database and establishing partnerships. Indeed, PP-CCV´s In-service Teachers Training Plan is verified by trainers from the Institute for Astrophysics and Space Science (IA), with pedagogic accreditation and endorsement by several institutions. We work with several governmental "School Association Training Centers" and the Regional Government of the Azores and Madeira autonomous regions. We also work with international partners, such as the International Astronomical Union (IAU), the Network for Astronomy School Education (NASE), the European Association for Astronomy Education (EAAE), the European Southern Observatory (ESO), the European Space Education Resource Office (ESERO), and Scientix.

Regarding our database: as we already said, to receive a personalised attendance certificate after each school visit, teachers were asked to provide some data (name, recruitment group, and contact information), which, if they so desire, can be used to receive regular information about PP-CCV´s activity. So far, the database has 3660 entries.

This programme[3], available by application only, has had thousands of applications since 2017 from teachers with a diverse type of initial training (e.g., sciences, arts and languages) and ailing from all the Portuguese territories, plus some countries where Portuguese is one of the official languages, such as East Timor or Mozambique. After screening the applicants through a rigorous review process, we accepted about 1,000 applications (*Costa et al., 2022b*). The accepted applicant pool represented a global population of educators. Those who were not able to join in person were able to participate online.

Data from those courses (discussed below) revealed that teachers value PP-CCV's training: it is clearly linked to their disciplinary field, eminently hands-on, accredited and recognised for professional progression based on updated scientific results and processes. This type of training allows teachers to move from a professional obligation to a meaningful personal endeavour. It also allows the transformation of in-service training into real paths of professional development: teachers' autonomous learning of astronomy, carrying out astronomy education activities beyond the curricular imperative and stimulating collaborative work among peers.

PP-CCV´s Educational Programme assessment

Although we already have data to assess the PP-CCV In-service Teachers Training Plan, these data have not yet been published. Therefore, in this section, we will be restricted to the data from the assessment of the PP-CCV Educational Programme.

We used a questionnaire, participant observations and interviews to assess the effectiveness of PP-CCV's Educational Programme. The questionnaire was based on a survey produced by the Portuguese Agency for Scientific and Technological Culture (available in annexe in *Reis, 2021*) and adapted to fit PP-CCV's specific activities.

A preliminary version of the questionnaire was analysed and improved upon by an expert in science education and used in a pilot study (for facial and content validation). After the pilot study, we hosted the questionnaire online[4] and sent it to the teachers who accompanied their students to the PP-CCV.

We received 270 responses, analysed using a content analysis framework for open-ended questions and statistical analysis for closed-ended questions (*Costa et al., 2023*).

The results (*Costa et al., 2023*) show that 80.7% of teachers were happy about how they were welcomed, and 85.2% were happy about how they were accompanied throughout the activities. The planetarium shows were most appreciated, but the hands-on laboratories, which complement these shows, were also highlighted. Both activities were considered assets for teachers' classes, with the hands-on laboratories graded with an average of 4.4 and the immersive show with 4.7 (on a 1 to

5 scale). Both activities were also considered well framed in the syllabus, rating 4.2 on average; 97.4% of teachers said they would return to PP-CCV with their students and 72.2% with their families. The most positive aspects of the planetarium shows were the visual component, its framework in the syllabus, the interactivity with the students and the performance of the planetarians. Most visiting teachers (71.4%) thought the shows had no negative aspects. However, it was mentioned that PP-CCV should consider presenting longer shows (8.9%). Teachers often (42.9%) noted that allowing students to conduct experiments by themselves was the most positive aspect of the hands-on laboratories. Teachers also (22.9%) praised the performance of the planetarians. Many visitors (48.4%) stated that the laboratory activity had no negative aspects, but some (12.9%) mentioned that the student groups should be smaller in the future.

Final remarks

The results presented here demonstrate the effectiveness of connecting science education and science communication through outreach structures already established in research units. This allows the reciprocal opening of the school to the surrounding community and, very importantly, the reciprocal opening of science to society. Indeed, that enables the community to better understand an institution, allowing new projects to arise and facilitating improvements to programmes’ infrastructure.

To achieve this, outreach institutions must have a deep understanding of the school curricula and design their activities accordingly. This requires working with teachers, co-creating with them (e.g., the CoAstro project[1]), and valuing their input.

In the future, we want to engage more teachers to reach more students, especially those far away from the science centres (and research units in general – democratising access to science). We additionally want to produce educational resources with a particular feature: those based on scientific innovations directly linked to the syllabus. In this way, our materials can be repurposed as alternative resources for educators to engage their learners in the practice of science.

Notes

[1] COASTRO: @N ASTRONOMY CONDO: https://condominio.astro.up.pt

[2] At the Planetário do Porto website, visitors can choose didactic sequences by school year or subject. These sequences include shows and hands-on activities. http://www.planetario.up.pt/pt/planearescolas

[3] The Teachers Training Plan at the Planetárium do Porto: http://planetario.up.pt/pt/evento/formacaodocente23_24

[4] The online questionnaire can be found at this link: https://apps.astro.up.pt/inqueritos/index.php/265879

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Biographies

Ilídio André Costa has a degree in biology and geology education, a Master’s in astronomy education, and a Ph.D. in teaching and dissemination of sciences. He is a middle and high school teacher but was deployed to PP-CCV in recent years. In addition, he is an author of textbooks on Natural Sciences, a teacher trainer, and, more recently, a researcher at IA.

Ricardo Cardoso Reis has a bachelor’s degree in astronomy and a Master’s in science education and communication. He is involved in strategy for the promotion of scientific culture by producing and presenting planetarium shows, writing press releases about research, presenting telescope observation nights (and days), and guiding hands-on activities.

Elsa Moreira is a driven astronomer with several years of experience in science and astronomy outreach. She is dedicated to remaining current with the latest technologies, methodologies, and trends in astronomy dissemination, bringing forth technical abilities in communication and the desire to provide the public with more knowledge about our Universe.

Build your own cardboard planetarium: A DIY experience for students

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Planetarium, DIY, STEAM

Planetariums are usually known as non-formal learning spaces and an incredible way to communicate astronomical and scientific knowledge. However, this potential increases when we build a planetarium because we add knowledge and fun to the space. In this project, we report on constructing a planetarium for this innovative and stimulating learning environment. Currently, there are several models of planetariums, some simpler and others quite complex; however, they are almost always places of passive interaction. Here, we propose to build a cardboard planetarium, which allows a remarkable application of the STEAM strategy in a Do-It-Yourself (DIY) project that can actively involve children from age 12 directly in the construction process. We have designed and built a cardboard planetarium, 4 metres in diameter, with a capacity to host up to 20 children or 10 adults per session. The planetarium is composed of a dome and a base for support; both are constructed from cardboard with different thicknesses due to the individual function of each one. A pilot planetarium was successfully exhibited during a science festival in Portugal. There are plans to build other DIY planetariums in countries across Europe.

Introduction

In a planetarium, people can observe a realistic view of the sky, but as *Plummer et al. (2011)* have noted, the audience of a planetarium session may be able to experience very complex or even impossible sights that cannot be commonly observed. For example, during a planetarium session, it is possible to see the sky from anywhere on Earth, or even in the Solar System, have lines linking the stars to form the constellations, zoom in to any planet to see fine details, or even observe the night sky without the atmosphere, and so on. There are several models of planetariums, from simple pin-hole-based star projectors to state-of-the-art digital projectors. No longer confined to a brick-and-mortar dome, planetariums can be portable, including smartphone apps that allow you to access planetarium software in the palm of your hand. With these, the user can change the view, the date and time, the constellation cultures, or the location on Earth and in the Solar System.

For many schools and astronomy clubs worldwide, the cost to construct a traditional planetarium or to acquire a portable planetarium can be prohibitive; in some cases, the price of this equipment can be higher than a school's annual budget. Do-It-Yourself (DIY) projects engage the public in a fun and educational way. *Hirshon (2020)* cited many DIY projects that practitioners can reproduce at home, in a classroom, office or outreach setting to understand how specific subjects in science work. In fact, when learners work on a team-based DIY project such as the work presented here, they develop a deeper understanding of the subject through hands-on learning and peer teaching: an excellent combination of citizen science and communication.

Why a planetarium?

Astronomy inspires feelings of awe and curiosity, as demonstrated by *Oliveira (2019)*. However, observational astronomy can be difficult to engage with, given the uncertainty of weather and the ever-growing issues of light pollution, particularly in urban areas. The planetarium, therefore, functions as an ideal place to witness a truly dark sky: a dark sky oasis. Inside a planetarium, the operator controls all observational parameters, including clouds, sky brightness, location, and even the presence of an atmosphere. The planetarium provides more opportunities for people to engage with a true dark sky.

According to *Gomes et al. (2017)*, the stimulation and development of non-formal learning opportunities, when added to formal practices, can elevate scientific knowledge in general and specific ways. *Gohn (2014)* noted that non-formal education is an indispensable tool for shaping the citizen. The author cited this tool as independent of the individual's social level of schooling. *Allast et al. (2022)* pointed out that non-formal education is particularly important for young people, as it is less structured and more flexible than formal education, thus influencing the attention and imagination of the youth. Similar results are noticed by *Menezes et al. (2018)*, who analysed data from scientific events about communication and teaching in science.

Furthermore, *Langhi & Nardi (2009)* claim that while astronomy learning can happen in several places, planetariums can be a more effective and scientifically intriguing environment. *Oliveira (2019)* highlights the importance of the planetarium as a place to learn and explore astronomy and science in general for the first time. Planetariums present a unique educational experience: the audience is immersed in a dark room where they stay for a limited time, watching a prerecorded narrative or a live presentation from a trained guide.

DIY planetarium

A DIY planetarium uses low-cost materials and a direct application of STEAM methodology. DIY planetariums have been in development for many decades (e.g., *Watson, 1950; Brozis & Świderski, 2018; Regester & McGahee, 2019*), each demonstrating the benefits of hands-on projects in educational settings with a multitude of different materials and designs.

The STEAM methodology for a DIY planetarium is direct. For example, by planning the construction of a planetarium, learners not only explore concepts from science, mathematics, and engineering but also those of the arts, technology, and innovation. These skills are additionally put to use when creating scripts for planetarium shows. Furthermore, the multidisciplinary nature of astronomy means it is possible to draw on concepts from other fields of science, making the planetarium an ideal place to communicate science (*Langhi & Nardi, 2009; Kukula, 2017; Marques et al., 2021*).

Our cardboard planetarium

The geodesic is a commonly used representation of a sphere using minimal parts. It is defined by its frequency, which is associated with the degree of approximation between a geodesic and a sphere; high frequencies mean less difference. *Regester & McGahee (2019)* explain that this frequency is also proportional to the number of triangles needed to construct the geodesic hemispherical dome and the difficulty of mounting the structure. *Müller (2005)* has an extensive mathematical explanation of the geodesic approximation for constructing domes. Summarising, a geodesic with frequency 1 (1v) uses only four triangles and looks like a pyramid; frequency 2 (2v) geodesics use 30 triangles, producing a decent approximation of a sphere; however, a frequency 3 (3v) geodesic uses 75 triangles, producing a structure similar to the iconic dome of a planetarium. Frequencies 4v and 5v are even better approximations. However, construction becomes increasingly more difficult with increasing frequency. During the planning phase, we tested small-scale geodesics with 2v, 3v, and 4v frequencies. We chose 3v due to its balance between form and mounting difficulty.

There are several materials suitable for building a planetarium. For example, in *Regester & McGahee (2019)*, the authors used a PVC structure and vinyl, and in *Brozis & S´widerski (2018)*, the authors used a parachute as a screen. Each of these activities used the same geodesic frequency described here. In this work, we prioritised cheap and easy-to-handle materials, ultimately deciding to construct our planetarium out of cardboard. Among the various cardboard types possible, we decided to use flat corrugated boards in two different thicknesses, according to the function they would perform in the planetarium structure: dome or base (Figure 1).

In this project, we decided on a planetarium with a diameter of 4.0 metres, which implies an area of 12.36 m^2 on the floor. This dimension is sufficient to allow 20 children, or 10 adults at maximum, in each session. We had the opportunity to test this estimation at the FIC.A festival (Oeiras, Portugal, 10-16 October 2022) at which we held a session with a school class of 19 children (about 8 years old), a teacher and the operator of the planetarium.

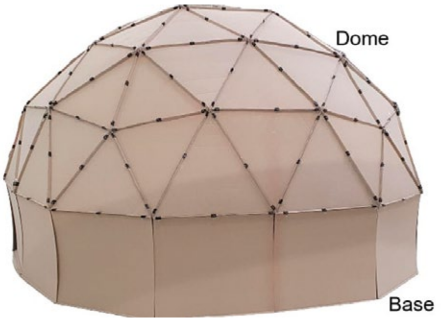

Figure 1 *Photo of the cardboard DIY planetarium mounted, indicating the dome and base.*

The dome

The dome used 3.0 mm thick cardboard cut into two types of isosceles triangles for a total of 75 triangle pieces. The two triangles are described below and graphically represented in Figure 2:

- Triangle X, a base of 81 cm and a lateral edge of 82 cm, a total of 45 triangles
- Triangle Y, a base of 81 cm and a lateral edge of 70 cm, a total of 30 triangles

To connect the triangles, we added tabs to each edge, shown in grey in Figure 2. These tabs must be folded for the assembly step. The dimension of each tab is 2 cm in height along all the triangle's edges. During our

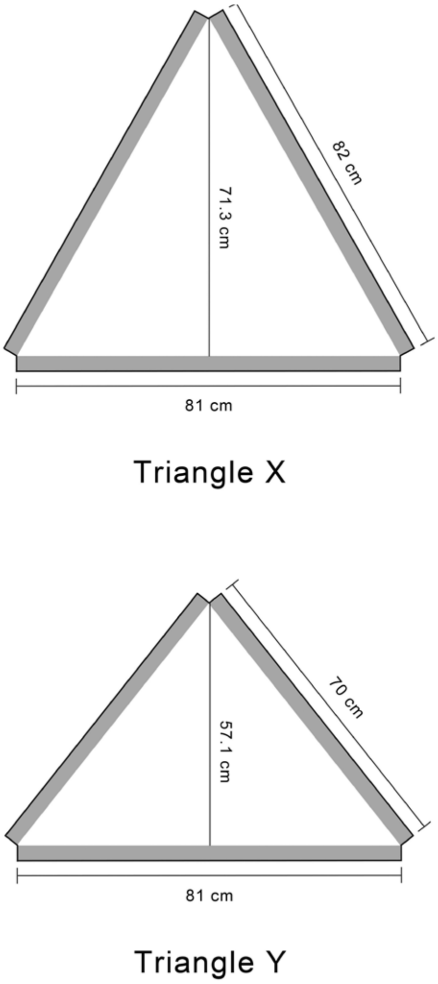

Figure 2: *Schematics of the triangles X and Y and their dimensions. Tabs (used for assembly) are shown in grey.*

planning phase, we tested several methods to join the pieces and found that binder clips were the best solution.

To cut the triangles more easily and ensure they are all the same shape, we created a wood template using a CNC machine. A Computer Numerical Control (CNC) machine processes a piece of tough material to meet specifications by following coded instructions and without a manual operator. In the absence of a CNC machine, the pieces can be cut using a template made from any sturdy material.

The inner part of the dome should be able to reflect the light from the projector, but the natural colour of the cardboard absorbs much of the incident light. Therefore, after the triangles were cut, we painted one face of each one with water-based white paint to mimic the projector screen inside the dome of a stationary planetarium.

The base

To make the base of the planetarium, which supports the dome, we created fourteen 81 x 74 cm rectangles from 5.0 mm thick cardboard. As we did for the dome's triangles, we added tabs on each rectangle edge to facilitate construction. The tabs on the edge of 81 cm were linked with the triangles on the end of the dome, again using binder clips. The final height of the base is 74 cm. This is lower than what might be ideal, however, we were limited by the size of the cardboard pieces. In fact, to build a complete base, it is necessary to use 15 pieces, but we used 14 because one free space would be the planetarium door.

In our previous tests, the base supported the planetarium dome well for three days. After that, we needed to change some rectangles because of the structural stress. This is a portable planetarium, and the structure is designed to be easily constructed and deconstructed for use in multiple locations. Based on our experience, the rectangles that form the base can be reused three times if they are used for less than one day in each iteration. As discussed below, the full planetarium constructed at FIC.A stood for the full week-long festival, providing a rough upper limit to the longevity of the planetarium base.

