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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2023 December 8 at 16^h 00^m
in the Geological Society Lecture Theatre, Burlington House

MIKE EDMUNDS, *President*
in the Chair

President. This is a hybrid meeting. Questions may be asked at the end of each lecture but you will be muted so please use the chat facility. Questions on-line will be monitored by Professor Steve Miller, RAS Council member. Moving on to the first presentation, the first talk is the RAS Diary talk and this will be given by Dr. Daniel Belteki: 'The making of an observatory — the early years of the Cambridge Observatory'. Daniel Belteki is a Research Fellow on the Congruence Engine Project at the Science Museum. His work explores the application of digital tools to the history of 19th-Century science, technology, and industry. His previous work focussed on the history of astronomy during the 19th Century, with a specific focus on the history of the Royal Observatory at Greenwich.

Dr. Daniel Belteki. I would like to start by thanking Mark Hurn, Librarian at the Institute of Astronomy at Cambridge, for many amusing conversations and also the Cambridge University Archives. I am also grateful to Dr. Roger Hutchins who has written what is, so far, the only modern history of the Cambridge University Observatory (CUO), and to Dr. Siân Prosser, Librarian of the RAS.

The CUO was not established in a vacuum. There had been prior observatories at Cambridge but they were not major institutions; they were attached to different colleges. One was set up at Trinity College around 1704, another at St. John's College which is actually associated with Thomas Catton. Pembroke College also had one which was associated with the Lowndean Professorship of Astronomy and established in 1749. There is a brief mention of the establishment of an observatory in 1790 but the idea died out.

In 1816 a proposal was made which would re-ignite the passion for a university observatory. Around this time the Analytical Society (AS) was founded; it was trying to convince the University, as well as the scientific network, that the analytical approach in mathematics coming from France needed to be taken up in order to make progress in astronomy. At the same time there were discussions between astronomers on how Greenwich Observatory and its publications were not as accurate as desired. *The Nautical Almanac* was based on Greenwich observations which were not accurate enough for quick and efficient navigation and transport on the sea. This group of astronomers came together and the result was the formation of the Astronomical Society of London which later became the Royal Astronomical Society (RAS).

In Cambridge there was the establishment of the Cambridge Philosophical Society, again recognizing a new venture taking place in science and the need for institutionalization — the qualification of these new ventures, and which helped to pave the way for what was to become the Cambridge University Observatory. The proposal in 1816 came from George Peacock, a mathematician and Fellow of Trinity College who later on became the Dean of Ely. He was a member of the AS and a Fellow of the RAS and was very much engaged in the reforms taking place within the University. He saw the Observatory as a tool to reform science alongside reforms in the exam system, in textbooks, and in the rules themselves. When new ideas and reforms were introduced there were counter effects. The opposition was mounted by men such as James Wood, the Master of St. John's College, and so there followed arguments which raged back and forth between the reformers and members of the establishment.

In 1817 Thomas Catton and John Haviland prepared estimates for how much it would cost to fit out the Observatory with instruments. They hoped that having the costing and the figures would persuade the University to do something. Also in 1817 a Grace was passed which accepted the need to produce a report about the value of the addition of the Observatory to the University, but there was a caveat.

The report states that it shouldn't be a university observatory — it should be funded by the Government and should not be for the benefit of the University, but for the benefit of the nation. The projected cost was no more than £10 000 of which £2 500 would be for instruments. The University recognized that it could not fund the entirety of this, but it could cover half the fund with the remainder coming from public subscription, and there was a suggestion that the Government should appoint and pay for two assistants. These would be nominated by the heads of the Senate, so this was aimed not at the reformers but at the establishment. It was rejected. Then there was a re-examination of the founding documents of the Plumian Professorship, and amongst the duties were publishing observations, and furnishing instruments as well as the assistants. Now there was a justification for the money to come from the Plumian Professorship, *i.e.*, from the University through endowment.

In 1820 a new proposal was put forward saying there should be new regulations for the Plumian Professorship, that there should be an observatory, and two assistants who are University graduates should be appointed by the Senate. It estimated the costs of salaries and emphasized a focus on meridional observations. This was in line with the motivation of the RAS and it was also stepping on the toes of Greenwich Observatory. The observations should be published annually and they should be distributed to most of the European observatories, with some small instruments available for teaching purposes. This was accepted and the work quickly gathered pace. Note that the Professor was not the observer but the manager of the Observatory.

The Grace was passed on 1820 May 5 and in the next three months more than £5 000 was received from Government funds or through subscriptions — a little later the instruments were ordered and in 1820 December a site was selected and once again there was a gap for the buildings. In 1822 a tender to complete the work was issued with completion in 1824.

In 1824 also it was realized that the cost would be double that of the initial estimate. The Senate did not agree to increase the funding but following negotiations another £4 000 was agreed, with another £3 000 granted in December. The final cost was £19 241.

The Plumian Professor in 1821 was Samuel Vince but he died that year and was succeeded by Robert Woodhouse. He was an important figure — he taught George Peacock and also propagated the analytical method to his students. Unfortunately, before Woodhouse could do much more he died, in 1827, but managed to install the main transit instrument and to make some observations with a Dollond refractor.

At this point George Biddell Airy appeared on the scene. He was very much seen as a member of the new movement and this put him in a very strong position to become Plumian Professor. He was appointed and began by asking the Senate to increase his salary. He argued that he would be paid less than the Chief Assistant at Greenwich and got an increase. His role involved three main duties: lecturing, maintaining and managing the Observatory, and to continue publishing the observations. He wanted to have an assistant but the amount being offered did not cover expenses so he set up a syndicate that reported to the University Senate. The syndicate was packed with members of the AS, the RAS, and the Cambridge Philosophical Society. In 1829 he hired Andrew Baldrey, a retired lieutenant, who was pointedly not a Cambridge graduate, and Airy was empowered to set the Assistant's salary.

Did Airy fulfil the duties of Plumian Professor? Yes, he managed the Observatory and also made observations during the first year of operation. In 1833 a new instrument, a mural circle, was set up and James Glaisher was appointed as a second Assistant, and subsequently made observations with it. Airy also saw it as part of his job correcting the meridional observations made by Greenwich as identified by the RAS. He also rejected the use of *The Nautical Almanac* and adopted the Paris observations.

The Observatory was seen as a tool for radical reform at Cambridge rather than as a scientific establishment. The operation was just catching up with the promoted vision for the Observatory in its early years.

The President. Thank you very much. Mr. Airy was a poacher turned gamekeeper presumably because he wanted to be Director of the Greenwich Observatory.

Dr. Belteki. Yes, if you'd like to invite me for a second talk [laughter].

The President. Questions from the floor? The Analytical Society was John Herschel and Charles Babbage?

Dr. Belteki. Yes.

The President. So, two of our founder members.

Professor Alex Schkochihin. Four hundred pounds per year? What is it in current money? This is important for the record. I want the answer minuted! [Laughter.]

The President. It's quite good! [Laughter.]

Dr. Jacqueline Mitton. At around the time you are talking about, one of the drivers in setting up observatories, particularly in the United States, was the observation of comets. It appears that this wasn't anything that drove the enthusiasm of Cambridge?

Dr. Belteki. The best way to describe it is that cometary observations don't bring in any money whereas if you are correcting the positional or the meridional observations used in *The Nautical Almanac*, which in turn gets used by ships for navigation, there is plenty of vested interest, not just from business, but from the Navy, to improve that, so the monetary interest lies mainly with the star catalogues. There is always a miscellaneous section at the end of the published observations that includes some comet observations but they are very rare.

Professor Lord Martin Rees. Just a couple of footnotes to this lovely talk. First, Airy, before he became Plumian Professor, was Lucasian Professor which was a chair held by Newton, and he wrote a pleading letter saying that he should have double the salary because he had to work at night as well as day [laughter]. The Observatory, which was located on top of Trinity's gatehouse, was put up for Newton's successor, Cotes, and had lapsed into disuse by the end of the century. Science did not really exist as a respectable subject until after this time and it was Whewell who was Master of Trinity and a great scholar who coined the word scientist. At the time he thought that science should not be taught to students, that it was transient — they should just learn the eternal truths of mathematics and theology [laughter].

The President. I assume that as a theoretician you only get half the salary [laughter].

Professor Steve Miller. There is a comment on-line from David and Kenneth Walter James. "I have just looked on-line and £500 in 1828 would be worth about £67 000". So just small change for you, Mike. [Laughter.]

The President. I wish! [Laughter.]

Professor Roger Davies. It is 2% of the capital cost of the telescope, so that tells you that it was a lot of money.

The President. Yes, if you could become Director of the *European Extremely Large Telescope*, you would do really well! [Laughter.]

Dr. Guy Morgan. When was the *Northumberland* refractor built?

Dr. Belteki. In 1834 — and Airy left the Observatory the following year; the installation of the telescope didn't happen until after he left, so it is interesting that he was writing a description of the telescope from Greenwich, even though it was back in Cambridge under a different Director.

The President. Thank you very much indeed [applause]. Note the large numbers that are talked about in the Society are salaries and not distances! [Laughter.]

Now we move on to the Group Achievement Award from the last year awarded to *MeerKAT*. This is going to be a double act. Rob Fender is going first and Ian Hayward second. Rob Fender is head of Astrophysics at the University of Oxford, and has a long history of working in radio astrophysics, with a focus on astrophysical transients in general and black-hole jets in detail. He was awarded the 2020 Herschel Medal of the Royal Astronomical Society. Rob is also a visiting Professor at the University of Cape Town. Ian Heywood is a senior researcher in radio astronomy at Oxford, a visiting Professor at Rhodes University in South Africa, and an honorary associate of the South African Radio Astronomy Observatory. His work encompasses all aspects of cutting-edge radio interferometry, including developing new and automated ways to process the huge volumes of data that characterize radio astronomy in the 21st Century.

Professor Rob Fender. The *MeerKAT* radio telescope arose from the South African bid in 2005 to host the *Square Kilometre Array* (*SKA*). The final *SKA* site decision in 2012 allocated the mid-frequency array (*SKA1-MID*) to South Africa and a low-frequency one (*SKA1-LOW*) to Australia. The *KAT-7* test array was complete by 2009 and was, to our knowledge, the first radio array on the African continent. *MeerKAT* is the first-phase *SKA-MID* and comprises 64 13·5-m dishes with UHF (0·6–1·1 GHz), L-band (0·9–1·7 GHz), and

S-band (1·8–3·5 GHz) receivers. The baselines extend to around 8 km, with a dense core containing a large fraction of the dishes, only 1-km across. The large number, and good distribution, of the dishes and hence baselines provides very good imaging on short snapshot.

MeerKAT was inaugurated on 2018 July 13 and began observations mainly across eight approved Large Survey Programmes (LSPs), tackling a very wide range of science. In the field of pulsars, *MeerKAT* is now providing the best timing accuracy, with an arrival-time accuracy better than seven nanoseconds. In the globular cluster NGC 1851 the first pulsar–black-hole binary may have been found. The *MeerTRAP* project, which piggybacks on regular observations, and is led by the University of Manchester, is detecting fast radio bursts in real time. The *ThunderKAT* LSP is tracking the power and evolution of relativistic jets within our Galaxy, arising from stellar-mass black holes and neutron stars in X-ray binary systems (XRBs). Particular examples include MAXI J1848, precisely tracked relativistic jets in a globular cluster XRB, and Circinus X-1, a neutron-star XRB where jets are punching a hole through the boundary of its nascent supernova remnant. In the remarkable case of the XRB Vela X-1, *MeerKAT* observations of the target system revealed both the first radio detection of a bow shock associated with the binary, as well as the serendipitous discovery, in the field, of the slowest-known radio pulsar.

Dr. Ian Heywood. A substantial fraction of *MeerKAT*'s LSP programme is devoted to observations of the neutral hydrogen (H I) gas in and around galaxies. Observed by means of its 1420-MHz (rest-frame) emission, observations of H I have been a valuable tool for radio astronomy for over seven decades. Serving as the raw fuel from which stars are born, the velocity of the gas can be measured by the Doppler shift of the line, allowing it to be used to trace the motion of gas in and around galaxies. The H I emission line is extremely faint, and the diffuse nature of the hydrogen clouds result in very low surface brightness; however, the imaging capabilities along with its extremely sensitive receivers are facilitating many new insights. Unprecedented views of the H I in nearby galaxies are being obtained through the *MHONGHOOSE* LSP, and an intensive study of the nearby Fornax galaxy cluster is revealing the role that H I plays in the life cycle of galaxies as they collide, with tidal streams containing a billion solar masses of H I being torn from galaxies in the process, seen with *MeerKAT* for the very first time.

A principal driving goal for the *SKA* since its inception has been to detect the faint H I emission at cosmologically significant distances, and *MeerKAT* is making inroads into this main scientific driver of its eventual successor. Surveys such as MIGHTEE and LADUMA are targeting the very distant Universe using deep radio-continuum, spectral-line, and polarimetric observations to provide information on the magnetic fields in and between the galaxies. These surveys are observing fields with unprecedented optical and infrared imaging to look back billions of years to determine the physical processes and environmental conditions that govern how galaxies have formed and evolved over cosmic time.

As *MeerKAT* celebrates the completion of five years of full operations with a conference in Stellenbosch, South Africa, we conclude by returning to our own Galaxy, and revisiting the image that was used to introduce the telescope to the world at its inauguration in 2018 July. The inaugural image of the centre of the Galaxy revealed the chaotic environment around the four-million-solar-mass supermassive black hole that lurks at the centre of our Galaxy with never-before-seen clarity and depth. The image was a fitting demonstration of the capabilities and potential of *MeerKAT*, and that it was produced so soon in the life of the telescope stood as testament to the ingenuity of our South African colleagues who designed and built it. Since then the Galactic-centre data has been used to shed light on the decades-old mystery of the origin of the population of mysterious magnetized filaments that are only seen in that region, as well as having provided the serendipitous discovery of the giant 1400-light-year bubbles of radio-emitting gas, driven by an explosive event in the heart of our Galaxy several million years ago. It is this latter result amongst others that were cited in the Group Achievement Award for *MeerKAT*, and we look forward to many more ground-breaking discoveries with the telescope in the years to come.

The President. Thank you very much for a beautifully illustrated talk. I can't help thinking that some of those images should be in the Royal Academy across the road. May I invite questions in the room to both speakers?

Dr. Arvind Parmar. Is there any evidence on the evolution of these filaments with time?

Dr. Heywood. Not to my knowledge. We have a time baseline of 30 years. I could estimate the resolution you would need to detect motion given the speed. It's probably worth looking at. They are hundreds of light years long and lots of them have compact sources embedded in them. In fact, a lot of the theories about the origin of these features invoke a compact object or a stellar source with a magnetic field and particles. It's not unreasonable to start to detect proper motion in those if they are in the Galactic centre given high enough resolution.

Professor Miller. I have a question from Zaid. Why is Sgr A called a star but is a black hole?

Professor Fender. I think that it is more properly called Sgr A*. The brightest radio source in the constellation got the label Sgr A as is traditional but once they began to resolve that source they realized that it was a very bright extended source with an extremely compact feature in the middle so it became Sgr A*.

The President. Any more questions? If not, we'll thank our speakers again [applause].

We now move on to David Hosking who won the 2022 Michael Penston Thesis Prize. He is going to talk about 'Cosmic voids filled with reconnecting magnetic fields from the early Universe'. David is a Postdoctoral Fellow at the Princeton Center for Theoretical Science (PCTS) and a Research Fellow at Gonville & Caius College, Cambridge. He uses a combination of analytical theory and numerical experiments to study waves, instabilities, and turbulence in astrophysical fluids and plasmas. Dr. Hosking earned his Masters in Mathematics and Theoretical Physics in 2018 and his DPhil in Astrophysics in 2022, both from the University of Oxford. He was awarded the 2022 RAS Michael Penston Prize for his DPhil thesis, which proposed a theory of the decay of magnetohydrodynamic turbulence that combined new statistical invariants with a view of magnetic reconnection as the dominant dynamical process mediating decay.

Dr. David Hosking. According to some theories of cosmology, magnetic fields were generated during inflation or phase transitions in the early Universe. It is widely hypothesized that the relics of these primordial fields (PMF) might still exist today, within the voids of large-scale cosmic structure. This idea suggests the remarkable possibility that measurements of the magnetic fields in voids could be combined with a theory of the evolution of PMFs to provide constraints on early-Universe physics.

Although precise measurement of the magnetic fields in voids is not yet possible, a lower bound on their strength can be deduced from gamma-ray observations of blazars (active galactic nuclei with jets that point towards Earth). If present, extragalactic magnetic fields (EGMFs) in voids would scatter the electrons produced in the electromagnetic cascades of TeV gamma rays emitted by blazars, thus suppressing the number of secondary (GeV) gamma rays received at Earth. Such suppression is indeed observed by the *Fermi Gamma-ray Space Telescope*, and has been used to argue that the fields in voids can be no weaker than around 10^{-17} Gauss (assuming a coherence length of 1 Mpc). Although this lower bound is extremely small by usual standards (magnetic fields in galaxy clusters are 100 billion times stronger, for example), early attempts (using ideas from the theory of decaying turbulence) to estimate how strong the primordial magnetic fields would have needed to be in the early Universe to leave a relic of this strength today found that they would have needed unreasonably large energy, even larger than the radiation density of the Universe (specifically, under the scenario that they were generated at the electroweak phase transition without strong parity violation).

On the other hand, significant evidence emerged in the mid-2010s from numerical simulations of decaying magnetic turbulence that the canonical models did not describe the evolution well. For example, these simulations showed that magnetic fields have a tendency to increase their characteristic size as they decay, a phenomenon that became known as 'inverse transfer'. My PhD thesis provided the first theoretical understanding of these effects, showing that they follow from the requirement that decay conserves the fluctuation level of magnetic helicity (a topological quantity related to twists and linkages of magnetic-field lines) that arises in large volumes. Furthermore, I argue that a corollary of this topological constraint is that the time-scale for decay is not set by ideal dynamics, as had previously been assumed, but the time-scale on which magnetic fields reconnect (changing their topology, but, crucially, preserving their helicity). The electrical resistivity of the primordial plasma was large compared to its viscosity (because it was hot and rarified) so reconnection of primordial magnetic fields would have been a slow process. The decay of primordial fields would therefore also have been slow: the relics of any given initial state would today be stronger by several orders of magnitude than was previously expected. In my thesis, I show that these results restore consistency between a magnetogenesis scenario at the electroweak phase transition and the observational constraints. As the observational constraints on relics of the primordial fields improve (particularly with the next generation of CMB experiments, which will produce improved upper bounds on their strength), the theory that I have derived in my PhD thesis will provide a means to use them to constrain the physics of the early Universe.

The President. Time for a question or two. Any questions in the room?

Dr. Quentin Stanley. Are you able to observe any differences with the magnetic fields depending on which parts of the void you are looking for? Are you expecting them to be homogeneous? If it goes against that will it modify your theory?

Dr. Hosking. I emphasized in my talk a particular region of parameter space where the fields in the voids are small scale. That the fields will be small scale is a prediction of the theory, provided that magnetogenesis occurred at a phase transition. There are other ideas based on magnetogenesis during inflation that lead to homogeneous fields: in that case, the theory of decay has to be revised. We do have some ideas about how to do that, although I didn't have time to speak about them today.

The President. One last question.

