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Case study of developing an affordable undergraduate observatory

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Abstract

Astronomy is one of the few sciences where the data (star-light) can be seen by all. Yet, there is a disconnect between a typical undergraduate lecture and, for example, where a planet may be in the sky and how to observe it. With the advent of moderate cost, high-quality 'back-garden' astronomy, and standard computers powerful enough to produce original research, we show it is possible to build a small observatory capable of actual astrophysical research for a modest budget ≈£30 000. We detail the iterative process of planning, funding, results and student-projects, that we followed over 4 years from a Raspberry Pi camera and home-owned telescope, to a permanent roll-top observatory with two fully automated telescope systems capable of undergraduate use and astronomical science. We report on projects ranging from early-years projects based on observational planning, data analysis and some restricted actual observations, to more open-ended final-year projects to observe, e.g. planetary transits, variable stars or high-resolution planetary imaging. We hope this work may act as a blue-print or encourage and aid other small to medium sized higher-education institutions and astrophysics groups to also develop their own undergraduate observatory.

Keywords: observatory, undergraduate, astronomy, astrophysics

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1. Introduction

For astrophysics teaching in higher-education there is a choice to be made in what is taught in the traditional experimental-laboratories and what student-projects are offered. Whereas, for optics experiments for instance, there are a plethora of standard experiments at the right level and at low-cost, from diffraction to spectroscopy, for astrophysics and astronomy there is not the same obvious set of introductory experiments with real astrophysics applications. At our institution we have a new 'Physics with Astrophysics' degree program and in the main Experimental Physics and Computing unit in the first and second years, that all our Physics and Physics with Astrophysics students take, there are several astro-based data analysis 'experiments' and a few more complex astro-projects, for example, using a loudspeaker on the end of a spinning arm to mimic the Doppler effect of a binary star system. While these all teach the scientific-method, they do not take advantage of arguably the most important feature of astrophysics; the data that are available in the night-sky. Many students are inspired to choose their course because of this and the beautiful astro-photography from the Hubble Space Telescope, yet often there is a disconnect between the night-sky and their degree course. It is, for example, one thing to learn about right-ascension and declination in a lecture theatre, and another to use it to find an object in the night-sky—that can only really come about through use and practice. The missing link is hands-on observational astrophysics.

Observational astrophysics has all the elements of the complete scientific process: scientific question, hypothesis, observational planning, measurement through observation, data analysis and conclusion. Of this process, the main difficulty is the measurement through observation; actually getting students to take their own data. There are many ways around this step, from archival data to simulation. But, if that step can be performed by students themselves, the complete scientific process is not only a strong learning tool, but can be inspirational. A major road-block is the difference in scale from a typical lab-based physics experiment and a working and useful observatory.

In the UK there are ≈35 Universities offering some variant of an Astronomy or Astrophysics degree programme. According to their promotional material we can divide the observational facilities into three categories: 16 have large-scale purpose built buildings and domes often relatively historic in nature; 7 with small roof-top telescope systems; a few with access to larger scale observatories in for example the Teide Observatory in Tenerife; and 13 with no mention of an observatory.

To create a new large-scale facility would require a 'top-down' approach from senior university managers with an associated teaching and scientific business case for a major investment of resources. It is unlikely that such a strong science case can be made in today's modern world of remote professional observing and space telescopes. There is also the risk that such facilities would be so specialised that only final year students would be able to use them and then only under tight supervision.

To address these issues, we have pursued a 'bottom up' approach. Over the past few decades, the quality and specification of equipment available to the 'back-garden' amateur astronomer has become of such high specification and performance it can provide—in certain circumstances—data to match that of similar professional setups. We have treated the development of our undergraduate observatory as we would any other (admittedly high-end) undergraduate physics laboratory experiment. The relatively low cost of high quality of telescopes and cameras etc has allowed us to open up observational astronomy and astrophysics to a broad range of students.

