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Building a low budget planeterella for auroral outreach incorporating physics student co-creation principles

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ABSTRACT

A planeterella (an auroral simulator) has been built at Nottingham Trent University within the cost of a student postgraduate Masters project budget (£100). This instrument is currently only the third working planeterella in the UK, and while not as sophisticated as it's two older cousins, it still demonstrates the space physics principles at the same time as providing an educational and inspirational benefit. The final equipment has proved successful in engaging students, stakeholders, and the public with 'seeing' magnetic fields and auroral processes. The build requirements and method are provided to allow other higher education institutions to be able to create their own planeterella as scientific demonstrations and student projects; only requiring small budgets and common equipment borrowed from physics teaching and research laboratories.

Key words: Instrumentation – Planeterella – Outreach – Student co-creation.

1 INTRODUCTION

1.1 Education background

Teaching space physics to undergraduate students is a highly empirical process, involving theory, mathematical derivations, data analysis, and potentially computer simulation. While topics such as thermodynamics have common experiments such as heat engines or specific heat calculations which are available in undergraduate laboratories, this is harder to produce for the more niche field of solar-terrestrial physics. Having experimental equipment provides a range of benefits for physics student understanding and engagement of the curriculum (Evagorou et al. 2015).

While developing physics experimental equipment for demonstration is beneficial for science outreach and public engagement, the effects on including these within undergraduate lectures is limited without additional pedagogical techniques being applied (Moll & Milner-Bolotin 2009). To maximize the student benefit the principle of co-creation is essential (Dollinger, Lodge & Coates 2018). For practical experimentation skills, the primary idea behind this is that the students play an active role in developing their own learning, taking a role in the design and build process, and can be implemented in the form of students developing their own laboratory experiments (Craifaleanu & Craifaleanu 2022). This can then support lecture material in a module, or assist with producing a peer developed and marked assessment (Doyle, Buckley & Whelan 2019).

Undergraduate and postgraduate independent project work is a requirement for accreditation of an honours degree by the Institute of Physics (IOP 2022). Involving student co-creation of equipment into these projects is a clear way of supporting student learning, as well as enhancing employability with a number of hard and soft skills. This also has the benefit of linking to some of the essential requirements of a physics degree such as the ability to '*Plan and execute an open-ended extended research project*', '*Demonstrate some originality during an extended investigation*', and provide '*Approaches to skills development encompass both generic and subject-specific skills. It may well be most appropriate to develop both within the physics context.*' (QAA 2019).

This study looks at demonstrating one of the most visually appealing and engaging aspects of geophysics (e.g. Hechter 2020), the aurora. Observed as a result of space weather interactions, this instrument provides a simulation of how a current flows through space between the sun and Earth, meaning that the space between both objects is not a vacuum but a rarefied plasma.

1.2 What is a planeterella?

The idea of the Terrella began with the Norwegian physicist Kristian Birkleand, who had an extremely eventful history. His background, research, and biography has been covered in many forms of media—and makes for an excellent outreach talk. For further information see Egeland & Burke (2010). It was during the later years of his life that he gained enough funding to build his first, and subsequent, Terella's. The idea of a Terella is that a large magnet within a metal sphere is hung from the top of a partially evacuated chamber and charge is fed to it. At a specific range of vacuum and charge conditions, the potential difference allows air glow to form from the electron flow interacting with the rarefied gas. The whole instrument produces an effect visually similar to the aurora. The discovery of electrical currents being the cause of the Northern and Southern lights led to the current flow along geomagnetic field lines being called Birkeland currents.

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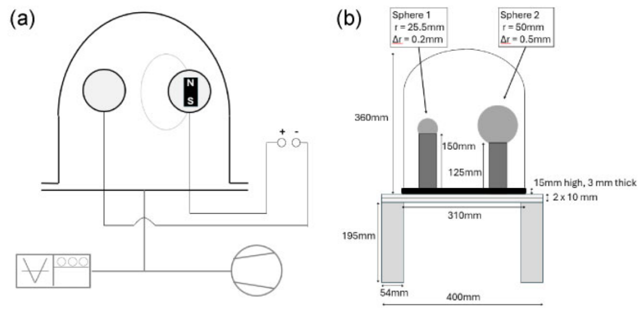

Figure 1. (a) A simplified sketch of the planeterella instrument setup. Two metal spheres connected to a current, one with a magnet inside and one without, are contained within an evacuated chamber. The vacuum pump is connected to the chamber with a pressure gauge attached. (b) The NTU planeterella setup with sizes included in mm, the addition of a rubber seal (black box) is necessary to preserve the vacuum. Materials used are perspex, wood, rubber, glass, and aluminium. With a reduced air density the electrons can flow across the gap at a lower potential difference, as they travel they are caught upon the magnetic field and transfer energy to the small amount of air within the system causing airglow.