Professor Eric Priest. Nice talk, very interesting. One of the problems with using magnetic helicity is that a lot of the MHD-turbulence experiments cannot use a well-defined expression for magnetic helicity because they are periodic. Do you have a periodic system? Magnetic helicity is not well defined. One way around that is to use a sophisticated invariant called field-line helicity. I wonder if you had considered that?

Dr. Hosking. I know about this idea. I don't know exactly how one would construct a theory like the one in my thesis using field-line helicity, but it would be interesting to look into how that would work. Your question, I think, drives at the issue that magnetic helicity is only well-defined if one restricts attention to a closed volume; otherwise, it depends on the choice of gauge. In our case, the volume is not closed, but we find that rapid decay of correlations in space, which we do have, also allows one to prove that the theory is gauge invariant.

Professor Priest. Well, I have lots of other technical questions.

The President. I think you should meet up afterwards. Thank you very much indeed. [Applause.]

Just a couple of things. At the railway station this morning I noticed that the Moon and Venus were in a very nice conjunction which is supposed to be even better tomorrow morning. John Zarnecki has alerted me to the fact that the aphelion of Comet Halley should occur at 1 am on Saturday morning, in other words, in about nine hours' time. He has checked previous perihelia and aphelia which have occurred since we were founded in 1820 and he reckons this is the closest occurrence of any aphelia or perihelia to any RAS meeting. Halley is about 35 AU away and is starting to come back in. It should be visible again in 2061. I give notice that the next A&G Highlights meeting will be on Friday, January 12th, 2024. I remind you of the drinks reception to be held in the RAS Council Room and I also have great pleasure in wishing you a very happy Christmas and a productive New Year.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2024 January 12 at $16^{h}\ 00^{m}$
in the Geological Society Lecture Theatre, Burlington House

MIKE EDMUNDS, *President*
in the Chair

President. Good afternoon. Welcome. This is a hybrid meeting. Questions can be asked at the end of the lecture but as you will be muted please use the chat facility. Your questions will be read out by the Assistant Editor of *Monthly Notices*, Dr. Pamela Rowden. A list I don't mind is the list of awards. In the New Year's Honours list the following Fellows of the Society received honours: Professor Emma Bunce (former President) is awarded an OBE, Professor Mike Cruise (former President and current Treasurer) an OBE, Dr. Maggie Aderin-Pocock a DBE, and finally a CBE has been awarded to Professor Philip Diamond, Head of *SKA* at Manchester. Very well done to all [applause].

I am now going to announce the RAS Awards for 2024. This is the 200th anniversary of the first award of the Gold Medal, which in 1824 went to

Charles Babbage and Johann Encke. Honorary Fellowships are presented to Professor Ganesan Srinivasan(A), Raman Research Institute, Bangalore, and Dr. Nicola Fox (G), NASA's Science Mission Directorate. The James Dungey Lectureship goes to Dr. Gabrielle Provan, University of Leicester. The Harold Jeffreys Lectureship goes to Dr. Jessica Irving, University of Bristol, and the George Darwin Lectureship to Professor Chiaki Kobayashi, University of Hertfordshire. The Group Achievement Award (A) goes to the *JWST–MIRI* Team, and the Winton Award (G) is given to Dr. Andy W. Smith, Northumbria University. The Winton Award (A) goes to Dr. Chris Lovell, University of Hertfordshire, the Fowler Award (G) to Dr. Christopher Smith, Huddersfield New College (Sixth Form), whilst the Fowler Award (A) goes to Dr. Leah Morabito, Durham University. The Service Award (G) is given to Professor Ian McCrea, Rutherford Appleton Laboratory. The Service Award (A) goes to Professor Ian Robson. The RAS Higher Education Award is given to Dr. David Cornwell, University of Aberdeen, and the RAS Secondary Education Award to Arabi Karteepan, Croydon High School. The RAS Primary Education Award is given to Teresa McGrory, St Joseph's Catholic Primary School, and the Annie Maunder Medal to the AMT Mobile Planetarium Team, University of Namibia. The Jackson-Gwilt Medal (A) is awarded jointly to Dr. Keith Bannister, CSIRO, and Professor Ryan Shannon, Swinburne University of Technology. The Price Medal (G) is awarded to Professor Christopher Davies, University of Leeds. The Chapman Medal goes to Professor Valery Nakariakov, University of Warwick. The Eddington Medal goes to Professor Pedro Ferreira, University of Oxford. The Herschel Medal (A) is awarded to Professor Emerita Roberta Humphreys, Minnesota Institute for Astrophysics. Finally, the Gold Medal (G) goes to Professor John-Michael Kendall, University of Oxford, and the Gold Medal (A) is awarded to Professor Gilles Chabrier, École Normale Supérieure de Lyon, CNRS and University of Exeter. Many congratulations to the award winners. The medals will be awarded at NAM during the summer and we will be hearing lectures from some of them during the coming year.

The first talk today will be given by Dr. Matina Gkioulidou who is a space physicist at Johns Hopkins Applied Physics Laboratory. The talk is about different space-plasma regimes from the magnetosphere to the heliosphere's interaction with the local interstellar field. She is project scientist of NASA's *Interstellar Mapping and Acceleration Probe* (*IMAP*). She is also the lead on *IMAP*'s ultra-energetic neutral-atom camera. She has been a member of NASA's 'Living with a star' programme-analysis group and Geospace Environmental Model Steering Committee and NASA's Heliophysics Advisory Committee. We very much look forward to her talk on 'The *Interstellar Mapping and Acceleration Probe* Mission: Exploring our solar neighbourhood'.

Dr. Matina Gkioulidou. The heliosphere — our home in the Galaxy — is the region of space surrounding our Solar System and dominated by the Sun's presence. It is formed by the million-mile-per-hour solar wind, which blows outward from the Sun to all directions in space, inflating a bubble in the local interstellar medium. The heliosphere provides a shield against the harsh radiation present in the Galaxy, thereby creating and maintaining a habitable Solar System. Understanding the physics of this boundary and its dynamic changes over time can help us comprehend how our Solar System can support life as we know it.

NASA's *IMAP* mission (https://imap.princeton.edu/) will be launched in 2025 on a two-stage Falcon-9 rocket from Kennedy Space Centre and reach its final orbit at L1 using on-board propulsion. With a suite of ten instruments and an international team of 25 institutions, *IMAP* simultaneously investigates two of the most important problems in space physics today: the acceleration of particles expelled from the Sun to high energies, and how the interaction of these high-energy particles with the local interstellar medium shapes our heliosphere.

Four of the instruments on *IMAP*, namely *SWAPI*, *SWE*, *CoDICE*, and *HIT* are taking *in-situ* measurements of energetic particles that are expelled from the Sun's atmosphere, including solar-wind ions and electrons, as well as suprathermal and pickup-ion populations. The *MAG* instrument measures the vector magnetic field to the spacecraft, a crucial measurement to understand particle acceleration within solar-wind structures. *IMAP*'s *I-ALiRT* architecture provides near real-time observations of solar wind, energetic particles, and magnetic fields at L1, measurements necessary for space-weather prediction.

When the energetic charged particles from the Sun reach the outer heliosphere, they charge-exchange with interstellar neutrals and transform into energetic neutral atoms (ENAs). ENAs retain information of the original charged particles, but losing their charge allows them to travel through space unbounded by the Sun's magnetic field, and eventually reach *IMAP*. Three of the instruments on *IMAP*, namely *IMAP-Lo*, *IMAP-Hi*, and *IMAP-Ultra*, covering energies from 10 eV to 300 keV, capture those ENAs, creating all-sky maps of the interaction of our heliosphere, our own habitable astrosphere, with the local interstellar medium.

IMAP also samples interstellar particles, from neutral atoms, to interstellar dust. *IMAP-Lo* derives interstellar neutral O, H, and He flow speed to better than 5% accuracy, fundamental for understanding the kinetic properties of the local interstellar flow, and thus establishing how the interstellar flow interacts with and influences the global heliospheric structure. The *IMAP-Lo* deuterium/hydrogen ratio provides input on stellar evolution, and its contribution to the local matter inventory. The *IDEX* instrument provides the first accurate, *in-situ* measurements of the flux, size distribution, and composition of interstellar dust grains flowing through our Solar System. Dust can interact with everything (electromagnetic radiation, cosmic rays, gas, *etc.*) and it provides a surface for chemical reactions, therefore, it carries information about remote processes through space and time. *IDEX*'s much higher observation rate than previous dust-particle instrumentation (100 particles per year) provides an unparalleled opportunity to sample directly and thereby discover the chemical makeup of solid matter in our galactic environment with unmatched resolution. Finally, the *GLOWS* instrument, measuring UV Lyman-alpha radiation, maps the heliospheric backscatter glow, providing complementary ionization and radiation-pressure measurements, as well as solar-wind measurements, needed to interpret the directly sampled interstellar hydrogen.

In summary, *IMAP* is a ground-breaking mission that uses state-of-the-art instrumentation to create a comprehensive map of the Sun's environment, including high-energy particles and magnetic fields in interplanetary and interstellar space.

The President. Thank you very much, indeed; and the launch date is when?

Dr. Gkioulidou. April 29 to May, 2025.

The President. Any questions in the room, first of all? You are talking about the composition of interstellar dust. Does it actually measure composition or just size and density?

Dr. Gkioulidou. Because you can have mass resolution, you can get all different dust particles.

The President. But you can do the main composition of the particles?

Dr. Gkioulidou. Yes, the composition and the size.

Professor Richard Ellis. Would you be able to get any information on the interstellar magnetic field, like its fine structure?

Dr. Gkioulidou. We will not have a direct measurement of that; however, with ENA imaging and knowing what kind of particles we have and how this structure is at the interstellar boundary, we can infer what the magnetic field can look like. When I said that, the modellers got riled up and they went back to the drawing board; they had to figure out that the magnetic field must be draping round the heliosphere in order to get that structure at 90 degrees perpendicular to the magnetic field. We can make inferences but not direct measurements.

The President. Thank you very much [applause].

Our next contribution is associated with the other specialist meeting here today. 'Simulation-based inference on the Kilo Degree Survey' and Kiyam Lin is giving the talk. He is a final-year PhD student at University College London and works on the task of statistical inference powered by machine learning applied to the large-scale structure of the Universe. Kiyam has so far greatly enjoyed his PhD at UCL since the machine power of computation in general has brought to life tackling problems that are simply too hard with pen and paper. Prior to his PhD, Kiyam had spent several years working in industry after graduating from Imperial College London with an MSci in physics. During those years Kiyam dabbled extensively in both data science and animation work and is bemused by the fact that the nature of work between industry and academia is often very different, even if, in both instances, one is working on analysing data. You come back from industry; we normally send people out, so we are very interested to hear your contribution.

Mr. Kiyam Lin. Cosmic shear is the process by which the images of galaxies are minutely sheared by the gravity from the (mostly dark) matter between the source galaxies and us, the observers. Whilst this phenomenon has proven to be an excellent probe of large-scale structure in the Universe, the statistical analysis of this data has historically involved many statistical simplifications. These simplifications, however, will need to be discarded if we wish to leverage the power of the data that is beginning to stream in from new cosmological probes such as the recently launched *Euclid* space telescope.

The goal of this statistical analysis is often to infer the cosmological parameters of our Universe; for example, one such parameter would be the density of dark matter. There are, however, growing new avenues of doing this statistical inference that requires far fewer simplifications. One such avenue is to learn directly from realistic simulations that propagate all of the physics from the early Universe and its quantum fluctuations to the present-day observations of the night sky with the effects of observing conditions.

This methodology is often called simulation-based inference. In essence, by running lots of these realistic forward simulations, one always has a chance of happening to simulate a Universe realization that is similar to the one we observe today. As one can imagine, however, doing so in such a simplistic manner would result in a huge amount of computational waste as the vast majority of parameter combinations would produce results that are nothing like what we observe today.

Similarly, there isn't often just one optimal parameter value, but rather we want to find the range of possible parameter values, *i.e.*, the probability distribution of parameter values. As such, thanks to the reality that physics often creates smooth probability distributions, we can make use of machine learning to learn the probability distribution from a relatively sparse smattering of simulation runs that span the parameter-value ranges of interest.

In lieu, we can now perform parameter inference whilst keeping as much of the effects of the real physics in there as possible, minimizing the statistical simplifications required to perform successful inference, and gain tight fits on parameters. All of this is to prepare for the new exquisite data we expect to gain from the upcoming stage-IV cosmology surveys such as the *Euclid* space telescope and the Legacy Survey of Space and Time at the *Rubin Observatory*, to name but two.

The President. Thank you very much — statistics clearly put for once! Questions?

Dr. Robert Massey. It's probably really unfair, but you have probably seen the story today about giant arcs and structures. It may not be closely connected to your research but do you have a view on that?

Mr. Lin. I've been here the whole day. I've not seen the news. I'll check it out.

Dr. Quentin Stanley. Is this fit dependent very much on the model or are you able to extrapolate from it that you cannot get a good fit and therefore the physical model needs to be modified?

Mr. Lin. That is a really good point. We have to calculate our observations from data and that relies on the model and also we are always modelling to do the simulation. Anyway, it would be very weird not to be able to model one part without the other part, and so you'll always get a good fit given what you have; however, we can then do something called model comparison where you can find out what kind of physical model fits the data better. Because things are relatively self-consistent, if you think back how to observe the data and you measure them with the model you'll also be able to model a simulation to do this.

The President. I'm put in mind of a criticism Fred Hoyle once voiced. "A fit with no parameters is best, you might learn *something* from a fit with one parameter, if it's two parameters you could fit anything". Thank you very much indeed [applause].

Now we move to a popular event — the George Darwin Lecture. We're delighted to have Dr. Dominic Bowman of Newcastle University today. Dominic completed his PhD in astronomy in 2016 at the University of Central Lancashire under the supervision of Professor Donald Kurtz. He was the recipient of the Springer Thesis Prize for outstanding PhD research. In 2017 he began a postdoctoral research position at KU Leuven, Belgium, and in 2020 he was awarded a Competitive FWO Research Fellowship in massive-star asteroseismology. In 2023 September Dominic began a readership faculty position at Newcastle University and currently holds a prestigious Royal Society University Research Fellowship and ERC/UKRI Frontier Research Grant: SYMPHONY. Dominic has been invited many times as a speaker at international conferences and has won prestigious prizes for his research excellence including the KU Leuven Council Research Award in 2020, the Henri Vanderlinden Prize of the Royal Flemish Academy of Belgium for Science and the Arts in 2022, and the George Darwin Lecture today. In addition to being an outstanding researcher Dominic is passionate about teaching at the BSc/MSc/PhD level and engages regularly in advocacy and mentoring activities for all ages and backgrounds. It's a real pleasure to invite you to give this year's George Darwin Lecture entitled 'Asteroseismology unlocks the hidden physics of stellar interiors'.

Dr. Dominic Bowman. Twinkle, twinkle, little star, how I wonder what you are? More and more these days, I find myself drawing parallels between encouraging curiosity in infants and my research career as an astronomer and academic. It turns out that this particular nursery rhyme must have stuck with me since it is quite an apt summary of my research field known as asteroseismology. Stars appear to twinkle in the night sky because of the Earth's atmosphere. However, in reality almost all stars in the Universe are variable stars, changing their surface brightness periodically because of waves excited deep within their interiors. In my asteroseismology research, I focus on massive stars, which are stars born with masses larger than eight times the mass of the Sun. Massive stars are important metal factories in the Universe, providing chemical feedback to their environments through their winds and explosive deaths as supernovae. Moreover, they are the progenitors of neutron stars and black holes, which can merge to produce important sources of gravitational waves for testing General Relativity.

Massive stars commonly pulsate in two main types of pulsation that are largely grouped into what we call sound waves and buoyancy waves, with the restoring forces being pressure and gravity, respectively. Mathematically, we describe the geometry of pulsation modes using spherical harmonics with three quantum numbers to define the radial order, the angular degree, and the azimuthal order of a particular pulsation-mode frequency. The observational data-driven goal of asteroseismology is thus to assemble long-duration and high-precision light-curve data sets of pulsating stars, calculate the amplitude spectrum of pulsation-mode frequencies and assign them unique spherical-harmonic-mode identification through pattern recognition, and ultimately to compare the frequency to theoretical model predictions. In so doing, we are able to constrain the stars' interior physical conditions with high precision. In recent years, we have experienced a space revolution in asteroseismology, heralded primarily by the ESA *CoRoT*, and NASA *Kepler* and *TESS* space missions, which have assembled light-curves of tens of thousands of pulsating stars. Thus, asteroseismology of many different types of stars within the Hertzsprung–Russell diagram has become possible on a grand scale only in the last two decades.

An important result from ensemble asteroseismology of pulsating stars spanning different evolutionary stages is the measurement of their interior-rotation profiles. In particular, the amount of measured differential rotation, which can be approximately defined as the ratio of the near-core and near-surface rotation rates, is observed to be smaller than expected from theoretical models of stellar evolution. Many pulsating dwarf stars seem to have quasi-rigid radial rotation profiles, with red giants exhibiting somewhat larger ratios, but still much smaller than stellar-evolution-model predictions. This means that a strong angular-momentum-transport mechanism must be operating across different stages of stellar evolution. Leading explanations for this missing mechanism are magnetic fields and the pulsations themselves, which are both efficient transport mechanisms for angular momentum and not necessarily mutually exclusive. A novel result within massive-star asteroseismology is the recent study of HD 192575 published in *Nature Astronomy* by my now-graduated PhD student, Dr. Siemen Burssens. Through our analysis we demonstrated how asteroseismology provides a clear differential rotation profile for HD 192575, and through comparison to stellar-evolution models we extracted an accurate measurement of the star's mass and age to better than 15% relative precision. This is the first time that various sources of observational and theoretical uncertainties were incorporated throughout the analysis, making these results particularly robust and accurate compared to the few other examples in the scientific literature to date.

A common question at astronomy conferences is: what about magnetic fields? Magneto-asteroseismology is becoming an emerging field to help in this regard. Through a combination of asteroseismic modelling, surface magnetic-field measurements from spectropolarimetry, and sophisticated magnetohydrodynamical simulations, magneto-asteroseismology yields the strength and geometry of magnetic fields that are buried deep within the interiors of massive stars. Particularly exciting is the prospect of being able to diagnose the presence of a magnetic field generated within a rotating convective core in a massive star. This framework been applied for the first time to the pulsating magnetic star HD 43317, which has a near-core magnetic-field strength of about 500 kilogauss, and thus acts as a valuable proof-of-concept study for future work.

In recent years a particular focus within my research has been the search for and interpretation of stochastically excited pulsations in massive stars. Such damped pulsations can be excited by turbulence at the boundary of convective cores in massive stars, which then propagate to a star's photosphere and become detectable as chaotic flux perturbations. Such a scenario is distinct from the periodic pulsations excited by a heat-engine mechanism in the outer envelope typically modelled in asteroseismology and producing delta-function-like peaks in the amplitude spectrum of a star's light-curve. On the other hand, stochastically excited pulsations from turbulent core convection produce a broad excess of power in the amplitude spectrum of a star's light-curve with periods of order weeks to minutes. Needing a description for this new phenomenon, we termed it stochastic low-frequency (SLF) variability and have since discovered it to be widespread across a large range of masses and ages. Through developing new numerical methods and techniques to characterize the signatures of SLF variability in time-series observations, I have also demonstrated how SLF variability can be used to infer the mass and age of a massive star, and in turn helped to bring about the emergence of blue-supergiant asteroseismology. In the years to come, my on-going ERC/UKRI SYMPHONY (StudYing Massive star PHysics Of blue supergiaNts with asteroseismologY) project at Newcastle University will build on this work and tackle the remaining uncertainties in our understanding of massive-star evolution using asteroseismology. Thankfully, massive stars clearly twinkle with there being much interesting work for us to do.

