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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2019 December 13 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

EMMA BUNCE, *President Elect*
in the Chair

The Chair. We have a really fantastic programme this afternoon and I'm delighted to introduce the first speaker, Professor Ken Pounds, from the University of Leicester, who's going to be talking to us about 'The foundation of X-ray astronomy in the UK (60 years old last month)'.

Professor K. Pounds. [A summary of this talk has appeared in the 2020 February issue of *Astronomy & Geophysics*.]

The Chair. Thanks very much, Ken, for a wonderful talk. [Applause.]

I'm delighted to introduce Eimear Gallagher from RAL Space and Nottingham Trent University, who was awarded the Patricia Tomkins Undergraduate Prize this year. Eimear is going to be talking about '*CHARM*ing — developing an astronomical heterodyne receiver for the *Large Millimetre Telescope*'.

Miss Eimear Gallagher. In this talk I will give a summary of the work completed over the course of an industrial-placement year at the Rutherford Appleton Laboratory within the Millimetre-Wave Technology (MMT) Group. The MMT Group are part of RAL Space based on Harwell Campus in Oxfordshire. The group specializes in the design, development, and manufacture of millimetre- and sub-millimetre-wave systems.

For the majority of my placement my work was on a project called ASTEC, the Astronomical Systems, Technology and Engineering Collaboration. This project was funded through the Global Challenge Research Fund award with the aim of developing links with Mexican researchers and training them in high-frequency-heterodyne-receiver development and use. We worked closely with staff from the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) to develop a receiver called *CHARM* (*Collaborative Heterodyne Astronomical Receiver for Mexico*) along with the project principal investigator at the University of Manchester.

The *CHARM* receiver is a 345-GHz 'plug and play' heterodyne receiver with the front-end and back-end integrated onto one optical table; it also has accompanying LABVIEW-based software developed by the MMT group. *CHARM* was developed for use at the *Large Millimetre Telescope* (*LMT*), a Cassegrain telescope system designed to operate at wavelengths from 4 mm to 0·85 mm (covering a frequency range of 75 GHz to 350 GHz). Located at an elevation of 4600 m on the Sierra Negra mountain within the Pico de Orizaba National Park, it is the largest steerable, single-dish, millimetre-wave telescope in the world and became operational in 2018 with its 50-m-diameter primary dish. This 50-m dish is yet to be characterized for wavelengths shorter than 1 mm. The *CHARM* instrument will allow this important performance step to be achieved and the telescope-aperture efficiency to be determined at approximately 0·86 mm, thus paving the way for future use of the telescope at sub-millimetre wavelengths. *CHARM* has two settings for astronomical observing — 'On the Fly' (OTF) and 'Position Switching' (PSW). OTF is commonly used for mapping extended sources, and includes rapid scanning of the area of interest, and PSW is used for smaller sources, and requires ON and OFF source integrations

RAL Space had previously developed and deployed an earlier variant of *CHARM*, the *Sub-Harmonic Image Rejection Receiver* (*SHIRM*), to observe atmospheric spectral lines. It was realized that the *SHIRM* system could also be used to observe a primary spectral feature that is relatively common within the interstellar medium, the carbon monoxide rotational transition (CO J=3–2) at 345·8 GHz. Therefore the *SHIRM* design was used as the basis for *CHARM* but also included upgrades to many aspects of the system, including new wide-band spectrometers and new IQ-down-conversion modules. The front-end mixer was also replaced to reduce significantly the system-noise temperature which also led to a change from a single-sideband switching system to a double-sideband system that provided the increased sensitivity needed for use at the *LMT*.

The design of coupling optics was also needed to interface *CHARM* with the *LMT*. Signals from the primary reflector of the *LMT* are directed to a 2·5-m diameter secondary and then a series of plane mirrors (M3 and M4) into a receiver-cabin area. We designed and developed a periscope system containing two further plane mirrors inclined at different angles to direct the beam towards the instrument. The optics on the instrument breadboard, including a rotating mirror for use with hot and cold calibration targets, were then used to direct the beam to the receiver feedhorn.

CHARM was successfully installed at the *LMT* in 2019 September and further observing is proposed for 2020 January onwards through the *LMT* observing season. The aim for the observing work with *CHARM* is to observe spectral lines around the 345-GHz region, specifically in young star-forming regions that could help us understand more about stellar evolution and to characterize *LMT* use and efficiency at that wavelength. This was the first demonstration of the *LMT* at 345 GHz and in the future could lead to an increase in the *LMT* VLBI capabilities. Future work proposed includes a cryogenic upgrade to the system to lower the system-noise temperature and increase the sensitivity of the instrument.

I would like to thank the RAS for inviting me to present at this meeting and to Patricia Tomkins and the Patricia Tomkins Foundation for the Undergraduate Prize. Also, my colleagues at RAL Space, Professor B. Ellison, Dr. N. Daghestani, Mr. F. Cahill, Mr. A. Obeed and Dr. S. Rea and our collaborators at INAOE, Dr. E. Colín-Beltrán and Dr. D Sánchez-Argüelles, and PI Professor G. Fuller at the University of Manchester.

The Chair. Thank you very much, Eimear, and congratulations again on your prize. That was a really amazing experience you've had. Time for a few questions.

Dr. C. Lee. You were funded by the GCRF. What was the role of Mexico in your collaboration?

Miss Gallagher. It was mainly a knowledge-transfer programme. We actually had an engineer from the *LMT* in Mexico who came and worked at RAL Space for a few months and then went back to Mexico, with a further couple of months in the UK. It was mainly training by us for staff at the *LMT* because very often their instruments are developed by outside groups and brought in, and this was an opportunity for staff at the *LMT* to learn how to develop their own instrumentation.

Professor M. A. Barstow. Sounds like you had a great time. So the first question would be "did you enjoy yourself?"; but doing a one-year undergraduate placement in astronomy is quite unusual — I don't think I've heard of that before. So has it affected the way you see your future career in any way?