Assembling our planetarium

To help us during this stage, we decided to label each tab of the triangles with a letter; the sides should only be joined if the letters match. For Triangle X, the base is labelled A and the legs are labelled B. Similarly, for Triangle Y, the base is labelled A, and the legs are labelled C.

The dome assembly used a layer scheme. That is, we connected the triangles to form the central pentagon at the top of the dome and then continued to the next layer. Figure 3 shows the complete scheme of assembling the dome. Each layer approximates a ring of triangles, represented by light (ring 1) and dark (ring 2) grey in Figure 3. This procedure made assembly easier and the links stronger, as we had more time to connect the tabs. Time is an important factor: after starting the assembly process, we needed to construct each ring quickly, as the structure may collapse if the dome stays unbalanced (i.e. if one side is bigger than the other) for a long period of time.

Figure 4 shows the step-by-step process of assembling the dome, which we have also demonstrated in a YouTube video[1]. At the end of the process, the dome has a height of 1.9 metres and a diameter of 4 metres.

Up to this point, two or three people could do the whole process. However, connecting the base to the dome required more help: at minimum, six people. Four people held the dome aloft, and two others connected the bottom of the dome to the rectangles from the base.

The connection of the base must be stronger to support the structure; it is a good idea to reinforce all links between the rectangles with duct tape, for example. In addition, warning tape (e.g., a red and white band) should be placed along the bottom edge of the rectangles on the inside surface of the structure so the audience does not get too close to the wall.

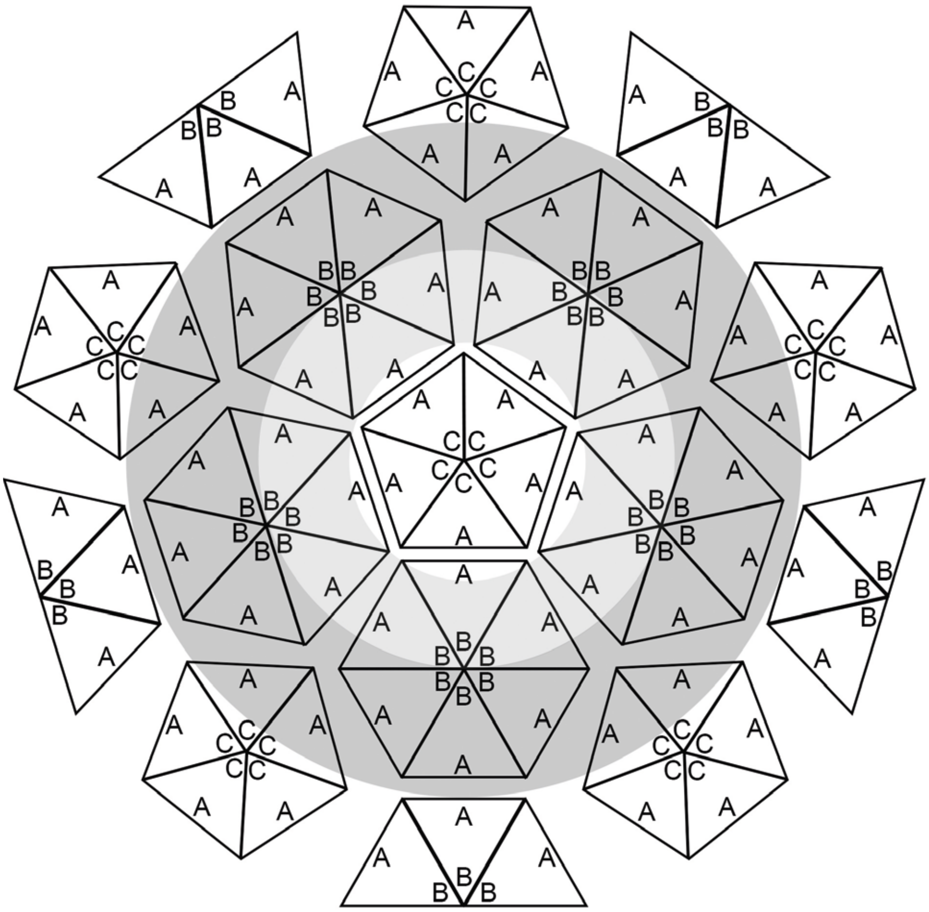

Figure 3: *Assembly scheme of the dome. The triangles from Figure 2 are shown in formation with the construction rings in greyscale.*

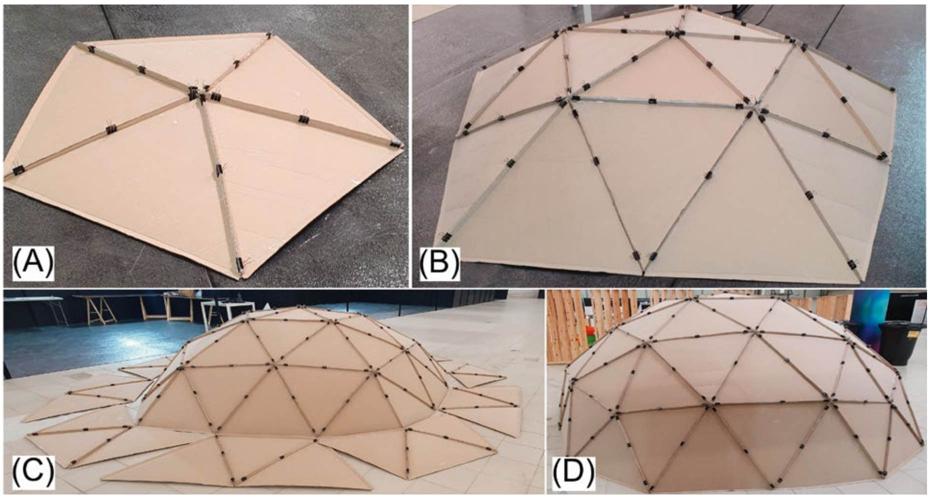

Figure 4: *Step-by-step process of the assembly of the triangles: (A) the central pentagon, (B) adding the first layer, (C) positioning the last layer and (D) the dome mounted.*

The complementary systems

The complementary system comprises two parts: the projector system and the comfort system. Both components require electricity, so the DIY planetarium design must consider this.

The projector system consists of commercial devices, like a laptop, speakers, a projector, DSLR camera lenses, and a custom-built support printed using an ordinary 3D printer. Figure 5 shows this projector system with its two camera lenses. An upcoming article will discuss the projector system, the geodesic approximation used, and the different frequencies possible in depth.

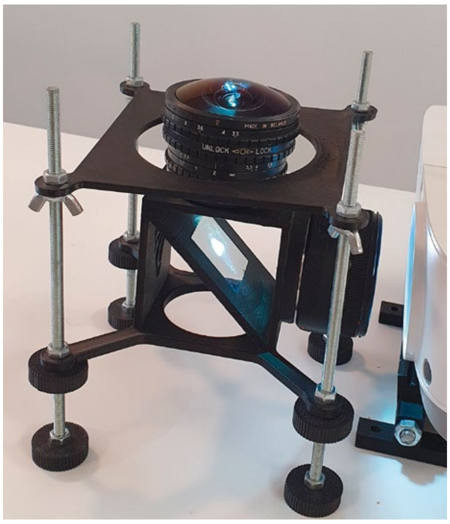

Figure 5: *The projector system that is used inside the cardboard DIY planetarium.*

One of the two lenses has an aperture size of 50 mm and a focal ratio equal to 1.8 (f1.8); the ratio of the focal length of the lens to its aperture), which focuses the light from the projector via a small flat mirror inside the custom-built support. The other is a fish-eye lens with an f3.5. focal ratio and a focal length of 8 mm, which uniformly spreads the light onto the dome's interior. These specifications are necessary to guarantee the correct projection inside the planetarium and the correct optical alignment with the custom-built support used.

We used a 4,000 lumens full-HD LED projector that is sufficient to project a dark sky with a good resolution in the dome. An ordinary laptop installed with Stellarium[2] and VLC[3] was used for the planetarium live session and videos. We chose these because both are open source and available for multiple platforms.

The comfort system consists of a small low-noise fan to keep air moving inside the dome and ensure all inside are comfortable.

The next step: D.O.M.E. Project

During the presentation of our DIY cardboard planetarium in the FIC.A festival in 2022, we noted that many teachers demonstrated intent to replicate this project in their schools, and students demonstrated a genuine interest, too. This result was bigger than we imagined when we started this project. Our idea was simply to show an alternative to a portable planetarium in a DIY project.

Therefore, after this good reception, we decided to implement a formal project with support from the Erasmus+ Programme of the European Union and partnerships in three countries, namely Greece, Ireland and Portugal. We named this the D.O.M.E. Project, an acronym meaning Design your Own Multimedia learning Environment.

This project is divided into two parts, the first of which was the pilot in January 2023. Three Oeiras, Portugal schools built their own DIY cardboard planetarium during their Science Club classes. Students aged between 10 and 16 worked on these prototypes and did a final presentation to the local community in early July 2023.

The next part will start in October 2023, when some schools from each partner country will build a DIY cardboard planetarium and prepare their own planetarium presentation. The final results of this work will be available on the project's website[4], along with all documents necessary to replicate this project in your community, ensuring its sustainability and legacy. We hope this will be a helpful resource, allowing students, teachers, and communities to actively engage in the planetarium experience.

Conclusion

The realisation of the cardboard planetarium project marked a significant achievement in creating an innovative and engaging learning environment for astronomy and scientific exploration — the successful mounting and operation of the planetarium during the week-long[5] FIC.A Festival in Portugal showcased its potential as a dynamic platform for educational outreach. Students aged 8 to 17 from over 20 school classes participated in immersive planetarium sessions. The project effectively demonstrated its ability to captivate and educate a diverse audience.

Even more, the cardboard planetarium project engagement of local schools, where the students created their own planetarium during school time, highlighted the importance of integrating creativity, hands-on learning, and scientific knowledge dissemination. By leveraging the appeal of a DIY project to build a cardboard planetarium, the project effectively offered a tangible and exciting means of imparting complex concepts to learners of all ages. As this initiative gains momentum and inspires the creation of similar projects, this project stands as a beacon of educational innovation and collaboration in astronomy and STEAM education.

Acknowledgements

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Notes

[1] YouTube link for dome construction: https://youtu.be/iDMfMsSIO24

[2] Stellarium software: https://www.stelarium.org/

[3] VLC software: https://www.videolan.org/vlc/

[4] D.O.M.E. community portal: https://www.dome.nuclio.org/

[5] In the construction presented here, the dome and base structure lasted the entire week-long FIC.A festival. However, we cannot guarantee that the base's structure from the same design will hold longer than that. Refer to Note 4 for other designs from the D.O.M.E. project.

Biographies

Vinicius de Abreu Oliveira has a PhD in physics and astrophysics from the Federal University of Santa Maria (2009), Brazil. He has much experience as a professor and researcher in astronomy, physics and space geoscience. In 2015, Vinicius started to work in astronomy outreach, using a mobile planetarium. Since 2022, he has worked as the Project Manager at NUCLIO in Portugal.

Frances McCarthy is the Education & Outreach Officer at MTU Blackrock Castle Observatory. She studied physics and astronomy at the University of Toronto, Canada. She has worked in formal and informal education environments in Canada, the UK and Ireland and develops and delivers education workshops and activities for all ages. She has worked in planetariums since 1984, at European Small and Portable Planetarium Conferences and the annual conference of the British Association of Planetaria.

Niall Smith studied astrophysics at the University College Dublin. He lectured in the Department of Applied Physics & Instrumentation at Cork Institute of Technology for 18 years before becoming the Institute's first Head of Research in 2005. In 2020, he was awarded the SFI Research Image of the Year for work on using astrophysics techniques to determine the efficacy of masks against Covid-19.

Priscila Doran has an MSc in biology and is a certified trainer. She coordinates interdisciplinary projects that connect art and science and collaborates on the creative design of NUCLIO's dissemination material.

Emmanuel Chaniotakis has an MSc in physics and has worked as a researcher at the RnD department of Ellinogermaniki Agogi School in Greece since 2015. He has a long experience as a high school and university physics tutor in Greek private educational institutions.

Gustavo Rojas has a PhD in astrophysics from USP, Brazil. He has worked as an astrophysicist at São Carlos Federal University, Brazil, and since 2012, he has been a member of the organising committee of the Brazilian Astronomy and Astronautics Olympiad (OBA). Additionally, he has acted as the team leader of the International Olympiad on Astronomy and Astrophysics (IOAA) for Brazil and Portugal.

Rosa Doran has a PhD in Science Education from the University of Coimbra and is a certified trainer by the Scientific and Pedagogical Council of Continuous Training (University of Minho, Portugal). She is the president of the executive council of the Global Hands-on Universe Association, the chair of the Galileo Teacher Training Program, the vice-chair of the panel of education of COSPAR, and the co-chair of the IAU/PLOAD.

Did you know that Stellarium, the free planetarium software, allows you to experience the sky with the star lore of more than 30 cultures? These include educational information, traditional names, and artwork from the Aztec, Maori, Dakota/Lakota/Nakota, Sami, and Tupi-Guarani cultures, and many more. Pictured here is the star lore of pre-Colombian Mayan civilisation. The accompanying information is a brief introduction to Mayan astronomy and constellations, compiled by two researchers at the Archaeoastronomy and Cultural Astronomy Department at Space Sciences Faculty, Universidad Nacional Autonoma de Honduras: Eduardo Rodas-Quito and Javier Mejuto, who is also the IAU National Outreach Coordinator for Honduras.

Image Credit: Stellarium

The NOVA Mobile Planetarium: Ten best practices for planetarium projects based on an astronomy education success story

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Keywords:
Mobile Planetarium, Astronomy Education, Best Practices, Immersive, International, Science Communication

The Netherlands Research School for Astronomy (NOVA) has operated a Mobile Planetarium for over 14 years. Between 2009-2023, the project reached more than 400,000 learners and their teachers across the Netherlands. The project has been popular with schools since the beginning but continues to grow and reach increasing numbers of learners and schools each year. A project like the Mobile Planetarium does not continue growing this way without developing key ingredients or best practices. In this article, we describe the NOVA Mobile Planetarium project in detail and the challenges faced over the last 14 years. Reflection on the different aspects of the project has led to 10 best practices which have been critical to the continued success of this project. In this article, we aim to share our experiences to help other mobile planetarium projects around the world.

Introduction

The NOVA Mobile Planetarium project has been visiting schools across the Netherlands since 2009. Between 2009-2023, the project reached more than 400,000 learners and their teachers, and the demand for school visits continues to grow. In this article, we reflect on the last 14 years to understand which ingredients have led to our success, even in the face of challenges such as the Covid-19 pandemic. After introducing NOVA, we describe in detail the project's key features, including the technical setup, the planetarium team, and our educational vision and approach. In the sections following, we convey practical aspects relating to a typical planetarium visit and how this is funded. We additionally reflect on the project's flexible ethos, particularly during challenging times. Finally, we discuss special projects, collaborations with other projects and our vision for the future.

We have synthesised these reflections and ingredients into 10 best practices, which provide a blueprint for a successful mobile planetarium project. These are presented separately from the main text to highlight this information further. To aid the reader, we have clearly linked each best practice, listed at the end of this article, to one or more sections in the text.

NOVA

NOVA is the partnership of four Dutch astronomy university institutes in Amsterdam, Groningen, Leiden, and Nijmegen. NOVA aims to bring together astronomers, foster collaborations and be the hub for projects on a national scale (e.g., building instruments for telescopes) and national memberships to large international organisations (e.g., the European Southern Observatory). In addition, NOVA facilitates national-level public engagement and school-level education projects through its dedicated Information Centre (NOVA-NIC).

In 2009, during the UN/IAU International Year of Astronomy, the NOVA-NIC began a mobile planetarium project for primary and secondary-level education. The project aims to give "every child in the Netherlands an unforgettable science experience during their school career" (*NOVA, 2018*).