Finally, I would like to thank all those who have supported me over the years, especially my mentors, Professor Donald Kurtz and Professor Conny Aerts, and the Royal Astronomical Society's awards committee for the distinct privilege of being awarded the 2023 George Darwin Lecture.

The President. Thank you for what we all agree was a superb lecture. Questions from the floor?

Reverend Garth Barber. What is your view about what is happening to Betelgeuse?

Dr. Bowman. Betelgeuse is the subject of an on-going debate in that we are not sure what evolutionary phase it is in. Is it or isn't it in the core-helium-burning stage? There was a remarkable drop in its brightness and I was actually a visiting astronomer at ESO's La Silla observatory in Chile at the time. I was almost bribed to point the *FEROS* spectrograph at Betelgeuse which would almost certainly have burned the CCDs. It has dropped in brightness by a substantial fraction. There are two ideas. One, which has come out as consensus, is that red supergiants create a lot of dust in the interstellar environment and this gets in the way between us and the star and some of the photosphere will be obscured. I think this explanation has a lot of merit but can be challenging since it requires ultra-precise interferometry such as with *ALMA* to test it. The other theory is that the pulsation and the convection have a non-linear interaction such that the convection can be suppressed by the pulsations and *vice versa* and that will give rise to a cooler star. That is difficult to model and to test, which is why people have been putting effort into testing the dust hypothesis, which I think has been proven to have been fairly well accepted now.

Dr. Gkioulidou. A very impressive talk. I am going to ask you about magnetic fields. I think you said with asteroseismology you can give us the upper limit of the strength of the magnetic field. I think I missed why is it that the more massive stars have weaker magnetic fields.

Dr. Bowman. There is a big diversity in the strength of magnetic fields in massive stars. Typically they are about 1 kilogauss, which is much stronger than the Sun, for instance, but 10% of the massive stars have this strong type of detectable magnetic field. Why this is only 10% of massive stars can be potentially explained by the formation process and/or binary-star evolution. If you take two stars and merge them together you can make a magnetic field. But within that population of magnetic massive stars it can be anything from a few hundred gauss to a few dozen kilogauss which is a large range. I wouldn't say that magnetic fields were weaker, rather there is an unexplored diversity in the field strengths of massive stars and their mechanisms to create them.

Professor Kathy Whaler. I am a geophysicist and not used to oscillations to study the Earth so the question may be a little silly. You showed one example where the peak of $m = +2$ was missing, so you have four out of the five. How do you know it was +2 and not –2?

Dr. Bowman. This is a technicality that I tried to skip over but you have definitely picked up on it so thank you for the question. It is not uncommon for frequencies within a multiplet to have different amplitudes. This depends on the inclination of the star and there can also be a rotation-related boosting factor as well. It can be the case that for rapidly rotating stars the prograde modes have a higher amplitude than the retrograde modes, for example. For this particular star at the time of our original study we thought that there is a fifth frequency which is hiding in the noise. That study was based on one year of *TESS* data and the *TESS* mission is still going. In a follow-up study we have tried to find that little peak and it is actually there. At the time I would say that we were perhaps actually hedging our bets, but the S/N was quite low — it was there but just at a very low amplitude.

Professor Whaler. I could identify something that was equally noisy. My other question was what about the Väisälä frequency? Do you probe this as a function of depth throughout the star? How do the values compare to the rotational frequencies of stars?

Dr. Bowman. I should say that for the stars we are looking at, we're actually in the so-called gravito-inertial regime where the frequencies of gravity-mode oscillations are comparable to the star's rotation frequency. For rapidly rotating stars, the methodology I have described here and the mathematics of spherical harmonics only applies to perfect spheres, so when we solve this forward-modelling problem we have to use the Laplace tidal equation, for example, instead of applying brute-force spherical harmonics, so there is a bit of uncertainty based on what rotation regime you are in. Normally we would derive the rotation frequency independently first and then undertake forward asteroseismic modelling to infer the Brunt-Väisälä frequency profile, then go back just to check that it is consistent with the rotation frequency.

The President. Anything online? In the room?

Professor Ellis. I learned a lot. For those of us working on galaxies, the main-sequence (MS) lifetime of a massive star is really important. Even a small extension of the MS lifetime of the most massive stars would change fundamentals such as if galaxies re-ionize the Universe. What is the extension that is possible by this mixing and rotation to the classical ages of the most massive stars. Is it 10% or 20%?

Dr. Bowman. The scary answer is that for some stars it is a factor of two. But this is probably not the case for all stars. I didn't really mention it but the overshooting value is really just a proxy to make the convective core a little bigger so that the star will live longer. The value for this particular star (HD 192575) is pretty representative for most single stars in this mass regime and that will correspond to an increase in MS lifetime of about 20–30%. There are extremes: for some stars this value is zero, so your MS standard prescription is fine, but if this values gets to a factor of two larger then we are reaching 100% uncertainty on the age of a star. That is something we should fix, right?

Professor Ellis. Absolutely!

Mr. Horace Regnart. Thank you for a brilliant presentation of brilliant research. May I add a strictly non-critical comment. A geophysicist friend described to me how the rotation of the Earth caused the water flowing approximately north-south in the River Mississippi to be slightly higher on one side than on the other side and that the Coriolis effect is actually a pseudo-force.

Dr. Bowman. I agree with that. I think the Panama Canal has the same phenomenon.

Professor Peter Coles. You talked a lot about the amplitude of the different modes or oscillations. Is it possible to get any information about the phases of these modes, particularly if they are coupled together for instance?

Dr. Bowman. This is what I did my PhD thesis on, using observations of the so-called δ Scuti variables. The fundamental data of linear asteroseismology is just the pulsation frequencies. In the non-linear asteroseismic interpretation which we are developing you include the amplitude and phase information. For a stochastically-excited mechanism we would expect a random distribution of phases. For a coherent oscillator like a δ Scuti variable, or a double-mode Cepheid, for instance, it is not realistic, in my opinion, to say that the fundamental mode has no knowledge of the first overtone mode. They will interact and can be revealed through an amplitude-modulation mechanism such as the Blazhko effect but also the phase differences of those modes and when they come into resonance and when they go out of resonance. I would say that for some stars we have done quite a lot of work on that, but for the massive stars that I talked about today there has been effectively very little done on non-linear mode interactions. That would be a very interesting thing to push our models to explain.

Professor Coles. Can one actually measure these phase correlations?

Dr. Bowman. Yes. The phases come from the light-curve and in comparison to models you can see how this relates to other astrophysical phenomena; if you are in phase or out of phase with convection, for example.

The President. Thank you very much indeed, again. [Applause.] I heard something being said in the front during the lecture: "Thank God we live near a boring yellow star" [laughter]. May I remind you that there is a drinks reception in the RAS Council Room immediately following this meeting and I give notice that the next Monthly A&G Highlights meeting of the Society will be on Friday, 9th February.

SYNODIC PERIODS AND ORBITAL ECCENTRICITY

By B. Cameron Reed

Department of Physics (Emeritus), Alma College, Michigan

The effect of orbital eccentricity on the synodic period of a planet is examined at an undergraduate level. In the case of Mars, the effect is not dramatic but is certainly detectable in that the times between just a few successive oppositions can vary by values on the order of a month. This analysis could be appropriate as supplemental classroom material or as the source of a homework exercise.

A standard element of traditional astronomy education is to show how Copernicus and Kepler used measured synodic (s) periods of planets to determine their sidereal (T) periods, with the two being related by

$$T = \frac{s}{(s \mp 1)}, \tag{1}$$

where the upper (lower) sign holds for a superior (inferior) planet and all periods are measured in Earth years. Recall that the sidereal period is the physically important one, being the time required for a planet to orbit the Sun with respect to a distant star as seen by an observer outside the Solar System; this is the period that appears in Kepler's Third Law. However, this cannot be observed directly by Earth-bound observers, as we also orbit the Sun. Rather, what we can measure is the synodic period, the time required for a planet to return to the same location in the sky relative to the Earth and Sun, typically a conjunction, opposition, or elongation. I will use the term 'alignment' in a generic sense to cover all these possibilities.

An informal survey of various lower-level undergraduate texts reveals that some derive Eq. (1) while others simply quote it or give only a qualitative description. Some apply the concept with a focus on lunar phases more so than planetary orbits, while in others the reverse is the case; my concern here is with planets. Whatever the level of treatment, however, the assumption is always that the orbits are *circular*, although some do remark that this is an approximation. An inquisitive student might then ask: "How would the eccentricity, even if modest, affect the synodic period? Also, since the speed of a planet in its orbit is always varying, would the time between successive alignments be truly periodic?"

This paper describes an analysis of this situation and a program developed to run corresponding numerical calculations. For simplicity, I do assume that Earth's orbit is circular, while that of the target planet has some eccentricity ε.

Fig. 1 illustrates an alignment between the Earth and a superior planet, whose major axis lies along the horizontal direction. At the moment of alignment, the apsidal angles φ_E of the Earth and φ_P of the planet are identical. Call this common angle φ_0, and the time at which this occurs to be t_0. The problem is to determine the angular position and time of the next alignment. Note that this does not require that the Earth and planet again align along the specific direction φ_0, only that they align along the same value of φ. All angles are measured in radians.

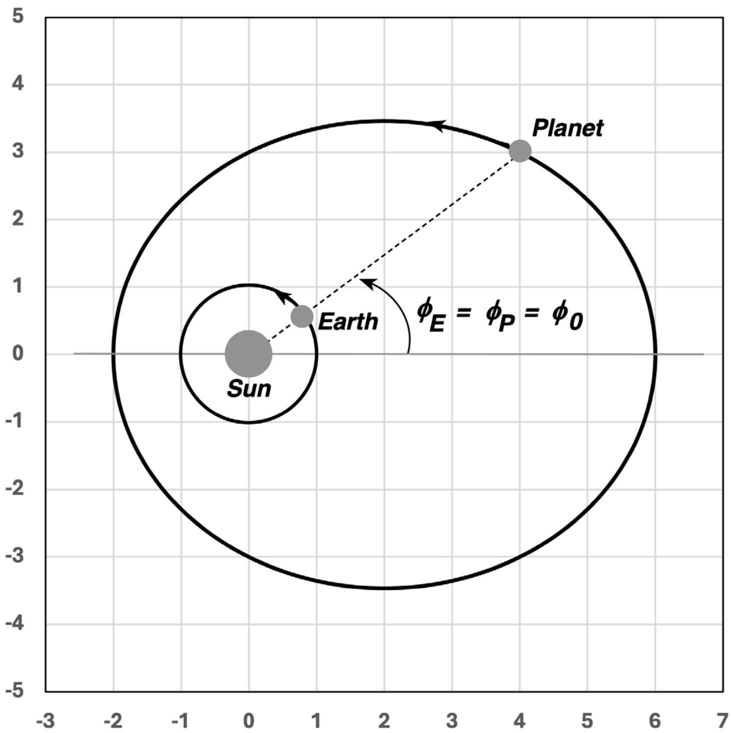

FIG. 1

Scale drawing of Earth with a superior planet in opposition at common apsidal angle $\varphi_E = \varphi_P = \varphi_0$. Scales are in AU, with the Sun at the origin. The planetary orbit has $a = 4$ AU and $\varepsilon = 0{\cdot}5$.

For the Earth in its circular orbit with sidereal period T_E (later to be set to 1 year), the orbital angular speed is constant at $2\pi/T_E$. At some later time t, Earth will be at apsidal angle φ_E given by

$$(\varphi_E - \varphi_0) = \left(\frac{2\pi}{T_E}\right)(t - t_0). \qquad (2)$$

Now, it is shown below that for the planet with sidereal period T_P, any later time t will correspond to apsidal position φ_P according as

$$(t - t_0) = \frac{(1-\varepsilon^2)^{3/2}\, T_P}{2\pi}\,[f(\varepsilon, \varphi_P) - f(\varepsilon, \varphi_0)], \qquad (3)$$

where the function $f(\varepsilon, \varphi)$ is determined in Eq. (8) below.

If Eq. (2) is solved for $(t - t_0)$ and the result substituted into Eq. (3), we have

$$(\varphi_E - \varphi_0) = (1-\varepsilon^2)^{3/2}\left(\frac{T_P}{T_E}\right)[f(\varepsilon, \varphi_P) - f(\varepsilon, \varphi_0)]. \qquad (4)$$

The condition for the next alignment is that in the case of a superior (inferior) planet, the elapsed apsidal angle for the Earth has moved ahead (fallen behind) that of the planet by 2π radians:

$$(\varphi_E - \varphi_P) = \pm 2\pi, \tag{5}$$

where the upper (lower) sign again applies for a superior (inferior) planet. Using this expression for φ_E in Eq. (4) gives

$$(\varphi_E - \varphi_0) \pm 2\pi - (1-\varepsilon^2)^{3/2}\left(\frac{T_P}{T_E}\right)[f(\varepsilon, \varphi_P) - f(\varepsilon, \varphi_0)] = 0. \tag{6}$$

This is an equation of constraint for the next alignment at apsidal angle φ_P. Once this position has been determined, the corresponding time can be determined from Eq. (2) or (3), and the position and time can then be treated as (φ_0, t_0) for determining the next alignment. The process can then be continued for as many synods as desired.

To determine the function $f(\varepsilon, \varphi)$, we appeal to the standard result that for an elliptical orbit of eccentricity ε and period T, the time to travel from apsidal angle φ_0 to angle φ is given by

$$(t - t_0) = \frac{(1-\varepsilon^2)^{3/2}\,T}{2\pi}\int_{\varphi_0}^{\varphi} \frac{\mathrm{d}\varphi}{(1-\varepsilon\cos\varphi)^2}. \tag{7}$$

Unfortunately, the exact closed-form solution of this integral involves computing the inverse-tangent of the product of a factor involving ε times the tangent of $\varphi/2$. Whenever a calculation involves an inverse-tangent, quadrant ambiguities come into play. In the present case this is compounded by the fact that φ accumulates to several multiples of 2π radians as subsequent alignments are sought. To avoid this complication, I treat the integral by a binomial expansion of the denominator to second order in ε, presuming that ε is not too great. (For the same reason, I avoid introducing Kepler's equation, which also involves a tangent.) The function f of Eq. (4) is the indefinite integral:

$$\begin{aligned} f(\varphi, \varepsilon) &= \int \frac{\mathrm{d}\varphi}{(1-\varepsilon\cos\varphi)^2} = \int(1 + 2\varepsilon\cos\varphi + 3\varepsilon^2\cos^2\varphi + \ldots)\mathrm{d}\varphi. \\ &= \varphi(1 + \tfrac{3}{2}\varepsilon^2) + 2\varepsilon\sin\varphi + \tfrac{3}{4}\varepsilon^2\sin(2\varphi) + \ldots . \end{aligned} \tag{8}$$

To evaluate these calculations, I prepared a double-precision FORTRAN program into which the user enters the desired planetary sidereal period T_P in years, the eccentricity, and the apsidal angle φ_0 of an initial alignment. The program computes the aphelion and perihelion distances of the planet to ensure that no Earth-orbit crossings occur, and then determines apsidal angles and times for 100 subsequent alignments.

Preliminary calculations indicated that the time between successive synods does indeed vary somewhat around the textbook value that would be computed from Eq. (1), so the program takes a brute-force approach. Beginning at a trial value of φ_0 + 0·02 radians and going in steps of 0·02 radians, the constraint equation is evaluated until it changes sign; a bisection routine is then used to pin down the apsidal angle of the next alignment to a tolerance of 10^{-8} radians. The 'initial angle' φ_0 is then reset to the position of the alignment so determined, and the calculations reiterated to determine the next alignment. The program runs

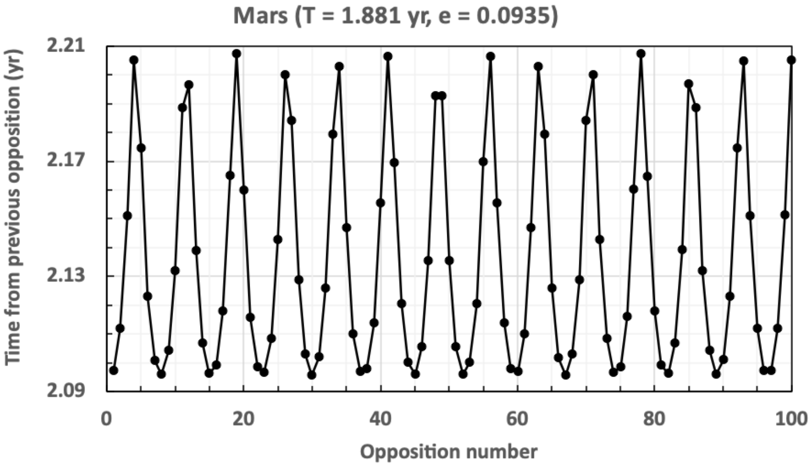

FIG. 2
Times between successive oppositions of Mars; $T = 1{\cdot}881$ yr, $\varepsilon = 0{\cdot}0935$, $\varphi_0 = 0$.

to about 250 lines including extensive comments and executes in a few seconds on a desktop computer.

Fig. 2 shows results obtained for Mars, for which a NASA website gives $T_P = 1{\cdot}881$ years and $\varepsilon = 0{\cdot}0935$.[1] Our inquisitive student is indeed correct. Synodic periods vary from about 2·09 to 2·21 years, a spread of some 44 days. The average over 100 synods, 2·1357 years (s.d. = 0·0380 years), is close to the value that would be computed from Eq. (1), 2.1351 years. Runs with increasing assumed eccentricity show a trend to increasing average, but also with increasing spread and with the nominal value always well within the spread.

The quasi-periodicity evident in Fig. 2 hints at a phenomenon known to ancient astronomers: that oppositions of Mars show a repeating pattern with respect to background stars in that nine nominal synodic periods of 2·1351 years corresponds to a little more than 19 years. Venus exhibits a similar effect, with five of its 583·9-day synodic periods spanning almost exactly eight years. This sort of effect is by no means guaranteed; the synodic period needs to be close to a rational-fraction number of years.

Synodic periods are now of largely historical interest, but it can be enjoyable to explore the nuances of what we learned in foundational classes. I would be happy to share the FORTRAN code with any interested reader.

Reference

(1) https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

REDISCUSSION OF ECLIPSING BINARIES. PAPER 19: THE LONG-PERIOD SOLAR-TYPE SYSTEM V454 AURIGAE

By John Southworth

Astrophysics Group, Keele University

V454 Aur is an eclipsing binary system containing two solar-type stars on an orbit of relatively long period (P = 27·02 d) and large eccentricity (e = 0·381). Eclipses were detected using data from the *Hipparcos* satellite, and a high-quality double-lined spectroscopic orbit has been presented by Griffin[1]. The NASA *Transiting Exoplanet Survey Satellite* (*TESS*) has observed the system during eight sectors, capturing ten eclipses in their entirety. V454 Aur is unusual in that the primary star — the star eclipsed at the deeper minimum — is less massive, smaller, *and* cooler than its companion. This phenomenon can occur in certain configurations of eccentric orbits when the stars are closer together at the primary eclipse, causing a larger area to be eclipsed than at the secondary. We use the radial-velocity measurements from Griffin and the light-curves from *TESS* to determine the masses and radii of the component stars for the first time, finding masses of 1·034 ± 0·006 $M_\odot$ and 1·161 ± 0·008 $M_\odot$, and radii of 0·979 ± 0·003 $R_\odot$ and 1·211 ± 0·003 $R_\odot$. Our measurement of the distance to the system is consistent with that from the *Gaia* DR3 parallax. A detailed spectroscopic study to determine chemical abundances and more precise temperatures is encouraged. Finally, we present equations to derive the effective temperatures of the stars from the inferred temperature of the system as a whole, plus the ratio of the radii and either the surface brightness or light ratio of the stars.