Here we report our experience, in some detail, of the process of planning, building and using a new small scale observatory at the University of Bath in the UK, named the Bath Physics Observatory (BPO). We began with a Raspberry Pi camera and a telescope loaned from a member of staff on a roof-top, and over 4 years built up results, and funding and recently opened our new purpose built roll-top observatory (see figure 1(a)) housing two permanently mounted ∼200 mm computer controlled telescope systems. This has now been used by our students both in

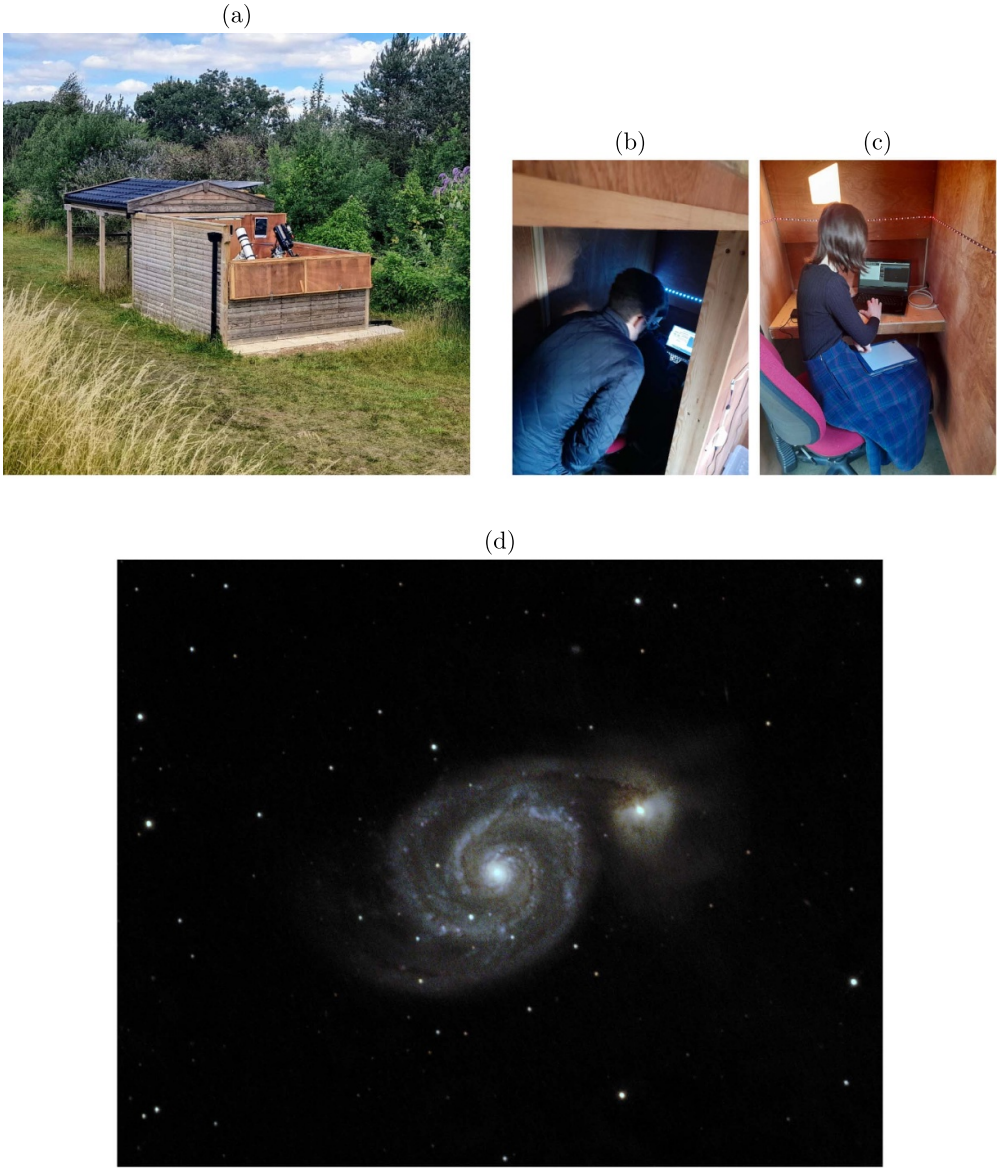


Figure 1. (a) The BPO roll-top building open during the day with both telescope systems visible in the main bay. (b) and (c) Undergraduate students using the observatory at night, and during the day for calibrations. (d) Astrophotograph of M51, the Spiral Galaxy. Taken at the BPO using RGBL filters and cooled monochrome camera, each channel with approximately 30 min exposure.

their early years and their more extended final year projects.