Miss Gallagher. Yes, very definitely. I was very lucky to get that year placement at RAL Space. I'm an astrophysics student at Nottingham Trent, and I had no experience with heterodyne receivers or anything like that. I didn't know very much about millimetre-wave technology at all when I started, so it really has been quite a learning experience over the last year, and it has very definitely changed the way I thought about things. I'm quite lucky that I've been offered a job at RAL Space so I will definitely be staying in the millimetre-technology field and continue with astronomical instrumentation.

The Chair. Any more questions?

Professor Jane Greaves. I was just wondering what the tuning range of your receiver is, and can you exploit the full width of the atmospheric transmission window? It must be quite wide from that site.

Miss Gallagher. Yes, our local oscillator can be tuned from 316 to about 360 GHz, but our main focus at present is in the 345-GHz region just to see how well the *LMT* works.

Professor Greaves. Yes, that sounds really impressive.

The Chair. Thank you very much again [applause]. Our next speaker is Dr. Ingo Waldmann from UCL who is also the recipient of the RAS 'G' Fowler award this year. Ingo is going to be talking about 'Characterizing exoplanet atmospheres with artificial intelligence'.

Dr. I. Waldmann. To date we know of over 4000 extrasolar planets — planets orbiting other stars — in over 3700 planetary systems. The speed of discovery of these foreign worlds has been exponential in the last two decades and with the NASA/*TESS*, ESA/*Gaia*, and the ESA/*Plato* missions (amongst others), this trend is likely to continue. For most planet systems we only know the masses and radii, giving us the bulk density. Though interesting, to characterize these worlds fully, we require a knowledge of their chemistries. By analysing the atmospheres of extrasolar planets we can shed light on a whole host of planetary characteristics. To name only a few, we can infer their formation histories, whether significant impact events have taken place in recent times, what their climates and cloud coverage are, the rate of atmospheric escape due to stellar radiation or otherwise, whether the atmospheres are primordial or secondary in nature, possible biomarkers, volcanism, *etc.*

In order to analyse an extrasolar planet's atmosphere successfully, we require an interdisciplinary approach starting with the detection of the exoplanet, the observation and analysis of the planet's atmospheric spectrum, the interpretation of the observations through radiative transfer and 3D atmospheric models of the planet, and the design of custom-built observatories such as the ESA *Ariel* mission. In this talk I will briefly touch on how modern machine-learning techniques have helped to detect planets and to characterize their atmospheres.

Of course, this is not all my own work but I will be presenting the work of the ExoAI group at University College London. Currently eight members strong, we focus on developing modern deep-learning algorithms to facilitate exoplanet research.

First consider detecting exoplanets with direct imaging. Directly imaged exoplanets are hot, giant planets that orbit the host stars at a significant distance, often at many tens of astronomical units. These planets are typically ten orders of magnitude fainter than their host star but can be detected with the latest generations of coronagraphs such as the *VLT/Sphere* and *Gemini/GPI* instruments, amongst others. When the starlight is blocked out by the coronagraphic mask, not all of its light is removed perfectly but a so-called 'speckle pattern' persists. This pattern is still many times brighter than the nearby planet and very often very hard to disentangle from the planet's signature. Here, deep learning can help. Yip *et al.* (2019) have developed a Generative Adversarial Neural Network (GAN) to learn the underlying statistical distribution of speckle patterns, then to reproduce accurately their behaviour, and ultimately to subtract them from the original image to reveal the planet underneath. GANs have been at the forefront of neural-network development for several years. They are very flexible in what they can learn and represent and have been used to generate photorealistic images of people or landscapes in recent machine-learning literature. The GAN is in fact made out of two competing neural networks, one is called the 'Generator' and one the 'Discriminator'. The Generator produces images out of a random-noise instance whilst the Discriminator compares these images to real training data and judges them to be real or not. As the networks progress, the Generator will become better at simulating real data until the Discriminator can no longer differentiate between fake and real data. At this point both networks have reached a Nash equilibrium, and training is completed. GANs very effectively learn complex patterns, such as our speckle pattern. The trick here is the statistical absence of a real planet signal. As directly-imaged planet-detection frequency lies around one percent of all stars observed, we can statistically exclude there to be a planet signature present in the speckle distribution learned by the GAN. We have hence a 'clean' representation of the residual stellar noise that we, in theory, can extract from the raw data. Current tests on *Hubble Space Telescope* and ground-based *Keck* data indeed look very promising that this methodology will outperform existing methods. Techniques such as this one will be instrumental in the future of planet detection using big-data approaches.

Most planets detected to date are not directly-imaged planets but in fact so-called transiting planets. These are planets close in and transiting our line of sight. When a transiting planet hosts an atmosphere, some of the stellar light, typically of the order of 1 in 100 000 photons, will filter through the thin atmospheric annulus of the planet. Depending on the wavelengths observed, we can detect the spectroscopic signatures of molecules in the atmospheres of these planets. This is called transmission spectroscopy.

As with the detection of directly-imaged planets, in transmission spectroscopy the sought-after science signal is often buried deep in stellar and instrumental noise. Here again, efficient and robust data analysis is the key to unlocking the planet's characteristics.

The best and most stable observations of exoplanet atmospheres are conducted from space using the *Hubble* and *Spitzer* space telescopes. Though they are the best instruments available to us, both telescopes suffer from instrument systematics often several orders of magnitudes stronger than the underlying atmospheric signatures. Here machine learning has had some legacy in dealing with these data. The most commonly referred to algorithms are Independent Component Analysis, Gaussian Processes, and Wavelets. Morvan *et al.* (2020) present a new way of de-trending time-dependent instrument noise from time-series data obtained by the *Spitzer/IRAC* camera. In that study we used long–short-term memory (LSTM) neural networks based on the Amazon DeepAR forecasting model of Salinas *et al.* These deep LSTMs are trained on the instrumental time-dependent noise characteristics of so-called 'out of transit' data, time-series data obtained before and after the planetary transit itself. We then use this learned behaviour of the instrument to predict its response during the planetary transit event. We have demonstrated our new methodology on six transits of the hot-Jupiter HD 209458b originally published by Agol *et al.* We find significantly better agreement between transit depths of the six transits than the original analysis. This probably indicates that much of the variability in transit depth observed of this planet (and likely others) could be attributed to an insufficient removal of instrument systematics rather than planetary variability.