In comparison a planeterella is an enhancement of the original Terella designed by l'Institut de planétologie et d'astrophysique de Grenoble (IPAG) to be sturdier, safer, and able to provide more research aspects. It consists of two metal spheres, one magnetized and one not, acting as anode and cathode. The airglow forms around the magnetized sphere showing photon production along field lines, an idealized sketch of the process is included in Fig. 1a). The development of the planeterella and background to the iterations of the equipment are fully described in Lilensten et al. (2013). This paper includes the advances and research that can be achieved with the planeterella, currently in its third iteration with moving cameras, movable (and rotatable) spheres, and the ability to pump a range of gases into the sealed environment to change the emission lines observed.

It should be noted that in this study only the costs of the first iteration are included which are given as 8000 Euros in 2013, using a Bank of England inflation calculator this would result in a current cost in 2024 of more than £9k (or 11.5k USD), well outside most university outreach or student project budgets.

Within the UK there are two planeterellas that are working and advertised to the physics community. The first, is at the University of Leicester and has been running since 2011, being taken to a range of public facing events to great success (University of Leicester 2024). While the second instrument is newer and housed at the University of Southampton (University of Southampton 2024).

The rarity of the instrument has meant that the literature behind the instrument development and operation is also sparse. The Lilensten et al. (2013) paper would be considered the primary source, however there are several BSc project theses on the planeterella emission from Eindhoven University of Technology (Hendriks 2018; Laarman 2019), and several AGU conference presentations. This paper aims to remedy this lack by highlighting the construction and challenges of building the instrument. This has relied upon the supervisors experience with the planeterella at the University of Leicester, as well as a trial and error approach.

1.3 Project objectives

These instruments are demonstrated to only small groups of the public due to the difficulty in transport, location, staff expertise, and cost. This project was designed to allow a low budget planeterella, focusing on sustainability, to be created through trial and error. As part of the BSc project aspect it would allow a student to experience the industry R&D process, as well as produce a piece that would inspire future students.

The scholarship aspect of the project is to demonstrate that a suitably keen student can co-create some of the most complex equipment, and give them confidence in themselves. The final product was planned to be mobile enough to demonstrate to stakeholders including the public, peers, and university staff.

2 SPECIFICATION

2.1 Requirements of a planeterella

The planeterella has no patent associated with it from its developers CNRS, due to the original Terella not being patented and the ethical approach towards public outreach being available for all. As such there is a 'Gentleman's agreement' in place where CNRS will provide plans free for public institutions (Lilensten et al. 2013). While this is excellent for building appropriate instrumentation, it only provides a challenge around technician and staff time. By asking students to determine the theory and then design the instrument themselves, there is an appropriate level of student planning, acquisition, independence, negotiation, and budgeting involved. This involvement means that learning outcomes of relevant physics modules from across the curriculum are thought about in a much higher level of detail. The technician and staff time requirement is still a challenge although this is reduced slightly by the student input.

The specifications for the instrument are included below:

(i) Build an instrument to be shown to an audience of up to 10 people

(ii) The main audience for the instrument would be prospective students and parents at open days, as well as other physics undergraduate students

(iii) Documentation must be produced to allow future student projects to conduct their own research or develop the instrument further

(iv) The instrument needs to be built on a Masters project budget of roughly £100, not including borrowed equipment

(v) The planeterella must be modular to allow transport within a car and allow for rapid reconstruction

(vi) The maximum time for design, build, and presentation is eight months

(vii) A full set of risk assessments needs to be produced before any building takes place and for demonstration of the instrument

From the diagram in Fig. 1(a), it can be seen that there are some main pieces of equipment that need to be sourced. These are a glass dome, a base, vacuum pump, hollow spheres, a magnet, and a high voltage power supply.