Quotes from final-year project students using our telescopes for the first time:

- 'It's incredible to be able to work with such hands-on equipment and use it to measure objects so far away.'
- 'Fantastic to get a project with real hands-on experimentation that allowed us to get a taste for observational astronomy.'

This report is written to capture the course of our development, difficulties encountered, strategies used to move the project forward and some technical details. We hope the lessons

learned, and path taken, will be generally applicable and allow other institutions to develop their own small-scale observatories.

2. Observatory details

The observatory is a wooden 3.6 m × 3.0 m roll-top design (cost including installation ∼£8000), which includes a 1 m × 3.0 m warm room for the observers, and an open 2.5 m × 3.0 m telescope bay with drop down sides from the company 'Home Observatory UK' (www.homeobservatoryuk.com/). It was installed by the company atop a professionally built 4 m × 4 m base of compacted hardcore, sand and a top layer of paving slabs. At the desired site of the two telescope piers, the slabs were removed and the ground excavated to a depth of about 0.5 m and a diameter about 0.5 m. These holes were filled with concrete. The set concrete bases were drilled and suitable threads glued in place allowing for firm attachment of observatory piers (Pulsar Anti-Vibration Observatory Pier).

We have subsequently kitted out the inside of the observatory with: built-in desks on each side of the warm-room so two students can work simultaneously; red LED lighting in the warm room and adjustable colour LED lighting in the main bay. We have recently installed (figure 2(e)) two 150 W solar panels on the sliding roof to charge two larger capacity Li-ion 12 V battery packs (PowerOak Bluetti PS6S/AC50s 500Wh solar AC/DC generator). These have 12 V output for the go-to mounts, 5 V for USB power and if needed 240 V AC output. Li-ion batteries are known to keep a high output, near 12 V, over a majority of their discharge output. This is essential to power the go-to mounts to allow accurate and reproducible targeting—see figure 2(f).

The control system uses a Raspberry Pi 4 with a 64 GB SD card running the free-ware Astroberry server. The Raspberry Pi is kept in a sealed box inside the telescope bay with direct USB input from all the controlled instruments: main camera, filter wheel, go-to mount, motorised focuser, GPS, and guide camera. These are all controlled via the INDI framework seamlessly in the built-in free and open-source programs Kstars (Planetarium software) and Ekos (Complete astrophotography and observatory control framework)—see [1–3]. The Instrument Neutral Distributed Interface (INDI) protocol is used as a link between software and hardware, and the INDI Library is specifically for controlling astronomical equipment. The operators in the warm-room had laptop Chromebooks and made WiFi connections to the Astroberry hotspot to control the systems. The Ekos system allows for easy high-accuracy polar-alignment after an initial polar-alignment using the usual polar-scope found in a majority of go-to mounts.

Here we will highlight the main benefits of using Ekos. Once operational, a typical workflow for an observation is:

- Automatic slewing to a desired target only if that target meets a range of criteria, distance from moon, altitude etc.
- Automatic focusing using a user-defined algorithm and set of criteria.
- Plate-solving and adjustment to ensure highly accurate pointing. This is critical so that students can be confident that their chosen star was right at the centre. Dithering can also be added if required.
- Tracking using the guide camera to ensure long (30 min) exposures can be taken with little to no discernible star-trailing.
- Then the list of exposures, repeats and filters can be worked through until all are completed.
- If the observations are stopped due to dawn or poor conditions, then that list can be easily restarted at that point during a subsequent observing night.

The level of automation can be adjusted to the student project.

Table 1 provides details of our two telescope systems, one a Ritchey–Chretien reflector (∼£1000) and one a apochromatic refractor (∼£1700), and our guide telescope. Table 2 details our two main imaging cameras and our guide camera.

For quantitative imaging the ZWO ASI1600MM Pro Monochrome camera is used (∼£1500). The sensor is a CMOS chip with a peak quantum efficiency of ∼60% in the visible spectrum and average efficacy ∼40%–50% over



Figure 2. (a) The final choice for the observatory site. (b) 'Home Observatory UK' building the roll-top observatory. (c) Digging holes for concrete support of telescope piers. (d) Mixing concrete for pier bases. (e) Installing solar panels. (f) Inside the completed telescope main bay.

that range. It has a two stage peltier cooler and can reach 40 °C below ambient and at −20 °C has a dark current per pixel ∼0.005 e/s. The read noise, at a gain of one electron per photon is ∼1.7 e per pixel.