The project has grown significantly in recent years. The planetarium now visits around three times as many schools per week compared to its first years of operation. The project has also developed new, innovative content, including introducing real astronomical data into the dome. In the last few years, the planetarium has not only expanded within the Netherlands but has also been involved in developing new planetarium projects in Namibia (e.g. *Honsbein et al., 2023; Holt et al., 2020b*) and Chile (e.g., the 100 planetarium project led by former ESO Alma Director Thijs de Graauw).

The NOVA Mobile Planetarium

The NOVA Mobile Planetarium operates three inflatable domes, the most recent addition in 2023. The domes have an internal diameter of 5.5 metres and accommodate around 30 visitors, approximately 1 school class. The NOVA-NIC coordinates all mobile planetarium visits to schools in 9 out of the 12 Dutch mainland provinces. Two further domes based in Groningen and St Eustatius cover the three northernmost provinces of the Netherlands and parts of the Dutch Caribbean, respectively. The Groningen and St Eustatius planetariums are coordinated separately, although NOVA provides software support and advice to both projects. Figure 1 shows an internal

Figure 1: *Inside the dome of the NOVA Mobile Planetarium inflatable domes at a school in the Netherlands. The presenter is explaining the Moon's craters. The presenter and equipment sit in the middle of the dome; visitors sit on cushions around the dome's edge. Image Credit: J. Holt/NOVA.*

view of one of the NOVA Mobile Planetarium domes.

The NOVA Mobile Planetarium runs state-of-the-art planetarium software with a customised dashboard that allows for full flexibility during shows and was designed according to our didactic approach. With just one or two mouse clicks, presenters can rapidly change the imagery to answer questions on topics as diverse as satellites, objects in our Solar System, other galaxies and black holes in quick succession.

The three NOVA mobile planetariums use different high-quality laser projectors to project onto the dome. All projectors have a high resolution (WUXGA 1920x1200 & 4K UHD), a high optical output (6500, 6000 & 5000 lumens) and a large contrast (ranging from 1:20,000-1:500,000). Two projectors use a fixed, custom-made optical block to project the image onto the dome. The other projector has interchangeable lenses and is, therefore, capable of flat-screen and dome projection.

Several additional small items complete the NOVA Mobile Planetarium setup, including a table, 32 cushions, and two 20-metre extension cords (one of which is suitable for outdoor usage; though the planetarium dome is designed for indoor use, occasionally, the planetarium is used outside on a marquee with a floor). The full planetarium setup can be transported in a small car, with vulnerable components secured in custom-made flight cases.

The NOVA Mobile Planetarium: A team with specialised skills

The NOVA Mobile Planetarium project and team are coordinated by the NOVA Education Manager based at NOVA-NIC. The Education Manager is supported by a Planetarium Expert. Planetarium shows are given by both the Education Manager and the Planetarium Expert, but predominantly by a team of 35 university astronomy students. The domes are transported by a pool of more than 10 drivers. Only the Education Manager and Planetarium Expert are NOVA staff; Planetarium Presenters and drivers work freelance. Our experience has been that having well-qualified individuals at all levels of the planetarium is integral to its success. In this section, we discuss in detail the individual skill sets of the team.

The Education Manager

The NOVA Education Manager is a part-time role; the current Manager (an astrophysicist with more than a decade of experience in public engagement and education) combines this role with science education research at a separate institute. Historically and currently, the NOVA Education Managers have had the interest in astronomy and educational skills needed to give shows at schools regularly.

The Planetarium Expert

The Planetarium Expert holds a joint master's degree in astrophysics and science communication. Over the last decade, the Planetarium Expert has become skilled in planetarium programming, developing custom content to facilitate fully live and interactive planetarium shows. The Planetarium Expert continues to give shows regularly.

The Planetarium Presenters

Astronomy and astrophysics students are invited to work as Planetarium Presenters at any time from the start of their second year in university. Planetarium Presenters work freelance but are required to give a minimum commitment to give shows at least one day per month for at least one year. In general, Planetarium Presenters continue to work for the planetarium for much longer than this, typically until they finish their studies. Initially, most Planetarium Presenters were senior-year bachelor's or master's students. However, following a significant rise in bookings, the Planetarium Presenter Team now includes people from their second year in university to PhD students.

At the time of writing, the Planetarium Presenter Team is approximately 50 per cent male and female and includes presenters from different cultural and ethnic backgrounds. NOVA has chosen to work with a team of students to increase the accessibility of the role models – for upper-secondary school learners, the age difference between the Planetarium Presenter and the visitor can be as little as 1-2 years, meaning that learners can much more easily identify with the presenter and visualise themselves as an astronomy student (e.g., *van Gurp, 2022*). In addition, small inaccuracies in student explanations – which came across to learners as "astronomers don't have to be geniuses" – were cited as positive experiences that helped them to make the final choice to apply for a university course in astronomy and (astro)physics (*van Gurp, 2022*).

The Planetarium Transport Team
The rising popularity of the mobile planetarium called for a larger team and efficiency in logistics. A pool of freelancers transports the planetarium, most of whom are students. The planetarium is typically collected at the end of the school day and immediately driven to the next location for the following school day in a continuous relay. This approach is not only efficient and cost-effective, but it is also much easier to arrange cover should a driver unexpectedly be unavailable at the last minute.

Live and interactive planetarium shows

The NOVA Mobile Planetarium shows are fully live and interactive. There is no set script, and each show is tailored to the knowledge level and interests of the visiting group. For school visits, the contact teacher is asked in advance which age group(s) will visit the planetarium and whether certain topics should be covered in the shows to align with the classroom curriculum. In addition, Planetarium Presenters are trained to encourage planetarium visitors to ask questions, usually by asking the audience questions.

A typical show has a standard story build-up or learning pathway: shows start close by and move slowly further away, literally and figuratively. For example, the planetarium software is set to the location and start time of the physical show, which moves forward in time to explore what is visible during the coming night and then progresses through the Solar System to other parts of the Milky Way and beyond. In addition, concepts discussed can slowly become more complex and abstract, the precise level of which is determined by the age group and knowledge level of those in the planetarium. This didactic model is illustrated with a few examples of learning pathways in the planetarium in Figure 2.

The choice for live and interactive planetarium shows that build up from familiar experiences (e.g., phases of the Moon, the seasons or the tides) to more abstract ones (e.g., stars and planets outside our Solar System and galaxies beyond the Milky Way) is based on several science education principles:

- The level of the planetarium show should be appropriate for the knowledge level and curriculum of the age group. For example, from the middle of primary school in the Netherlands, it is possible to show the Universe to the largest scales (e.g. with the Bright Galaxy catalogue) when the focus is on the number and different types of galaxies. Asking questions and encouraging learners to ask their own questions allows the Planetarium Presenter to better judge the level of the group, in addition to the information already received from the school. The group will lose interest if the content is too difficult or easy (*Vygotsky, 1978*).
- (2) The group's interests should (at least partially) influence the precise topics in the planetarium. This increases motivation and interest and boosts learning (e.g., *Marell & De Vaan, 2020*).

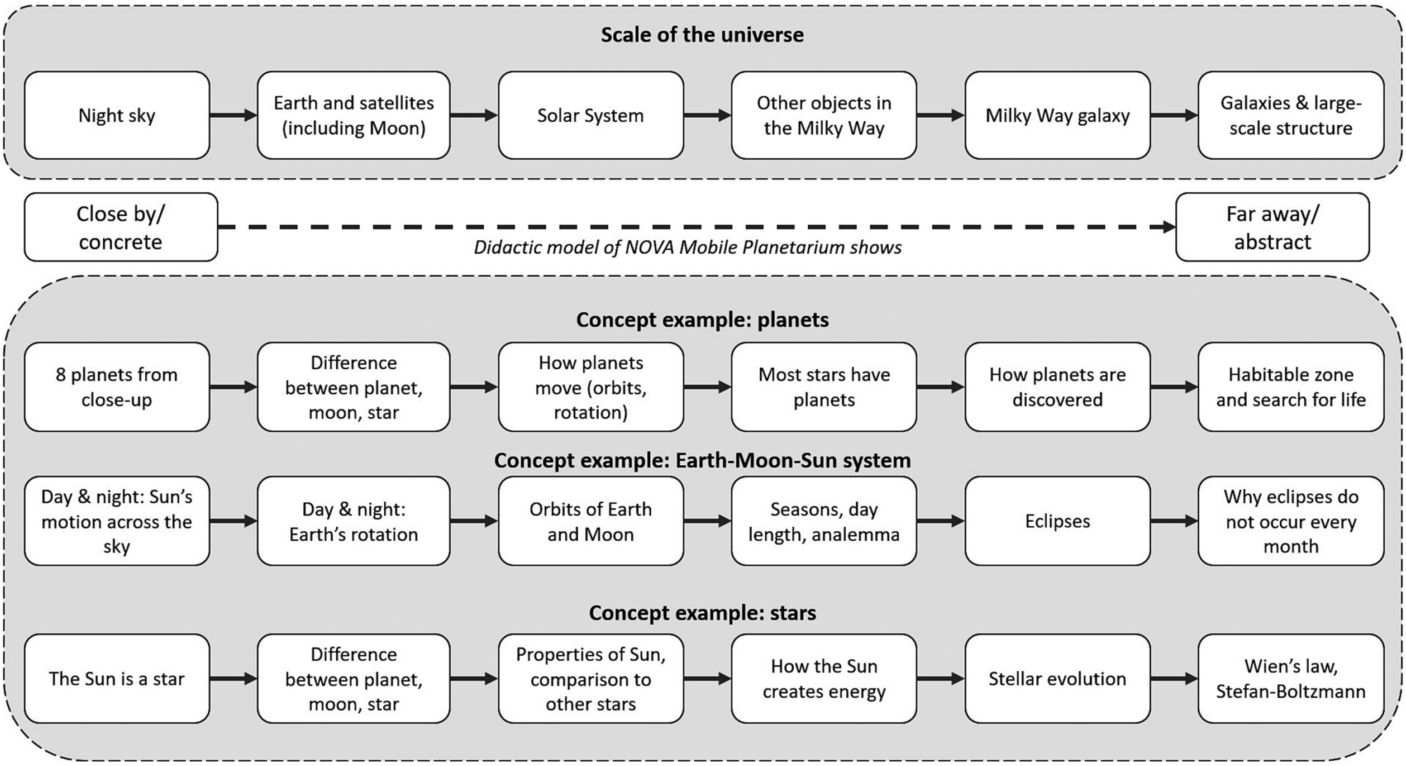

Figure 2: *The NOVA Mobile Planetarium shows are not scripted. Shows follow a standard story build-up or learning pathway, from close-by the learner to far away, both in terms of physical distance and level of conceptual abstraction. Here, these two ideas are illustrated with several examples. Note that the physical and conceptual scales are not linear and do not necessarily correspond.*

- Research has shown that the immersive environment of the planetarium plays a significant role in visitor experience, particularly in knowledge retention (e.g., *Zimmerman et al., 2014*). Another powerful visualisation tool within the planetarium is the ability to compare in real time various properties of different astrophysical objects (e.g., differences in size between various planets, moons or stars). Figure 3 illustrates this with a specific example from the NOVA customised dashboard.
- The three-dimensional space in a planetarium dome is particularly effective in teaching three-dimensional concepts (e.g., *Sumners et al., 2008; Plummer, 2009*) compared to how astronomy and astrophysics are conventionally taught. It is, therefore, crucial to schedule sufficient time inside the planetarium, allowing time to answer learners' questions within the planetarium environment. It is also crucial to compare and link astrophysical facts and concepts to experiences the planetarium visitors will relate to. For example, it can be much more meaningful to inform learners that the *International Space Station (ISS)* is approximately the size of a football field instead of giving the precise size in metres.

Whilst many planetariums in the Netherlands offer films and pre-scripted planetarium shows, some also offer live shows. However, these typically follow a pre-scripted show read aloud by a live planetarium guide. The NOVA Mobile Planetarium approach of fully live and interactive planetarium shows is employed by only a relatively small number of planetariums in the Netherlands. This approach is only possible because all planetarium presenters have a strong background in astronomy and astrophysics. This approach, combined with the focus on full lessons rather than short experiences, allows planetarium presenters to use the dome environment to answer visitor questions.

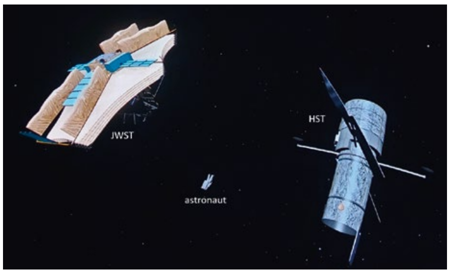

Figure 3: *Size comparison between the* James Webb Space Telescope (JWST), Hubble Space Telescope (HST) *and an astronaut. The visual comparison of the telescope sizes to tangible objects, such as a person, is more meaningful than quoting the precise size in metres. Image Credit: J. Holt/NOVA.*

A typical planetarium visit

The NOVA Mobile Planetarium currently visits more than eight schools across the Netherlands each school week. One Planetarium Presenter attends a school for each visit and gives all planetarium lessons that day.

The day of the visit

A school visit typically begins between 07:30 – 08:00, with lessons beginning at around 08:30. Schools provide a draft timetable, including a minimum of two breaks. A school visit ends no later than a typical day at primary school (15:00), after which the planetarium is disassembled and transported to the next location.

Maximum number of lessons per day

The maximum number of lessons is 6-7 (45-50 minutes) at secondary schools. At primary schools, 6-8 lessons are typically given with a mix of shorter and longer lessons. This is because the attention span of the average child increases dramatically between the ages of 4 and 11 years (e.g. *Betts et al., 2006*). The number of lessons is restricted to ensure each group spends enough time in the planetarium, and as such, only one Planetarium Presenter is required. Research shows that the immersive environment of the planetarium itself, plus the ability to visualise three-dimensional concepts, is key to the impact of a planetarium visit (e.g., *Sumners et al., 2008; Plummer, 2009; Zimmermann et al., 2014*). Many shorter lessons without breaks are untenable for one Planetarium Presenter alone and often lead to a double programme, consisting of a short planetarium experience followed by classical mini-explanations outside the planetarium. We typically avoid this type of programming because it requires more personnel to make the day workable. Exceptions are only made for special events, such as teacher conferences (where the goal is to give as many teachers as possible an idea of what the project can offer) or an event such as an eclipse (with a custom-made short presentation).

Despite the strict maximum number of lessons for school visits, the NOVA Mobile Planetarium averages 200 learners per day with each of our planetariums.

Further contact with the school

A planetarium visit begins several weeks or months before the actual visit. Promotion is through the NOVA website[1], newsletter, social media accounts and attendance at teacher conferences. All bookings are made by the initiative of the school, and all schools are allowed to request topics to be included. After the visit, schools are asked for feedback. Any issues are discussed and fed back to the individual or team of presenters as appropriate. Positive feedback is always shared with the whole team to boost the team's feeling of achievement.

Special Events

The planetarium is also available for educational events (e.g., University open days) and occasional private hires. All events are agreed on individually and can occur in the evenings or weekends. Planetarium shows at events typically last about 25-30 minutes. Events such as these usually have a full schedule, so it is common for more than one Planetarium Presenter to attend. At these events, the number of visitors can easily reach 400-500 per day per dome.

The NOVA Mobile Planetarium budget

The NOVA Mobile Planetarium project is a low-budget, non-profit project. NOVA, its universities and other research organisations have sponsored some of the high costs, such as purchasing the planetariums and essential upgrades and repairs. NOVA also pays the salaries of the Education Manager and the Planetarium Expert. The schools and events visited cover day-to-day running costs (transport and presenter freelancer reimbursement). Schools in the Netherlands typically have a budget for activities through the educational budget (most common for secondary schools) or the annual voluntary parental contributions (most common for primary schools). Extra financial support also comes from contributions for private-hire events. Should any funds remain at the end of a financial year, these are used to cover maintenance costs or upgrades.

Flexibility

Flexibility is a key pillar of the NOVA planetarium team ethos, whether trying to squeeze in an extra last-minute booking or going the extra mile to ensure a visit can still go ahead when faced with unexpected obstacles. This has never been more true than during the Covid-19 pandemic. Whilst most planetariums worldwide were forced to close for an extended period, the NOVA team was determined to find a way to continue reaching learners across the Netherlands. In this section, we summarise a few key points and refer the readers to *Holt (2020a), Holt & Hanse (2021)* and *Holt, Hanse & Baan (2021a)* for more details.