With the advent of dedicated spectroscopic instruments in the next decade, such as the ESA *Ariel* mission, data analysis needs to move away from the *ad-hoc* and hands-on descriptions of systematic noise towards more robust and data-driven approaches. Here deep learning can provide a promising new pathway to increase data-calibration accuracy beyond what is currently possible.

The Chair. Thank you very much, Ingo. When you were talking about your machine-learning techniques for detecting exoplanets using the transit method, do your techniques allow you to differentiate between an exoplanet and maybe an exo-cometary signature?

Dr. Waldmann. I don't know. I don't think we've really ever seen an exo-comet in test data so I don't know whether we have the sensitivity for that sort of study. We'll try to find planets first.

The Chair. Any other questions?

Dr. G. Q. G. Stanley. With the machine learning, give us an idea of the magnitude of what you're going through. How many images are you using to learn?

Dr. Waldmann. The more the better, really. At the moment, *Hubble* only has 1500 images; that's why we need to augment our dataset so dramatically. The *Subaru Coronagraphic Extreme Adaptive Optics* instrument will give you about ten terabytes a night of images and that's about the magnitude we're looking for. So we're starting to work with them on actually predicting adaptive-optics behaviour on the chip directly, and then we're looking at hundreds of terabytes a night of data that needs to go through. But usually, the more data the better. The real issue is finding the computational resources, if you're not Google, to train your neural network, quite often.

Dr. Stanley. And in that, you've obviously got to know which are the positives and negatives to tell it. So how are you handling that side with this amount of data?

Dr. Waldmann. Well it can't be immediate training directly on the fly — you need to do some processing on that, so the idea is that the initial training is done on the synthetic data sets because we understand them and we can benchmark against that. It's a sandbox system. And once that's done, when that's ready, we can do something like transfer learning where we augment our training for real data. And that is then more robust. It's actually a very interesting active research field. It's called a 'teacher, student' neural network which is trained on synthetic data; for example, it teaches a neural network what it actually should look for. It's a very active field of how you can attach probability to this.

Dr. Stanley. Just one supplementary question if I may. Will you have edge processing coming through on this one, so that eventually it can be rolled out very easily, so it has all learning in there?

Dr. Waldmann. Exactly, so once it's learned, it is very simple and very fast, it is basically just multiplying four or five matrices together. So for classification with a neural net, you're talking, on a normal laptop, of a microsecond or so. This is very, very fast, so you can actually put this into chips directly; we're looking into this a little bit because that would actually speed up the classification process quite significantly if you build it into hardware.

The Chair. Well done, thank you very much [applause].

I'm delighted to introduce our final speaker for this afternoon, who is Professor Chris Lintott, from Oxford University and recipient of the RAS 'A' Group Achievement award this year. Chris is going to be telling us about 'Wonders of the Galaxy Zoo: morphological studies with a crowd.'

Professor C. J. Lintott. I'd like to begin by thanking my collaborators in the Galaxy Zoo team, particularly Project Scientist Karen Masters at Portsmouth and Deputy Project Scientist Brooke Simmons at Lancaster. When we look at astronomical objects we make a series of simple measurements to help us analyse them — defining properties such as mass, colour, brightness, and occasionally shape. In the case of galaxies the shapes that they show to us appear to fit a simple diagram known as the Hubble Tuning-Fork Diagram. There are two branches for spiral galaxies, barred and not barred, and as the bulge becomes less prominent then the spiral arms become more loosely bound. This is wrong. It now turns out that there is no connection between the bulge width of the galaxy and the tightness with which the spiral arms rotate. From Sloan Survey data we find that galaxies with small bulges can have any arm winding — there is no correlation between the two properties. We know this because we have used citizen science to do a large morphological survey of galaxy shapes. The project, which launched in 2007, caught on very quickly and we were getting thousands of morphology estimates every hour. Lots of people looked at each galaxy and we were able to get statistically significant results. This led to the Zooniverse project in which a volunteer has found exo-comet signs in *Kepler* data.

We looked at 12 years' of Galaxy Zoo work and we asked the original collaborators to check because there was a paper in the literature which claimed a cosmological excess of anti-clockwise spirals — which makes no sense. In a sample of 250 000 spiral galaxies we found that a majority appeared to show the arm winding was anti-clockwise. The brain interprets two-dimensional images as three-dimensional but if you watch the images long enough then they can appear to flip direction and we think that this is what is happening here. Galaxies that are close together will spin in the same direction — they inherit the spins from the larger cosmological structure — the whole bulk of 900 000 well-classified galaxies.

Brooke Simmons at Lancaster has been looking at subsets of the data, one of which is the bar fractions of galaxies over cosmological time. There was an epoch in the past when barred spirals were very rare. My student Sandor Kruk, who is now at ESTEC, found a population of dwarf galaxies in the Sloan Survey with offset bars which may have been caused by near-miss interactions. We cannot see any evidence for interaction.

The advantage of big datasets is that by filtering the data to look at particular subsets we can still find a lot of evidence. NGC 4395 is a nearby flocculent spiral which has significant star formation occurring. It is a disc galaxy with no bulge so it is guaranteed merger-free since it became a disc. We can use this as an aid to study mergers in galaxy populations. NGC 4395 has a particularly light black hole — about ten times smaller than typical values. This suggests that black-hole masses are built up by mergers. Brooke Simmons and Rebecca Smethurst looked at a sample of 101 galaxies without bulges from Galaxy Zoo and compared them with normal galaxies. Galaxies grow black holes to the size that we expect without the benefit of mergers.

We have an *HST* programme to look at galaxies in detail to try and understand secular growth in galaxies. From the work by Simmons and Smethurst we discerned two facts. We measured flow of material onto the black hole and also the outflow rate in the form of jets. We find that the inflow rate was much higher in systems with mergers than in merger-free systems. The outflow rate from jets in supermassive black holes is higher from galaxies which have had mergers. We think that this has something to do with black-hole spins.