Table 3 presents the pixel resolution and field of view for the various combinations of telescope and camera systems. Each telescope system is mounted on a Sky-Watcher EQ6 Pro SynScan mount, has a ZWO EFW8 filter wheel with LRGB

Table 1. Technical details, focal length, aperture diameter and f-number, for the two main telescopes and the guide scope.

Telescope	Focal length / mm	Aperture diameter / mm	f-number
StellaLyra M-LRS Ritchey-Chretien	1600	200	$f/8$
TS Optics Apochromatic refractor Triplet Photoline	910	130	$f/7$
Sky-Watcher EvoGuide 50ED Guidescope	242	50	$f/4.8$

Table 2. Technical details, pixel-size, number of pixels and cooling ability, for the two main cameras and the guide camera.

Camera	Pixel size / μm	Pixels	Cooling
ZWO ASI1600MM Pro Monochrome	3.8	4656×3520	$\Delta T = -40\,^{\circ}$C
ZWO ASI178MC Colour	2.4	3096×2080	No
ZWO ASI120MM Mini Monochrome	3.75	1280×960	No

Table 3. The resolution in arcsec per pixel and the field of view (FOV) for the various telescope and camera combinations. Note, the colour camera uses a 2×2 matrix of pixels to produce a colour image so the imaging arcsec / pixel will be double that stated in this table.

	Camera					
	ZWO ASI1600MM Pro Monochrome		ZWO ASI178MC Colour		ZWO ASI120MM Mini	
Telescope	FOV / arcmin	arcsec / pixel	FOV / arcmin	arcsec / pixel	FOV / arcmin	arcsec / pixel
StellaLyra M-LRS Ritchey-Chretien	38.0×28.7	0.49	16.0×10.7	0.31	—	—
TS Optics Apochromatic refractor Triplet Photoline	66.8×50.5	0.86	28.1×18.9	0.54	—	—
Sky-Watcher EvoGuide 50ED Guidescope	—	—	—	—	68.2×51.1	3.2

filters, H-alpha, O-III, and S-II filters and a ZWO EAF (stepper) focus motor.

2.1. The observatory site

Instead of picking the very best observing site, atop a mountain in the Atacama desert, we were faced with various competing requirements and practicalities. We began with an extensive search of our institution's land and it was surprising what land the institution owned outside the main campus. As our funding was purely for purchasing equipment we had to work with the institution to find as many possible suitable sites that could house a small observatory building with minimal requirement for any building work etc. We considered:

- Roofs, sports pitches and surrounds, parkland, rural research sites.

- The proximity of each site to amenities, toilets, electricity, car-parks, internet, etc.
- A rough survey of the main light-pollution at each site.
- Possible safety implications, e.g. using a roof maybe good for security, but could be a problem for any structure in a violent storm.
- Local Planning Permission considerations. Some sites would require a full planning application to the local council with associated costs. Some land would not.
- Availability of the site for use. Several identified possible sites turned out to have long-term plans that even a temporary observatory site would interfere with.
- Weather. Our main campus is atop a hill, on clear nights due to a temperature inversion the low-lying land surrounding the hill often suffers with mists and fogs, so low-lying sites were ruled out.

The site finally chosen is at the edge of our main campus and is essentially in a rural setting. It is near the side of a sports-pitch and the Sports Department were very supportive of the plan as long as we did not encroach on their playing and training areas—see figure 2(a). The site needed no planning consent as long as the structure was not permanent. To ensure this we purchased a wooden roll-top observatory (figure 2(b)) rather than a dome and installed a paving slab base rather than a fully concrete base. We did however excavate two sizeable holes under the location of the telescope piers to fill with concrete to give a good firm and decoupled foundation to the telescopes themselves—figures 2(c) and (d). The site is a 10 min walk from the main campus including toilets, 24 hr coffee machine and vending machines. The main source of light pollution is the campus and the nearby flood-lit sports pitches. However, those lights are usually off by the time of astronomical twilight. We have no mains electrical power at the site and no means of supplying it with mains power. Instead we have two large capacity lithium ion batteries and a set of solar panels. This supplies us with ample power for a full night's observations. Being on campus also means the campus security can be swiftly onsite if required for any reason.