Instead of accepting a long closure, NOVA invested in a high-quality flat screen and made modifications to the software, reaching out to schools with the message that the planetarium team would think outside of the box and be flexible. Whilst most school activities were heavily restricted for most of the pandemic, those deemed essential for educational purposes were permitted access at the discretion of individual school management teams. Many schools identified the NOVA Mobile Planetarium programme as a key part of their science teaching and granted access, providing the basic mandatory Covid-19 measures were adhered to. As such, planetarium visits using a flat-screen commenced in early July 2020, just 3.5 months after the first lockdown, and continued throughout the pandemic, with interruptions only during periods of full lockdown in the Netherlands.

This flexible approach has led to a rapid increase in the project's reach (Figure 4). Even before the end of all Covid-19 restrictions in the Netherlands in May 2022, planetarium bookings had increased to 1.5 times pre-pandemic levels, and growth has steadily continued, with bookings in mid-2023 at almost 3 times pre-pandemic levels. Furthermore, there has been a significant change in the types of bookings. Before the pandemic, approximately 80 per cent of bookings were for secondary schools. Currently, only 40 per cent of visits are to secondary schools, and more than 50 per cent are to primary schools. Bookings at other events have returned to pre-pandemic levels.

Special projects and collaborations

The NOVA Mobile Planetarium project regularly works on special projects. These projects aim to increase the possibilities for the Planetarium Presenters during their shows and enable them to discuss and answer questions about topics currently in the public eye whilst still making use of the unique possibilities in the planetarium. Key areas of interest are:

- Developing content around current topics of interest, including a solar or lunar eclipse or the launch of new space telescopes such as *JWST* and *Euclid* and their science.
- Incorporating real data into the planetarium. Examples include using cosmological simulations (e.g., from the EAGLE and Illustris collaborations), images of the supermassive black holes in the centres of M87 and our own Milky Way galaxy from the Event Horizon Telescope (EHT) consortium and actual exposures from the MeerLICHT and BlackGEM telescopes in the project Stargazing Live! (*Holt et al., 2022a, 2023b; Bredeweg et al., 2023a,b,c*). Planetarium content is available via *NOVA (2023)*.
- Collaborating with science education researchers to create lessons linked to the planetarium project using smart education tools (e.g. *Bredeweg et al., 2023a,b,c; Holt et al., 2022a, 2023*). Schools regularly request lesson materials to expand on topics covered in the planetarium. Lesson content is available in English and Dutch (*NOVA, 2023*).

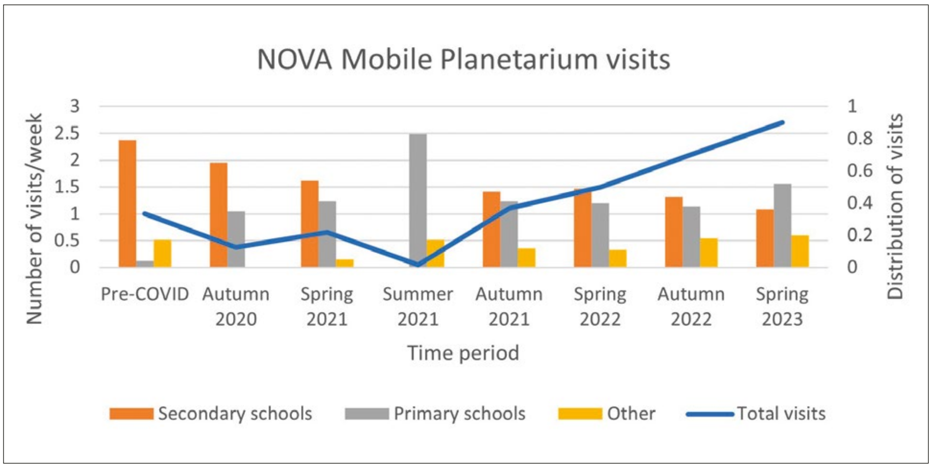

Figure 4: *The distribution of NOVA Mobile Planetarium visits. Line chart/left-hand y-axis: The total number of visits as a function of pre-Covid-19 levels (based on average visits per school week). Bar chart/right-hand y-axis: Distribution of visits per type (secondary school, primary school and other). This graph does not include planetarium shows given in the supported domes in Groningen and St Eustatius or the shows in Museon-Omniversum in The Hague.*

Supporting others

The NOVA Mobile Planetarium team is actively involved in supporting other planetarium projects across the world. It is important that established projects, such as the NOVA Mobile Planetarium, support other projects. This is not only beneficial to the other projects but also brings important learning opportunities for the NOVA planetarium. The following subsections describe the projects that are supported, to varying degrees, by NOVA.

The Museon-Omniversum Planetarium in The Hague, The Netherlands

Museon-Omniversum is a museum with a large (300 pax) dome theatre. NOVA began collaborating with Museon-Omniversum in late 2020 and now runs all of its planetarium activities, including bi-monthly Star Parties for different levels, themed evenings (e.g. *JWST, Euclid*) with a guest speaker and school lessons.

The mobile planetarium project in St Eustatius, Dutch Caribbean

This planetarium was set up in 2020 and is run by the former NOVA Education Manager. NOVA provides software support, and ideas are exchanged regularly.

The mobile planetarium project of the Africa Millimetre Telescope (AMT) in Namibia

NOVA provides the AMT-planetarium project with the highest level of support. See, for example, *Holt (2020b), Holt et al. (2022b), Honsbein et al. (2023)* and The Africa Millimetre Telescope Project website[2] for more details.

The 100-planetarium project (fixed domes) in Chile

Former ESO-ALMA Director Thijs de Graauw is embarking on an ambitious project to build 100 fixed planetariums across Chile. NOVA regularly provides advice for this project.

Future plans

The NOVA Mobile Planetarium project is successful and established. In the pre-pandemic period, the project was already reaching approximately 30,000 visitors per year and had been achieving this for many years. At the time of writing, the NOVA Mobile Planetarium project is running at capacity and cannot currently fulfil all booking requests. However, as discussed above, new situations, whether it is a global pandemic, supporting a new planetarium project in another country, or even the introduction of new team members, can give a change in perspective to transform a project to the next level.

The relative quiet of the pandemic period allowed several new projects and collaborations to start. In addition, the team reflected on the visits to the mobile planetarium in the Netherlands. By creating an interactive map of all visits since 2009, it became clear that there is a problem with the distribution of visits: under-resourced areas of the bigger cities and large rural areas of the Netherlands are structurally missed. The NOVA Mobile Planetarium needs to increase the diversity of the schools and learners it reaches.

The planetarium team is actively working towards finding a solution to this problem. NOVA has recently secured funding to purchase a new planetarium and undertake a small research project to understand why the project is not reaching certain areas of the country. This research will be done in late 2023 and will devise a plan to reach out to these areas. The team is currently applying for more funding to implement this plan. One expected outcome is the need to fund partially subsidised visits, either for visits to schools that cannot pay the planetarium costs or special events for teachers to introduce them to the project. NOVA currently visits more than 300 schools per year with 2 domes. With the addition of the third dome, we aim to increase the number of visits by 50 per cent within the next 5 years to 450 schools per year, of which half of the new schools are drawn from underserved areas.

Conclusion

We describe the NOVA Mobile Planetarium project run by the NOVA Information Centre in the Netherlands. Between 2009-2023, the mobile planetarium reached more than 400,000 learners and their teachers. Since the start of the pandemic, the project has entered a new phase, including new projects and collaborations both in the Netherlands and abroad. The planetarium visits have also rapidly expanded over the last eighteen months, with visits at almost three times pre-pandemic levels. In this article, we reflect on the last fourteen years and propose 10 best practices as a blueprint for a successful mobile planetarium project.

10 Best Practices for Mobile Planetarium Projects

BP1: Live and interactive planetarium shows

Give live and interactive planetarium shows. Tailor your shows to include recent events (e.g., an eclipse) and results (e.g., new data from *JWST* or *Euclid*) and allow questions from the audience to influence what you include in a show. This is a didactically strong and highly motivating approach, matching the show's content and level to the audience's interests and background.

See Sections: *The Nova Mobile Planetarium*; *Live and interactive planetarium shows*; and *Special projects and collaborations*.

BP2: Need for experts at all levels of the planetarium team

BP1 requires that the planetarium presenters have a solid background in astronomy. Running a successful planetarium is a profession in its own right and requires experts with specific skills in the management team. We argue that a successful planetarium requires a management team with experience and skills in astronomy, science communication, science education, science education research and planetarium programming. The management team should also be hands-on, regularly visiting schools and giving shows.

The correct skills and hands-on experience allow the management team to provide the right kind of training to the planetarium presenters and give insights into how best to develop the project in the future.

See Sections: *The NOVA Mobile Planetarium: A team with specialised skills*; *Live and interactive planetarium shows*; and *Special projects and collaborations*.

BP3: Work with a diverse group of astronomy students as accessible role models

Astronomy students have a solid background in astronomy (**BP2**). Working with a diverse group of students (e.g. good male/female mix and including team members with a variety of ethnic and cultural backgrounds) ensures learners see various role models. In addition, a small age gap between presenter and learner increases the likelihood that learners will see the presenters as role models. Interestingly, the fact that students sometimes make small mistakes and/or do not know the answer to questions has also been found to be inspiring to learners as they realise that an astronomer or scientist is not necessarily perfect. Further, the student presenters' humility to recognise and accept mistakes demonstrates a positive learning mindset for the young learners in the planetarium.

See Section *The NOVA Mobile Planetarium: A team with specialised skills*.

BP4: Create new content

Astronomy is a rapidly changing science. It is necessary to create new content to keep up-to-date, cover recent events and new results, or run special projects such as data-to-dome projects. Creating new content is also essential for live and interactive shows (**BP1**) in which the audience asks questions about what is covered in the planetarium show. Audience questions also lead to new ideas for further expanding the possibilities in the software. Creating new content is only possible with the right kind of expertise, motivation, and flexibility in the team (**BP2, BP5, BP10**).

See Sections NOVA and Special projects and collaborations.

BP5: Be flexible

A successful planetarium is flexible in all areas. For example, flexibility in content allows the team to give interactive shows (**BP1**), create new content to discuss recent events and results and explore new ideas, such as incorporating real data into the dome (**BP4**). A flexible approach is inspiring and motivating for both the team and the visitors and can only be achieved with the right kind of team (**BP2**) that listens to and supports others (**BP7, BP8**) and strives to do better (**BP10**).

See Sections: NOVA; The NOVA Mobile Planetarium: A team with specialised skills; Flexibility; and Special projects and collaborations.

BP6: Quality over quantity

Though it may be tempting to think that you have twice the impact with twelve twenty-minute classes compared to six fifty-minute classes on one day, research shows that it is the immersive environment and 3D-learning space of the planetarium which have the biggest impact on learning (e.g., *Plummer, 2009; Sumners et al., 2008; Zimmermann et al., 2014*), not the volume of shows. Giving visitors the full immersive experience and answering their questions using the power of the planetarium may be more impactful than simply holding more shows (see also **BP1, BP2, BP4, BP5, BP10**).

See Sections Live and interactive planetarium shows and A typical planetarium visit.

BP7: Seek out feedback

For any project going into schools, it is important to engage with teachers. Make personal contact with teachers during the booking process, on the day of the visit and afterwards. Always ask for feedback and take it seriously. Discuss issues promptly with individuals or the whole team when necessary. Sharing positive feedback with the whole team is motivating and has many positive effects, including that team members may be more willing to be flexible and cover a visit at the last minute, or they may discuss the planetarium amongst their peers, resulting in many new applicants wanting to work for the planetarium. Feedback does not necessarily need to be gathered by a formal evaluation tool to be important and useful either in the short or long term (**BP10**).

See Sections A typical planetarium visit and Flexibility.

BP8: Supporting others

Once a planetarium project and an expert team are well established (**BP2**), it is good to share that knowledge and expertise with other projects. This can be a mutually beneficial experience: different perspectives and support can lead to valuable feedback (**BP7**), new content (**BP4**), and increased visibility that will invariably extend both projects' reach (**BP10**).

See Sections NOVA and Supporting others.

BP9: It doesn't have to be free

Many astronomy education activities are free for participants and schools. If the project brings clear added value, there is no reason not to ask (at least some) schools and educational events to contribute to the basic costs, such as transport and support for the student presenter. Whilst the situation will vary per country, there will be some schools (e.g., private schools) and events that can afford to contribute towards a visit or potentially even sponsor a visit to schools that cannot afford it.

See Section The NOVA Mobile Planetarium budget.

BP10: Do not be satisfied with the status quo

A truly successful project will always actively look for ways to improve. Feedback (**BP7**), content development (**BP4**), and working to support other planetarium projects (**BP8**) will lead to small steps forward. Still, it is also important to look critically at what you do, reflect on the bigger picture and strive to improve. Sometimes, just one question can make the difference (e.g., How are the school visits distributed?).

See Sections: NOVA; The NOVA Mobile Planetarium: A team with specialised skills; Flexibility; Special projects and collaborations; and Supporting others.

Notes

[1] The NOVA website: www.astronomie.nl

[2] The Africa Millimetre Telescope Project website: https://www.blackholehunters.space/

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The UNAM/AMT Mobile Planetarium: Lessons learnt on how to run a student-driven mobile planetarium project in Africa

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The UNAM/AMT Mobile Planetarium travels to Namibian schools and presents live astronomy shows, introducing school children to astronomy and science in general. Mobile planetariums face a host of specific challenges, especially logistical ones. Moreover, very few planetariums are situated in the Global South (*International Planetarium Society, n.d.*), where documentation (e.g., *Carlson, 2020; Olivier, 2014*) on them is limited, mainly focusing only on stationary planetariums in Africa and, in most cases, are not easily accessible. Here, we detail the challenges faced and share our lessons learnt in an African context, particularly revolving around the use of student volunteers as the backbone of the project. We will also contribute insights into how to deal with vastly different school environments. The logistical issues and lessons discussed here span the mobile planetarium's electricity requirements, how to manage heat build-up in the dome, and how to deal with the lack of large indoor spaces that our mobile planetarium usually requires. We additionally discuss the challenges around funding for the project. The work presented here was adopted and adapted as a scaled version of the successful NOVA Mobile Planetarium Project in the Netherlands (e.g., *Holt, 2022; NOVA, 2023*), noting that Namibia provides a very different outreach setting. In summary, a solid logistical and organisational basis is invaluable, as well as seamless teamwork and the right approach to secure future sponsors for the mobile planetarium project.

Introduction

The UNAM/AMT Mobile Planetarium project was created as part of the more comprehensive Africa Millimetre Telescope (AMT) project (*Backes et al., 2017*). The AMT is an upcoming radio telescope that will serve as part of the global Event Horizon Telescope array (*La Bella et al., 2023*) as well as monitor Active Galactic Nuclei as a standalone telescope (*Backes et al., 2019*).

Since the AMT project is a joint project between Namibia and international partners, it is important for Namibia to stand on equal ground with its partners. Inequity between partners from the Global North and the Global South is a general problem in North-South research partnerships (*Flint et al., 2022*). It is also an issue in astronomical collaborations (*Dalgleish, 2021*). Efforts are underway to solve this ongoing, multifaceted issue (*Perivoli Africa Research Centre, n.d.*). Having sufficient, well-educated Namibian astronomers is part of the journey towards more equity. Also, more generally, the development of local astronomy in Africa helps to drive socioeconomic development (*McBride et al., 2018*) and would put Africa in a position to challenge and add to existing science, as Backes argues (*Brits, 2022*).

In 2014, the Namibian Government reaffirmed its commitment to positioning Africa as an emerging hub for astronomical sciences and facilities (*South African Government, 2014*). In 2021, it launched the Namibia Space Science and Technology Policy. As per the mission of this policy, the Namibian Government is "to create platforms and an enabling environment for the development, promotion, coordination and optimisation of space science and technologies for the Namibian nation" (*MHETI, 2021, p. 10*).

Despite the progress in developing astronomy in Africa in recent years (e.g., *Backes et al., 2018; Pović et al., 2018*), Africa still lacks sufficient astronomers. This is exemplified in Ghana (*Sapah, 2023*) and Namibia, as Backes laments (*Woodall, 2022*). The mobile planetarium project, initiated by the University of Namibia, Radboud University (RU), and the Netherlands Research School for Astronomy (NOVA), serves to remedy this, amongst other goals.