Having narrowed down our original dataset to 2000 galaxies, then 100 galaxies with offset bars, we went one further and concentrated on one particular object. Some years ago one of our public collaborators, Hanny van Arkle, a Dutch schoolteacher, came upon an object which she could not identify. It was a fairly large area of what seemed to be green, glowing gas, close to the galaxy NGC 2947. It became known as Hanny's Voorwerp (Dutch for 'thingy') and she was keen to know more about it. We found that it was at the same distance as NGC 2947 and was of similar size but it appeared to contain no stars which might excite the gas to the observed temperature of 50 000 K. We then realized that it must have been illuminated by activity from NGC 2947 which, 50 000 years ago, was probably the brightest quasar in the sky with an apparent magnitude of 8 making it visible in binoculars. Hanny came to a meeting of the American Astronomical Society. This case led to the discovery of other objects like it, most of which turned out to be gas clouds around AGNs. About one-third have shown rapid fading and these are now being followed up.

The richness of the data generated by the citizen scientists is immense. For the future, lots of the team are now involved in *LSST* and also *Euclid* where millions of galaxies will be available to classify morphologically. My student Mike Walmsley has built a Bayesian neural network which classifies galaxy-image shapes with uncertainty so we get a probability distribution of galaxy properties. This machine has been cloned 20 times with each clone being slightly different. We look for galaxies where each individual machine is certain but disagrees with each other, and those are the galaxies which we show to our volunteers. If you go to Galaxy Zoo today there is a button marked 'enhanced' which shows the galaxies that the neural network machine most needs help with.

I deliberately made this a science talk. Morphology is not just text-book science. There is a real sense of excitement in what we have been doing. Volunteers have been classifying hundreds of thousands of galaxies and most did not consider astronomy but were excited because they had the chance to contribute to science.

The Chair. Wonderful — thank you very much Chris. Questions, please, from the audience.

Dr. P. Allen. Thanks Chris, that's made me really think. I've come up with two questions. They're both related to the spirals and seeing things both ways round. Have you taken the spirals one way, spirals the other way, and put it in to some machine-learning detection system? Obviously, it won't be fooled, but has the experiment been done?

Professor Lintott. It would be fooled because it would depend on the training data. As people in fields like face recognition are discovering, machines inherit our human foibles when we train them on our data. And so they would be fooled. The thing we haven't done is that there's been some suggestion that it's to do with the fact that we read from left to right so I need to go back and run this project in a language like Japanese or Hebrew that reads right to left and see if we get the opposite result. So that's the next experiment.

Dr. Allen. I think that actually impinges on my second question, which is, do we know why humans have this perception bias?

Professor Lintott. No, but it's linked to the fact that our brains are not set for 2D images, they're expecting three dimensional objects and there are choices that your brain makes and there are biasses in those choices. If I showed a cat rotating to a large audience for a long time, we would tend to pick anti-clockwise slightly more than clockwise, but I don't think it's known why that's true.

Dr. Allen. I just wondered if left-handed or right-handed people classified differently.

Professor Lintott. The rotating-figure illusion doesn't have a left-handed, right-handed thing. We did end up at some point with people classifying galaxies in brain scanners but that's a whole other story.

A Fellow. By the way, Japanese doesn't read right to left.

Professor Lintott. Oh, does it not? Oh sorry, thank you. Probably good to know.

Dr. P. Wheat. You're trying to get real truth really with these galaxy morphologies but actually you're looking at the images on the screen; certainly you're looking in two dimensions therefore the orientation of that galaxy to us must have some biasses or some part of it, so how do you de-construct that?

Professor Lintott. With difficulty. You're absolutely right, the inclination is a problem. A lot of the time we can make simplifying assumptions about the shapes of the galaxies, so, for example, if you assume the disc is circular rather than elliptical you can make a guess at the inclination. Really though, you think carefully about those effects and hope that they even out in a large population, because, after all, the inclination should be, on large scales, random. The other thing we're doing, of course, is we're looking at a projection of the stars, not at the way anything is moving in the galaxy, and one of the most interesting things that's happening at the minute is the connection of the kind of work I've been talking about with surveys like *MaNGA* which is using an integral field unit (IFU) to look at the kinematic classification. And so our hope is that we can use these large-scale samples classified with visual morphology and then use *MaNGA* and other IFUs to explain what we're seeing by looking at a smaller number of galaxies in detail. But you're right, the Universe continues to be annoyingly distant and two-dimensional as viewed from Earth.

Mr. R. O'Brien. I wonder whether we do have a real asymmetry or whatever it is. After all, the *Planck* data shows that cold spot, and there's only one, and there's an asymmetry in the cosmic dipole, so perhaps we have a left-handed Universe.

Professor Lintott. Michael Longo is the guy who published the initial claim. I can tell you we see no evidence because when we show people mirror images we can measure that bias and then account for that, and once we've done that we see no evidence for an excess. Longo still thinks he's now correct in his method and he still claims that there is indeed an alignment with some of the cosmological features. Such a result would be brilliant fun, because it would bring down several pillars of modern cosmology, but I don't think we have the evidence for that yet.

The Chair. Thank you very much, Chris [applause], and thanks to all our speakers for a wonderful session this afternoon. It just remains for me to remind you of our drinks reception in the RAS library immediately following this meeting. And finally I give notice that the next monthly A&G Open Meeting of the Society will be on Friday the 10th of January 2020. So we look forward to seeing you all next year.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2020 January 10 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

NIGEL BERMAN, *Treasurer*
in the Chair

The Chair. Good afternoon everybody. The President, Professor Cruise, unfortunately cannot be here this afternoon. He sends his apologies and good wishes to everybody but it means you've drawn the short straw and I'm having to do the formalities. Welcome to the start of the bicentenary year of the Royal Astronomical Society: this Sunday, 12th of January, marks the 200th anniversary of the dinner, which apparently was held in the Freemason's Tavern in Holborn, when 14 gentlemen set up the foundations of this Society. That dinner marked the start of the celebrations which will take place this year. The first of those events is the reception for Fellows, Friends, and others, which will be at the Langham Hotel on the 23 of January.