One other aspect is vandalism. Our site, although on University grounds, is open to the public. The choice of wooden shed, rather than dome, was to lessen the attractiveness of the site. There are no markings or other feature on the shed. We hope it mostly looks like a sports grounds keepers shed. The shed and contents are insured through the main institutional policy. So far, over more than a year, we have had no incidents.

We did also have the offer of a very dark site, but as this was a 40 min car journey from the campus we felt it unsuitable for the stated aims of our observatory, namely to be an easily and frequently used student observatory.

A typical observing night will begin just before astronomical twilight in order to set up and open the observatory. Students generally do not work past midnight, but observations can be carried on by a member of staff if required. All students are issued with a head-torch with white and red LED functions and are required to save the University Security direct number into their mobile phones. University Security are on call 24 h, and we alert them at the start and end of an observing session. There is good phone reception at the site, good enough to use as a mobile hot-spot for internet connection to the Astroberry-Pi if required. A basic first-aid kit is kept in the observatory. The main hazards are trips in the dark or hitting one's head on the low-roof line of the warm-room. The University Library, open 24 h, is a 10 min walk from the observatory and has hot drinks and snacks from vending machines as well as toilet facilities

3. Teaching range

There is a wide spectrum of student-level observational astrophysics, from designing optics and grinding mirrors, to applying for time on fully automated dedicated teaching telescopes. Due to our degree program being Physics with Astrophysics, rather than Physics with Astronomy or any other combination, we made the decision that the ultimate aim was to embed the observatory itself as part of the scientific process, rather than make the whole process about the observations. In other words, to create an observatory that could be easily used by students once they had decided on

a target list and exposure times etc rather than one requiring constant (but necessary) optical alignment, or polar alignment or other detailed experimental points. That way students can focus on the science of the project, determining the subset of targets given the observatory's location and the date and time, rather than, say, spending hours in the field getting the telescope pointing correctly. As detailed below, we have run projects dedicated to characterisation of the observatory, including polar alignment etc but now we are in a position for most students to use it as just-another-scientific-instrument, albeit one which requires a bit more training and nonstandard lab hours.

Students can manually take exposures and 'point-and-click' targets (see figures 1(b) and (c)). The Astroberry Raspberry Pi software [1] running the Kstars [2] planetarium software and Ekos [3] observatory control system allows a further range of automation. By using pre-defined lists of targets, exposure and filters, the computer-controlled queue system can automatically work through their observational programme.

At all points of developing the observatory we ran final-year student projects. For these open-ended projects it is the demonstration of the scientific method that is most important rather than the final results. For earlier year students, we felt that ease of use was more important. This also means that from the supervision perspective, once target lists are ready and the weather clear, one or two nights is enough for students to take all their data. This removes some of the burden on staff supervisor's time and also on the level of supervision required on the night. It also allows, if required, a staff member to take the observations if the timings of weather windows does not match with student availability.

4. Staff team

There was a core team of four teaching and research active academics that have lead this project. Although the group was somewhat serendipitously formed from like-minded people, the following aspects were central to our success. Our institution has a 'work load model' to try an ensure a fair allocation of work across all academic members of staff. Our home department supported each group member from the outset with a reasonable allocation of hours per year of our time to dedicate to developing and running the observatory. This helped to cement the project in the main departmental work and strategy.

4.1. Group expertise

- To ensure the overall project was firmly embedded in our degree program it was vital that we had representation from a cross-section of teaching academics across all aspects of the degree program. Our group had the co-academic lead of the main Year 1 labs, the head of the Year 2 labs, and the Year 1 Python leads.
- Scientific track-record in small-telescope astrophysics. This gave us a robust scientific case-for-support (see below) alongside a purely teaching case.
- Expertise in small-telescope practical astronomy. Vital to give accurate consideration to the purchase of equipment and the actual set-up of observatory.
- Reasonable level of do-it-yourself skills for, e.g. woodworking or concreting.

4.2. Individuals

4.2.1. Dr Peter A Sloan. 'Observatory Director': Senior Lecturer (Associate Professor) for 11 years. Experimental physicist with 20 years experience of research in single-molecule physics [4]. Overall academic coordinator of the Year 2 Experimental Physics and Computing course. Very novice, but keen, amateur astronomer.