Introduction

Detached eclipsing binaries (dEBs) are our primary source of directly measured masses and radii of normal stars[2–4], obtained from the analysis of time-series photometry and radial-velocity (RV) measurements. Early studies of these objects were hampered by the difficulty of obtaining high-quality photometry covering all orbital phases[5,6], particularly with the equipment in use at the time[7–9].

Improvements required the availability of extensive observing time on small telescopes (*e.g.*, refs. 10,11), preferably operated robotically (*e.g.*, refs. 12,13). The operation of an increasing number of small survey instruments for stellar variability (*e.g.*, ref. 14) or planetary transits[15–17] has resulted in the acquisition of extensive photometry for millions of bright stars. Some of these targets are dEBs for which precise radii could be obtained[18,19].

The recent generation of space telescopes dedicated to the detection of transiting extrasolar planets from time-series survey photometry — such as

CoRoT[20], *Kepler*[21], and *TESS* (the *Transiting Exoplanet Survey Satellite*[22]) — has hugely increased the extent and precision of photometric archives[23]. This has led to a fundamental change in the number of dEBs both known[24–26] and analysed in detail[27–29].

It is more difficult to obtain good observational datasets for dEBs with longer orbital periods (P). On the spectroscopic side, the velocity amplitudes scale according to $P^{-1/3}$ so the size of the measurable signal decreases. On the photometric side, the eclipses become longer and rarer and thus poorly suited to ground-based observation. However, as P increases, photometric study gets harder more quickly than spectroscopic study due to the more time-critical nature of the required observations. The result is that extensive sets of RVs have been obtained for some longer-period dEBs without the accompanying photometric analysis needed for the determination of the full physical properties of the component stars. This was the situation for V454 Aur, except that high-quality photometry is now available from *TESS*. The current work presents an analysis of these new data and the first measurement of precise masses and radii of its constituents.

TABLE I

Basic information on V454 Aurigae.

Property	*Value*	*Reference*
Right ascension (J2000)	$06^h22^m03^s.06$	30
Declination (J2000)	$+34^\circ35'50''.5$	30
Henry Draper designation	HD 44192	31
Hipparcos designation	HIP 30270	32
Gaia DR3 designation	3440630513359154688	30
Gaia DR3 parallax	15·3669 ± 0·0217 mas	30
TESS Input Catalog designation	TIC 138333980	33
B magnitude	8·22 ± 0·03	34
V magnitude	7·65 ± 0·01	34,35
J magnitude	6·589 ± 0·023	36
H magnitude	6·374 ± 0·027	36
K_s magnitude	6·297 ± 0·018	36
Spectral type	F8 V + G1–2 V	1

V454 Aurigae

V454 Aur (Table I) was found to be eclipsing using data from the *Hipparcos* satellite[32] and given its variable star name by Kazarovets *et al.*[37]. The object was subsequently observed by Griffin[1] (hereafter G01) in Paper 160 of his 'Spectroscopic Binary Orbits from Photoelectric Radial Velocities' series, alongside V455 Aur (since revisited by Southworth[38]) and UW LMi (reanalysed by Graczyk *et al.*[39]).

G01 originally added V454 Aur to his observing list based on its overluminosity (from the *Hipparcos* parallax) being an indication of binarity[40]. He corrected the original suggested period of 3·2057 d to its true value of 27·02 d using a set of 62 spectral cross-correlation functions[41] observed over a time interval of 386 d. The substantial orbital eccentricity means the RVs of the stars are significantly different at times of eclipse, a fact used by G01 to confirm the presence of both primary and secondary eclipses by the weakening of the dip of a given star in the cross-correlation functions★ (see his fig. 2).

★ despite noting a "complete lack of meteorological coöperation" for some of these observations

G01 estimated a light ratio of approximately 0·58 from the ratio of the cross-correlation dips: this should be interpreted as the ratio of spectral-line strengths in the wavelength interval close to the peak of the Johnson B band. From this and the colour indices of the system, he inferred spectral types of F8 V and G1–2 V.

The only other published information worth mentioning at this point are measurements of the effective temperature ($T_{\rm eff}$) and iron abundance ([Fe/H]) of the system. Both come from the Geneva–Copenhagen Survey[42], and are $T_{\rm eff} = 6064 \pm 80$ K and [Fe/H] = −0·08 (Casagrande *et al.*[43]) and $T_{\rm eff} = 6030$ K and [Fe/H] = −0·14 (Holmberg *et al.*[44]).

The BV magnitudes in Table I come from the *Tycho* experiment[34] on the *Hipparcos* satellite. Each comprise the average of 85 measurements, well-distributed in orbital phase and with only a few obtained during an eclipse. The JHK_s magnitudes are from 2MASS[36] and were obtained at a single epoch corresponding to orbital phase 0·679, which is not within an eclipse.

Photometric observations

V454 Aur has been observed in eight sectors by *TESS*[22], beginning with sector 20 (2020 January) and ending in sector 73 (2023 December). Data in all sectors were obtained at a cadence of 120 s as well as other cadences including 20 s, 600 s, and 1800 s. We downloaded all 120-s cadence data from the NASA Mikulski Archive for Space Telescopes (MAST*) using the LIGHTKURVE package[45]. We adopted the simple aperture photometry (SAP) data from the *TESS*-SPOC data reduction[46] with a quality flag of "hard". These were normalized using LIGHTKURVE and converted to differential magnitude.

The resulting light-curves are shown in Fig. 1, divided according to sector. It can be seen that six primary eclipses were observed, and all are fully covered. There are also seven secondary eclipses, but only four are fully covered by the available observations. The eccentric nature of the system is clear from the facts that the secondary eclipses are longer than the primary eclipses, and they do not occur midway between successive primary eclipses. In the following analyses we adopt the standard approach of labelling the deeper eclipse as the primary eclipse, the primary star (star A) as the star eclipsed in primary eclipse, and the secondary star as star B.

We queried the *Gaia* DR3 database† and found a total of 82 objects within 2 arcmin of V454 Aur. Of these, the brightest is fainter than our target by 5·94 mag in the $G_{\rm RP}$ band, and the brightest star within 1 arcmin is fainter by 7·77 mag in $G_{\rm RP}$. We therefore expect the *TESS* light-curve to suffer from contamination at a level below 1%.

Light-curve analysis

V454 Aur contains two well-detached stars and the *TESS* data are extensive, so the system is well suited to analysis with the JKTEBOP‡ code[47,48] (version 43). Fitting the full 128 226 data points simultaneously took a significant amount of computing time, which could be avoided by rejecting data away from eclipse and thus of negligible information content. We therefore extracted the ten fully-

*https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

†https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/355/gaiadr3

‡http://www.astro.keele.ac.uk/jkt/codes/jktebop.html

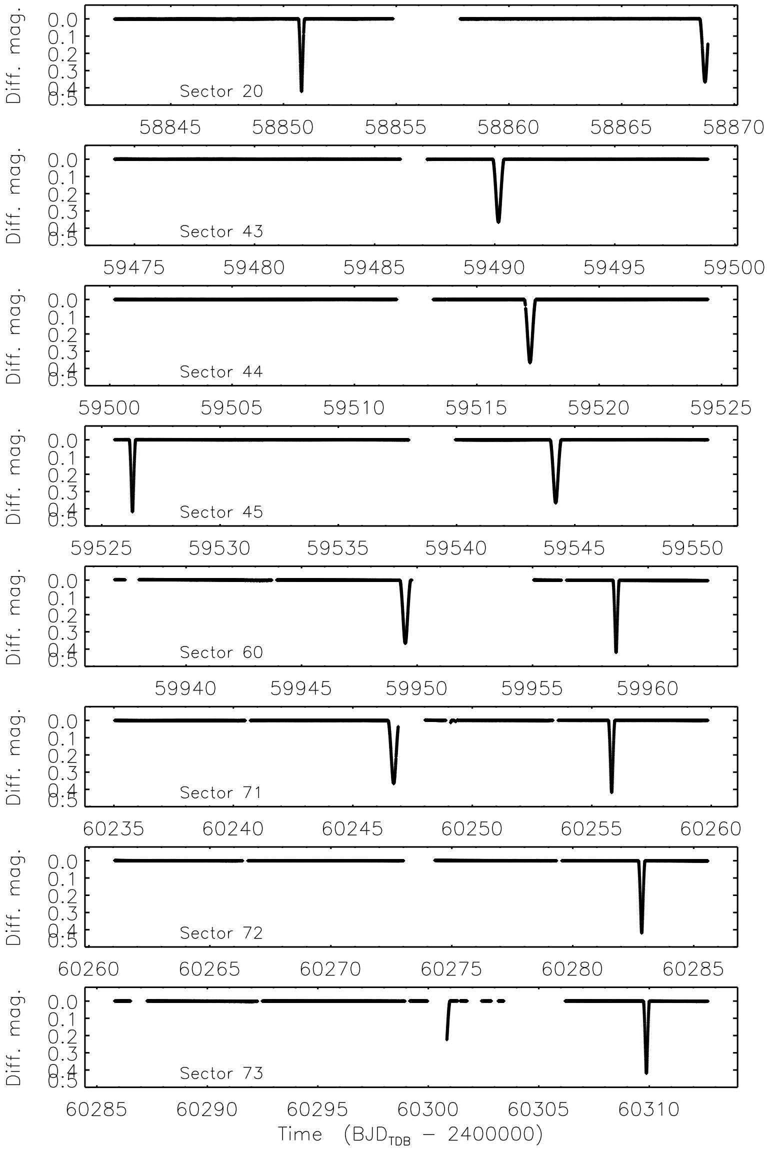

FIG. 1

TESS short-cadence SAP photometry of V454 Aur. The flux measurements have been converted to magnitude units then rectified to zero magnitude by subtraction of the median. Each panel shows one *TESS* sector (labelled).

observed eclipses from the light-curve, including 0·3 d (primary) and 0·45 d (secondary) of data outside eclipse, giving a more tractable 5053 data points for detailed analysis.

The fitted parameters were the fractional radii of the stars (r_A and r_B), expressed as their sum ($r_A + r_B$) and ratio ($k = r_B/r_A$), the central-surface-brightness ratio (J), the orbital inclination (i) and period (P), and a reference time of primary minimum (T_0). Orbital eccentricity (e) and the argument of periastron (ω) were fitted *via* the combinations $e \cos \omega$ and $e \sin \omega$. We also fitted for a second-order polynomial brightness variation for each eclipse to remove any remaining slow changes in brightness due to either instrumental or astrophysical effects.

Limb darkening was included using the power-2 law[49,50] with the linear coefficient (c) fitted and the power coefficient (α) fixed to a theoretical value[51,52]. The two stars have sufficiently similar limb-darkening characteristics that we assumed the same coefficients for both. We initially included third light as a fitted parameter, but found that it always became small and insignificant. We therefore fixed it at zero for our definitive solution, which is given in Table II.

Our initial solutions of the light-curve with reasonable estimates of the starting parameters yielded an unexpected outcome. The particular geometry of the orbit of V454 Aur means that the stars are significantly closer to each other during primary than secondary eclipse, which combined with $i < 90°$ means less of the stars are eclipsed during secondary than primary. The only way to get the secondary eclipse deep enough to match the data is for star B to be both larger *and* hotter than star A. In support of this counterintuitive result is that the value of ω from the light-curve differs by 180° from the spectroscopic one (G01). We confirmed it by fitting for the RVs from G01 simultaneously with the *TESS* light-curve and finding that our identifications of the stars are swapped relative

Table II

Parameters of V454 Aur, with their 1σ uncertainties, measured from the TESS sector-55 light-curves using the JKTEBOP code.

Parameter	*Value*
Fitted parameters:	
Primary eclipse time (BJD_{TDB})	2459526·296873 ± 0·000015
Orbital period (d)	27·0198177 ± 0·00000082
Orbital inclination (°)	89·2084 ± 0·0023
Sum of the fractional radii	0·44456 ± 0·00033
Ratio of the radii	1·2368 ± 0·0027
Central-surface-brightness ratio	1·2059 ± 0·0020
LD coefficient c	0·623 ± 0·010
LD coefficient α	0·545 (fixed)
$e \cos \omega$	0·246836 ± 0·000018
$e \sin \omega$	0·28965 ± 0·00023
Velocity amplitude of star A (km s^{-1})	52·75 ± 0·17
Velocity amplitude of star B (km s^{-1})	46·95 ± 0·11
Systemic velocity of star A (km s^{-1})	40·41 ± 0·02
Systemic velocity of star B (km s^{-1})	40·48 ± 0·02
Derived parameters:	
Fractional radius of star A	0·019875 ± 0·000039
Fractional radius of star B	0·024582 ± 0·000010
Light ratio ℓ_B/ℓ_A	1·8448 ± 0·0053
Orbital eccentricity	0·38056 ± 0·00017
Argument of periastron (°)	49·562 ± 0·025

to Griffin's. V454 Aur is therefore a rare example of a dEB where the secondary star is larger, hotter, and more massive than the primary. This can only occur for specific ω values in an eccentric orbit.

Once a suitable solution was established, we ran Monte Carlo and residual-permutation solutions[53] to obtain reliable error bars[38]. We fitted both the *TESS* and RV data, allowing a separate systemic velocity for the two stars. The best fits are given in Fig. 2 for the light-curve and Fig. 3 for the RV curves, and the properties are collected in Table II. The solution is extremely well-determined, with uncertainties in the fractional radii of 0·2% for star A and 0·04% for star B. We imposed a minimum uncertainty of 0·2% on the fractional radii based on the independent-analyses tests described by Maxted *et al.*[54] for the similar system AI Phoenicis. Our results are in good agreement with those of G01, after accounting for his different choice of primary star. The light ratio also agrees with the value found by G01; it should be remembered that the wavelength interval observed by G01 is significantly bluer than the *TESS* passband.

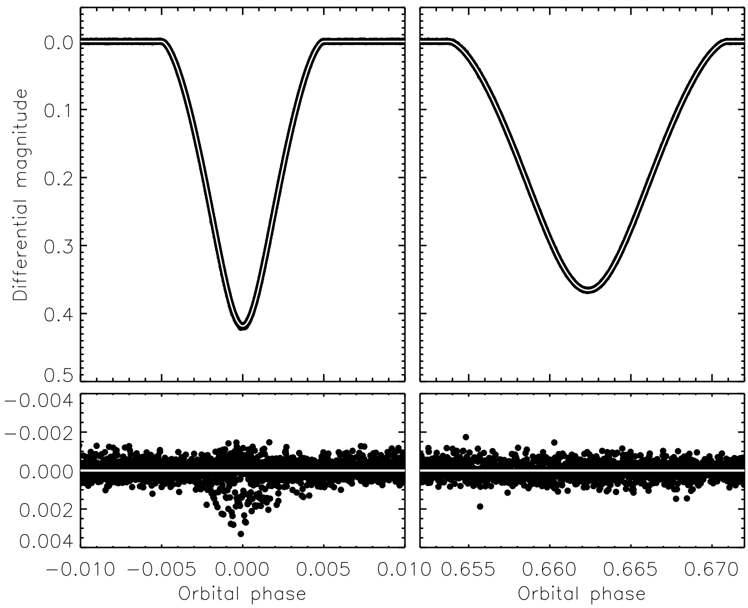

Fig. 2

JKTEBOP best fit to the 120-s cadence *TESS* light-curves of V454 Aur. The data are shown with filled circles and the best fit with a white-on-black line. The residuals are shown on an enlarged scale in the lower panel.

Physical properties and distance to V454 Aur

We determined the physical properties of the V454 Aur system using the results in Table II from the JKTEBOP analysis. We did this using the JKTABSDIM code[55] to utilise its distance-measurement capabilities. The results are given in Table III and show that the masses are measured to precisions of 0·6–0·7%, and the radii to 0·2–0·3%. Using the $T_{\rm eff}$ values determined in the next section, we

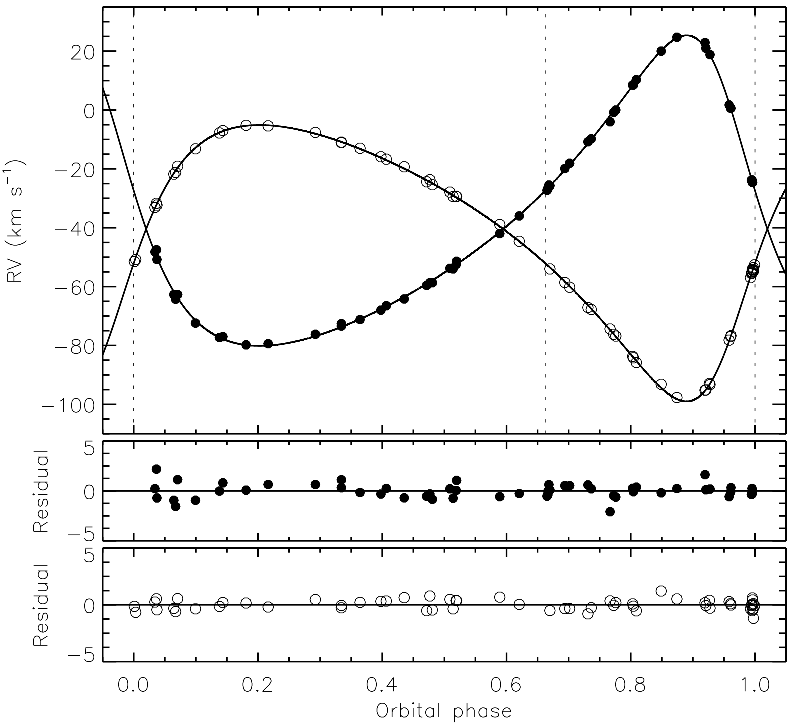

FIG. 3

RVs of V454 Aur from G01 (filled circles for star A and open circles for star B), compared to the best fit from JKTEBOP (solid lines). The times of eclipse are given using vertical dotted lines. The residuals are given in the lower panels separately for the two components.

have calculated the luminosities and bolometric absolute magnitudes of the two stars. To our knowledge, this is the first published measurement of the radii of these stars.

The trigonometric parallax of V454 Aur in *Gaia* DR3 is 15·367 ± 0·022 mas, a distance of 65·07 ± 0·09 pc, which allows a consistency check. We used the *BV* and *JHK* magnitudes in Table I, the distance-determination method from Southworth *et al.*[55] and the surface-brightness calibrations from Kervella *et al.*[56] to measure a distance of 63·67 ± 0·76 pc in the K_s band. An interstellar extinction of $E(B-V)$ = 0·02 ± 0·02 mag was imposed to obtain consistent distance measurements in the optical and near-IR passbands. This extinction is appropriate for such a nearby object, and consistent with the $E(B-V)$ = 0·055 ± 0·027 mag given by the STILISM* extinction maps[57,58].