I have a very pleasant duty next, which is to announce the RAS 2020 awards. It's quite a long list so I am not going to go into any details about the recipients, just give the names. If you happen to be present when your name is read out, you might stand up and be recognized by the assembled fellowship. The Gold Medal, in Astronomy, goes to Professor Sandra Moore Faber, and in Geophysics, to Professor Yvonne Elsworth. The Chapman Medal goes to Professor Cathryn Mitchell; the Eddington Medal to Professor Steven Balbus; the Herschel Medal to Professor Rob Fender; the Jackson-Gwilt Medal to Professor Roland Bacon; the Price Medal to Dr. Philip Livermore; the Annie Maunder Medal to Professor Roberto Trotta; the Patrick Moore Medal to Dr Caroline Neuberg; and the Agnes Mary Clerke Medal to Dr. Michael Hoskin. The Fowler Award (Astronomy) goes to Dr. Amaury Triaud, and in Geophysics to Dr. Craig Magee. The Winton Award in Astronomy goes to Dr. Thomas Collett, and in Geophysics to Dr. Michele Bannister. The Group Award for Astronomy goes to the Astropy Project Team committee whilst the Geophysics Group Achievement Award is given to the project team committee of the *STEREO* Heliospheric Imagers Team. The George Darwin Lecture will be given by Professor Ofer Lahav; the Gerald Whitrow Lecture by Professor Andrew Pontzen; the James Dungey Lecture by Dr. Sarah Matthews. And the Service Award is given to Ms. Kim Burchell. [Applause.] So congratulations to all of those.

And now we can get on with what you're here for, which is the programme of speakers this afternoon. It looks from this programme like we're going to go past, present, then future, but the first speaker this evening is well known to you — it is Dr. Allan Chapman, who will be speaking on 'Ancestors and descendants: the RAS and the origin of the British learned society'.

Dr. A. Chapman. [It is expected that a summary of this talk will appear in a future issue of *A & G*.]

The Chair. We're a little bit behind time. Maybe just one or two questions for Dr. Chapman who has given a great talk. Maybe I can ask one. In our modern era, are we still, although we have ale and things to help our Fellowship, free and unconfined?

Dr. Chapman. Less free and unconfined. But nonetheless, I think, a major thing to work for, internationally.

Dr. G. Q. G. Stanley. I enjoyed that immensely, I think everyone did as well. Given the premise that one wasn't going to play with snakes, kill dogs, or hunt stags, would you say we can learn from this the best way to prove your thesis, or get funding for blue-sky thinking, is to ensure our meeting is in a pub?

Dr. Chapman. Why not? [Laughter.] The important thing is, the democracy of a pub, or, of course, in the early days, as well, a coffee house. Exactly the same thing.

The Chair. If there are no more questions, once again, Dr.Chapman, I will thank you very much. [Applause.]

That was the past, we move on to the present with Professor Anton Ziolkowski who will talk about 'Understanding the physics of the planet Earth'

Professor A. Ziolkowski. I must begin by thanking my co-author, Aftab Khan, and people who have offered very helpful advice on the content, including Richard England (Leicester), Ian Bastow (Imperial), Nick Kusznir (Liverpool), Sheila Peacock (Blacknest), and Kathy Whaler, Andrew Curtis, and Mark Chapman (Edinburgh).

Solid-Earth geophysics applies the principles of different branches of classical physics to investigate the interior of the Earth. One of the first things to notice is that the physical properties we would like to find do not always overlap between branches of physics. Gravity and seismology share density of mass as a common parameter, but electromagnetism shares no physical properties with seismology and gravity, and thermal conductivity can be determined from observations of heat flow, but is not directly related to the other methods of investigation.

Subsurface density variations cannot be determined from gravity measurements alone: structural constraints are required, and we turn to seismology for help. Seismograms from distant earthquakes consist of compression, shear, and surface waves, in that order, and the time difference between the arrival of the first compressional, or P-wave, and the arrival of the shear, or S-wave, is related to the distance to the earthquake and the velocities of P and S waves in the Earth. Because the P-wave and S-wave velocities depend on density, we can find density variations in the Earth from P-wave and S-wave velocities.

Seismology is different from the other methods in that it provides clear events that arrive at times which depend on velocity and distance. Given the data — times, distances, and types of wave — we can calculate the velocities directly. For all other kinds of geophysical data we rely on inversion, which is a kind of trial-and-error method to fit a model to the data that best minimizes the error. We are now getting quite good at inversion and find that we can get better results by applying it to seismic data too.

About fifteen years ago the oil industry began applying electromagnetic methods to determine whether subsurface structures, found in deep water by seismic exploration, contained oil, before deciding where to drill. That is, deep-water electromagnetic measurements were made to rank drilling prospects found by seismic exploration. Inversion was used to interpret the electromagnetic data using 3D models of the subsurface resistivity. The resistivity models were derived from seismic data and well logs. But seismic and electromagnetic data do not share common physical properties. How did the oil industry relate resistivity to seismic velocity? Well, rocks are complicated: they have pores that contain fluids. Porosity can be estimated from seismic data and resistivity can be estimated from porosity — all based on theoretical and empirical rock-physics relations tested in laboratory experiments. Rock physics is becoming the cement that connects different branches of physics to improve geophysics.

Beyond that, we are also now beginning to apply Bayes' theorem to improve our estimates of Earth properties from geophysical data. Until now, most of the effort in inversion has been devoted to finding efficient ways to minimize the error between our modelled and synthetic data. We are now finding that we can improve the estimate of the best-fitting Earth model by considering the effect of prior knowledge on the range of validity of each parameter in the model. This prior information is just as important as our efforts to minimize the error.

An up-to-date example of the application of diverse geophysical measurements to understanding the Earth is the 2017 paper of Livermore, Hollerback and Finlay, who analysed *Ørsted*, *CHAMP*, and *Swarm* satellite data plus ground-based observatory magnetic data and found a high-latitude accelerating jet in the Earth's core, now moving at about 40 km/year.

The Chair. Thank you very much, Anton. We have time for a few questions. Do you think there's more room to improve on the Bayesian techniques that you've shown us?