2.2 Safety restrictions

As part of developing employability skills in a work like environment, the student was required to consider the equipment development from a Health and Safety perspective. There are two major aspects of safety involved in a planeterella. The first is the strong magnetic field required to ensure the airglow is visible. Rare earth (such as neodymium) magnets are the easiest type to use, although finding these magnets in high strength can be expensive and difficult. A range of magnets were available as part of research laboratories in the

Table 1. A list of the main equipment needed for the planeterella build. The price of some of these pieces has been estimated due to not being able to purchase the same equipment—in particular the glass dome. Additional sundries are not included as prices are negligible.

Item	Cost (£)	Acquired	Comments
Steel sphere, hollow	1.04	Purchased	25 mm radius
Steel sphere, hollow	6.40	Purchased	50 mm radius
PLA for 3D printer	26.36	Purchased	1.75 mm, 500 g
Plastic base	39.75	Purchased	400×400 mm, 10 mm thickness, cut to size
Wooden legs ×4	3.90	Recycled	54×54×196 mm each
Copper wire	8.19	Recycled	Roughly 1.5 m total
Bungs	0.24	Recycled	Rubber
Vacuum pump	5068	Recycled	Edwards dry scroll pump nXDS6i
Hoses and valves	287	Recycled	
Neodynium magnet	12	Recycled	400 mT at surface
EHT power supply	195.55	Recycled	Philip Harris B8R02653
Pressure Guage	158.23	Recycled	Edwards D39560000 analogue guage
Glass Dome	250	Recycled	155 mm radius 360 mm high
Total	6056.66		Total purchase of £74

medical imaging group, a magnet with a strength at 0.4T at the surface was selected for use. Before this magnet could be transported to the student area of the lab a transport risk assessment was written, with such a strong magnet the risk of induced currents while transporting is high. The highest risk aspect the magnet can have is to effect cardiac implantable electronic devices, the most common example would be an internal pacemaker. Jongnarangsin, Thaker & Thakur (2009) calculated that a strength of 10 Gauss at 10 mm distance was strong enough to cause disruption in a pacemaker. With a magnet of 4000 Gauss the safe distance for these devices will be non-trivial to calculate, and will depend on the magnetic permeability of any shielding materials such as a carrying container when transporting, or the dome when installed in the instrument.

The second safety issue is the high breakdown voltages required to allow the charge to flow between the two spheres. Only high voltage and not high current is required to run a planeterella, so the power output is relatively low. The potential for electrical burns and/or shocks is still present and needs to be considered, particularly for outreach purposes. The student produced two risk assessments, one for construction of the planeterella and the second for demonstrating the instrument. These were reviewed by the project supervisor and lead technician and then stored on record following NTU policy.

3 THE NTU PLANETERELLA

As the plans were not sought from CNRS the student project followed a plan of experimentation to develop the instrument. The process involves an industry R&D application of trial and error with a new product to develop the skills of the student and improve their future employability. Budgetary requirements were the primary driver with sustainability a close second, meaning that the use of recycled materials is essential. This allows the construction of new equipment while still considering the environmental impact. The materials required for the instrument and what was either borrowed or recycled are shown in Table 1.

The completed planeterella was built within four months, with the highest difficulty being maintaining a low pressure environment with wiring entering the instrument. This issue was solved by drilling holes in the base and running wires through rubber bungs pushed into the holes in the plastic base. A greased rubber seal was also made to surround the glass dome to ensure reduced air leakage. The final instrument runs at a maximum vacuum of 0.1 mbar, and is provided with 1.9 mA at 560 V, producing a visible airglow.

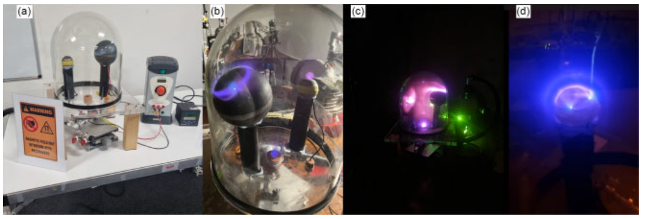

Figure 2. The NTU planeterella. (a) An image of the equipment while switched off. (b) The planeterella running normally in standard room lighting. (c) The planeterella running normally in a dark room. (d) The planeterella running with the current in reverse. The glow is provided by Nitrogen excitation, as the electron flow imparts kinetic energy to the static neutrals, this energy is then lost as photon emission.