Effective temperature from surface brightness ratio

No published spectroscopic $T_{\rm eff}$ measurement exists for the individual components of V454 Aur. G01 inferred spectral types of F8 V and G1–2 V, which correspond to $T_{\rm eff}$s of approximately 6150 K and 5800 K in the calibration of

*https://stilism.obspm.fr

TABLE III

Physical properties of V454 Aur defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 61).

Parameter	*Star A*	*Star B*
Mass ratio M_B/M_A	$1{\cdot}1235 \pm 0{\cdot}0045$	
Semi-major axis of relative orbit ($\mathcal{R}^N_\odot$)	$49{\cdot}24 \pm 0{\cdot}10$	
Mass ($\mathcal{M}^N_\odot$)	$1{\cdot}0336 \pm 0{\cdot}0059$	$1{\cdot}1612 \pm 0{\cdot}0081$
Radius ($\mathcal{R}^N_\odot$)	$0{\cdot}9787 \pm 0{\cdot}0027$	$1{\cdot}2105 \pm 0{\cdot}0025$
Surface gravity (log[cgs])	$4{\cdot}4711 \pm 0{\cdot}0020$	$4{\cdot}3370 \pm 0{\cdot}0014$
Density ($\rho_\odot$)	$1{\cdot}1024 \pm 0{\cdot}0069$	$0{\cdot}6546 \pm 0{\cdot}0015$
Effective temperature (K)	5890 ± 100	6170 ± 100
Luminosity $\log(L/\mathcal{L}^N_\odot)$	$0{\cdot}016 \pm 0{\cdot}029$	$0{\cdot}281 \pm 0{\cdot}028$
$M_{\rm bol}$ (mag)	$4{\cdot}699 \pm 0{\cdot}074$	$4{\cdot}036 \pm 0{\cdot}071$
Interstellar reddening $E(B-V)$ (mag)	$0{\cdot}02 \pm 0{\cdot}02$	
Distance (pc)	$64{\cdot}20 \pm 0{\cdot}80$	

Pecaut & Mamajek[59]. Two measurements exist from the Geneva–Copenhagen Survey[42,43] and are $T_{\rm eff} = 6064 \pm 80$ K and 6030 K; both come from photometric calibrations based on Strömgren *uvbyβ* indices and were obtained under the assumption that it is a single star. The *Gaia* DR3 GSPPHOT value is 6003 K[60] whilst the *TESS* Input Catalog[33] lists a slightly lower 5758 ± 136 K.

We therefore sought to obtain $T_{\rm eff}$ values for the two stars based on the $T_{\rm eff}$ of the system from Nordström *et al.*[42] and the known radius and surface brightness ratios from the JKTEBOP analysis. This is a straightforward procedure, but is not (to our knowledge) present in the literature so is outlined here.

First we make the assumption that the $T_{\rm eff}$ of the system ($T_{\rm sys}$) corresponds to the sum of the luminosities of the two stars (L_A and L_B) so

$$\begin{aligned} L_A + L_B &= 4\pi R_A \sigma T_{\rm sys}^4 + 4\pi R_B \sigma T_{\rm sys}^4 \\ &= 4\pi R_A \sigma T_{\rm eff,A}^4 + 4\pi R_B \sigma T_{\rm eff,B}^4 , \end{aligned} \quad (1)$$

where R_A and R_B are the stellar radii and σ is the Stefan-Boltzmann constant. Dividing by $4\pi\sigma$ and collecting terms gives

$$(R_A^2 + R_B^2) T_{\rm sys}^4 = R_A^2 T_{\rm eff,A}^4 + R_B^2 T_{\rm eff,B}^4 . \quad (2)$$

Replacing R_B with kR_A allows us to cancel out the radii:

$$\begin{aligned} (R_A^2 + k^2 R_A^2) T_{\rm sys}^4 &= R_A^2 T_{\rm eff,A}^4 + k^2 R_A^2 T_{\rm eff,B}^4 \\ (1 + k^2) T_{\rm sys}^4 &= T_{\rm eff,A}^4 + k^2 T_{\rm eff,B}^4 . \end{aligned} \quad (3)$$

Making the assumption that the radiative properties of the stars in the *TESS* passband are good proxies for their luminosities means that we can use the central-surface-brightness ratio, $\mathcal{J} = T_{\rm eff,B}^4 / T_{\rm eff,A}^4$ to get rid of $T_{\rm eff,B}$:

$$(1 + k^2) T_{\rm sys}^4 = T_{\rm eff,A}^4 + k^2 T \mathcal{J}_{\rm eff,A}^4 = (1 + k^2 \mathcal{J}) T_{\rm eff,A}^4 . \quad (4)$$

We then rearrange to get the final result:

$$T_{\rm eff,A} = \left(\frac{1 + k^2}{1 + k^2 \mathcal{J}} \right)^{1/4} T_{\rm sys} \quad (5)$$

after which we can obtain the $T_{\rm eff}$ of star B from

$$T_{\rm eff,B} = \mathcal{J}^{1/4} T_{\rm eff,A} = \left(\frac{1 + k^2}{1\mathcal{J} + k^2}\right)^{1/4} T_{\rm sys} \,. \tag{6}$$

Due to the definition of $\mathcal{J}$ in the JKTEBOP code, this formally requires the two stars to have the same limb darkening. However, the bias induced by this is small in general, and zero for V454 Aur as the same limb-darkening coefficients were used for both stars when fitting the light-curve.

Following this procedure for V454 Aur yields temperatures of $T_{\rm eff,A} = 5890$ K and $T_{\rm eff,B} = 6170$ K. The uncertainties in k, $\mathcal{J}$, and $T_{\rm sys}$ were propagated using a Monte Carlo approach, and are dominated by that in $T_{\rm sys}$. We arbitrarily increased the uncertainties in $T_{\rm eff,A}$ and $T_{\rm eff,B}$ to 100 K to account for neglecting the wavelength dependence of $\mathcal{J}$ in the above analysis. There will be an additional bias contributed by the assumption that the $T_{\rm sys}$ can be obtained from photometric indices of the combined system, but we lack the information necessary to quantify this (specifically the light ratios of the stars in the *uvbyβ* passbands). The $T_{\rm eff}$ measurements presented here are simplistic, which means they are both limited and useful.

Effective temperature from light ratio

The JKTEBOP code is well-suited to determining $T_{\rm eff}$s *via* the central-surface-brightness ratio as this is one of its native parameters. However, some light-curve models work instead with the light ratio so a different approach is needed to determine $T_{\rm eff,A}$ and $T_{\rm eff,B}$ from $T_{\rm sys}$. The equation is derived below for completeness, with the light ratio specified as $\ell = \ell_B/\ell_A$. Beginning with Eq. 1 we can also write:

$$L_A + L_B = L_A(1 + \ell) = 4\pi R_A \sigma T^4_{\rm eff,A}(1 + \ell) \,. \tag{7}$$

This step also requires the assumption that the measured light ratio in the observed passband is a good proxy for the luminosity ratio of the stars.

Substituting R_B with kR_A, cancelling $4\pi\sigma R_A$ as before, and then rearranging yields the final result:

$$T_{\rm eff,A} = \left(\frac{1 + k^2}{1 + \ell}\right)^{1/4} T_{\rm sys} \,. \tag{8}$$

The similarities between Eqs. 5 and 8 are clear and are as expected from the physics of the situation. A similar approach but eliminating L_A instead of L_B gives the equation for the secondary star:

$$T_{\rm eff,B} = \left(\frac{1 + 1/k^2}{1 + 1/\ell}\right)^{1/4} T_{\rm sys} \,. \tag{9}$$

For the record, this approach gave an identical result for V454 Aur as the surface-brightness method above.

V454 Aur in context

The outstanding characteristic of V454 Aur is, to us, the precise determination of the physical properties of two solar-type stars in an orbit of such a long period. In order to confirm and contextualise this, we sought comparable systems. For this we used the *Detached Eclipsing Binary Catalogue*[62] (*DEBCat**), which lists all

*https://www.astro.keele.ac.uk/jkt/debcat/

known dEBs with mass and radius measurements to 2% precision and accuracy. We required both components of a dEB to have a mass between 0·9 and 1·3 $M_\odot$ and a surface gravity of log $g > 4{\cdot}0$ (c.g.s.), and the system to have a period of 10 d or more. A total of 14 dEBs (including V454 Aur) satisfy the above criteria, of which V454 Aur has the third-longest period.

The dEBs are listed in Table IV along with selected properties (mass, radius, period, eccentricity). Twelve of the 14 have a significant orbital eccentricity ($e >$ 0·16), but any interpretation of this is complicated by the fact that eccentricity increases the likelihood of eclipses occurring[63,64]. Six of the dEBs were discovered in data obtained by space-based searches for transiting planets, and a further four have been studied using such data. Three of the 14 dEBs (Kepler-34, TIC 172900988, and Kepler-1647) have been studied in detail primarily because they host transiting circumbinary planets, and in these systems the presence of transits allows additional constraints on the properties of the inner binary system[65]. The list in Table IV highlights the obvious advantage of extensive space-based photometry in the analysis of dEBs with long orbital periods and thus infrequent eclipses.

Table IV

Identifications and properties of dEBs with similar properties to those of V454 Aur, sorted in decreasing order of period.

Name	P (d)	e	$M_A/M_\odot$	$R_A/R_\odot$	$M_B/M_\odot$	$R_B/R_\odot$	*Reference*
KX Cnc	31·220	0·470	1·134	1·053	1·124	1·059	66
Kepler-34	27·796	0·521	1·048	1·162	1·021	1·093	67
V454 Aur	27·020	0·381	1·034	0·979	1·161	1·211	This work
KIC 7821010	24·238	0·680	1·277	1·276	1·221	1·210	68
LL Aqr	20·178	0·317	1·196	1·321	1·034	1·002	69
TIC 172900988	19·658	0·448	1·228	1·383	1·202	1·314	70
V565 Lyr	18·799	0·020	0·995	1·101	0·929	0·971	71
LV Her	18·436	0·613	1·193	1·358	1·170	1·313	72
KIC 7177553	17·996	0·392	1·043	0·940	0·986	0·941	73
V963 Cen	15·269	0·422	1·081	1·445	1·075	1·421	39
AI Dor	14·905	0·195	1·102	1·092	1·103	1·098	74
Kepler-1647	11·259	0·159	1·221	1·790	0·968	0·966	75
HP Dra	10·762	0·037	1·133	1·371	1·094	1·052	76
KIC 2306740	10·307	0·301	1·194	1·682	1·078	1·226	77

Conclusion

We have presented an analysis of the dEB V454 Aur, which contains two solar-type stars on a relatively long-period (P = 27·02 d) and eccentric (e = 0·381) orbit. We have determined the masses and radii of the component stars using light-curves from eight sectors of *TESS* observations and extensive RVs obtained by Griffin. Our work provides the first published measurements of the radii of these stars.

The system has the unusual characteristic that the star eclipsed at the deeper (primary) minimum is less massive, smaller, *and* cooler than its companion. This occurs because the stars are further apart during secondary minimum in this eccentric orbit, so a smaller fraction of the stars are eclipsed. More importantly, the physical properties are precisely determined and the stars are so far apart that tidal effects are negligible so they accurately represent the outcome of single-star evolution.

We used the measured temperature of the system plus the ratio of the radii and central surface brightnesses of the stars to determine their individual temperatures and thus luminosities. Our measured distance to the system is consistent with that from the *Gaia* DR3 parallax. A detailed study of the spectral characteristics of the stars could yield improved $T_{\rm eff}$ measurements as well as photospheric chemical abundances. V454 Aur is therefore a promising candidate for conversion into a benchmark for the evolution of solar-type stars.

From a brief comparison of the masses, radii, and $T_{\rm eff}$s of the stars to the PARSEC 1·2S theoretical stellar-evolutionary models[78,79], we find that the properties of the system are consistent with a solar chemical composition and an age in the region of 2·3 ± 0·2 Gyr.

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Note added in proof

After the completion and acceptance of the current work, an analysis of V454 Aur was given by Yücel, Canbay & Bakiş (arχiv:2404.18171). All parameters found by those authors agree with those found in the current work, representing a useful cross-check of our results. There were two significant differences. First, Yücel *et al.* chose to identify the more massive star as the primary component. Second, the uncertainties in radius found by those authors are much larger (2–3% *versus* our 0·2–0·3%). The latter point is probably because the 120-s cadence data, and the data from sectors 71 to 73, were not available to Yücel *et al.* at the time they began their analysis. Our results should be preferred as they are based on more extensive and better-sampled photometry.

CORRESPONDENCE

To the Editors of 'The Observatory'

Future Tense?

One of the hot topics in modern cosmology is the so-called 'Hubble tension': some measurements of the Hubble constant, which tend to be based on objects relatively nearby (compared to the scale of the observable Universe), indicate a value of around 73 km/s/Mpc, while others, based mainly on the cosmic microwave background (which is almost at the distance of what is normally known as the radius of the observable Universe, though in practice the CMB itself is often that limit), give about 67 km/s/Mpc; the formal disagreement is at the four-to-six-σ level.* There is no shortage of suggestions; a recent review[1] with 1005 references gives an idea of the activity in the field, and 1095 citations indicate a fair amount of interest. The topic is now important enough for even just *one aspect* of it ('early dark energy') to have its own annual review[2]. There is no consensus as to which, if any, solution is correct. However, probably at most one is correct, otherwise there would be a (probably much stronger) Hubble tension in the opposite sense. Thus, in order to convince the community that a particular solution is correct, one needs to show that all others are wrong.

Papers which show that other papers are wrong are an essential part of science, but rewards are not high. If one does not convince the community, the effort is wasted. If one does, then perhaps people will stop citing the original

*Some of us might remember when the Hubble tension was between 50 (or even 30[3]) and 100, with a similar formal statistical incompatibility. Interestingly, proposals for new physics and so on were rarely mooted as a potential explanation. One reason for the difference might be that the current tension seems to be between different methods whereas in the days of the Sandage–de Vaucouleurs debate it was between different teams of observers. Another difference is that whether the Hubble constant turns out to be 67 or 73, something in between, or higher/lower than both (in some sense, the probabilities of the last two are the same), there will be no dramatic consequences, whereas back in the day a Hubble constant of 100 was incompatible with the then-in-vogue Einstein–de Sitter cosmological model given the (relatively certain) age of the Universe. Although Sandage favoured a low value for the Hubble constant throughout his career, later on his dislike of the cosmological constant seemed, at least to me, to reinforce his belief in a low Hubble constant (since that would allow the Einstein–de Sitter Universe with no cosmological constant with about the right age).[4] The current standard cosmological 'concordance' model of a low-density Universe with a positive cosmological constant fits well with the age of the Universe and any value of the Hubble constant still in the running.

paper, but by the same token there would be no need to cite the rebuttal. Also, in order to show that a paper is wrong, one has to know the material better than the person who wrote the original paper. (There is also the problem that if one shows that the original paper is correct, many journals won't publish such a confirmation, even though that is also an essential part of science, thus reducing the motivation for exploring a topic without knowing the outcome, which of course is the way it should be done.)

What can we expect in the future? I doubt that all of the suggestions (except perhaps the one, correct suggestion) will be shown to be wrong on their own terms (as opposed to being a good theory which is merely ruled out) on a case-by-case basis. Solutions for which some testable prediction is confirmed could be seen as more likely, and of course those with failed predictions could be ruled out. Many of the solutions are *ad hoc* in the sense that it was the Hubble tension itself which led to their proposal; that is not necessarily an indication that they must be wrong, and sometimes there is some additional justification. I'm happy to be corrected, but as far as I know there was no theory which *predicted* the current Hubble tension of about 6 km/s/Mpc (with statistical uncertainties claimed to be much smaller); while technically postdictions are just as good, predictions are more impressive.

Whether the solution turns out to involve interesting new physics or some banal explanation, perhaps the most interesting result will be that a consensus on the cause of the Hubble tension will rule out all of the other proposed explanations with one fell swoop.

Yours faithfully,
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REVIEWS

The Reinvention of Science. Slaying the Dragons of Dogma and Ignorance, by Bernard J. T. Jones, Vicent J. Martinez & Virginia L. Trimble (World Scientific), 2024. Pp. 493, 23 × 15·5 cm. Price £45 (paperback; ISBN 978 1 80061 360 7).

Most readers of *The Observatory* would be able to construct a historical timeline of our subject: perhaps by an ordered list of the kings and queens of our particular realm, and at least for the western story, the list goes something like: Babylonians, Greeks, Anaximander, Aristarchus, Ptolemy, Aristotle, Copernicus, Tycho, Kepler, Galileo, Newton, Einstein — then boom: the explosion of knowledge and us.

A few learned souls might add Giordano Bruno or the oddly named medieval Oxford scholar Robert Grossetestes — but even fewer know Copernicus's publisher and by what process he was selected. The authors tell us he was chosen *via* a centuries-long thread that starts with a text book on optics based on the writings of the Islamic scholar Alhazen in about the year 1000. This original work tumbled through the early centuries of the second millennium and along the way got translated into Latin and was subsequently published by Petreius in Germany in 1535. That published book was acquired by a friend of Copernicus and shown to him and thus he approved the publisher. It is that extra depth that makes this *Reinvention of Science* so different from many other history-of-science volumes and such a pleasure by which to be enveloped. You may also note that my list of kings and queens does not in fact include any queens and the authors would be very keen to correct that error. I should at least add Henrietta Leavitt, Cecilia Payne, Marie Curie, and Mary Anning. But wait! — Mary Anning was a fossil hunter not an astronomer. Indeed, the book is titled *The Reinvention of Science*, and although mostly told through the story of the unravelling of the evolution of the Universe, its much larger remit covers all of the relevant physics and thus geology and the ancient history of the Earth — including dinosaurs.

The opening chapter starts not with the Babylonians, as most traditional science histories do, but with Albert Michelson assembling his interferometer in the basement of a building borrowed from Edward Morley (his own laboratory, that he had been setting up for four years, had been destroyed by fire). Michelson and Morley were attempting to measure the Earth's movement through the luminiferous ether, and as we now know, no such movement was detected and also no such ether. The ether is the first of the Dragons, the slaying of which this book describes. Dragons are here defined as invisible, undetectable entities that are required to support the prevailing scientific consensus on the nature of the Universe at the time they were first postulated. The Crystalline Spheres holding up the stars is another, much earlier one. As the authors remind us such spheres were not such a crazy idea in a world in which unseen forces, like gravity, acting over long distances were unknown. If not crystalline spheres what else could fit the observations? The same rationale guides our thinking to this day.

As well as slaying Dragons the authors also challenge Dogma, one such being the requirement for the right sort of man to be engaged in and to write papers about science. This dogma excluded the acknowledgement of women's contributions for centuries and for just about as long, maybe longer, people of the wrong colour or social class. The authors are at some pains to ensure that the relevant women are mentioned, and celebrated, and also the common folk of whatever gender. For example, Milton Humason, Edwin Hubble's poorly educated mule driver, removal man, and telescope handler, who through determination and delicacy of touch, developed into the key scientist in recording the spectra of faint galaxies to enable the expansion of the Universe to be deduced.