Professor Ziolkowski. We don't do enough work to see, to have statistical characterization of the phenomenon we're looking at, and that's what the priors are. How do you parametrize the statistics of what you're looking at? I will use a geophysics example not an astronomical one as I haven't a clue how to do it. Suppose that you're drilling in a new place, or let's say it is near to an older place, let's say it's in the North Sea, you're in a part of the North Sea where there is lots of other information. That other information in nearby fields can guide you, with the statistics of the geology for the new place that you're drilling nearby. So it's going to have the same rocks, the same sandstones, shales, limestones and so on, that have properties that you know well, so you can characterize them. And that is prior information. It is not directly applicable to the place you are now but you've got to use it because that's all you know. And I should say the military has been using Bayes' rule for years and years even when it wasn't popular with scientists.

The Chair. Thank you very much. Any more questions?

Mr. C. Taylor. The core movement that you referred to, the 40 kilometres/year — is there any connection there with the inner-core super rotation, about which a good deal of fuss was made in the mid-nineties, and, I think, the story has still been rumbling on since, but any connection since?

Professor Ziolkowski. Well, I have to tell you that I am not an expert on the rotation in the core, but there is one in the room, and that is Kathy Whaler who is behind you.

Professor Kathy Whaler. Can I have this time to make a quick comment? Thank you, Anton, as well for introducing the topic. That jet is at the top of the outer core, and it's along the cylinder that is lined with the rotation. So there is a connection down to the inner core. And you're quite right that the jury is very much still out on the idea of inner-core super-rotation, but certainly these ideas of westward drift at the top of the outer core turning to eastern drift by differential rotation is still a theory that's being looked at, but in fact we suspect that the data about the inner core, on which those super-rotation studies were based, is more complicated than the initial analysis.

Mr. Taylor. Thanks very much.

The Chair. We now have a talk from Dr. Megan Argo. We've heard about the 200 years of the past, we've heard about the present, and she's going to tell us about, in a blink of an eye, the next 200 years.

Dr. Megan Argo. In 2020 the Royal Astronomical Society celebrates its 200th anniversary. From the first meeting, when fourteen gentlemen sat down to dinner at the Freemason's Tavern in London in 1820 January, the Society has grown to a diverse membership of more than 4000 geophysicists and astronomers, both amateur and professional. Astronomy has come a long way in that time, and our understanding of the Universe has changed fundamentally. What didn't we know 200 years ago? Where is astronomy going next? I've been tasked with describing where astronomy might be heading in the *next* 200 years. Something of an ambitious aim! I can fairly confidently predict that almost any prediction I make will turn out to be wrong, but I'm always up for a challenge, so here goes.

When looking forward, it's important to consider first where you've come from. What did we not know 200 years ago that we now take for granted? In 1820, we didn't yet have Maxwell's equations or relativity, nobody had yet measured the distance to anything outside our Solar System, and we didn't know the shape of our own galaxy, the cosmic microwave background, exoplanets, black holes, gravitational waves … . It's been extraordinary. The next 200 years will probably be more extraordinary.

For some inspiration, I asked Twitter what they thought might be in store for astronomy in the next 200 years. There were many suggestions, from both professional and amateur astronomers, as well as interested folk who wouldn't call themselves astronomers. Many of the suggestions could comfortably come under G rather than A, but who's counting? The overwhelming response was that we will discover life of some sort. The most likely is simple forms of life, bacteria and the like, either under the Martian surface, or in the liquid oceans of Europa or Enceladus.

Given the hopes and suggestions of this (very unscientific) cross-section of humans, how are we progressing towards these predictions?

Following on from the *Trace Gas Orbiter* in 2016, in the middle of 2020 ESA and Roscosmos will launch the second part of their ExoMars programme, a rover which will be able to drill down to a depth of two metres and take sub-surface samples — exploring the mineralogy of Mars and looking for biomarkers. The rover also hosts several cameras, both visible and infrared, as well as spectrometers for sample analysis, and ground-penetrating radar to determine sub-surface water content. It might find life, but even if it doesn't it will help hugely in our understanding of the Martian surface and its history, and help us prepare for future sample-return missions.

Looking a bit further ahead, *JUICE* is a joint ESA/NASA large mission to explore Jupiter, it's icy moons, and the interactions between them. Scheduled for launch 2022, it will arrive in 2029 after several flybys in the inner Solar System. The aim is to study Jupiter as an archetype for gas giants, observing its atmosphere, magnetosphere, rings, and satellites. The spacecraft will make fly-bys of Europa, looking at its surface composition and geology, and searching for pockets of liquid water under the surface. Callisto flybys will not only be used to study this ancient, cratered world that may too harbour a subsurface ocean, but to move to a position for a capture into Ganymede's orbit. Ganymede is the only moon to have a magnetosphere. *JUICE* will study Ganymede's internal magnetic field and the interaction with Jupiter's, as well as the moon's atmosphere, surface, subsurface, and interior, investigating the moon as a planetary object and possible habitat. Eventually *JUICE* will run out of propellant and the mission will end with a grazing impact, returning close-up images of Ganymede's surface before it crashes.

What about telescopes? The most famous of the upcoming projects is probably the *James Webb Space Telescope*. Development of this telescope began in 1996, and it is scheduled (at the time of writing) for launch towards L2 in 2021 March. With half the mass of *Hubble*, it will have five times the collecting area; its 6.5-m mirror and huge heat shield will allow it to observe from the middle of the visible band through to the mid-IR (0·6 – 27 μm). The aims of the telescope stretch from direct imaging of exoplanets and novae, to observing the formation of stars and planets, to spotting the first galaxies at high redshift, helping us understand the evolution of the Universe.

On the ground we also have several impressive facilities to look forward to. Personally, I'm excited to see what comes from the *Large Synoptic Survey Telescope*, now renamed the *Vera C. Rubin Observatory*. With an 8·4-m primary mirror, this is far from the largest of the planned telescopes we will see in the next 200 years. But with its 3·2-gigapixel camera, field of view of 3·5 degrees, and ability to cover the sky quickly, this telescope will provide astronomers with a huge amount of data that will allow us to explore the transient universe, find and track vast numbers of asteroids and comets, explore weak gravitational lensing over large areas of the sky, and many other exciting science goals. Producing many thousands of transient alerts each night, and more than 200 000 images per year, this telescope is going to keep astronomers very busy! With so many transient alerts needing follow-up, our pipelines are going to have to be very clever, and amateur astronomers could very well find themselves making valuable contributions to following up interesting events.