4.2.2. Dr Steve R Davies. 'Technical Director': Senior Lecturer (Associate Professor) for >20 years. Experimental Astrophysicist using terahertz radiation for molecular-line radio astronomy. Joint academic lead of the Year 1 Experimental Physics and Computing course, co-lead in the Year 1 python course. Expert small-telescope 'amateur' astronomer.

4.2.3. Dr Victoria Scowcroft. 'Scientific Director': Lecturer (Assistant Professor) for 4 years. Active researcher into variable stars, including

with small-telescope observations from a roof in Los Angeles [5]. Co-lead in the Year 1 Python course and member of the Year 2 Experimental Physics and Computing course. Core member of the Astrophysics Research group at the University of Bath.

4.2.4. Dr Gary Mathlin. Teaching focused Senior Lecturer (Associate Professor) for >20 years. Background in astronomy and astrophysics with supervision of astrophysics based final year student projects for the majority of the past 20 years. Member of the Year 2 Experimental Physics and Computing course.

4.3. Future membership

With the observatory now established, and wanting to open it to more users, we aim to include other members of staff. For example using the unique fibre-optic facilities and expertise at the University of Bath to enhance our spectroscopy, or perhaps attempt to use adaptive optics on our small scale telescopes [6]. However, we cannot get away from the drive needed of the original core team to establish the facility and it may be important to keep that slightly pioneering spirit of can-do to ensure the observatory flourishes in the future.

5. Phases of observatory development and funding

We approached the project in three distinct phases. This allowed a step-wise, iterative, development with clear goals and results at each stage. We felt this was more manageable, and more likely to succeed rather than a grander 'from zero to fully-operational' observatory. As the time we had allocated to this project was modest we also simply did not have the resources, nor the finances, to fully plan and design an observatory from scratch. There are, of course, funding resources associated with the regular student laboratory courses at departmental level, but we were encouraged to always look outside of the immediate funds of our home department. The exact funds available will not be exactly mirrored in other institutions, but again, it may be instructive to detail the levels of funding we were able to attract.

5.1. Phase-1: pre-funding student projects

Prior to the formation of the observatory group, there had been a number of telescope themed final year student projects. These used a range of personally owned telescope systems. Following the formation of the observatory group, to focus on the development of the observatory, we ran several such projects at different locations within our institution's estate to (1) test the viability of different possible observatory sites, (2) demonstrate the over-subscription of these hand-on astrophysics observational projects and (3) give the project staff the time to overcome and identify the major obstacles (see site choice etc) in developing an observatory. Example of a student project abstract:

> **Bennett** and Wilton 2018/19: **Automating a telescope for variable star measurements:** Using Raspberry Pi computers, stepper motors, Pi Camera modules, and a telescope, a system has been designed and built which can be used to observe variable stars with a view to calculating the distance to them. The system is able to track stars as the Earth rotates using a feedback loop with a camera and stepper motors. Observations of stars have been made, and Gaussian radial profiles have been found. Aperture photometry has been performed on observation data, and digital flux values have been calculated. Although the distance to a variable star has not been measured with the system yet, the proof of concept has been successful, and the framework is in place for this to happen.

5.2. Phase-2: tripods and go-to telescopes

Based on a successful bid to an institutional level teaching-equipment development fund we raised £6250 to purchase: two heavy-duty go-to equatorial-mounts; a 200 mm f/8 RC reflector telescope and a 130 mm f/7 Apo refractor telescope; a small pixel colour camera; a larger