In my reviewing notes for this book I find I often comment on the clarity of description. The overall tone is measured and scholarly and yet also light. For example, there is a beautifully concise description in Chapter 1 of Epicurean thought finding its way into the western world and giving us the concept of atoms and even the idea of heat as movement of atoms and almost the first inklings of Brownian motion. Another beautifully concise passage of just over two paragraphs, in Chapter 17, covers the description of the contents of the

Universe. As a further example of the extra detail provided, this passage notes that of the everyday baryonic matter which makes up just about 5% of stuff in the now-standard description of the Universe, just 0·5% is luminous objects: stars and galaxies, and 4·4% is non-luminous other stuff. The remaining dark matter is non-baryonic and about which we currently know very little. We are equally clueless about the almost 70% of stuff described as dark energy.

The authors' lightness of touch is seen in references to popular culture — The Simpsons and The Flintstones being offered as examples of how one side of a debate can become unquestioned dogma in a serious discussion on the causes of the extinction of the dinosaurs. As every school child knows, meteorite impact is the accepted cause, and yet the case for an extended demise through vulcanism is currently an equally strong candidate. This section also notes the advantage of having a good publicity machine when competing for limited publicly funded research money, but also the potential disadvantageous effect of bandwagons illustrated by a Walt Disney film that popularized the erroneous myth of lemming suicides.

Not just the past, but the present and future are also covered with the same measured tones. The final half of the book deals with the current state of physics, with detailed descriptions of the recent detections using the new techniques of gravitational-wave astronomy, and the search for polarization of such waves as signatures of primordial gravitational radiation. The final chapter deals, perhaps a little too uncritically, with the march of the machines and the possibilities of artificial intelligence as a potential tool for assisting in the analysis of forthcoming huge data sets.

In addition to the main text there are 73 pages of notes, and I had great fun checking and following links to the web pages; there is a ten-page index of names and 26 pages of subject index. So as well as clarity, detail, and scholarship one can also add thoroughness. At £45, however, this is quite expensive for a paperback, even one of 493 pages, and as a physical item the appearance may not reflect that price. Textually there are just a couple of obvious typos and the proof reading or editing goes awry for a few pages in the middle section. A huge omission for such a general title would seem to be that, other than a glancing mention of the Egyptians and China in the first chapter, the parallel history of science in non-western countries is barely mentioned. However, within the context of current science the content is very good — the layout and text are beautiful and there is so much wisdom and pleasure contained within these pages that I believe the price to be worthwhile.

All of us who paddle in the streams of scientific enquiry have our toes and our souls soaked in the search for fundamentals. Some in sleek clipper ships crash through the deepest oceans of abstruse mathematical scholarship while others paddle in the muddy, murky waters of experiment and instrumentation — all of us believing that we follow a flow, a direction to the one path of truth. But is finding truth the same as finding the good?

In conclusion I was tempted to quote the final philosophical sentence of the last chapter, but that would be as crass as giving away the ending to a detective novel. I will instead quote from the very beginning. In the preface Neil deGrasse Tyson, the director of the Rose Planetarium in New York, has said on Twitter and television "science is true whether or not you believe in it",

I can only add that in looking for the good as well as the truth this book offers both, a scientific truth and a book that is very good — almost excellent. — Barry Kent.

The Allure of the Multiverse: Extra Dimensions, Other Worlds, and Parallel Universes, by Paul Halpern (Basic Books), 2024. Pp. 308, 23 × 13 cm. Price $30·00 (about £24) (hardbound; ISBN 978 154160217 5).

[*The Observatory* has received two reviews of this book and the Editors feel that our readers will enjoy both, coming as they do from our two most prolific and experienced reviewers.]

Most people…many people…well, anyhow your present reviewer, sometimes wish they had done some things differently, rent or buy, accept that job instead of this, maybe even marry someone else*. This must be part of the attraction of the idea of reincarnation. Could it also be part of the charm of multiverses? Maybe you don't get to try the other fork in the road, let alone a spoon†, but somewhere/when another 'you' does. This frivolous thought is just about the only motivation for multiverses not addressed in this volume by the science historian and author Paul Halpern, professor of physics at St. Joseph's University.

Not that the book is wholly solemn! If you enjoy a chase sequence, I recommend pp. 174–175, the lead up to inflationary cosmology, and there are leaking balloons among his highly original analogies. *Allure* is organized in a semi-historical fashion. Chapter 1 starts with Kepler. Later chapters each take one sort of multiverse idea and follow it down to extinction of viability or the present. These include additional dimensions (with a fine explanation of Kaluza–Klein theories); Hugh Everett's many-worlds interpretation of quantum mechanics (in which everything that can happen does happen, just mostly not on our time line, so that somewhere, Schroedinger's cat lives to be at least a 100); anthropic and Mixmaster universes; inflation, strings, and cyclic universes. As well as many ideas, many people appear, some with firm views pro or con on the ideas. Stan Deser, for instance, appears just before page 1 saying "I think we have enough *tsuris* with one Verse." Deser had in common with Halpern childhood knowledge of Yiddish from parents and grandparents. With some embarrassment, I found myself on page 24 (part of the Introduction) quoted on the 'pro' side, on the grounds that there have turned out in the Universe to be many planets, many stars, many solar systems, many galaxies, clusters, and superclusters thereof, so why not many universes? (I meant to count the number of people indexed and the fraction you might have been expected to have heard of before (in a sort of inverse of *Wer zaehlt die Voelker — nennt die Namen*) but kept getting interested in what Halpern had to say about my favourites and so never got past the middle E's (Queen Elizabeth II and George Ellis) with the count.) So, acquire the book, count how many of your scientific and other heroes are mentioned, and generally enjoy it all! — Virginia Trimble.

Paul Halpern, professor of physics at St. Joseph's University in Philadelphia, has written 18 popular-science books, though this is the first I have read. In

*Not your present reviewer, who continues of the opinion that Joseph Weber (who makes a cameo appearance in this volume as a participant in the Chapel Hill conference on General Relativity, later called GR1) was unquestionably the best husband in all the possible multiverses.

†The suggestion "when you come to a fork in the road, take it," is attributed to Yogi Berra. Stanley Deser made use of the phrase in a recent autobiography reviewed in these pages (143, 242, 2023), but we are saving him for a quote later about multiverses.

contrast to some other books mainly about the Multiverse[1–3] or dealing with it to some extent[4,5], some reviewed in these pages[6–9], this book is somewhat less technical and takes a broader perspective (*e.g.*, pointing out that the term 'Multiverse' was coined by William James, though in the context of moral philosophy rather than cosmology); as such, it is perhaps a good first book on that topic (but shouldn't be the last). The introduction sets the stage, introducing various types of Multiverses and discussing historical ideas. The first chapter is basically an overview of classical physics, starting with the idea of recurrence, which is a sort of Multiverse in time rather than space, including ideas which were once taken more seriously than they are now, such as a putative connection between spiritualism and the fourth dimension. The second chapter is devoted to the first serious attempt to incorporate higher-dimensional space into physics (though not — yet — in the context of a Multiverse), Kaluza–Klein theories, the idea being to describe electromagnetism as well as General Relativity in the language of a geometrical theory with one more spatial dimension, and explaining quantization by having that dimension curled up. It is a very good non-technical description. While such theories themselves are now a backwater in the history of physics, they later influenced other ideas such as string theory. The next two chapters cover quantum mechanics and cosmology, providing an overview of those aspects relevant to the idea of the Multiverse. The next few chapters discuss various ideas which lead to the concept of a Multiverse, such as eternal inflation, string theory, and cyclic cosmologies (again, more a Multiverse in time than in space). Chapter 8 explores time travel, which in some interpretations can lead to multiple universes if a traveller returns to the past: one in which he returned to the past and one in which he didn't, perhaps because he had killed his grandfather (or taken some less drastic but just as effective measure).

The first three of Tegmark's[1] four Levels of Multiverses are all discussed: the part of our Universe beyond our horizon, different universes of which ours is but one example, and the many worlds of the many-worlds interpretation of quantum mechanics. The idea of a universe splitting due to the actions of travellers in time is a new aspect. However, the emphasis is not so much on different types of Multiverses but rather on different ideas which can lead one to the concept. On the other hand, Tegmark's Level II Multiverse — which is probably the one (apart from the trivial Level I) most are most willing to accept — is discussed mostly in the context of eternal inflation, although the general idea is much older (*e.g.*, ref 10). In general, the title is a good description of the book: it is about the allure of the Multiverse, *i.e.*, what makes it an attractive idea in various contexts, rather than more technical aspects. As such, the necessary background material blends well with and complements those parts more about the Multiverse *per se*.

The final chapter, somewhat misleadingly entitled Conclusions, spends, in my view, too much time discussing the general idea of a Multiverse, or parallel worlds, in popular culture. While Halpern makes it clear that such ideas have practically no overlap with the scientific ideas of the Multiverse, by the same token they really don't belong here. Towards the end, though, is a good summary, emphasizing the fact that in many other contexts most are content to accept things which are not *directly* observable (*i.e.*, the interior of black holes, the inflaton, the 'dark ages' of the Universe), even though they might use the lack of direct detectability as an objection to the Multiverse.

My copy is an uncorrected page proof, courtesy of the author, though presumably very close to the final product since, apart from figure captions at the end of the book rather than accompanying the figures, it looks very much like a normal book; the contents as well appear to be almost final. There are only a few actual typos and a couple of phrases which probably read other than intended. As usual, I would have phrased a few things differently, but on the whole the book is well written and one notices Halpern's experience as an author — not just in terms of style, but also with regard to presenting everything at the right level. Although it is not a highly technical book, there are none of the typical oversimplifications often encountered in popular-science books. All but one of the 22 black-and-white figures scattered throughout the book are of people. There are no footnotes and endnotes are all references to sources such as articles and interviews, most by Halpern himself with the scientists he writes about (a frequent contributor to this *Magazine* also makes an appearance). There is no index (a possible difference from the final version); the further-reading list (three-and-one-half pages of small print) is particularly thorough.

This is an enjoyable book which manages to weave well together the concept of the Multiverse, current ideas in physics related to it, and the (sometimes quite old) history of those concepts. — PHILLIP HELBIG.

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Scientific Debates in Space Science. Discoveries in the Early Space Era, by Warren David Cummings & Louis J. Lanzerotti (Springer), 2023. Pp. 264, 24·5 × 16 cm. Price £64·99 (hardbound; ISBN 978 3 031 41597 5).

Although the subtitle of this book is 'Discoveries in the Early Space Era', it might equally have been 'The Scientific Method in Theory and Practice', for its focus is not so much on informing us of present understanding of a number of high-profile topics principally in planetary and space-plasma physics, but unusually and interestingly on providing an account of how such status was achieved through the contentions of past years. Typically, the time-frame considered spans the 1960s to the 1990s, some controversies lasting longer than others, with emphasis on the protagonists involved, many now deceased, and their mutual interactions. To this purpose, the authors have evidently immersed themselves at length in the literature of the period, allowing the proponents to speak directly for themselves by quoting short sections verbatim from key published works, illustrated by original figures. Each topic is rounded out, however, with a 'Continuing Understanding' coda, bringing things briefly up to date.

Of the topics considered, three lie in the field of space-plasma physics, two of which concern the solar wind. The first deals with the nature of the outflow, whether supersonic as proposed by Gene Parker or subsonic as suggested by Joseph Chamberlain, an issue debated in the late 1950s and early 1960s before being quite rapidly resolved in favour of the former by the first thermal-plasma measurements by Soviet and US spacecraft. However, the subsequent issue of the distance to the shock that terminates the supersonic outflow, and from thence to the heliopause boundary with the interstellar medium beyond, was only resolved by *Voyager* particle and field data during the past ~20 years, following a debate that lasted for almost 50 years. The third issue covered in space-plasma physics concerns the properties of the Earth's magnetosphere, whether magnetically 'open' as proposed by Jim Dungey in 1961 or closed as argued by Alex Dessler, on which indirect evidence in the 1960s and 1970s and direct evidence principally in the 1980s and 1990s ruled in favour of the former.

In addition to briefer discussions of some less-controversial topics such as the discovery of the Earth's radiation belts by James Van Allen, the book also covers four significant debates in planetary physics. The first two concern the origin of the Earth–Moon system, the subject of many past hypotheses but now considered to have resulted from the impact between a Mars-sized body and the early proto-Earth, and, much later in Earth's history, the cause of the Cretaceous–Paleogene mass extinction event and its association with the Chicxulub asteroid-impact crater originated by Alvarez *père et fils*. A related topic concerns the depth of the dust layer on the lunar surface produced by meteorite bombardment, which Tommy Gold in 1955 suggested might be sufficiently deep in some locations that astronauts would disappear up to their armpits or beyond, a speculation happily disproved by space missions preparatory to the Apollo landings.

More infamously, in 1986 Lou Frank proposed on the basis of spacecraft ultraviolet imaging initially intended for auroral studies, that the Earth's upper atmosphere is being continuously bombarded (several per minute) by small cometary bodies that would have profound significance for Earth's water budget. This assertion triggered 17 years of lively debate involving no less than 32 papers, comments, and rebuttals published by Frank and colleagues, together with experimental studies by others, that ended with the general perception that these signals were, after all, due only to instrumental effects within the auroral-camera system, a conclusion that appears never to have been acknowledged by the proponents. As the contents of this fascinating book make clear, though the 'scientific method' of testing, verification, and refutation does eventually sift the scientific wheat from the chaff, the length and nature of that process may depend significantly on the human personalities involved. — Stanley W. H. Cowley.

The Era of Multi-Messenger Solar Physics, edited by Gianna Cauzzi & Alexandra Tritschler (Cambridge University Press), 2023. Pp. 160, 25 × 18 cm. Price £120/$155 (hardbound; ISBN 978 1 009 35288 8).

This volume is the Proceedings of IAU Symposium 372, co-ordinated by IAU Division E with other working groups, which was held in Korea in 2022 August at the tail-end of the Covid pandemic. The nearly 80 contributors were mostly from Asia but with some from the US. The main motivation for the meeting was the recent solar space missions, *Solar Orbiter* and the *Parker Probe*, and the *Daniel K. Inouye Solar Telescope*, largest ground-based solar observatory in the world, still in its commissioning phase at the time of the conference. The 'multi-messenger' of the conference title refers to the way these and other solar observatories are gaining knowledge of, for example, the connection of the magnetic fields in the distant solar atmosphere with the magnetic field at the solar surface.

With such new observatories in operation, or about to be, I expected review articles that summarize the subject for those not immediately involved, but it was surprising that there was only one of real use, putting things into a historical context. There are, however, extensive original research articles on novel techniques like machine-learning, the association of coronal mass ejections with flares using statistical methods, and the capabilities of the Atacama millimeter-wave *ALMA* array applied to solar observations. Among the many short contributions from participants was one that caught my eye, connecting avalanches of MHD waves to nano-flare heating of the corona.

The high price tag of this slim volume will obviously be a deterrent to prospective buyers including even university libraries, and there is also the factor that many of the papers in these proceedings will now have appeared in solar physics journals. The quality of production is high, as would be expected from this publisher, but there are no coloured figures which would have been welcome for interpreting the many detailed images of the solar surface in some of the papers. — Ken Phillips.

On the Origin of Time: Stephen Hawking's Final Theory, by Thomas Hertog (Penguin), 2023. Pp. 326, 23·4 × 15·2 cm. Price £10·99 (paperback; ISBN 978 180499112 1).

Belgian cosmologist Thomas Hertog was one of Hawking's last collaborators; the book was written, at Hawking's request, to popularize their joint work, which goes against some of Hawking's earlier work. In some sense, it is similar to another book[1] recently reviewed[2] in these pages in that it is about Hawking, working with Hawking, and the results of that work, though this book concentrates more on the science. An undergraduate at the Flemish-speaking Katholieke Universiteit Leuven (Georges Lemaître was associated with the mostly French-speaking Université catholique de Louvain, which moved to Louvain-la-Neuve when the old site became Flemish-speaking in 1968), and after master's and doctoral degrees in Cambridge (the latter with Hawking), Hertog, after working in the USA, France, and Switzerland, returned to Leuven as a professor in 2011 (and is now head of the theoretical-physics group at the department of physics and astronomy). His collaboration with Hawking extended essentially until the latter's death in 2018.

The basic idea of Hawking and Hertog (H&H) is that, similar to biological evolution, the Universe — not just the outcomes of the laws of physics but the laws themselves — is best understood as the contingent result of (quantum) branchings during its history (perhaps influenced by future events), rather than something which one could, at least broadly, derive from first principles, thus going beyond the classical difficulty of computing deterministic outcomes *in practice* and even beyond quantum indeterminacy. If that sounds vague, then that is because it is, at least to me. Those interested in a short summary (but too long to reproduce here) by Hertog himself can read the section starting with the last third of p. 188.

Hertog does a good job of providing a necessary overview of the history of cosmology, especially since the advent of relativistic cosmology somewhat more than a century ago, with the narrative becoming narrower and deeper as the main topic of the book is approached. A longer-than-normal preface introduces Hawking and the H&H collaboration before the first chapter gives some necessary background on cosmology, from ancient times until today, and black holes. It is a good and interesting overview, and also discusses biological evolution and how one usually makes sense of it by following it backward in time. Then follows an overview of (the history of) relativistic cosmology, which is not too biassed in favour of Lemaître but perhaps still gives Friedmann somewhat too short a shrift. (Lemaître was a very important figure, but it might be reading too much into his works when it is claimed that he was the first to engage in quantum cosmology, not just metaphorically, but also that he foresaw Everett's many-worlds interpretation of quantum mechanics, 'decoherence', and even the H&H top-down approach to cosmology.) That sets the stage for an overview of quantum mechanics and the concept of duality, which will play an important role later on, and the no-boundary proposal of Hawking and Hartle according to which in some sense time turns into space in the early Universe and that space is curved so that asking what was before the Big Bang makes as little sense as asking what is north of the north pole. Modern inflationary cosmology and the idea of the Multiverse are introduced before noting that Hawking in his later years distanced himself from the latter. (Unfortunately, the Multiverse discussed is only that of eternal inflation; there are different types of Multiverses, some of which have been discussed in books[3–5] reviewed in these pages[6–8].) The meat of the book is in Chapters 6 and 7, the two longest chapters, which discuss quantum cosmology and the holographic principle, often in the context of the H&H top-down approach to cosmology. The final chapter, much shorter than the others, is much more philosophical in outlook, which to some extent feels tacked on, something I have encountered before[3,6]. Whatever one thinks of the ideas of Hannah Arendt and H&H, it seems a bit of a stretch to invoke the former in support of the latter.

The book is reasonably well written with about the usual number of typos and questionable style choices. Some things seem a bit confused, such as referring to the CMB as a "cosmological horizon" and the light deflection at the surface of the Sun as seen from Earth as less than "a few arc seconds" (it is about 1″·75). While Dicke was already doing science in the 1930s, I don't think that he was thinking about the Anthropic Principle (AP) then. Hertog's teleological description of Carter's formulation of the AP contrasts starkly with that of Lewis and Barnes[9,10], who claim that Carter has often been misinterpreted. A galaxy "nugget" instead of "core" was presumably garbled somewhere in translation, but is at least amusing. Of course General Relativity is concerned with gravitational waves, not gravity waves, and by now we should all know that Wheeler didn't coin the term 'black hole' (though he did popularize it). I don't know why Hubble's equation $v = Hr$ should be "infamous"; more important is that it is very general, not just in the case of a constant rate of expansion. It is certainly true that Einstein initially thought that non-static cosmological models were irrelevant mathematical curiosities; I don't know why the same claim is made about Friedmann. I'm not sure why Faraday is claimed to be Scottish; perhaps confusion with Maxwell. Our backward light cone converges primarily due to the expansion of the Universe, not due to the presence of matter within it. Zwicky wasn't the first to contemplate dark matter, not even the first to use the term (though arguably the first to claim that there is more of it than of ordinary matter). Regarding traditional observational cosmology, the description is wrong in a way strikingly similar to (but probably independent of) that in another book recently reviewed in these pages[11]. There are a few other things which are at best confusingly formulated and some interpretations with which I and many others disagree (though most of the latter are not important for the main narrative).