Being a radio astronomer myself, I am also particularly looking forward to the *Square Kilometre Array*. The *SKA* will be a radio telescope covering so much of the spectrum that it requires more than one type of antenna technology, with different parts being built on different continents. The host sites for the *SKA*, the Murchison region in Western Australia and the Karoo in South Africa, are already both hosting precursor arrays that are important technology testbeds, as well as being excellent observatories in their own rights. With 13 member countries, 100 organizations in 20 countries involved in development of the *SKA*, this is a major engineering project. Among the science goals are the study of galaxy evolution, cosmology and dark energy, strong-field tests of gravity using pulsars and black holes, the origin and evolution of cosmic magnetism, finding out how the first black holes and stars formed, and searching for signatures of life in the cosmos. Will we find it? Maybe not, but if we don't look the chance is of finding it is definitely zero.

But it's not all exciting observations, new telescopes, and deeper surveys. As a community, whether professional or amateur, whether we work in the optical, radio, or any other part of the spectrum, we will all have to deal with the proliferation of satellites in low-Earth orbit. In recent months, SpaceX have begun launching the first of what will be 12 000 *Starlink* satellites into orbit.

These satellites, approved by the relevant regulatory authorities, are already causing problems for astronomers, both amateur and professional. And it is only going to get worse. SpaceX have requested permission to launch another 30 000 satellites, and many other companies, among them Amazon, are requesting clearance to launch similarly large networks. To put this in some perspective, with the naked eye we can see about 10 000 stars across both hemispheres. The rate satellites are being launched today is frightening.

On the one hand, these networks will provide cheap internet access for many remote places where fibre, cable, or connecting to existing satellite networks is prohibitively expensive. But it is creating a huge headache for astronomy. Yes, the positions of these satellites can be predicted, but the sheer number of them (one per square degree just with *Starlink*) will lead to large losses in observing time for any ground-based telescope, and a massive interference problem for radio astronomy. How can we get round this?

Astronomers have been considering telescopes on the Moon since at least the 1950s. These days it seems more and more like a sensible idea. The Moon has many advantages: no atmosphere, low gravity, no people/streetlights/satellites (very few, anyway). We already build telescopes and put them in remote places, often operating them from many hundreds of miles away, and we know how to build electronics to survive the harsh conditions of space. Experiments are being done that create a parabolic surface from slowly rotating ionic liquids. Low-frequency radio telescopes require no moving parts. Technically, we have the capability to do this. I'm not sure STFC would pay for the observing trips though.

Incidentally, while writing this talk I came across details of a scientific discussion meeting to be held at the Royal Society in 2020 March on exactly this topic. Organized by Joseph Silk, John Zarnecki, Ian Crawford, and Martin Elvis, the meeting will look at how infrared and low-frequency radio astronomy from shaded crater floors and the radio-shielded lunar far side can have a unique science impact potentially at modest cost. Maybe it's not so far-fetched after all.

Of course we could always go further and put all our telescopes in deep space. This is expensive, but with the development of re-usable rocket technology it may be a step closer. Of course, how you get your data back from a deep-space observatory is another challenge to consider.

One future space telescope that will sit some distance from the Earth is *LISA*, the upcoming space-based gravitational-wave observatory. Gravitational-wave detectors on the ground are doing incredible things, but some signals we want to observe have wavelengths larger than the diameter of the Earth — to detect them we need to have detectors separated by vast distances and connected by lasers, and that is exactly what *LISA* will do. Measuring the separation of satellites 2·5-million kilometres apart to centimetre accuracy is a technical challenge, but not an insurmountable one. Once operational, *LISA* could discover ultra-compact binaries in our Galaxy, mergers of supermassive black holes, extreme-mass-ratio inspirals, among other exotic possibilities.

One no-brainer of a prediction is that we will discover more exoplanets. The number of known exoplanets has been increasing each year since the first was found in 1995. If we extrapolate this trend line (in a very crude and not very rigorous way) we find that by 2220 we will know of over 21 million exoplanets! Obviously, this extrapolation is nonsensical, but the numbers will definitely increase dramatically. We are bound to find many systems that look familiar, and many others that challenge our models of planetary formation. We may even start to find systems that are habitable to humans, even if we lack the rocket technology to reach them (yet).

Has anyone seen Orion recently? Have you noticed how faint Betelgeuse has become? There has been much speculation (and a lot of excitement) recently that Betelgeuse may be on the verge of going supernova. One of the ten brightest stars in the sky (until recently), Betelgeuse is a red giant more than eleven times the mass of the Sun. Massive stars have short lives and explode catastrophically, so Betelgeuse will eventually go supernova — but maybe not in the next few months (likely not even in the next 200 years). Since October last year, Betelgeuse has dimmed by one whole magnitude (a factor of 2·5 in brightness). So, is it about to go supernova? Or is there a more mundane explanation? Unfortunately for us, the more mundane possibilities are probably more likely. One suggestion is an increase in dust production, thought to be common at this stage of massive-star evolution. Observations are (of course) underway to test the various theories. If it did explode, we would be able to see it during daylight, before it faded and eventually developed into a supernova remnant. Situated about 650 light years away, it might have exploded yesterday of course, and we wouldn't know about it for quite some time. One thing is certain: when it does explode, every telescope on the planet will be watching.

We've looked at some of the upcoming technology, the advances in capability we will get in the future, and some of the things we might discover. The safest prediction I could possibly make is that we will discover the unknown unknowns. Every step forward in observational capabilities has led to discoveries that we could not have predicted. Deeper observations reveal new things. If we are going to continue to explore the cosmos in the next 200 years and beyond, we need to keep developing and enhancing our multi-wavelength (and multi-messenger) coverage. We need to go deeper, we need to look further, we need to be open to the idea that the things we look back on in 200 years time will be those we have no concept of today, the things we don't know are there to be discovered.