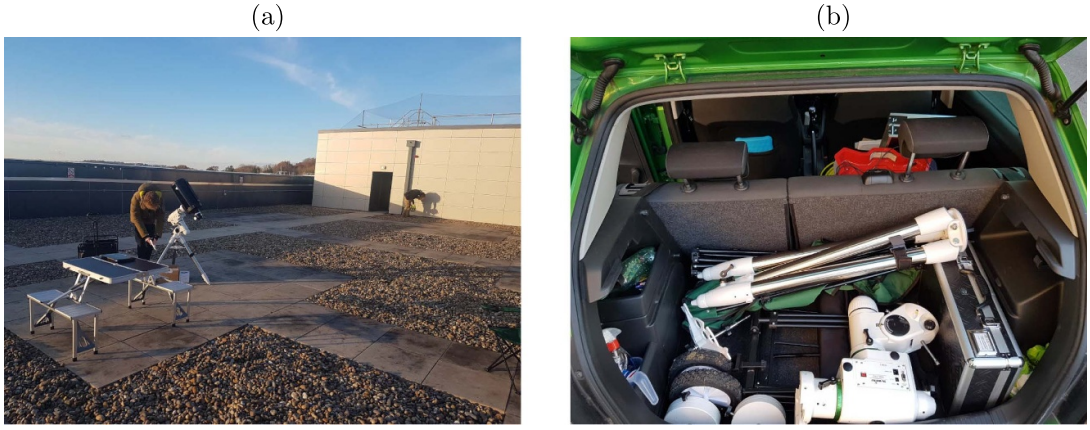


Figure 3. (a) Students on roof with telescope tripods. (b) Portability of telescope systems to test different possible sites.

pixel cooled monochrome camera and filter wheel set.

This allowed us to run several final year projects to demonstrate the step-change in observational quality over the previous projects—see figures 3(a) and (b). Example of a student project abstract:

> **Walker** and Herbe-George, 2019/20: **Setting up the Bath backyard telescope.** The extent to which a small 8 inch telescope paired with a 16 megapixel camera can be used for stellar observations is quantified by observing and analysing the apparent magnitudes of RR Lyrae variable stars. The entire observation process that this involves is (investigated and) carried out step by step, including: planning and target selection; telescope setup and alignment; image collection; data reduction and analysis. Programs are written to substitute 'black boxes' [i.e, pre-existing programs] encountered throughout to guarantee full understanding of the processes. It was found that more images were required to confirm the observed RR Lyrae behaviour exhibited by V579 Per, and that in general the calculated apparent magnitudes of V579 Per and SU Dra in each RGB pass band were within 7% of the literature values. In particular, when the standard star HD 22 732 was used as a zero point calibrator, the resulting apparent magnitudes for V579 Per lay within 1% of the true values.

5.3. Phase-3: observatory building and permanently mounted telescopes

We were then in a position to apply for two sets of funding in parallel: One to an Alumni fund at our institution for £7500 to purchase a purpose built roll-top observatory to allow the permanent mounting of our two telescope systems, the other applying again to the institutional level teaching-equipment development fund for £4500 for a second cooled monochrome camera and filter wheel system and observatory piers to allow permanent fixing of the 'goto' mounts.

Subsequent to that we have been granted further £5000 to purchase a spectrometer designed for small-telescope observations and two large-capacity battery packs and roof-mounted solar panels (the site does not have mains electric power).

Finally, an application to the national Royal Astronomical Society (RAS) to fund a summer students (August 2022) was successful. Their role was to develop teaching and training material to

allow easier use of the observatory by our regular undergraduate students (and other staff). We should note that although the RAS Summer Student remit [7] is focused on research, we have now had this project funded twice. The first time we could not take it up as COVID and lockdown interrupted us.

The observatory was fully operational from February 2022. During February–March 2022 we ran a second year student project with two teams of 5 students. Each team had an 'experimentalist' who took data from the observatory over a few nights. Example of a student project abstract:

> **Sparkes 2021/22: Investigating the suitability of a small telescope to observe variable stars.** Variable stars are significant because they can be used as standard candles. Knowing the position and distribution of variable stars allows cosmologists to study the structure and distribution of the Universe on a galactic and an extra-galactic scale. The purpose of this project was to investigate whether observations of variable stars using the Richtey–Chretien reflecting telescope are useful and informative. Lightcurves from observations on 20 March 2022 of RV UMa, an RR Lyrae type variable star, were compared with archival data and it was found that the observations on the 20th fit closely to the lightcurve obtained from archival data.

Given our collective experience of applying for regular research funding, or other teaching funding, we have been pleasantly surprised by our success rate (100%) so far. We would be surprised if such a willingness to fund a student-observatory was specific to our institution.

Another avenue of funding that we did not explore is through public-engagement. Many national scientific funding bodies or association have separate funds for public-engagement. As we had been given funds specifically for teaching, we felt it inappropriate to use the equipment and observatory for such activities. However, if another member joins the group with a view to public engagement that does open up new routes to funding, and could spread the joy of observational astronomy and astrophysics.