During testing there needed to be easy movement of components and as such generic forms of re-adhesive putty were used to hold columns and the spheres in place. The adhesive qualities do seem to lessen under vacuum (which is of interest for future undergraduate study) but this has allowed a low cost method of testing sphere locations, as well as reducing waste.

The final construction is shown in the panels in Fig. 2, with the scale diagram and sizes shown in Fig. 1(b).

3.1 Operation

A typical demonstration runs in the following way. Audience members are questioned discreetly as to whether they have any form of implanted electronic medical device, any who answer positively are asked to stand a distance of at least 2 m away from the dome. The instrument takes approximately 150 s to get down to a vacuum which allows airglow to start being seen by the human eye (∼0.2 mbar), this allows some discussion of atmospheric pressure and how much air is in the chamber with the audience while waiting. The link to breakdown voltages of air with lightning, and the similarity to Van de Graff generators create a relatable analogy for the audience as well. At this pressure the main lights in the room are still on and viewers are able to see the analogous auroral oval airglow. Essentially, an airglow torus around 10 degrees from the north pole of the magnet, explanation begins with how similar this is to Earth. The discussion then moves to charged particles following field lines and progressing to why airglow is produced and why it is purple. Getting the audience to participate in answering questions of the style 'what the air is made of' and 'what would happen if different gases were present' provides a sense of inclusion.

Ensuring all audience members stay still, the main lights are switched off to allow the dimmer airglow around the field lines to be seen. Explanations are given of magnetic boundaries, pressure in the solar-terrestrial environment, and the magnetic field lines not being able to penetrate the far charged sphere. Once questions have been asked the current is switched off and the polarities reversed, allowing current to flow from the magnetic sphere to the non-magnetic sphere as seen in Fig. 2 panel (d). The reversed current produces an all over airglow, highlighting the difference between magnetic and non-magnetic planets.

Further discussion about the history of Kristian Birkeland, magnetic experiments, or aurora on other planets usually follow for any interested audience members.

4 CHALLENGES AND SOLUTIONS OF THE BUILD AND PROJECT

While the instrument has been built successfully the process had a number of key points that provided challenges for the staff, student, and technicians during the build. We include these here along with solutions. Some of these solutions were implemented at the time of build, and others are just better solutions based on a completed build and practice.

Soldering wires to spheres

The spheres have a relatively large surface area and a high thermal conductivity, making soldering wires to the inside exceptionally difficult as the solder does not melt and condense appropriately. The solution to this problem was an 1800 W heat gun rather than a soldering iron. Heating the entire area up and then allowing to cool provided more time for solder to attach the wire to the surface.

The bell jar

Finding a suitable container is one of the hardest parts as this is potentially a specialized and expensive piece of equipment. The bell jar was the first piece to source and determined further equipment. Building an indent into the base required a circle to be cut out of the perspex, and this required a laser cutter in another laboratory due to the size. Testing the bell jar was also required to ensure no cracks or fatigue was present. This was performed by holding the jar up and ringing it with a sharp percussive blow, a ring indicates the jar is intact and a thud would indicate it had a structural defect.

Wires into the dome without losing pressure

While there are specific glasswork techniques to able to seal around an object, this was neither within our budget or scope. Holes were drilled in the perspex base and small rubber bungs used to block the holes. These bungs had a very small drill pushed through the centre of them and the wires pulled through with tweezers. While this has worked it holds the potential for low level leaking. Any future attempts could cover the wires in a slow setting adhesive or polymer (e.g. PVA glue) before being pulled through the plug to eliminate any small gaps.

Conversion between student design and practical elements

Time was lost between the design (what would be ideal) and the build (what is realistic). This provided an excellent learning experience in both negotiation and the realities of turning research into a real world application for the student. The solution was to identify what reusable material was available both within the technicians workshop, and by discussing material properties with research staff. It highlighted that there is no full inventory of everything a university department has in all labs, but that one might be very useful.

One day per week of project labs

From the student and technician perspective having only one day a week to be able to work on the build was difficult. Any parts that needed build time would have to wait between sessions, and could rely on workload of the technicians as well. The solution is for the student to develop an appropriate time plan in the initial stages with contingency for mistakes and problems to arise. In particular matching student coursework submissions, and hence increased stress, to times of the year.