Namibia is a vast country with very clear and dark skies, so the goal of the planetarium is not necessarily to show the night sky as one would see it in a dark sky region but to alert children that the field of astronomy exists via a fun, easy, and memorable experience, and therefore kindle the next generation of Namibian astronomers (*Radboud University, 2019; Radboud University, n.d.a*). More generally, astronomy is a "Gateway Science" (*Salimpour et al., 2021*), and planetariums are valuable tools for education and outreach towards young children because of their interactive and engaging nature (e.g., *Plummer, 2008; Sumners et al., 2008*). Sparking enthusiasm for astronomy in schoolchildren is especially important since astronomy is only briefly covered in the Namibian school curriculum when the Solar System is introduced. It is also worth noting that the goal of this planetarium project is not science education but outreach. As *Pössel and Liefke (2022)* note, education and outreach, though complementary, have fundamentally different goals.

As an additional motivation for the schoolchildren, the presenters of the planetarium are Namibian students in physics or astronomy and serve as role models for the possibilities of an astronomy career. A discussion on the project's success is not yet possible but will be included in future research. Aside from this broader goal, the mobile planetarium also raises awareness of Namibian youth and the general public about the AMT project (*Radboud University, 2019; Radboud University, n.d.a*).

The UNAM/AMT Mobile Planetarium Project

Pilot Phase

In April 2019, NOVA conducted a pilot project using one of their mobile planetariums. This programme, operated by NOVA and supported by the Rössing Foundation, RU, and UNAM, toured through Northern and Eastern Namibia and hosted two events in Windhoek (*Holt, 2020*). During this time, the inflatable dome visited ten schools and one university and reached 1,588 students in total (*Rössing Foundation, n.d.*). The project was deemed a great success and has since been adopted as a central element of the AMT Social Impact Plan (e.g., *Dalgleish et al., 2022; Holt, 2022*). This initial pilot phase of the mobile planetarium project did not yet have a set project structure or event structure, and the AMT was also not mentioned when talking to the learners.

Main Phase of the Project

A planetarium dome explicitly bought for the AMT has been in Namibia since 2019. The project's main phase was supposed to start in 2020 but was postponed due to the Covid-19 pandemic and related travel restrictions. Thus, only in May of 2022 were the first Namibian students trained in the operation of the mobile planetarium by a NOVA expert. In addition to lectures and technical training, trainees gained practical experience by presenting shows to learners. Since the inaugural show in May 2022, presented by the Namibian students themselves, the mobile planetarium project has visited schools, universities and corporations regularly; the common frequency is one or two events per week. Recently, we welcomed the 5,000th visitor to the planetarium. As of April 2023, 9,816 individuals[1] have attended the mobile planetarium, with over 5,000 attendees counted in 2023 alone.

The Mobile Planetarium Team

Currently, the mobile planetarium is coordinated with the help of two UNAM and RU staff members and operated by nine voluntary students from the University of Namibia. Of the nine students, two are undergraduates in physics, five are master's students in astrophysics, and one is a PhD student in physics, specialising in radio astronomy. For an extended period of the project, the students organised the school events themselves, a task now taken over by a staff member. The students run the planetarium shows and all associated tasks independently and autonomously. This is a great learning experience for the learners and the student volunteers who learn through project-based learning (*Buck Institute for Education, n.d.*).

It is also worth noting that the team consists of six students who identify as women and three students who identify as men; for example, in the USA (*Porter & Ivie, 2019*) and Africa (*Pović et al., 2021*), the fraction of women-identifying astronomers is small. In the USA, 21% of physics Bachelor's degrees were obtained by persons who identify as women (*Porter & Ivie, 2019*). In contrast, the corresponding figure in our team is 43%, while 100% of current physics undergraduates identify as women.

Organisational structure

When speaking about organisational structure, we do not refer to hierarchical structures but rather a more horizontal structure with lateral leadership. We have defined the following roles: presenters, pre-talkers, post-talkers, organisers, tally clerks, media and marketing, spokespersons, correspondents, and educators, with the latter three roles being more overarching and not strictly required for any single event. Every person can and should fill more than one of these roles, depending on what is relevant to the event.

This structure ensures two things simultaneously:

- Everyone has a clear role, and team members do not enter into conflict over assigned duties at a given event.

- If the roles are well-defined, then there is always a team member who is individually responsible for every task that needs to be completed.

The above is a well-known management practice (e.g., *Flint & Hearn, n.d.*).

Roles are allocated according to skills (with team members trained to fulfil particular tasks) and preferences. This approach allows the volunteers to assign themselves according to their likes and dislikes and allows them to fluidly take on new roles as they learn and develop new skills. This way, the team structure arose organically; volunteers were not forced into a predetermined structure. This structure is crucial because the project relies on a large team of student volunteers, as preference alignment is tied to improved performance (*Willems & Walk, 2013; O'Keefe & Linnenbrink-Garcia, 2014*). This also highlights our use of project-based learning as a pedagogical approach to improve their skills and prepare them for the workforce. This fluid team structure does not seem to be a common practice among other established mobile planetarium projects that often have a team of contractual workers operating the planetarium (e.g., *The Travelling Telescope, 2015*), but we have found this to be most successful.

The Planetarium Logistics & Events

The mobile planetarium fits nicely into the back of a large pickup truck while still leaving space for the driver and four potential passengers, such as the students who run the planetarium shows. Currently, most of our planetarium events are conducted in Windhoek, our base of operations. The challenges associated with expanding the visits to sites outside Windhoek are discussed in the Challenges Section.

The UNAM/AMT Mobile Planetarium project primarily focuses on bringing the planetarium to schools and running shows for learners (and preferably their teachers). The planetarium is large enough to accommodate 30 children or around 20 adults. Each school event with the planetarium can reach up to 300 attendees; we typically reach 260 learners during a single event. Typical visits conducted at schools in Windhoek are around five to seven hours. Included in this time frame is one hour on either end of the event that is used for setup and disassembly of the planetarium. The planetarium is also used for public and corporate events, essential for networking and opening avenues for potential future sponsorships.

Initially modelled after the three NOVA mobile planetariums in the Netherlands, the shows are live, interactive and individually customisable (*NOVA, 2023*). *Holt (2022)* notes that these shows' success is due to their live and interactive nature rather than running pre-made films. At one event with the planetarium, multiple consecutive shows can take place inside the planetarium.

With experience, the structure of our shows evolved into what it is today; all talks are realised without any technical aids like slides or blackboards. The typical sequence is as follows:

(1) We give a pre-talk; *Okwei et al. (2022)* note that this introduction enhances learners' understanding of the astronomy concepts presented. The content of this pre-talk differs depending on the age group.

- Younger children (aged 12-13): 10-15 minutes maximum. There is a brief introduction to the AMT project without explaining its scientific purpose. Instead, this pre-talk piques the children's interest and gets them excited about astronomy. Usually, we ask the learners basic questions about the Solar System. We explain the rules of the planetarium extensively to ensure that the learners do not damage the equipment. Figure 1 shows a team member giving a pre-talk to a group of preschoolers.
- Older children and adults (aged 13 years and above): 20-25 minutes. The AMT project is introduced in detail, its impact on Namibian society, and why Namibia is an ideal location for this observatory.

(2) After explaining the safety instructions, we invite the learners into the planetarium for a session inside the dome, modelled after those from NOVA (*Holt et al., 2023*).

- Younger children: 20-40 minutes maximum. In our experience, content for this age group that revolves around the Solar System works best, as this is a topic with which Namibian schoolchildren are usually already familiar. In the presentation, the learners observe the Earth from above, and the presenter discusses one or two planets in the Solar System in detail. Other topics are only covered if one of the attendees of the planetarium asks. Local links to telescopes in Namibia, like the High Energy Stereoscopic System telescopes (H.E.S.S.; *de Naurois, 2018*), are frequently mentioned.

Figure 1: *A team member giving a group of children a pre-talk before they enter the planetarium. Image Credit: Barbara Kerkhof*

- Older children and adults: 30-60 minutes maximum. The Milky Way is projected as a visible light image as seen from Earth in clear areas with no light pollution. Different invisible emissions, such as gamma rays and hydrogen emissions, are displayed and explained, along with satellites, space junk, and different space telescopes. The Earth and the rest of the Solar System are seen from above, later zooming out to the rest of the galaxy, travelling to the supermassive black hole in the centre of the Milky Way (a natural link to the local AMT project) and then zooming out to the entire visible Universe.

(3) Structured post-talks are only offered to younger children. We ask learners to share their experiences with the planetarium team, which serves to better gauge their interests and adjust the content of the show. We also emphasise that the AMT needs supporting staff in addition to astronomers. For older children and adults, interested learners often independently approach team members for more input on astronomy.

The Role of School Teachers

School teachers play a crucial role in the project; they often learn about the planetarium by attending networking events and experiencing the planetarium shows themselves. Teachers usually establish the first contact with the team and request a school event. Teachers also help raise awareness of the project in the community, as educators from different schools frequently communicate and recommend the mobile planetarium experience to other schools.

Further, teachers have a fundamental role in engaging their pupils in astronomy in the long term, beyond short planetarium visits. To support this, we recommend interactive and easily accessible smartphone applications teachers can use to teach astronomy concepts. Follow-up communication with teachers a few weeks after the planetarium visit has revealed that when teachers cover astronomy topics in school, they frequently mention the planetarium visit to illustrate a concept that they are currently teaching. The teachers also better understand the value of smartphone applications as a learning resource after seeing learners' enthusiasm in the interactive planetarium environment. However, it is important to note that the planetarium experience does not directly influence the content that teachers cover in the classroom. Rather, teachers refer back to the learners' past planetarium experience as a convenient illustration when teaching an astronomy concept that is already in the curriculum, such as planetary motion.

Challenges

Since we are based in Africa, our mobile planetarium faces many specific challenges that might not be present to such a degree outside Africa. These are project-specific challenges but also structural issues.

The project-specific challenges include but are not limited to the need for seamless teamwork, significant logistical efforts (e.g., the need for electricity and a vehicle to transport team members and the mobile planetarium), training the student presenters extensively, and developing effective show-running techniques.

A Science Outreach Project in Africa

Besides project-specific challenges, there are also broad structural challenges in Africa that must be considered. Countries in the Global North, where most planetariums are based, have, in general, much higher Gross Domestic Products than countries in Africa (*The World Bank, n.d.a*). In addition, countries in the Global North allocate a much higher fraction of their annual budgets to science projects (*The World Bank, n.d.b*).

Since there is monetary support for science projects in the Global North, it is evident that implementation structures, such as established partnerships with other research institutions and governments, the recruitment of qualified staff, scholarships for PhD students, supply chains for specialised equipment, and project management policies are also present. In Namibia and Africa as a whole, these implementation structures, though present, need to be more sophisticated, largely due to the lack of funding. This issue is exemplified by the state of the Namibian National Commission on Research, Science and Technology, which has faced "numerous budget cuts" by the Namibian government in the past, according to Keramen (David, 2020) and therefore struggles to uphold its mission. Additionally, the Global North has a large pool of educated and specialised staff for any such project. This disparity is largely due to the difficult and unequal access to universal and comprehensive education in Africa, as illustrated by the state of education in Sub-Saharan Africa (*Lewin, 2009*). Further, "brain drain" – the phenomenon where well-educated persons emigrate from a country – continues to be a problem in Africa (*Tebeje, 2005*).

Thus, management of these challenges needs to be considered. In this section, we will primarily focus on the project-specific challenges of our planetarium, but we will also discuss funding issues as part of broader structural challenges. Discussing the inadequate or lacking implementation structures in Africa in detail is out of the scope of the article and partly inherent since this is exactly the issue that the AMT and the associated planetarium project seek to alleviate.

Team & Training

In similar European projects, such as the *Astronomy-to-go* mobile planetarium project operated by the University of Vienna, mobile planetarium members can perform all tasks necessary to keep the show running (*A. Caldú, personal communication, April 14, 2023*). In our project, only one-third of the team members have received full training in running the actual planetarium show. Our experience shows that operations are possible even with only a partially trained team, though this does come with challenges. We handle this by ensuring multiple team members can do any particular task. If only a single person can do one such task, then this person becomes a limiting factor in the availability of the whole planetarium. This point is crucial as most team members are full-time students or work full-time (e.g., tutors or high school teachers) and might not always be available for the events. Hence, clear, consistent, and advanced communication is vital.

We have also adopted the strategy in which team members mentor and train their teammates in the hopes that, eventually, all team members should have the knowledge and skills needed to perform all necessary tasks. This ensures the team's maximum efficiency in running the shows.

Logistics

Locations

As discussed above, much of our operations lie within Windhoek; visits within city limits are typically about half a day. However, the trip can extend over several days when reaching out to schools outside Windhoek. Additional considerations include accommodations for the team members, funding to support the visit, coordinating team members' schedules over extended periods, and maximising efficiency by visiting multiple schools in one trip.

Another layer of difficulty is the transport of the planetarium and the team members. Not only does our planetarium project not have a dedicated vehicle of its own, but none of the student team members have a driver's licence, as this is typically out of financial reach for students in Namibia. As a result, non-student team members must accompany the student volunteers to every event. Due to these reasons, for now, the planetarium events have been largely restricted to Windhoek.

Heat mitigation

Heat build-up is a common issue in mobile planetariums, especially in Africa, where solar irradiance is much higher (see Figure 2, left, for a temperature schematic). Other planetarium projects manage this heat build-up with an air-conditioning unit inside the planetarium itself (*A. Caldú, personal communication, April 14, 2023*; *J. Holt, personal communication, April 19, 2023*). We do not have such an air-conditioning unit at our disposal, and thus, other strategies are needed. The first strategy is to place the planetarium in a large indoor space, shielded from direct sunlight, and, in the best case, in a room with good insulation. In addition, we mitigate the heat within the dome by deflating the planetarium completely in between one session and the next. This effectively fills the planetarium with ambient air again. If operating the planetarium in exposed environments, we schedule shows during cooler months to operate in an outside environment.

Space requirements

Since the mobile planetarium is a large, hemispherical dome, we need to find venues that can accommodate the dome's size and leave sufficient space to move around the outside of the dome. In addition, scraping damage to the dome by the ceiling must be prevented. See Figure 2 for more information on the dimensions of the planetarium used in the UNAM/AMT Mobile Planetarium project.

Contrary to Europe, in Namibia and Africa in general, large indoor spaces are rare. We have adopted site pre-visits by team members as an integral part of our organisational strategy to avoid potential misjudgement of the space requirements by the school. In the case of remote locations, where additional site visits are logistically prohibitive, extra emphasis is placed on accurately communicating the spatial requirements.

Electricity requirements

The mobile planetarium requires electricity to run with its air compressor, laptop, and digital projector. This may be unavailable in some rural areas – for the planetarium or the school. Though we have a diesel generator at our disposal, this has not been used as grid electricity has thus far always been available. In addition, the generator creates noise, is not environmentally sustainable, and runs on expensive fuel. As technology improves and becomes more efficient, using devices like portable solar cells may be a useful alternative. The Outlook and Future Development Section details the future development of the project in this regard.

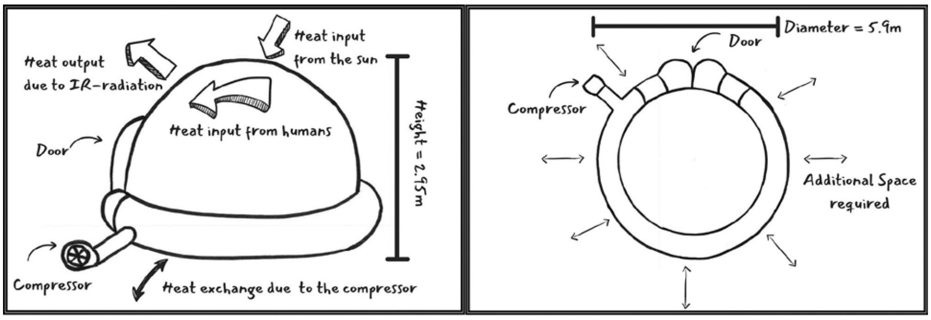

Figure 2: Left*: A rough sketch of the planetarium system indicating most of the various heat loss mechanisms and heat sources in the planetarium. The arrows indicate the effective heat flow. Note that the arrows are not proportional to their contribution to the planetarium's actual temperature development.* Right*: A bird's eye view sketch of the planetarium with the diameter of the planetarium shown and the additional space required showcased through arrows that are pointing radially out. Image Credit: Queen "Delight" Namene*

Staffing at events

We have found that two team members are always needed as a bare minimum. Otherwise – particularly during pre-and post-talks – team members become overwhelmed with the volume of tasks. On the other hand, we found that a maximum of five team members should be present at any event. With more volunteers present, their time may not be used efficiently, or they may compete for tasks. These minimum and maximum values will vary depending on the specific school environment. However, utilising more team members for one event on a shift basis can be beneficial, particularly if the event is long and team members need breaks.