There are a few black-and-white figures scattered throughout the book as well as eight pages of slick-paper colour plates, most of which I haven't seen elsewhere. Particularly interesting are hand-made sketches and plots by

Lemaître and a Dutch-caption cartoon of de Sitter, in the shape of (the mirror image of) λ (symbol for the cosmological constant) blowing up the Universe like a balloon, noting that the cosmological constant is responsible for the expansion.* The bibliography is not a list of references (which appear in the end notes) but more a (good — I've read almost half) list of suggestions for further reading. Endnotes (24 pages) contain references, additional information, or both; there is a 15-page small-print index.

I didn't find the book convincing; whether that is the fault of Hertog or my own I don't know. The work of H&H not only goes against some earlier work by Hawking but also takes a definite stance on two rather hotly debated topics, namely the AP and the Multiverse.† A common criticism of those two topics is that they (can) explain (everything) in hindsight but lack in predictive power. That is also true of the H&H top-down approach to cosmology. (As my late history teacher used to say, just an observation, not a judgement.) Their comparison with Darwinian evolution is apt (and the title is a reference to Darwin's *On the Origin of Species*); details are not predictable from the theory itself, because randomness (mutations in the former case, quantum effects in the latter) plays a key role. Of course, the theory of evolution is good science, but differs from traditional physics theories in that the goal is not a series of increasingly fundamental explanations. (Reductionism also applies to evolution, of course, in the sense that mutations and so on are understood at a low level. The difference is that, at least in practice, that reductionism cannot be used to predict the higher levels.) The difference from other high-level topics in physics (chaos, complex systems, *etc.*) is that H&H claim that not just the outcomes of the laws of physics are emergent, but also the laws of physics themselves. That certainly qualifies, in the words of Carl Sagan, as an extraordinary claim which requires extraordinary evidence. The idea of H&H might work in some sense, but it remains to be shown that it works better than the AP and/or the Multiverse in cases where both approaches claim to be able to explain the same phenomena. Although even staunch supporters of the AP usually reject a strong version‡ which claims that observers (whether human or not, whether sentient or not) in some sense cause the Universe to exist, it is strange that H&H, while rejecting even the weak AP (which some would regard as a trivial tautology), have their own bizarre idea, namely that a delayed-choice double-slit experiment[16] can be explained by the choice affecting the past ('retrocausality', an interpretation not shared by Wheeler, who suggested that and other similar experiments); strange enough for explaining non-intuitive aspects of quantum mechanics, but quite a stretch for explaining the origin of the laws of physics.

There are two related problems which sometimes occur with (semi-)popular books about topics which are relatively new. One, which doesn't apply here, is that it is often not clear what is new and/or controversial and what is consensus. The other is more common: on the one hand, there are technical monographs, original papers, theses, and so on, and on the other (semi-)popular books and articles, with nothing in-between. The latter is difficult to avoid, perhaps

*That is actually not the case. There are expanding and contracting universes with and without a cosmological constant (which could be positive or negative). Historically, the first relativistic cosmological model was Einstein's closed-space static universe and the second de Sitter's flat model with exponential expansion, both of which have a positive cosmological constant (but of course Einstein's didn't expand). That was a time when even experts were confused.[12,13]

†My own view is that a significant fraction of the debate on those topics is due to confusion of terminology, people talking past one another, and so on; I discuss that in a recent article[14]. (Of course, there is genuine difference of opinion as well.)

‡Bostrom[15] counts thirty versions of the AP.

because of the lack of sufficient readership. Although a generic problem, it also applies here: those interested in more details have few if any options other than delving into the (sometimes very) technical literature. As it is a generic problem, the author is not to blame, but it is something which the reader should keep in mind.

Despite my reservations, the book succeeds in its goal of presenting the basic idea of top-down cosmology for a more general readership and can be a first step for those interested in the topic — it just shouldn't be the last step as well, but a big jump will be needed between the first and last steps. Other modern ideas such as the holographic principle and the black-hole information paradox are explained well, so it can be a jumping-off point for those interested in modern ideas in quantum cosmology and related fields. — PHILLIP HELBIG.

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The Einsteinian Revolution. The Historical Roots of His Breakthroughs, by Hanoch Gutfreund & Jürgen Renn (Princeton University Press), 2024. Pp. 249, 23 × 15 cm. Price £28/$32 (hardbound; ISBN 978 0 691 16876 0).

The Einstein industry marches on, almost 70 years since it was begun by the sorting of the mass of papers he left in Princeton at the time of his death in 1955. Those papers and the rest of Einstein's estate were left to the Hebrew University of Jerusalem, which still owns copyrights and such, though the on-going 'publications of everything' (the Einstein Papers Project) is now headquartered at Caltech, under the general editorship of Diana Kormos Buchwald. This enables the present authors to cite everything he wrote in the form CPAE* Vol. Number, Document Number, Page Number. We thereby gain access to the actual texts of letters he wrote to his first wife, to his friends Michele Besso and Marcel Grossman, and to very many of the other physicists and mathematicians who were his contemporaries. An unfortunate result is that the published Einstein papers also end up being cited in the form CPAE 2, Doc. 3 and CPAE 6, Doc. 21, rather than by year, volume, and page number

*CPAE is the Collected Papers of Albert Einstein in *Annalen der Physik*. Those two are *Zur Elektrodynamik bewegter Körper* (from the wonder-year of 1905) and *Die Grundlage der allgemeinen Relativitätstheorie* (published in 1916).

Authors Hannoch Gutfreund and Jurgen Renn have already made, jointly and severally, major contributions to the Einstein industry. What new insights are they now providing? Their major claim is that, for all the 1905 contributions and GR, Einstein adopted a new point of view to existing data and ideas, in the way that Copernicus had revolutionized astronomy in 1543 by adopting a Sun-centred rather than Earth-centred point of view. The authors describe such revolutions as "Copernican". The contrast is with "Galilean Revolutions," which arise from new data. At least that was true for Galileo's influence on astronomy, though his pioneering thoughts about motion were of the Copernican type, and these two sorts, the authors conclude, are a better match to what has happened in science than are the "paradigm shifts" of Thomas Kuhn. Einstein himself is quoted as saying that "A theory can be tested by experience [that is experiments and observations], but there is no way from experience to the construction of a theory."

I found particularly interesting the 1905 Einsteinian advances, for each of which the authors point out (p. 135) someone else who formulated some of the same physics, but without the very broad range of knowledge (scientific and philosophic) that AE brought to bear: for statistical mechanics, Josiah Willard Gibbs (of Yale); for the light quantum hypothesis, Paul Ehrenfest; for relativity theory, Henri Poincaré (who dispersed his insights among several papers, without managing to bring them together as Einstein did); and for Brownian motion, Marian von Smoluchowski*. This left to Einstein the tasks of formulating these four topics (as well as some earlier arguments for the reality of atoms) in more or less the way we now understand them.

Gutfreund and Renn also look backward to the Newtonian revolution (the establishment of classical physics), which they regard as also of the Copernican form, for which the shift in point of view was to regard motion on Earth and motion in the cosmos as the same sort of thing, rather than distinguishing 'forced' and 'natural' motion. They mention in passing other past revolutions: the chemical (periodic table); the Darwinian (evolution by natural selection); the geological (mantle convection, plate tectonics, and continental drift) in the past; and more recently the molecular-biology revolution and the artificial-intelligence (AI) revolution.

Many more insights and examples are to be found in *The Einsteinian Revolution*, but I want to use the AI revolution as an excuse to focus for a paragraph or so on a prime mover in Einstein scholarship — Gerald Holton, Mallinckrodt Professor Emeritus of Physics and History of Science at Harvard. He was there at the beginning, having been sent to Princeton to help Helen Dukas sort through that wilderness of papers in Einstein's home and office. He has written (to paraphrase) "only Einstein, only there, only then". And just last week, when I e-complained that a new computer was being fractious, he e-warned me to stay on good terms with it, because this might be the first warning that machines are going to take over the world. — VIRGINIA TRIMBLE.

*Marian von Smoluchowski (1872–1917), the person you are least likely to have heard of before, of those mentioned here, remained an Einstein correspondent up to the time of his death.

Lithium Across the Universe, by Eduardo Martín (IoP Publishing), 2022. Pp. 214, 26 × 18·5 cm. Price £120/$190 (hardbound; ISBN 978 0 7503 3621 5).

Appearance of the element lithium in astronomical locations occasions so much spectroscopic examination and theoretical pondering that this IoP book (also available as an e-book) by Eduardo Martín should be welcomed by astronomers across the age spectrum from fresh research students through the experience continuum to retirees. This reviewer, now off the top end of the age spectrum, learnt a lot about the abundance of lithium in a wide variety of astronomical environments.

The origins of my interest in lithium in stars were stimulated through an encounter over a cup of tea with John Alexander at an RAS meeting in Burlington House. John told me of his idea that lithium in a red giant's atmosphere could be augmented if the giant were to capture terrestrial planets from its 'solar' system. John's idea is detailed in Correspondence to this *Magazine* (**87**, 238, 1967). Just imagine if John's proposal had then initiated an observational search for stars hosting planets!

Martín's book discusses the major astronomical environments in which lithium atoms are spectroscopically detected and the likely controlling influences on the lithium abundance in those environments are aired. Open issues are often adequately highlighted. Just two areas are mentioned here: the Big Bang and Li-rich red giants. Hopefully these and other open observational and theoretical issues will soon attract enthusiastic inquisitive individuals on the young portion of the age spectrum.

One key environment is, of course, the Big Bang. With completion of accurate mapping of the cosmic microwave background, key cosmological parameters are now so well known that the post-Big Bang composition may be rather securely predicted: almost pure hydrogen composition with contaminants D, He-4, He-3, and Li-7 may be safely predicted. Except for Li-7, as measured from the Spite plateau provided by the Li I resonance line at 6707Å in metal-poor dwarfs, these predictions may be deemed to match observations traceable to the Big Bang. Li-7/H on the Spite plateau is about a factor of a few below its predicted value. Martín refers to this situation: "The jury is still out on the resolution of the cosmological lithium problem." As an observer, one expects the resolution will come from observations!

Martín's text also discusses stars exhibiting lithium abundances — almost exclusively Li-7 —where the inferred surface abundance is not yet fully understood. Historically, the initial example was provided by the very strong 6707Å Li resonance doublet first reported decades ago in photographic spectra of certain carbon giants: Martín illustrates a segment of Sanford's (1950) classic atlas showing the strong Li doublet in the N-type carbon star WX Cyg. A large range in Li abundances among K and M giants is also now known with very Li-rich examples an infrequent occurrence. The statistics for surface Li abundances in red giants are aired by Martín but, I feel, the likely required combination of 'nuclear' origins of a Li enrichment in a stellar interior and the transport of that synthesized Li to the surface are provided an inadequate airing. Lithium synthesis is quite appropriately named as 'the Cameron–Fowler' mechanism but a reader new to this fascinating topic and hoping to resolve outstanding issues would be challenged by reading just this book to explain how the Cameron–Fowler mechanism is expected to enrich red giants in lithium. Of course, exploration of published literature is to be encouraged. New observational and theoretical results are sure to be presented at RAS meetings in coming years! — David Lambert.

Annual Review of Earth and Planetary Sciences, Vol. 51, 2023, edited by R. Jeanloz & K. H. Freeman (Annual Reviews), 2023. Pp. 695, 24 × 19·5 cm. Price $511 (about £400) for institutions; $122 (about £95) for individuals (hardbound; ISBN 978 0 8243 2051 5).

This year's volume of *Annual Review* opens with a remarkable autobiography of Estella Atekwana, biogeophysicist, to which the present writer can personally relate and recommend to all aspiring scientists who face challenges. I hope it is also read by those in positions to lighten the burdens of such colleagues.

The regular scientific-article section as usual covers a broad range of topics within Earth science including Solar System, climate change, the trendy new subject of machine learning (is this an oxymoron?), and the solid, liquid, and gaseous spheres of Earth. There is room herein to comment on only too few of these excellent papers. We are seeing increasing treatments of the interface between society and Earth science these days and I would particularly highlight a beautifully written chapter on 'Communication and Behavior Science' to improve the ability of society to make decisions regarding climate change, by authors Maibach and others. The recommendations, *e.g.*, simple, clear messages, have, however, clear application elsewhere in scientific writings! Another favourite I recommend is the chapter on 'Machine Learning in Earthquake Seismology' by Mousavi and Beroza. This short but to-the-point chapter provides a helpful primer and summary for those who might be wondering what this subject is and whether it is useful. Another of my pet favorites is the chapter 'The Mid-Pleistocene Climate Transition' by Herbert. It boldly states upfront and throughout that a complete explanation of the pattern of climate oscillations during the Pleistocene is still out of reach. Continued study of the interplay of multiple environmental processes, rather than focussing on Earth's orbital variations alone, is the present trend. I am glad scientists have not given up on this stubborn problem! I have room only to mention one more favourite and, after some hand-wringing, it has to be the chapter 'The Rock-Hosted Biosphere' by Templeton and Caro. There are 10 000 times more cells in Earth's crust than there are stars in the Universe, so this little-emphasized subject is not insignificant. In addition to summarizing the current state-of-play in the subject, the text emphasizes what we don't know, which is certainly enough for a fair few PhD projects, to say the least. A good read for aspiring students then. Abject apologies to the authors of the other excellent papers in this year's volume. Readers of this short report will just have to go out and purchase of a copy of their own (highly recommended)! — Gillian Foulger.

Planetary Systems Now, edited by Luisa M. Lara & David Jewitt (World Scientific), 2023. Pp. 425, 23·5 × 16 cm. Price £130 (hardbound; ISBN 978 1 80061 313 3).

We are currently in the middle of a revolution in our understanding of planetary systems. There is now a dauntingly large amount of knowledge for the new student embarking on the study of planets. *Planetary Systems Now* attempts to provide a broad overview of the state of the field of planetary science as of early 2021. The book is based on an on-line school aimed at early-career researchers: 'Planets, Exoplanets and their Systems in a Broad and Multidisciplinary Context'.

The 14 chapters are reviews of their individual fields authored mostly by the lecturers at the on-line school. Unlike a typical textbook, the range of authors makes for a broad and diverse book and allows up-to-date results from a wide range of topics to be presented by experts in those topics. Each chapter is self-contained and understandable without having to read those preceding it. On the other hand, the book lacks consistency in symbols used and style across the various chapters. There is also, on occasion, significant overlap between chapters, particularly Chapters 4 and 5, which explore the atmospheres of terrestrial planets. Each chapter is concluded by an "abbreviated" version of the question-and-answer sessions that followed the lectures during the school. These sections are a useful addition that would not be found in a standard textbook. In general, these are interesting and provide further helpful insight, though I am not sure why the question with the answer "I can't remember" was included.

Planetary Systems Now is, in general, easy to read and contains many useful figures (often printed in beautiful full colour). It contains many examples of the latest thinking and results in each field in the pre-*JWST* era; for example, the lack of a significant spike in impact rate during the so-called 'late heavy bombardment', and a substantial chapter devoted to interstellar planetesimals — the first of which was only identified late in 2017. There are also, helpfully, many pointers to other published reviews for those looking to delve deeper. This book is probably of greatest interest to those beginning research in planetary or exoplanetary science, or existing research students seeking to broaden their background knowledge. If there is not a similar school that you can attend, I recommend this book as a good substitute. — Philip J. Carter.

William Frederick Denning. Grand Amateur and Doyen of British Meteor Astronomy, by Martin Beech (Springer), 2023. Pp. 334, 24 × 16 cm. Price £34·99 (hardbound; ISBN 978 3 031 44442 5).

This is a very interesting and valuable biography of W. F. Denning, an individual who spent most of his life in Bristol, and whose work on meteor showers won him the Gold Medal of the RAS. I must take issue with 'Grand Amateur', a term invented by Allan Chapman in *The Victorian Amateur Astronomer* to describe those gentlemen who, upon retiring from business (if ever engaged upon it) devoted themselves to astronomy. They were wealthy, owned fine observatories, and had paid assistants. But Denning never fell into any of those categories, and it is not even certain that he ever enjoyed any systematic paid employment, other than as a journalist and writer. (As Beech shows, there is no proof that Denning was ever an accountant, like his father, as had once been thought.)

Beech writes very well, and gives us as comprehensive and lively a description of our subject's life that the reclusive Denning allows us at this distance in time. He has researched Denning for decades, and gives us a really good history of the rise of meteor astronomy, a summary of meteor physics, and of Denning's part in the field. Indeed, the young Denning was drawn into studying meteors by having witnessed the Leonid storm of 1866.

A lack of original Denning records is evident throughout this book. On display in its upper library, the RAS has Denning's meteor globe, donated by his family in 1942. But we know of only a few letters and notebooks. Fortunately there is an abundance of Denning in print.

Much of Denning's meteor work was conventional. His records of meteors were accurate, and his ability to sustain long watches was exceptional. In 1877 he was able to demonstrate the nightly motion of the Perseid radiant, as required by theory. But in deducing the coordinates of some meteor radiants, Denning tended to amalgamate observations over several nights instead of reducing them night by night, and in many instances he even combined observations made upon the same date over intervals of several years. In this way he deduced a great many "centres of radiation". We now know that the majority of these radiants were spurious, for he had greatly underestimated the number of sporadic meteors. Moreover, Denning put forward the idea that the radiant points of some showers, in particular the well-observed Orionids, were fixed in space. He clung to this idea till the very end of his days, even after he had served as the first Chair of the IAU Meteoritic Commission in 1922–1925, and by which time the tide had turned completely against him.

As Beech relates in detail, the rise of the American Association of Meteor Observers had brought Denning into direct conflict with its young and energetic leader, Charles Olivier, a trained scientist who insisted upon nightly data reductions. Denning had briefly seen office as the Director of the BAA Meteor Section, but his successors would adopt Olivier's principles to put their work on a sound scientific footing.

Although not mentioned in this biography, I would like to add that J. P. Manning Prentice, long-time BAA Meteor Section Director, showed convincingly in 1933–1936 exactly how Denning may have been misled in the specific case of the Orionids[1]. In fact the shower has several centres of radiation which are active over several nights and in just such a way that radiation from a certain fixed point could easily have been deduced over the period of ten days claimed by Denning.

We read about Denning's work on Jupiter (especially its Great Red Spot) and the other planets. His study of Saturn's Great White Spot of 1903 was particularly notable. Denning was also involved in the late-Victorian-era debate about large *versus* small telescopes. We then come to the matter of the short-lived Observing Astronomical Society in which Denning was closely involved: effectively a predecessor of the British Astronomical Association. Denning used to write regular summaries of the work submitted to it for the now defunct but excellent (1863–1886) periodical *The Astronomical Register*. We are presented with detailed descriptions and novel statistics and facts about the Society and its members. Denning is also remembered today as the discoverer of a comet and for being one of the discoverers of Nova Cygni in 1920. He abandoned telescopic work due to failure of his health in 1906, and by the 1920s was living in near-poverty. But he did not abandon naked-eye work, and he also studied natural history and meteorology.