6. Example extracts from successful funding proposals

To raise funds for the observatory we had three main themes to show the necessity of the observatory: timeliness, teaching, and science. As with most grant application showing the direct need and direct impact of the proposal was instrumental to the success of our bids. Although we felt the teaching case was strong, having a strong and realistic science case as well was probably key to our success and made our various proposals stand-out from other teaching focused cases. Although we have been relatively local and constrained with our proposals, we have been successful with all of them. This could be that the idea of an observatory is an easy concept for any reader to grasp—especially if early results (pretty astrophotography—see figure 1(d)) can be included [8]. The following are excerpts from a few of our successful proposals.

6.1. Timeliness

> 'The Astrophysics group in the Department of Physics at the University of Bath was founded in 2015, coinciding with the establishment of Bath's Physics with Astrophysics degree programs in the same year. Across all years we now have 124 students enrolled on Astrophysics programs. Until 2019, the department had no telescopes to underpin undergraduate project work for either BSc Final Year projects or undergraduate masters-level projects. Undeterred by the lack of equipment, in 2018, we ran three observing projects using telescopes kindly loaned by members of staff who happened to be amateur astronomers. These projects were heavily oversubscribed;

students were excited to experience hands-on astronomy.'

6.2. Teaching case

'The impact will be focused on our undergraduate students. Having a permanent observatory will give the Department (and the University) a facility is does not presently have. The observatory would give a group of students the possibility of learning how to observe, planning observation, real world experimental practice, and the ability to take research grade measurements to allow both 'undergraduate' experiments and actual research experiments. We would estimate at least 4 MPhys students per year, and 4 BSc students per year. With these numbers rising to 6 and 6 with the extra capacity offered by these requested items. Running over say, 5 years in the first instance, that is 60-ish students having high quality hands-on experiments.'

6.3. Science case

'To understand the working of the cosmos, we must first build a map. But how far away are the stars? All we have is a measure of their brightness. They could be bright and far away or close and dim. How would you know? It turns out a particular family of stars blink, or at least have variable brightness output. We can map the frequency of the blinking to their absolute brightness and hence for any such variable star measure its absolute distance. The first step is to map the frequency of variability to their absolute distance measured independently by their parallax. But parallax measurements can only be made on nearby stars, which means they are too bright for even the smallest (1 meter) professional observatory to measure. But they are just right for our small-telescopes.'

6.4. Specific example: spectroscopy

'... we request funds to purchase a high-quality optical spectrometer, designed for use on small telescopes, such as the ones we have.
Physics students hear about spectroscopy in many of their lecture courses, covering diverse areas of physics, including nanoscience, quantum physics and astrophysics. In various astrophysics lecture courses, they learn how to interpret observational spectra and extract from them the physical parameters of the objects being studied, such as temperatures, densities, rotational and radial velocities, etc. Understanding of these core ideas and techniques will be enhanced through making and analysing real, hands-on spectroscopic measurements to complement the textbook examples they see on the printed page or projected on the screen in the lecture theatre. We strongly believe that there is a great added-on value both to a student's understanding and personal satisfaction through non-trivial measurement of their own, hands-on, observational data, rather than just being given a bunch of numbers in a spreadsheet or pointed at a plot in a textbook.'

7. Summary, conclusion and future possibilities

We have reported on the step-wise development of an affordable (relative to regular University

level activities) observatory aimed to undergraduate teaching, both at final year project level, and regular early years undergraduate level. The excellence of 'amateur' astronomy equipment has brought the price of near research quality equipment to a level that is equivalent to any regular lab-based undergraduate experiment. We hope that our particular path may prove useful to other institutions either through the general themes we have reported, or the more technical details.

The development of the observatory has generated much interest within our home department and in our local community. Since we envisaged this resource as focused on undergraduate teaching, it has been difficult to balance our teaching time with requests for external activities. In the future we hope to embed the observatory in the departmental, or higher level, public-engagement plan so this resource can be used appropriately for the good of the students and wider public.

Data availability statement

The data used to generate figure 1(d) are openly available at the following URL/DOI: https://doi.org/10.15125/BATH-01225 [8].

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Ethical statement

Informed consent to publish was given by all participants (or their parent or legal guardian in the case of children under 16) for the work reproduced and photographs taken of human subjects.

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