Managing School Relationships

Regardless of the school environment, we have learnt that having a direct connection within the school is invaluable. Since, in Europe, schools pay for the planetarium to visit them, they have a vested interest in making those events a success and willingly provide organisational support in the form of a school contact (*A. Caldú, personal communication, April 14, 2023*). Since we do not charge the schools for the visit, we have to put a much stronger emphasis on ensuring the school's organisational support. This school contact could be any staff member from the school and usually is the one that requests a planetarium visit; a science teacher might be an obvious candidate, but not a mandatory one.

Finances

Necessity of sponsorships

The inflatable dome of the planetarium and the rest of the equipment, such as the laptop and the projector, were sponsored by Radboud University. However, one challenge for the planetarium is the long-term financing of the project. The Namibian schools are not charged for the visits, unlike in some other mobile planetarium projects (e.g., *NOVA, 2023*; *University of Vienna, n.d.*), due to our aim of equity in access to STEM outreach, and the planetarium does not receive direct university funding aside from in-kind staff support. Though some non-educational events have brought in some revenue, these funds are insufficient to cover the project's operational costs. Additionally, a crowdfunding campaign by Radboud University for the project only raised about 35% of the initial funding target of €25,000 (*Radboud University, n.d.b*).

Securing sponsorships

It is important to align sponsorship proposals with the organisation's mission, vision and overall strategy. Implicit choices are made when approaching sponsors, and any offers of sponsorships we receive are carefully considered. Support and sponsorships do not necessarily have to be monetary. For example, one sponsor has offered project management support, while another has offered to accommodate the team members in their lodges during longer trips outside Windhoek at a subsidised rate.

It is helpful to leverage pre-existing connections to establish a connection to the potential sponsor of the project. For example, the AMT hosted a networking event in May 2022, featuring representatives from most major banks in Namibia, all of whom experienced a planetarium show, including a Corporate Social Responsibility Manager. During a meeting in November 2022, the manager's bank expressed further interest and recently confirmed their commitment to monetarily sponsor the planetarium for three years.

Finding the right approach to securing sponsors can be difficult; there is no simple, one-size-fits-all solution. This task requires a significant amount of time, which is untenable for the team members who are full-time students or work full-time elsewhere. For that reason, a person in our team has adopted this task as part of their responsibilities. As a qualitative comparison between the success of the crowdfunding and sponsorship campaign, crowdfunding, as a short-term solution, allowed the planetarium to start operations, whereas sponsorships allow for long-term financial stability.

Outlook and Future Development

The UNAM/AMT Mobile Planetarium project is on the road to further growth. The planetarium project plans to organise events outside of Windhoek in 2023 and 2024 – we are aiming for roughly one event per week, with the ambition to visit every school in Namibia within the upcoming years (constituting nearly 865,000 learners in total; *Namibia Ministry of Education, Arts and Culture, 2023*). The more comprehensive AMT project is currently funded through 2029, so we are confident that the planetarium will operate until then at a minimum, given the condition that funding targets for the planetarium project are met.

In addition, there are many ways that we can improve the project, including:

(1) Given the growth expectation above, the project needs to recruit more students from the University of Namibia, including students in physics or astronomy and one or two students with a social science or science education background, per the planned impact assessments outlined below.

(2) Similarly, there needs to be additional considerations on how to run the planetarium events cost-effectively and time-efficiently. For this, we will build on the expertise of the NOVA project in the Netherlands, detailed in *Holt et al. (2023)*.

(3) There have been discussions within the planetarium team on how to make the planetarium interventions more effective in the long term:

- For this, it was proposed that we create educational materials for classrooms and students' communities, such as posters and handouts, following the experiences of *Arcand & Watzke (2010)*, using visually engaging astronomy images accompanied by information texts.
- It will also become necessary to increase our engagement of teachers through regional planetarium events and more.
- In the future, offering follow-up opportunities to interested learners might be possible, for example, pairing them with a student volunteer.

(4) To better understand our impact and effectiveness, we have begun an all-encompassing impact study of the AMT project – including the mobile planetarium as part of its social impact plan. The study will touch on topics including:

- What is the most effective way to gauge a learner's interest in astronomy? For example, we might ask the learners via a questionnaire before, immediately after, and some weeks after the planetarium event. In addition, we will investigate the differences between learners' experiences in cities (where there is some light pollution) and learners in rural areas.
- How could we restructure our planetarium events to allow for evaluation? This might have direct implications for the staffing at events as the current volunteers do not have the capacity to conduct in-depth evaluations.

(5) Our efforts to mitigate the heat in the dome have been partially successful. However, we find that, at times, our mitigation is not sufficient. We must find a more effective solution for this problem to reduce our dependence on ambient environments.

(6) The planetarium team is looking into alternative electricity sources to visit rural schools, such as supplementary photovoltaic equipment and a UPS-type set-up run on renewable energy, such as solar energy. This would serve as an energy source for the dome and demonstrate to the attendees the viability and advantages of renewable energy. A system design study is underway with the Renewable Energy group in the Department of Physics, Chemistry and Material Science at UNAM.

(7) To streamline the organisation of the planetarium events, we envision an application process for schools. The UNAM/AMT Mobile Planetarium project has gained substantial media attention (e.g., *Nel, 2022*; *Van der Schyff, 2023*; *Windhoek Express, 2023*), increasing our requests for school events. This approach requires additional consideration regarding equity, as the best-resourced schools will likely be the ones best informed about these (and similar) opportunities.

(8) The mobile planetarium project already has some social media activity[2], but we plan to introduce a more comprehensive social media strategy in the future.

Conclusions

One year since the inception of the UNAM/AMT Mobile Planetarium project, we have successfully implemented a student-driven planetarium programme in which, under the framework of project-based learning, students have been able to learn how to organise school events with the planetarium, navigate the social aspects of teamwork, to manage the finances and budgets, and to use science communication techniques effectively.

The initial model and support of the NOVA planetariums have been instrumental. Based on the vastly and constantly increasing number of requests for school events, we infer that we have successfully adapted the planetarium project to the Namibian environment.

In 2023, the planetarium project has picked up momentum, and we expect that trend to continue. Our engagement with the learners has been overwhelmingly positive, with many learners stating that they had great enthusiasm for astronomy after our shows, which is also exemplified in Figure 3. Scholarly assessment of this observation is beyond the scope of this article and will be covered in future research, detailed considerations on which can be found in the previous section. This indicates that our current methods are working well for us. This is especially meaningful to the project as our broader goal is to increase astronomy awareness in Namibian children. If engagement happens in a fun, easy, and memorable experience, that is even more beneficial to the project: it means that this experience in the planetarium might open Namibian schoolchildren's minds to considering a career in STEM or astronomy in particular. We conclude that we shall continue to operate the UNAM/AMT Mobile Planetarium project, confident that the project will continue to bear fruit.

Figure 3: *Enthusiastic children in front of the planetarium after a successful show with a team member in the background. Image Credit: Queen "Delight" Namene*

Notes

[1] When quoting the number of planetarium attendees, we think of the numbers as "individual planetarium experiences" rather than individual persons, as some enter the planetarium multiple times.

[2] Examples of social media activity of the mobile planetarium and the AMT: @blackhole-hunters on Instagram, @africa_mm_tel on X and https://www.blackholehunters.space/

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Empirical study on the digital planetarium system for measuring visual perception of the night sky: Analysis of impact from light pollution and astrotourism

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Planetarium, Light Pollution, Dark Skies, Digital

This year, 2023, marks 100 years since the first planetarium projector was unveiled. Planetariums were developed to faithfully reproduce starry skies. Although many empirical studies have been conducted using planetariums, few have focused on how individuals perceive starry skies projected onto planetariums. To understand this point in the context of Japanese university students, the present study analysed subjects' perceptions of the starry sky, using the effects of light pollution and their experience of astrotourism as variables. This study projected the night sky onto a digital planetarium at six sequential intervals of the naked-eye limiting magnitude. Although there is a sample bias and some limitations, the results may imply that subjects living in areas more affected by light pollution are more likely to perceive night skies as authentic at a lower naked-eye limiting magnitude. Additionally, astrotourism experience may correlate with the perceived ability to qualitatively identify many stars. These results may impact light pollution awareness and abatement efforts.

Introduction

This year, 2023, marks 100 years since Carl Zeiss first developed the optical planetarium and unveiled it in Jena, Germany. Following the opening of the first public planetarium in 1925, planetariums have been an important tool in advancing the general public's understanding of astronomy. One of the objectives of planetariums is to reproduce authentic night skies and contribute to astronomical education (e.g., *Okyudo, 2012; Tanaka et al., 2021*), and the technology is continually being improved to achieve this goal. Since the 1980s, the development of digital planetarium equipment that combines optical projectors and computers to project starry skies onto dome screens has led to a dramatic worldwide increase in the number of installations (e.g., *Lantz, 2011*). Several systems that project images of various media, such as a canvas for real-time or pre-rendered computer animations and live-capture images onto a full dome, are currently in operation and used for entertainment facilities and astronomy education (e.g., *Schnall et al., 2012*).

Japan is considered a "Planetarium Country" (*Watanabe, 2001*). Planetariums were first introduced in Japan in 1937, and since then, 473 planetariums have been installed, of which 295 are currently operational (*Japan Planetarium Association, 2023*). Japan has the third-highest number of operational planetariums after the USA and China, although Japan has more planetariums per capita than either country (*Worldwide Planetariums Database, 2023*). After World War II, some Japanese manufacturers began producing planetariums, and many large planetariums were built in Japan.

The number of planetariums in Japan significantly increased between 1971 and 1995 (Figure 1). This coincided with a period of economic growth and urbanisation,

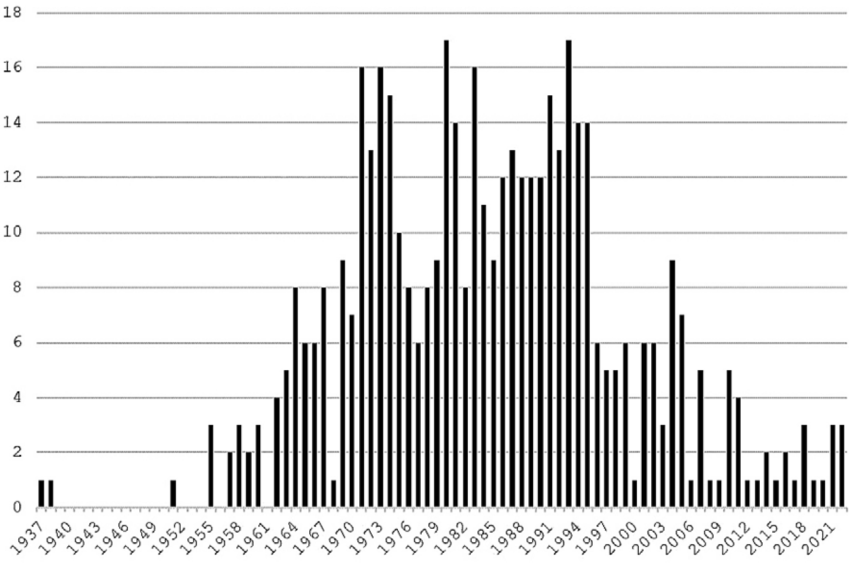

Figure 1: *The number of planetariums installed in Japan from 1937 to 2022. Image Credit: Data taken from Japan Planetarium Association (2023)*

implying that it overlapped with a period of significantly exacerbated light pollution, thus making it nearly impossible for many people in Japan to look up at the authentic night sky. Approximately 70% of Japanese residents no longer see the Milky Way near their homes (*Falchi et al., 2016*), which has an indirect influence on the increase in the number of planetariums installed in Japan (*Watanabe, 2001; Tanaka et al., 2017*). In fact, *Tanaka et al. (2017)* stated that the excessive amount of light pollution in our environment has led to the development of planetariums.

Japan is also considered a light-polluted country. Light pollution (LP) results from excess natural light levels at night caused by artificial light sources. It is one of the most prominent pollutants in modern society (e.g., *Cinzano et al., 2000*). LP is linked to human health disorders and impacts wildlife ecosystems (e.g., *Rich and Longcore, 2005*). Above all, stars and other celestial bodies are washed out by light that is either directed or reflected upward (e.g., *Longcore & Rich, 2004*). In other words, with more significant amounts of LP in an area, fewer residents can observe a dark night sky. *Cinzano et al. (2001)* identified Japan as a country with particularly serious LP, along with the USA and Europe. In a 2016 survey, Japan maintained its leading international position in the amount of artificial light radiation into space per unit area despite the significant development of neighbouring emerging countries (*Falchi et al., 2016*).

The growing worldwide awareness of and concern for LP is one of the factors behind the emergence of astrotourism (AT), in which individuals travel to search for authentic dark skies (e.g., *Collison & Poe, 2013; Soleimani et al., 2019*). *Pásková et al. (2021)* suggested that "the level of light pollution is not only monitored and predicted as a condition for astrotourism, but a new tourist attraction has also emerged — a destination of dark sky" (p. 6). In general, AT can be understood as a social practice of the general public, alienated from artificial light, seeking out the darkness that was the object of enlightenment in the past *(Edensor, 2017)*.

AT development has attracted the attention of local communities, amateur astronomers, tourism operators, and researchers because of its potential to meet sustainable development goals (e.g., *Rodrigues et al., 2014; Tapada et al., 2021; Sawada & Okyudo, 2022a*). AT could stimulate the economy in local communities (e.g., *Mitchell & Gallaway, 2019; Office of Astronomy for Development, 2023*), offer equal employment opportunities between women and men (e.g., *Dalgleish et al., 2021*), provide scientific astronomy communication for the general public (e.g., *Blundell et al., 2020*), and has potential for passing on star lore in local communities (e.g., *Sawada et al., 2023a*). In addition, AT encourages actions that preserve existing dark skies and restore them in areas where they have been lost to light pollution and other anthropogenic interferences (*Weaver, 2011*). DarkSky International (formerly the International Dark-Sky Association), an international organisation that promotes awareness of the issues of LP, also discusses AT as a solution to prevent LP (*DarkSky International, 2023*). As part of activities to promote AT, there has been some work done to host workshops on light pollution prevention for local communities (e.g., *Sawada & Okyudo, 2023*), in addition to advocating for regulations to protect dark skies (e.g., *Isobe & Sugihara, 1991*). In Japan, the rapid construction of planetariums and public observatories in the postwar period increased the popularity of visiting astronomy-related facilities. The 21st century saw increased astrotourists seeking authentic dark skies in the wilderness, mountains, and islands (*Sawada et al., 2023*).

While some researchers might argue that experiences in planetariums are not included within AT (e.g., *Weaver, 2011*), for people living in cities around the world, seeing the unobscured night sky is an extraordinary experience. Additionally, an increasing number of international studies refer to enjoying the night sky in a planetarium as AT (e.g., *Pásková et al., 2021*). This article will include AT as a factor in the perception of night skies.

This study aims to analyse how individuals perceive starry skies projected onto a planetarium, focusing on the impact of artificial light and AT experience.