The volume and mass

The difficulty with such an instrument, and it affects all planeterellas I have observed, is that they are big by necessity. Having an appropriate size glass dome that viewers can see into requires a decent volume and appropriate thickness of glass. This cannot be folded down or reduced in any way for transport. The vacuum pump required is extremely heavy, in our case, we had available the Edwards nXDS10i scroll pump weighing in at 25.8 kg. The extra pieces of equipment required including the base, hoses, power supply, and sphere can all add up in weight as well.

Available lighter oil based vacuum pumps have been tested but they are unable to pump the system down to the appropriate pressures. The Edwards mXDS3 pump is just capable of pumping down to the required pressure assuming a perfect seal around all other components, and weighs only 7.8 kg, but would require the purchasing as a separate item which is well outside the student budget. The glass can be replaced with a lighter density plastic but this would have to be specially made and is not sustainable. We have been looking at making custom fit carrying cases filled with shaped foam which reduces the difficulty in transport atop a wheeled trolley and allows items to be placed in a vehicle.

Safety

Each element of the trail and error process contains an element of risk and the student was tasked with writing all risk assessments for every process. These started with requiring editing but rapidly improved with student confidence. The paperwork of each step in terms of safety is not to be underestimated. This included simple procedures such as walking a 0.4 T magnet across campus safely, all the way to running 3 kV through wires in a dark room. Signs have been produced and any staff working with the instrument have had to read and sign the risk assessment. The complexity of how to build and disassemble the equipment in a safe manor has meant that the task of operating it has been left only to the authors to date, although two additional students have now been trained.

5 ENGAGEMENT AND BENEFITS

5.1 Student

The independent nature of undergraduate projects makes it ideal for a personalized targeted GRIT (growth, resilience, integrity, and tenacity) approach for support, in particular the trial and error method of testing equipment with initial poor success rate builds both resilience and tenacity. Although the definition of resilience is vague, we are defining resilience here as ‘positively transformed through an encounter with adversity, ultimately resulting in growth or learning’ (Brewer et al. 2019). While there were regular supervisory meetings, weekly group undergraduate project student discussions (*n*

= 8) provided a support network (Holdsworth, Turner & Scott-Young 2018) to build this resilience over time.

The growth aspect came through being able to describe the instrument to peers, academic staff, and at public events. At these events the process of explaining how the instrument works, and how each test has been approached, has led to a visible improvement in the students research skills (Feldon et al. 2011) as well as professional development (Saville et al. 2022) such as presentation skills, time management, and technical writing. An additional aspect of the project included sourcing an appropriate spectrometer from staff to enable data capture of the airglow emission, showing the monochromatic wavelength and allowing for techniques such as background removal and thermal broadening determination. The act of using a spectrometer on a student constructed piece of equipment links the core physics concept of spectrometry directly to the students work, it also has a specific correct answer as well (as air composition is known) which is rare in an undergraduate project.

More tangible student benefits during this project have been a high module grade for the module (Distinction – >74 per cent), as well as evidence for a range of employability skills. The student had the highest attendance and engagement in the group meetings with 92 per cent, missing only two of the 25 organized meetings, where the mean attendance was 76 per cent (19 of 25 meetings). The background of the instrument, setup of the demonstration, and the delivery of outreach, was also used as a basis for a portfolio of evidence in the science communication module also taken by this student. The student feedback about the project also highlights the benefits of this work. '*I feel that the project has greatly improved my public speaking skills and how to create a well-received demonstration for the public through the multiple open days the planeterella was demonstrated at.*'

5.2 Impact to date

As a visibly appealing piece of equipment, the planeterella is ideal for demonstrating to the external stakeholders. These sessions class as STEM outreach as defined by (Tillinghast et al. 2020). '*The act of delivering STEM content outside of the traditional student/teacher relationship to STEM stakeholders (students, parents, teachers...) in order to support and increase the understanding, awareness, and interest in STEM disciplines*'. While STEM outreach stakeholders can be a wide range of people (Appel et al. 2020), we have currently focused on academics, students, and the public.

The Planeterella has been shown at four internal NTU events, eight external NTU daytime events, an Open Dome public event (Brown 2024), and has been demonstrated as part of a physics seminar at Sheffield Hallam University to staff and students. External events are difficult to attend due to the issues mentioned in Section 4 however, travelling 40+ miles on public transport has been achieved with the instrument. In total a demonstration of the equipment has been provided to over 400 people, including physicists, the public, accrediting bodies, and university executives. The planeterella build and scholarship approach has been presented at the 2024 UK National Astronomy Meeting, features on a university webpage (Whittaker 024a), and has been included in a 'The Conversation' public article about the Northern Lights being seen at lower latitudes in this year (Whittaker 024b). The articles have been read by 50 k people in the English version, and roughly 15 k in the Spanish language version of the article.