The book is well printed and illustrated, using a plethora of Denning publications and a smaller amount of archival material. It is always clear and engaging, though more thorough proof reading would have helped in a few places: for instance, Denning's father's death (page 4) seems to have occurred in both 1884 and 1895.

It is sad that so few Denning manuscripts are extant, those that exist being limited mostly to the collections of the RAS and BAA. As Archivist for the latter organization I can add that the 1930s correspondence of Prentice suggests a reason. When Denning died, Prentice tried to obtain those old meteor records, intending to re-reduce them in what had become the accepted manner. But he formed the impression that Denning's family, with whom he had exchanged letters, required payment for them. As that was against his principles, Prentice did not continue the discussions.

Denning was a prolific correspondent with an international circle of pen-friends. Except in the earlier part of his career when Denning appeared and lectured in public (serving as President of the Liverpool Astronomical Society), his correspondents could only have imagined his character from his letters, and we still have to do the same today: in later life, Denning was a recluse who hardly ever met anybody. Beech gives us a detailed study of his astronomical work, with a great deal of fascinating contextual detail, and a very good outline of what is known of his private life. Concerning as it does one of history's greatest visual observers, I am sure that this reasonably priced biography will be found to be interesting and absorbing for many readers. — RICHARD MCKIM.

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A City on Mars: Can We Settle Space, Should We Settle Space, and Have We Really Thought This Through? by Kelly and Zach Weinersmith (Particular Books), 2023. Pp. 448, 24 × 16 cm. Price £25 (hardbound; ISBN 978 0 241 45493 0).

Perhaps because my parents were working for NASA at the time (my father indirectly at Chrysler, doing static testing of Saturn rockets, and my mother, who knew Wernher von Braun well, directly), as a child I developed an interest in space flight. We moved temporarily from Huntsville to Cape Canaveral for a few months around the end of 1968 and used to watch launches from the beach. When I was about 14, I started reading old-school pro-technology optimistic science fiction (initially because I had asked my father to bring me some books by Asimov — I was a fan of his non-fiction books — from the library and fiction books (ordered by author) were easier to find than non-fiction books (ordered by topic)). Despite exceptions such as Asimov's 'Ad Astra', which deals with public opposition to space flight, the general feeling was that the colonization of space would happen more or less naturally, and not that far in the future. However, it wasn't long before Apollo missions were no longer televised live, and the programme was cut short because the USA had won the space race. (Of course it was mainly about politics, and the first scientist on the Moon — geologist Harrison Schmitt — was the last person to set foot on it.) But that was seen to be a temporary setback due to distractions such as the war in Vietnam and the false dichotomy that other important issues, such as environmentalism, had to be addressed to the detriment of space flight. Though it was clear to me even then that science is better served by means not involving putting people into space (recalling Carl Sagan's description of the cost of space probes as "a penny a world for each person on Earth"), the conquest of space still seemed inevitable for other reasons, and a natural extension of the exploration and subsequent colonization of the Earth (whether by Europeans in the Age of Exploration or thousands of years earlier in various out-of-Africa migrations).

My interests then shifted. (My interest in astronomy didn't come from space flight, but rather grew out of a general interest in science, sparked initially by palaeontology. The fact that Asimov — although a biochemist by training — wrote much about astronomy was an important factor.) I still considered the general vision of the future more or less inevitable, but it was no longer clear when it would happen. More recently, things have changed, due not just to billionaire space geeks such as Elon Musk, Richard Branson, and Jeff Bezos actually doing something, but also to things such as physics Nobel laureate Gerard 't Hooft being an ambassador for Mars One[1] (an idea to send people on a one-way trip to Mars, financed *via* a proposed reality-TV show). It still seemed inevitable, but now on a much shorter time-scale, probably with permanent settlements on the Moon and Mars within my lifetime. However, I had become much less enthusiastic, due to the fear that human colonization of the Solar System would export the various problems we have on Earth, perhaps even magnifying them to some extent. (Consider the fact that former colonies of European nations are still strongly influenced by the culture of the mother countries hundreds of years ago, and there would be more contact — at least electronically, which these days is the primary route for the transmission of culture — between Earth and settlements on the Moon or Mars than there was between those colonies and their mother countries.) So it is something to be concerned with, even though, as with other causes, most individuals can do only a small amount.

Enter *A City on Mars*. The title sounds like something out of 1950s pulp fiction. The subtitle sounds much more pessimistic. I was drawn to the book because one of the authors is responsible for the SMBC web comic[2]*, which deals mainly with topics in physics, computer science, philosophy, and so on, and is obviously well informed, though not everyone will get all of the jokes. Most who believe that the conquest of space is possible and good tend to ignore potential problems, assuming that they will get solved along the way; most who are sceptical about either aspect haven't seen a reason to consider the details. What is needed is a balanced assessment and, in my view, that is what this book provides. Though written in an easy-going, humorous style, accompanied by a few comic-style black-and-white drawings, a huge amount of research has gone into this book, testified to not only by the approximately six hundred entries in the explicitly titled 'Partial Bibliography' (twenty pages of print substantially smaller than most small print) but also by the authors' collection of "twenty-seven shelves of books and papers on space settlement and related subjects." Also significant is that they didn't start out being sceptical and pessimistic: "We are space geeks. We love rocket launches.... We love visionary plans for a glorious future.... The data made us do it."

After a long Introduction about space myths, there follow twenty chapters collected into parts of two to four chapters each, the first five parts addressing biological and medical issues, possible habitats (only the Moon, Mars, and "giant rotating space wheels" are considered realistic enough to examine), artificial biospheres, space law, various scenarios (perhaps) allowed by those laws, and a final part looking at space society, expansion, and existential risk. Some readers might be surprised at just how inhospitable the Moon and Mars would be to settlers; it seems that most science-fiction space helmets are fitted with rose-tinted glasses. There is a large literature on the first three aspects, mostly optimistic and some of which I've encountered before. The last three are arguably more important: the first three might well have technical solutions (bottom line in many cases: we just don't know yet), but the last three involve politics, law, and sociology, and no quick solutions appear possible even if there were agreement with regard to the goals. As with regard to other topics as well, the easy-going narrative is backed up with copious references to the technical literature. (There are almost nine pages in very small print of end notes — in addition to the bibliography — with the disclaimer that they "contain only citations associated with quotes presented in the text and manuscripts we refer to directly".)

*Despite being a geek or nerd in some sense, I've never been interested in traditional comic books of any sort. I've also never played Dungeons and Dragons and didn't start programming until I was twenty-six.

Space law is complicated; no nation (nor person, nor any other entity) is allowed to claim anything not on Earth, though exploitation is allowed, which in some cases could result in *de facto* ownership. The authors make a good case that space law, despite its shortcomings, is still relevant, and that it is both possible and probable that it would be enforced.* Although the Outer Space Treaty essentially declares all extraterrestrial property to be commons, the stricter Moon Agreement didn't make it off the ground, so to speak. Cynics will, correctly, say that the self-interest of the spacefaring nations was the reason. On the other hand, despite self-interest, Antarctica and ocean beds are essentially treated as commons, and could be a model for extraterrestrial property. I found the ten chapters on space law and related issues very interesting, both because I hadn't read much about them and also because they are likely to be even more relevant than the more usual concerns. The authors, like many potential readers, certainly had an interest in space and so on before writing the book; the detailed yet clear legal chapters bring an important aspect to the topic.

The last part is concerned with economics (*e.g.*, the similarities and differences of space settlements and company towns), the question of the minimum population necessary for a vital independent settlement, and the possibility of space war. The same technology which can be used to deflect asteroids from Earth could also be used to deflect them towards Earth. Real or imagined benefits (many of which are debunked in the book) are often touted as a reason to settle space, but as always there is the question whether the potential benefits outweigh the potential dangers, especially as technology is evolving faster than morality. (H. G. Wells once described civilization as a race between education and catastrophe. Although one can argue that morality has significantly evolved for the better[3], for the past few decades it has been possible for one person to destroy, or at least seriously damage, all of humanity or a large fraction of it.) While the fear of law enforcement might suppress some over-ambitious tendencies, suicide bombers are clearly not thwarted by the death or any other penalty, and the fact that *Starlink*† satellites exist despite objections by the astronomical community and others demonstrates that laws and/or their enforcement might not evolve quickly enough to provide the needed safeguards.

This book covers a lot of ground (or space); navigation is aided by a thorough fifteen-page small-print index. It was an enjoyable and informative read, and is recommended not just to those with an interest in such topics (especially if they don't — yet — agree with the authors), but essentially to everyone, since the developments it is concerned with will potentially affect everyone. The arguments are clear and well documented and should convince the reader as they convinced the authors. I don't think that I can improve on the authors' summary, so I'll end this review by quoting part of it: "Our original assumption was that space settlement was coming soon.... We now believe the timeline is substantially longer and the project wildly more difficult and that the governance work to do is more about regulating the behaviour of Earthlings than designing a Martian democracy.... [W]e just cannot convince ourselves

*There are organizations which believe that they can legally sell property which they have claimed on the Moon, and there are gullible customers who buy it. That isn't mentioned in the book. Although the benefits from combating such fraudsters is presumably not worth the effort, the fact that they continue unabated does make me somewhat sceptical whether space law will be quite as binding as the authors suggest.

†Not to be confused with the former UK academic astronomical computing project of the same name.

that the usual arguments for space settlements are good. Space settlement will be much harder than it is usually portrayed, without obvious economic benefits. Attempting space settlement now may increase the likelihood of conflict on Earth in the short term and ultimately increase human existential risk.... We believe that space settlements are possible, and perhaps one day they could be done in safety. But doing something big requires us to assess the scale of the challenge. In healthy communities of thought, the [sceptics] aren't barriers on the road to progress, but guardrails.... Going to the stars will not make us wise. We have to become wise if we want to go to the stars." — Phillip Helbig.

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(2) https://www.smbc-comics.com
(3) S. Pinker, *The Better Angels of Our Nature: Why Violence Has Declined* (Viking), 2011.

A General Relativity Coursebook, by Ed Daw (Cambridge University Press), 2023. Pp. 527, 24·5 × 17 cm. Price £22·99 (paperback; ISBN 978 1 00 924244 8).

Like other books on a common topic, books on General Relativity (GR) can differ in the breadth and depth of topics covered, but also with regard to being 'maths first' or 'physics first' and which sign conventions are used. This book (neither broad nor deep, maths first, 'East Coast' sign convention (−+++, 'mostly plus')) reveals another difference: level of detail. This is an introductory book, introducing the necessary tensor calculus after an introductory chapter on the principle of equivalence before moving on to the Einstein equation and three applications (the Schwarzschild solution, Friedmann cosmological models, and gravitational waves), but differs from most other GR books in the level of mathematical detail. The mathematics is not more advanced than elsewhere, but rather spelled out, with the 'work shown'. It is thus similar to a series of lectures, and is indeed derived from lectures (so are some other books, though they have often gone through a greater transformation). Ed Daw is Professor of Particle Astrophysics at the University of Sheffield, has worked on searches for dark matter and gravitational waves, and has been lecturing on GR since 2003. The book fills the gap between more qualitative introductions to GR and books which leave out the needed details (or leave them as exercises for the reader). Although, as Daw points out, it is true that tensor calculus has many other applications as well, many interested in GR will have had no prior experience.

Daw obviously knows the material, and spends some extra time on topics which often prove difficult for many students. The book is well written and clearly structured. Chapter 8, on gravitational waves, goes a bit further afield by discussing some of the technical challenges in gravitational-wave detection. The final chapter is a guide for further reading, mentioning other books, other sign- and tensor-notation conventions, and so on. (Interestingly, Daw's favourite is Hartle's book[1,2], which is 'physics first'. I tend to prefer the 'physics first' approach, though 'maths first' is sometimes more useful for introductory books[3].) I was pleased to read of the Lorenz, rather than Lorentz, gauge (something even professionals sometimes get wrong), so put the appearance of the Lorentz gauge in Chapter 8 down to a typo. Although I often quibble about matters of style, this book is not the worst offender in that respect. There are neither footnotes nor endnotes, and a few black-and-white diagrams are scattered throughout the text. My only real complaints are that the 'References' chapter (actually, more accurate would be 'sources' or 'further reading' since, as with many textbooks, there are few actual citations in the text) sometimes lists outdated editions of books, and that the index (fewer than three pages, though in small print) is a bit too brief (this is certainly a book in which readers will go back and look things up; a few times I couldn't find in the index what I was looking for).

This should be neither the first nor the last book one reads on GR. Less technical introductions are useful, as this book essentially assumes that its goals are clear, and those needing more details must consult more advanced texts. This book is useful in that it provides a bridge between the two, consisting of the details of tensor-calculus manipulations and 'Index Tricks of the Trade' (sect. 2.9). Especially for those who like to learn their maths as needed as they go, this is one of the few books which fit that need.* — PHILLIP HELBIG.

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(5) P. Helbig, *The Observatory*, **136**, 204, 2016.

You Can't See in the Dark with the Lights On, by Kevin Krisciunas, with illustrations by Brian Quiroga (Innovative Ink Publishing), 2024. Pp. 30, 25 × 20 cm. Price $8·99 (paperback; ISBN 979 8 3851 1803 8).

The author and illustrator have dedicated this booklet "for everyone young and old who has wished to experience the joy of discovery." The target readership, however, seems to be children about the age of the boy who discovers the dark night sky. He looks about twelve in one drawing and eight in another. The text is entirely in verse, four to eight lines per page. Each line contains seven 'dah DUM' patterns, ending with a one-or-two syllable rhyme. The vocabulary extends to words like 'hemispherical' and 'planetarium' which might (or might not) need translation for younger readers.

The author provides an interesting comparison of distances: the size of a baseball diamond (Yankee Stadium) to an astronomical unit is very nearly equal to the ratio of the distance New York to Timbuktu to the distance from the Solar System to Proxima Centauri. A target reader will not, of course, need to use this to figure out the size of a baseball stadium as I did!

The main message is that very dark sites are wonderful and should be preserved, and author and illustrator drop quite a few factoids about stars, the Solar System, and the Milky Way in making their main point. My only serious quarrel is with the statement that "every star there ever was is in a constellation." I know where CM Tauri is today and roughly where it was a millennium ago, but its location as a newly formed main-sequence star of 8–10 solar masses occurred something like 10 million years ago, when the only patterns we would still recognize were the globular clusters and a few of the older open ones like M 67, the Hyades, and Pleiades. Many stars that are still around today are a few billion years old, and have been around the Milky Way many times, with (I suspect) no constellation-naming species to locate them.

*Another[4] reviewed in these pages[5] covers similar ground, but only with respect to cosmology.

Conflict-of-interest statement: My copy of *You Can't See in the Dark with the Lights On* was a gift from the author, who kindly inscribed it "to the most avid reader I know." — VIRGINIA TRIMBLE.

Data Modeling for the Sciences, by Steve Presé & loannis Sgouralis (Cambridge University Press), 2023. Pp. 415, 25 × 18 cm. Price £59·99/$74·99 (hardbound; ISBN 978 1 009 09850 2).

Data Modeling for the Sciences is an intermediate-level book for students and researchers who wish to gain either a wide coverage of data-analysis techniques, or a deeper understanding of the underlying principles, or both. It is wide in scope, covering everything from statistical principles, to the computational methods that are now the norm for analysis of data sets, which are rarely simple enough for analytic techniques to be applicable. The book therefore takes a more data-driven approach than many. One aspect that sets this book apart is the large number of problems that it sets, the bulk of them being computational, often generating synthetic datasets and subjecting them to the analysis methods presented in the book. The book is targeted at Masters-level students in the sciences, who will typically have the appropriate computational skills that are assumed, but also at more experienced researchers, who will also find it a very valuable resource. There are some sections that are marked as advanced, and some of these would probably require some time for Masters students to absorb. Unusually for a review, I more-or-less read the book from cover to cover, as I felt that there was a lot to learn from this book, and I was right, and found it a rewarding read. I found the ordering of topics quite interesting — for example, there is a long chapter on dynamical systems, and Markov processes precede the more foundational inference chapters. It meant that sometimes one has to pause to consolidate and work out how everything fits together, but that is no bad thing. I recommend the book strongly for anyone involved with analysis of data with any degree of complexity. — ALAN HEAVENS.

FROM THE LIBRARY

Modern Physical Laboratory Practice, by John Strong (Prentice Hall), 1938; 15th printing (Black & Son Limited), 1949. Pp. 642, 23 × 15 cm.

Why is this an astronomy book? Well, it was deaccessioned by the RAS a while back, after living there for more than 70 years. Second are the authors: John Strong is listed as Assistant Professor of Physics in Astrophysics at the California Institute of Technology (he headed a balloon-infrared group later in life and the second of his four collaborators was Albert E. Whitford, Assistant Professor of Astronomy at Washburn Observatory of the University of Wisconsin (later director of Lick Observatory and the chairman of the first, 1962, decadal review panel that attempted to set priorities for government funding for astronomical equipment (*etc.*) for the next decade)).

Third is the content. Although Chapter I begins with glass blowing (still useful in some branches of science, though maybe not in astronomy) and Chapter XX ends with casting replicas of small items using cuttlebone (now useful only for cuttlefish), quite a lot of the middle deals with optics, measurement of radiant energy, photoelectric cells, and photography, focussing on astronomical photography with special emulsions provided by the Eastman Kodak Company, whose astro-friendly director of research, C. E. K. Mees, appears several times in the text. Also to be found tiptoeing around in the footnotes are Karl

Schwarzschild (for reciprocity failure), Hubble (on detectability of very small images), and H. N. Russell (on converting stellar apparent magnitudes to other units like lumens). The author(s) suggest using Polaris as a standard; perhaps it was not a weakly pulsating Cepheid that year.

Most fun and impressive is the figure of the sensitivity of spectrum plates available from the Eastman Kodak Company. There were, in those days, no fewer than 19, all inevitably with near-UV and blue sensitivity (to be cut off by Wratten filters if you so desired), but with their long-wavelength ends extending to anything from about 500 nm to 1200 nm (1·2 microns). The names are all letters of the alphabet, in order O J H G T D B C F S U N K R L P M Q Z (perhaps the model for the various bands of radar called S, X, and so forth). By 1973, the survivors were O J G H D E H-alpha F N and Z (B and M were panchromatic).

Are there reasons to remember these? Perhaps if you are interested in digitizing old astronomical images. And perhaps there is more than the one bit of humour that I remember, featuring a senior astronomer instructing a graduate student in a dark room. The senior chap lit a cigarette while plates were still in the developer. The student gasped in horror at the thought of losing a night's work. But the mentor said, "Is OK, Chris. They are only O plates." (which did not respond to orange or red light). Of course plates could be sensitized in various ways, after which, the authors advised said plates should be kept in an icebox. — VIRGINIA TRIMBLE.

Here and There

NON SEQUITUR

The star's brightness was measured more than 300 times a second, and its diameter calculated with extreme precision from the fluctuations in its luminosity during the occultation: it's exactly 2,173 times as large as the Sun, and thus the smallest star ever measured. — *A History of the Universe in 100 Stars* (Quercus), 2023, p. 93.