Although there is a large accumulation of empirical studies using planetariums (e.g., *Plummer, 2009; Carsten-Conner et al., 2015*), few studies have focused on individuals' perceptions of starry skies projected onto a dome (*Tanaka et al., 2017*). Furthermore, few studies have focused on the internal factors of the respondents, particularly their AT experiences and the influence of artificial light (*Sawada et al., 2022b*). Empirical studies using planetariums, hemispheric domes, and full-dome projections include practical reports on recreating outer space through full-dome projection (e.g., *Wyatt, 2005*), a series of studies that incorporated planetariums into school education and measured the effects on astronomy and scientific learning (e.g., *Yu et al., 2016*), practical studies projecting a range of contents not related to astronomy (e.g., *Okyudo, 2012*), practical research for use in advanced occupational training simulations (*Blackham, 2000*), research for examining the applicability of VR technology in children with learning and cognitive disorders (e.g., *Adams et al., 2009*), studies examining the how immersive planetariums are and their effectiveness in comparison to other VR technologies (e.g., *Kuchelmeister et al., 2009*), and reports on the development of new projection systems (e.g., *Ott & Davis, 2007*). However, few studies analyse the subjects' perceptions towards starry skies projected onto the planetarium.

A series of studies by *Tanaka et al. (2017; 2019; 2021)* used the psychological method, in which data is collected from questionnaires to examine the factors that affect what is perceived as a faithful reproduction of stars in the planetarium, including the brightness of the projection and the size and colour of stars. The respondents evaluated their impression of a faithful reproduction of stars for each projection. However, this work does not sufficiently discuss participants' attributes that might impact their responses. We posit that people's ability to perceive starry skies differs depending on their living environment and the number of experiences of looking up at a true night sky. This study analyses individuals experiencing the night sky in a planetarium, considering the light pollution in respondents' neighbourhoods and their participation in AT. Specifically, this study empirically examines the relationship between respondents' attributes and their perception of the night sky as projected using a digital planetarium.

Experimental design and methodology

Hypothesis

To date, no empirical analysis has been found that examines the relationship between residential experience and perceptions of the night sky. However, in general terms, residing in areas affected by light pollution is likely to influence the perception of the night sky. For example, *Bogards (2013)* noted, though did not analyse empirically, that urban residents in the United States do not have a realistic understanding of a truly dark sky and might be satisfied even if they are not observing an authentic night sky.

The naked-eye limiting magnitude (NELM) is the apparent magnitude of the faintest object that is visible with the naked eye. It should be noted that Figure 2 shows the relationship between the NELM and other night sky brightness magnitudes and indicators. A high (~> 7) naked-eye limiting magnitude means that the faintest observable stars are very dim, indicating that the sky is dark with many visible stars.

Cohen (1988) noted that general tourists, except experts in the area (e.g., curators at a museum), tend to be satisfied with broader and less rigorous standards of authenticity towards tourism. Further, *Mccartney & Osti (2007)* noticed a relationship between the number of prior experiences a person had with an event and how authentic it seemed to that person. Applied to this experiment, we might expect that people who are significantly affected by LP and are not amateur or professional astronomers may mistakenly think an authentic night sky does not have many stars. Therefore, this study developed the following hypotheses:

H1. There is a negative correlation between the amount of LP near a subject's residence and the NELM at which the subject perceives a planetarium projection as an authentic night sky.

H2. There is a negative correlation between the amount of LP near a subject's residence and the NELM at which the subject considers there to be a high number of stars.

In this study, we used the light pollution map (*Román et al., 2018*) to determine the amount of LP near a subject's residence.

Additionally, we assume that respondents with more AT experience, including planetariums, are more likely to understand authentic night skies. Based on this assumption, we developed the following additional hypotheses:

H3. AT-experienced subjects perceive night skies as more authentic in higher NELM than AT-inexperienced subjects.

Figure 2: *A nomogram comparing different night sky brightness measurements. The red horizontal line indicates the natural night sky unobscured by light pollution. Image Credit: After IAU (n.d.)*

H4. AT experience is related to the ability to qualitatively identify a large number of stars.

This article examines these four hypotheses using the methods detailed in the following pages.

Experimental design and sample design

This empirical study was conducted in the digital planetarium at Wakayama University, Japan. The first planetarium with 2K resolution was installed in 2009 when the University opened its Faculty of Tourism. It has been used for academic research and educational practices, including live coverage of total solar eclipses, 360-degree video archives of traditional performing arts, and video projections of tourist destinations around Japan (*Yoshizumi & Okyudo, 2010; Okyudo, 2012*).

In 2020, much of the equipment was updated to enable projection at double the resolution. A fisheye lens (custom-ordered) and projector were used to achieve high resolution and contrast, in addition to sufficient brightness. The dome screen adopted a 5.0-metre decompression-type tilted dome at an angle of 15 degrees. A server with a dome content player was used as the projection system to project various images onto the dome screen. Figure 3 shows the digital dome system used in this study. Figure 4 shows the grid lines indicating the range of the video projector used in this system on the dome; the projection range on the dome screen is approximately 200 degrees horizontally and 120 degrees vertically. The system is intended for VR tourism studies and is not normally used as a planetarium. This means that the system does not have the function to project onto the entire hemisphere dome. However, the effective visual field of humans typically extends an elliptic range of around 30 degrees horizontally and 20 degrees vertically due to the spatial range of a visual field associated with particular perceptual and cognitive tasks. In addition, the supplementary visual field, the range which has no direct functional role in the perception of visual information, extends around 200 degrees horizontally and around 125 degrees vertically (*Hatada et al., 1980*). Therefore, the projection sufficiently covers the subjects' visual fields, taking into consideration head movements.

In this study, the night sky, reproduced by Stellarium (*Zotti et al., 2021*), was projected onto the digital planetarium. Stellarium is open-source software that allows a computer to use it as a planetarium. The software has a planetarium option, which can be exhibited in a 360-degree immersive environment in the dome. The realistic representation of a starry sky and its many customisable features makes it widely used in astronomy communication and education (*McCool, 2009*). Stellarium v0.22.0, released in March 2022, also added a switch from the Bortle scale to the NELM. This feature enables the test subjects to be provided with a variety of night-sky brightness magnitudes.

We conducted the experiment intermittently between August and November 2022. The maximum capacity of the dome is 15 people. However, the view of the night sky differs depending on the seating position, so each subject sat on a chair at the centre of the dome with a sufficiently effective visual field (Figure 3). In addition, the reactions of others may influence subjects' perceptions of the night sky. Therefore, the experiments in this study were conducted individually.

The experimenter projected the night sky from the NELM of 3 to 8 onto the planetarium (six images) for 10 seconds each. The experimenter sequentially displayed NELM images but did not provide information about the total number of images or their order to the subjects in advance. The experiment began with the room dimmed, but the subjects were not given time to adapt to the darkness before the experiment began. However, in this study, the experimenters determined that dark adaptation did not need to be considered after consultation with the co-authors. As this study examined the subject's perception of a change in the number of projected stars, not the overall brightness of the sky, dark adaptation was deemed unnecessary.

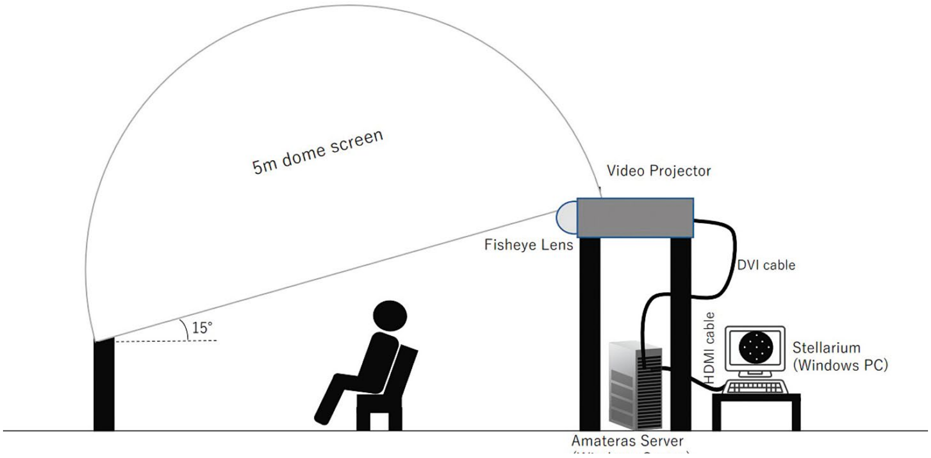

Figure 3: *A schematic of the digital planetarium system used in this study.*

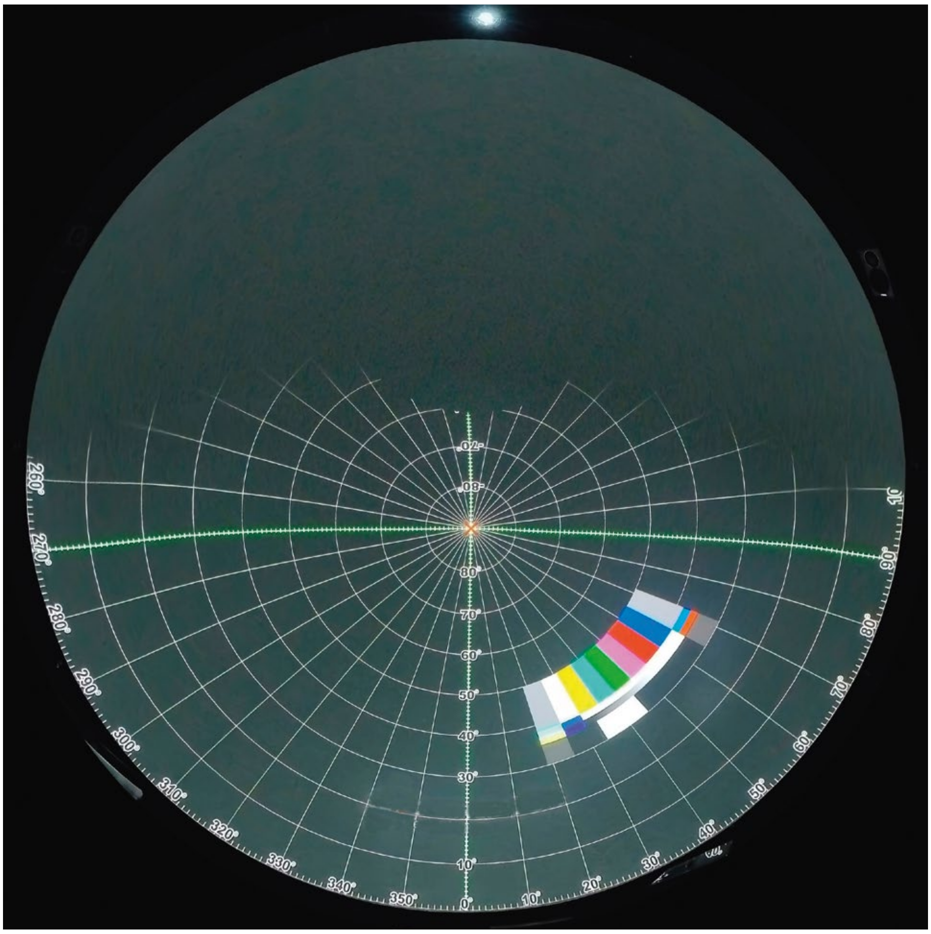

Figure 4: *Shown here is the omni-directional projection range of the video projector used in this study. The grid lines indicate the range of the video projector. The projection range on the dome screen is approximately 200 degrees along the horizon and 120 degrees in altitude.*

Due to the performance limitations of the projector, the NELM displayed in the software did not always match the NELM projected onto the dome screen. Since no significant visual differences were observed when night skies below a NELM of 2 were projected onto the screen, we decided to project the night sky above a NELM of 3 onto the screen. We set the projection to the night sky at 22:00 on 25 August 2022, when there was no moonlight influence, at the latitude and longitude of Wakayama University (34°15'56"N 135°9'5"E.). With this setting, the Milky Way was visible in front of the subject's field of view, and the Summer Triangle was near the zenith. The projected landscape was obtained from Wakayama University and originally processed in this study.

The experimenter asked the subjects two questions:

> *Q1. Please raise your hand when you feel the night sky is authentic.*
>
> *Q2. Please raise your hand when you feel there are a lot of stars.*

The experimenter ended the projection when the subjects answered both questions. Subjects were also allowed to raise their hands for both questions simultaneously. While the experimenter changed the night-sky brightness, the subject was covered by light shielding and could not see the dome screen. In this experiment, the light shielding was a cardboard box (30cm long, 40cm wide and 25cm deep) that the subjects put over their head to shield their vision.

The experimental sample comprised 30 undergraduate and postgraduate students from Wakayama University. Ten members of the sample were part of the Astrotourism Laboratory. All subjects attended basic astronomy lectures at the University; however, they were humanities and social sciences students and did not specialise in astronomy. Of the 30 original sample, 25 answered validly in both *Q1* and *Q2*; five respondents answered only one of the questions, and so their contribution was considered invalid. The valid samples may be biased, which could have significant effects on the data analysis and discussion. Before and after participating in the experiment, the subjects were asked to complete a questionnaire in Japanese using Google Forms, which is presented in more detail in the next section. The experiment took approximately 45 minutes per subject, including the time spent answering the questionnaire.

Questionnaire design

The post-experimental questionnaire was composed of three sections: demographics, AT experiences, and push motives for AT.

The first section involved the respondents' basic demographic and background data. This section consisted of seven questions and collected data on the subject's gender, age, visual acuity in both eyes and postcode of their current residence. "Residence" was operationally defined as staying in the same geographical space continuously for at least one year (*National Tax Agency Japan, 2022*). This section also collected information on how the participants moved over the past ten years, excluding studying abroad for less than one year. Visual acuity was self-reported, and some subjects responded using the "370 method", a qualitative measure of visual acuity that did not meet our quantitative standards. As a result, this item was not used in the analysis.

The second section collected the respondents' AT experiences. This section consisted of five questions. In this study, AT was operationally defined as participation in paid stargazing tours, including viewing educational planetariums implemented under compulsory education. Subjects' experiences were recorded as the number of times they participated in AT, ranging from zero to five or more times. The survey also collected information regarding with whom and when the respondents participated in AT.

The third section involved a list of 16 push motives for AT; however, a discussion of push motivations is out of the scope of this article.

Measurement and data analysis for LP in the subjects' residence

In our questionnaire, we asked subjects where they lived (that is, their current and previous postcodes) over the last ten years. We chose this time frame to align with the beginning of the Day-Night Band (DNB) data: the visible and near-infrared spectral imagery of the Earth under illumination conditions from full sunlight to night illumination with the half-illuminated lunar disk (*Liao et al., 2013*). The VIIRS-DNB is provided by the Suomi National Polar-Orbiting Partnership spacecraft(e.g., *Liao et al., 2013*). Of the 25 valid respondents, four reported an invalid postcode. This study used 21 samples to analyse *H1* and *H2*, which investigate potential correlations with geographical residence.

The postcodes were processed by the Geocoding Service provided on Google Maps to derive the geographical coordinates of a point corresponding to that postcode. These geographical coordinates were input into the VIIRS-DNB from the light pollution map (*Román et al., 2018*). In this study, geographical coordinates were input into the service to extract LP conditions in residential areas over the past decade. The analysis included four variables: mean, maximum, minimum, and latest values over the last ten years. Higher values from the VIIRS-DNB indicated worse LP.

Limitations of the sample

We would like to note that the sample size was very small, and the participants were likely biased. As noted above, due to issues with the sample, we had 21 valid contributions to test *H1* and *H2*, and 25 valid contributions to test *H3* and *H4*. In addition, ten individuals were part of the Astrotourism Laboratory at Wakayama University, and the others attended basic astronomy lectures at the University; both experiences are likely to impact respondents' answers to the experimental questions. Specifically, students who attend basic lectures may perceive more authenticity in higher NELM than those who do not. These biases may be important for determining the generalisability of the data. Future studies should consider using a larger sample size with demographics representative of the general public.

Data analysis and findings

As stated above, the experimental questions are:

> *Q1. Please raise your hand when you feel the night sky is authentic.*
>
> *Q2. Please raise your hand when you feel there are a lot of stars.*

Analysis of differences in background data

Of the final sample of 25 individuals, there were 23 Japanese students and two Chinese students, 17 of whom identified as women and eight as men. The mean age was 24.4 ($SD = 11.4$, $range = 18 – 63$). Results from *Q1* and *Q2* as a function of basic demographic and background data are provided in Table 1. The T-values in Table 1 (and also Tables 2 and 3) are derived from the Welch's T-test, a two-sample location test used to test the (null) hypothesis that two populations have equal means. These values are used to indicate the relative difference in the variation of the sample data. In other words, the greater the T-value, the greater evidence that there is a significant difference between the means of the two samples.