Audience engagement has been positive with in person comments including 'Why doesn't every university have this', 'It's a cool machine', 'Fascinating to see it close up', 'Can I build my own', and has led to a range of questions from the audiences. There has been a creative aspect to the work as well, with audience members discussing how the visuals make them feel and whether this is 'art or science' and linking the demonstration to other science phenomena such as lightning, UV fluorescence, and Faraday cages to name a few. An example of the positive public impact is included in Fig. 3, a picture taken during the Open Dome event posted to social media and reproduced (with the posters permission), comments alongside the post are listed within the caption.

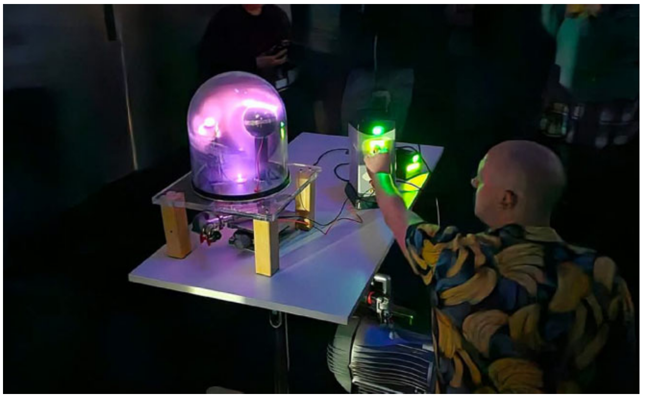

Figure 3. An image of the NTU planeterella in operation taken during a public event, image credit: Tony Booth. The use of automated increased exposure time on cameras allows for more physics information to be relayed in an outreach format; in particular about CCDs, requirements of telescopes, frames per seconds in films/games, and of course how the human eye works. Comments accompanying this social media post include: 'It was a great evening', 'Almost as cool as the real thing', 'great night I loved it', 'Fantastic machine creating the aurora.'.

6 CONCLUSIONS

The specifications of a planeterella built at Nottingham Trent University as part of an MSci integrated Masters project is detailed in this paper. This instrument has been built on a very small budget by using recycled materials, linking in with university targets on sustainability, and by borrowing equipment from a range of research and teaching laboratories on campus. The instrument contains all aspects of an industry R&D project and while the borrowed equipment is standard for a physics laboratory, there is a high level of technician input regarding cutting of materials, making air tight seals, and safely providing power.

As a visually appealing piece of equipment the planeterella is clearly useful for demonstrating concepts, and encouraging public interest, in electromagnetism. The rarity of these instruments across the world add to their appeal, and while specific plans can be requested from CNRS, designing and building from first principles provides a practical way of developing knowledge. This instrument provides one of the few practical lab based demonstrations of solar terrestrial physics, and also demonstrates complex ideas in electromagnetism, one of the largest knowledge gaps in incoming undergraduate students (Wu 2024).

The future of this instrument is twofold. First as a public engagement demonstration piece, it has already inspired the members of the public that have seen it and it will be used for future public science fairs. Secondly, the instrument will also benefit future undergraduate projects, an example would be determining the luminosity as a function of pressure and sphere separation distance. It will allow more creative projects to be developed with student initiative, this could include the ability to introduce gases other than air into the dome affecting the optical spectral emission lines and simulate the Earth's upper atmosphere. Movement, and increase, in the number of spheres and introduction of electromagnets is a later, advanced, stage of development as both of these concepts are incredibly difficult to achieve practically, it will take lateral thinking and student group learning to solve in a sustainable way. The planeterella is planned for use in the teaching of a new level 6 undergraduate module at NTU physics called 'Space Instrumentation and Observation', allowing students to simulate observing planetary aurora from orbit with CCD cameras, with the inherent data and engineering challenges highlighted to them in a problem-based learning format (Raine & Symons 2012).

DATA AVAILABILITY

The construction of this instrument is fully documented within this paper. Data collected on the spectral analysis of the airglow is not shown but can be requested for any interested parties.

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