The results summarised in Table 1 indicate that most of the respondents evaluated *Q2*

Variables. n = 25	Q1.		T-value	Q2.		T-value
	M	*SD*		*M*	*SD*	
1. Total	3.00	1.00	-	4.40	0.82	-5.42***
2. Gender						
Female (68%)	2.94	0.90	-0.37	4.24	0.90	-1.88
Male (32%)	3.13	1.25		4.75	0.46	
3. Age						
18 – 29 (88%)	3.13	0.99	5.38***	4.50	0.80	2.22
over 30 (12%)	2.00	0.00		3.67	0.58	
4. Nationality						
Japanese (92%)	3.13	0.92	3.04	4.39	0.84	-0.21
Chinese (8%)	1.50	0.71		4.50	0.71	

*** $p < .001$

Table 1: *Descriptive analysis of respondents' characteristics. The table shows the mean score, standard deviation and T-value for each respondent's characteristics (gender, age and nationality for a total of 25 valid entries) for* Q1 *and* Q2*. "M" shows the mean value, "SD" shows the standard deviation, and "p" shows the p-values. Higher mean scores indicate higher NELM and a dimmer night sky.*

as higher (dimmer) than *Q1*. That is, most respondents indicated an authentic night sky at a dimmer NELM than the NELM where they felt there were a lot of stars. By aggregating the totals, the mean for *Q1* was 3.00 (*SD* = 1.00), and that of *Q2* was 4.40 (*SD* = 0.82), with a statistically significant difference between the two ($p < .001$). There were no statistically significant differences between men and women for either question. Students in their teens and twenties (22 respondents) rated both questions higher than students in their thirties and above (3 respondents), with a statistically significant difference between those age groups in *Q1*. Though the sample size is far from ideal, this may indicate that older individuals may perceive authentic night skies to be at a lower NELM (brighter sky with fewer stars).

Analysis of correlations in geographical residence

We determined the Pearson correlation coefficient between the respondents' decade LP measurements at their residences, in addition to the results of their answers to *Q1* and *Q2* using the method detailed above and reported in Table 2.

We obtained 21 valid responses for respondents' postcodes, as some responses were invalid. Table 2 summarises responses to *Q1* and *Q2* as a function of mean, minimum, maximum and latest LP values over the course of their previous 10 years' reported residences. The results for *Q1* indicate that there was a moderate negative correlation for all items except the lowest LP measurement, which was statistically significant in all cases ($p < .05$). It should be noted that we carried out the Smirnov-Grubbs test (used to identify outliers in a univariate dataset), which led to the rejection of the null hypothesis for all items ($p > .05$). However, we noticed that the strong correlation coefficient might have been driven by three data points at the high LP end (e.g., Figure 5, which is shown to demonstrate the spread of the data), and as such, we removed them to test the robustness of the correlation. In doing so, we found that the correlation coefficient in this smaller sample was much less strong than in the original sample. We want to emphasise that it is very difficult to draw conclusive statements about correlation or outliers given such a small amount of data.

In addition, we did not find any correlation between the respondents' residence and *Q2*. Our data does not suggest a correlation between *Q2* and each variable in LP, which measures the subject's perception of the number of star results and the amount of LP. Figure 6 shows a scatter plot relating the latest LP measurements to respondents' answers to *Q2*.

Variables.	Q1.		Q2.	
	Correlation coefficient	T-value	Correlation coefficient	T-value
Mean LP	-.46 (-.23)	-2.26* (-0.63)	.19 (-.28)	0.82. (-0.66)
Minimum LP	-.30 (-.29)	-1.39 (-0.67)	.10 (-.10)	0.42. (-0.54)
Maximum LP	-.50 (-.28)	-2.50* (-0.66)	.21 (-.22)	0.96. (-0.63)
Latest LP	-.52 (-.22)	-2.64* (-0.62)	.10 (-.02)	0.46. (-0.48)

* $p < .05$

Table 2: *The Pearson correlation between the respondents' LP measurements and their answers (Q1 & Q2). The analysis included four variables: mean, maximum, minimum, and latest values of LP for respondents' residences over the last ten years; higher values of VIIRS-DNB indicate higher levels of LP. For each entry, we report these values for the 21 sample data set on the top row and the 18 sample data set (removing the three highest LP samples) on the bottom row in parentheses. T-value indicates the significance of the correlation coefficient.*

Analysis of differences in AT experience

Table 3 presents the T-test results of the differences in AT experiences. Of the original sample, 25 individuals answered both *Q1* and *Q2*. In this analysis, subjects with two or more AT experiences were considered "experienced", and those with one or less were considered "inexperienced". Assuming that subjects who experienced AT more than five times had experienced AT five times, the mean number of experiences for all subjects was 1.92 (*SD* = 1.85); as such, this is a lower limit for the average number of AT experiences. It is noted that the number of AT experiences may be higher than in the general public due to the bias in this sample.

The analysis results indicated that "experienced" subjects rated both *Q1* and *Q2* higher than "inexperienced" subjects. In particular, there was a statistically significant difference between these two populations for *Q2* ($p < .05$), implying that subjects with more AT experience had a better perception of the number of stars, in support of *H4*. However, we did not find any statistically significant differences for *Q1*, leading to the rejection of *H3*. The details of AT experience, such as when and where it was experienced, reach beyond the scope of this work.

Discussion and Conclusions

This study aims to analyse how subjects perceive starry skies projected onto a planetarium, with a particular focus on internal factors. This study tested four hypotheses. The analysis may suggest that *H1* and *H4* were supported, whereas *H2* and *H3* were rejected.

Discussion

H1. there is a negative correlation between the amount of LP near a subject's residence and the NELM at which the subject perceives a planetarium projection as an authentic night sky.

We found a negative correlation between the amount of LP in subjects' residences and the NELM at which they perceive an authentic night sky projected onto a planetarium. That is, our results may suggest that subjects living in areas more affected by LP are more likely to perceive night skies as authentic at a lower NELM

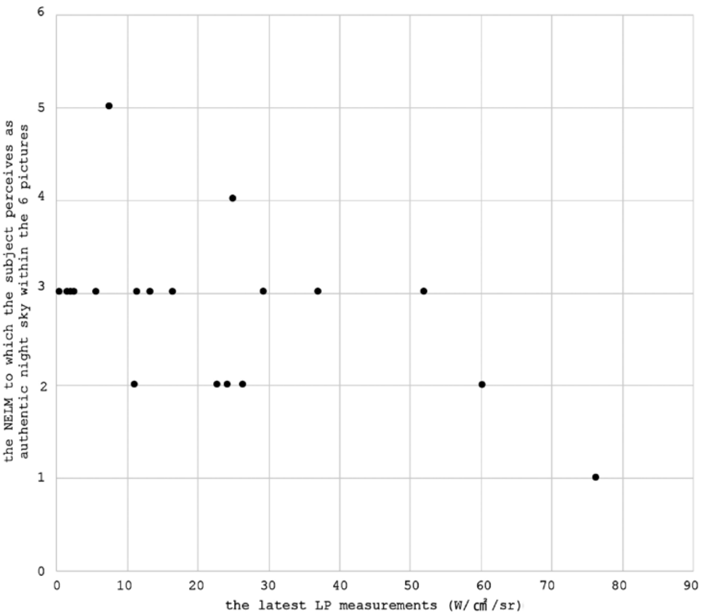

Figure 5: *Scatter plot showing the latest LP measurements and respondents' answers for the question,* Please raise your hand when you feel the night sky is authentic *(Q1; n = 21).*

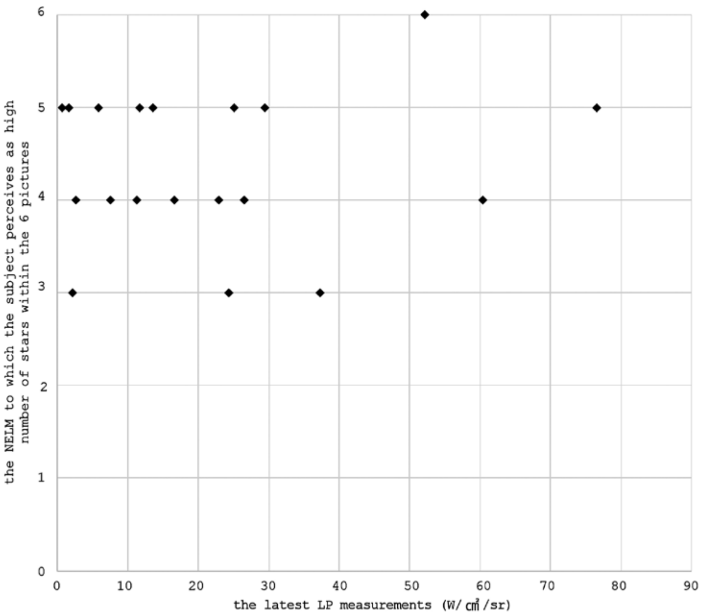

Figure 6: *Scatter plot showing the latest LP measurements and respondents' answers to the question,* Please raise your hand when you feel there are a lot of stars *(Q2; n = 21).*

Variables. n = 25	Q1. *M*	Q1. *SD*	T-value	Q2. *M*	Q2. *SD*	T-value
Experienced (48%) (Twice or more)	3.33	1.15	1.63	4.75	0.75	2.22*
Inexperienced (52%) (0 or 1 time)	2.69	0.75		4.08	0.76	

* *p* <.05

Table 3. *Descriptive analysis of participant responses to Q1 and Q2 as a function of differences in AT experience.*

(translating into fewer visible stars, consistent with their lived experience). The correlation coefficient between *Q1* and the Latest LP, which indicated the relationship between the subject's perception of authentic night skies and the latest LP, had the lowest correlation value ($r = -.52$; Table 2) compared to the other items. There is a possibility that the subjects more affected by the most recent LP impact are more likely to identify an authentic night sky at a lower NELM. However, to reiterate, it is difficult to draw conclusive statements about correlation or outliers given such a small amount of data.

H2. there is a negative correlation between the amount of LP near a subject's residence and the NELM at which the subject considers there to be a high number of stars.

Our data does not suggest a correlation between *Q2* and each variable in LP, which measures the subject's perception of the number of star results and the amount of LP. Therefore, it was suggested that the ability to recognise many stars was nearly the same regardless of where respondents live or have lived. In other words, this result may imply that people know that the sky should have more stars even if they live in a place with a bright sky. *Sawada et al. (2021)* indicated that the most sought push motive for Japanese astrotourists was "seeing beautiful starry skies". Though how "beautiful" is defined is subjective, it may be that providing a sufficient number of stars in AT activities, including planetariums and star parties, may improve satisfaction with AT experiences. Additional research into the relationship between the perceived beauty of the night sky and the number of stars, along with a comparison of outcomes from experiments both in a planetarium and outdoors, would enhance our comprehension of tourists' perceptions of the sky.

H3. AT-experienced subjects perceive night skies as more authentic in higher NELM than AT-inexperienced subjects.

Though our sample is biased toward those more familiar with astrotourism, our data does not suggest a correlation between the perception of authenticity of the night sky and AT experiences. The *H1* hypothesis was adopted, which means that subjects' perceptions of the authenticity of a night sky may be more influenced by their living environment than by their AT experience. A larger sample size is required to confidently adopt one hypothesis over another.

H4. AT experience is related to the ability to qualitatively identify a large number of stars.

Related to *H2*, we found that AT experience correlates with the ability to qualitatively identify many stars. *Tanaka et al. (2021)* found no relationship between personal data, such as astronomical observation experience, and the subject's perception of faithfulness as projected onto the planetarium. However, in contrast to these findings, this study revealed a relationship between AT experience and subjects' ability to perceive the number of stars. As we mentioned above, the data presented in Table 2 might indicate that people know, even if they live in a place with a bright sky, that the sky should have more stars. The ability to perceive the number of stars may be more likely affected by the number of observation experiences than their living environment. However, our study could not analyse when the subjects experienced AT. There may be changes in the perception of the number of stars depending on when the subjects participated in AT. It is also necessary to understand which AT experiences subjects experienced: a planetarium, a visit to an observatory, or some other dark-sky experience. It should be noted again that all subjects had attended a basic astronomy lecture, which may have been a major bias.

Limitations

This study had some limitations. First, the planetarium system used in this study was digital, which meant that the faithfulness of the night skies was insufficient. The absolute and relative star brightness and size of stars in our digital planetarium differ from those of real stars (*Okyudo, 2012*). Some researchers also implied that star images are more faithfully replicated in optical planetariums than digital planetariums (*Tanaka et al., 2017*). In particular, we did not measure the brightness ratio of the stars in this study; we simply projected the PC monitor input Stellarium onto the dome. Additionally, the resolution of the planetarium used in this study was 4K, which is slightly out of focus for human vision (*Okyudo, 2012*). Therefore, subjects' responses regarding their perceived NELM are not necessarily accurate. Future experiments using an optical planetarium should be conducted and compared with the night sky outside (*Sawada et al., 2022b*).

In addition, allowing the subjects to adapt to dark sky conditions may affect their perceptions of the sky under the dome. In this study, the experimenters determined that dark adaptation did not need to be considered, but further analyses may be required to get more correct data.

An additional limitation was that the participant sample was biased, as stated above. The study sample consisted predominantly of university students in their 20s, making generalisability impossible. This study also asked subjects to evaluate their willingness to participate in AT on a 5-point scale, most of whom rated it as 4 or higher ($M = 4.50$, $SD = 0.63$), likely skewed by the ten members of the sample who are part of the Astrotourism Laboratory at Wakayama University. In another survey conducted among 2,000 Japanese residents, 50.0% of the sample expressed interest in participating in AT, while the remaining 50.0% stated they would not (*Sawada et al., 2023b*). Though these two studies are not necessarily directly comparable, we expect the present study's participants are not representative of the general public. Beyond the biases of our participants, the sample size was very small. The results stated in this study should be carefully considered against our sample size. It is possible that with a larger group of participants who are more representative of the general public, we would garner considerably different results. Further analyses with larger sample sizes are required.

Conclusions and Suggestions for Future Work

The results of this study may have implications for suppliers of AT services, such as planetarians and organisers of star parties. This study may indicate a relationship between the level of light pollution in participants' neighbourhoods and their AT experience, influencing their perception of the night sky. Therefore, suppliers can vary their approach to AT based on their location and the individual astrotourists. Specifically, when AT occurs under the beautiful night sky (e.g., space with NELM 6th magnitude or higher) or in a planetarium, tourists may be satisfied simply by looking up at the starry sky. On the other hand, service providers may need to make more effort to entertain tourists in spaces with fewer visible stars. Although there is a sample bias and some limitations, this study implies that tourists from areas with low light pollution and those who are AT-experienced may not be visually satisfied if the night sky lacks sufficient stars. Therefore, in spaces where the night sky cannot be enjoyed visually, it may be necessary to improve tourist satisfaction by combining efforts such as enhanced astronomical explanations and utilising telescopes for observing celestial objects.

Although the main sample in this study consisted of Japanese participants, it is possible that results may differ for other cultural samples (e.g., *Ito et al., 2020*). However, the suggestion of a relationship between subjects' internal factors and their perception of the night sky should interest the readers of this issue.

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During 100 Hours of Astronomy, a 100-hour-long celebration of astronomy sponsored by the IAU Office for Astronomy Outreach, the amateur astronomers’ team from the Basra Governate brought a mobile planetarium to the Baghdad International Book Fair. In this image, we see visitors captivated by the digital planetarium show, underscoring the importance of planetariums to communicate astronomy with a wide public.

Image Credit: Basra Governate Amateur Astronomy Club/NOC Iraq Team

The 2022 IAU Office of Astronomy for Education Astrophotography contest invited photographers to submit still and timelapse images that showed celestial patterns with particular cultural significance. This image is one of the winners of the 2022 IAU OAE Astrophotography Contest in the category of still images of celestial patterns. Against a silhouette of baobab trees in Morondava, Madagascar, the Milky Way and several celestial objects, constellations, and asterisms stand out amongst the panoply of stars. The Milky Way, the image's most prominent feature, is significant to many cultures around the world and throughout history. Stellar views such as this are not available to a growing fraction of the world, highlighting the importance of planetariums as dark-sky oases in light-polluted areas.

Image Credit: Amirreza Kamkar/IAU OAE

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