My final prediction is something of a whimsical one, and that is that in 200 years' time we will all meeting by hologram from the comfort of our own homes, rather than travelling to London. The environmental price of travel may reach a level where travel is much less common, and if we do nothing about climate change then it is likely that Burlington House will be underwater anyway (at least that would solve the problem of the lease). But we may just decide that our time is better spent doing things other than sitting on a train for several hours. The image I've used here is from the movie *Kingsman*, where every hologram around the table is male; in 200 years, I would hope the gender balance of our community is somewhat better than that!

Those are my thoughts on the exciting telescopes, space missions, and potential discoveries to look out for over the next few (to 200) years in astronomy. If you had asked anyone else to give this talk, I'm sure they would have highlighted other things, but my final point remains: imagine how much about the Universe we still have left to discover. I can't wait to see what we find next.

The Chair. Thank you very much. Any questions?

Dr. Stanley. Many thanks for your presentation. One area you haven't mentioned is AI (Artificial intelligence). How do you see it being involved in the future?

Dr. Argo. Yes, I hadn't included it but that is one area where there will be progress and we are seeing it being more commonly used as the data sets we are processing are getting larger. We will need intelligent pipelines to cope with the data volume from the large survey telescopes — humans will not be able to deal with it. Indeed it will become a tool that will help us find details we may otherwise miss.

Dr. Stanley. And yes, we can expect to see AI appearing more on the edge and available to amateurs.

Dr. Argo. Absolutely. As the algorithms become more developed and easier to use, I think that is inevitable.

Mr. M. Rickard. Regarding the star field showing the *Starlink* satellites, do we know how this image compares to the final spatial distribution once the satellites have completed separating?

Dr. Argo. The prediction is that, just for *Starlink*, there will be one satellite per square degree. This will obviously depend on your position in relation to the satellite orbits, but that is about what we are looking at. When you factor in all of the other proposed networks of course, it will be far higher than that.

Mr. Rickard. On a more philosophical level, knowing as we do the benefits that having internet access has for a society, are we really right in complaining about increased difficulty in doing observations compared to the societal change a project like this could bring to a developing country?

Dr. Argo. That's a good point. I guess it depends on whether you see the night sky as an environment worth protecting. Providing internet access for areas where it is currently prohibitively expensive is a laudable goal, but at what environmental cost? I think what has angered many people is not the goal, but the lack of thought about what it would do to the sky. These companies are now at least acknowledging that their plans have unintended consequences and are talking to astronomers. Let's hope that continues.

The Chair. Thank you very much. The drinks party takes place immediately after the end of the meeting and I give notice that the next A and G Meeting will be on Friday the 14th of February.

WHATEVER HAPPENED TO THE DYER–ROEDER DISTANCE?

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The Universe is not completely homogeneous. Even if it is sufficiently so on large scales, it is very inhomogeneous at small scales, and this has an effect on light propagation, so that the distance as a function of redshift, which in many cases is defined *via* light propagation, can differ from the homogeneous case. Simple models can take this into account. One such model is known as the Dyer–Roeder distance. I sketch the history of this model and some applications, then suggest some reasons why it is still relatively obscure.

Introduction

Classical cosmology aims to determine the cosmological parameters λ_0 and Ω_0 by calculating the dependence of observable quantities, which depend on some sort of distance, on the redshift z for different values of those parameters, which are then fitted for *via* comparing calculations with observations. That includes not only the classical (and classic) tests such as the m–z relation, the angular-size–redshift relation, and number counts (*e.g.*, ref. 1), but also less straightforward calculations such as gravitational-lensing statistics (*e.g.*, ref. 2 and references therein). Usually, the distance is calculated from the redshift assuming an ideal Friedmann–Robertson–Walker (FRW) model. Since a look at the sky shows that the Universe is not homogeneous, at least not on the relevant scales (given by the angular size of an observed object), the question arises as to what extent this inhomogeneity can affect light propagation and hence the distance calculated from redshift, and thus the derivation of cosmological parameters *via* comparing theory with observations; in particular, under-dense lines of sight correspond to larger angular-size and luminosity distances. The simplest more refined model retains the background geometry and expansion history of an FRW model but separates matter into two components, one smoothly distributed comprising the fraction η of the total density and the other $(1 - \eta)$ consisting of clumps, and considers the case where light from a distant object propagates far from all clumps (and thus through under-dense regions).*

The plan of this paper is as follows. First I give a brief overview of the history of the Dyer–Roeder distance, then discuss various applications of the Dyer–Roeder distance in observational cosmology, before offering some reasons why it is not often taken into account and perhaps doesn't need to be.

Back in the U.S.S.R.

The first attempt to calculate distances in a universe with small-scale inhomogeneities was, as far as I know, that of Zel'dovich[4], though more are probably more familiar with the English translation[5]. I'll refer to both as Z64. In modern notation, Z64 considered the Einstein–de Sitter universe with $\Omega_0 = 1$ and $\lambda_0 = 0$. (I use terminology in which Ω refers to the matter content in units of the critical density; $\Omega = 8\pi G\rho/(3H^2)$, where ρ is the density, G the gravitational constant, and H the Hubble constant. $\lambda = \Lambda/(3H^2)$ is the dimensionless cosmological constant. The suffix 0 refers to the value today, since in general cosmological parameters are time-dependent.) That is, an Einstein–de Sitter universe on large scales, but allowing for inhomogeneities on small scales, though these do not affect the metric (in other words, no back-reaction — more precisely, one considers inhomogeneities so small that the effect on the metric is negligible on large scales, *i.e.*, the Universe is still well described by an FRW model overall, though the small-scale effects on light propagation can be non-negligible). The idea is that all matter is in galaxies and one sees distant objects between the galaxies.

The angular-size distance D^{A} is defined as ℓ/θ, where ℓ is the physical length of an object and θ the angle between the two sides of the object as seen by the observer. It is essentially the proper distance at the time the light was emitted, corrected for curvature effects if, unlike the Einstein–de Sitter model, the

*Since α is almost universally used to denote the gravitational-lensing bending angle, Kayser *et al.*[3], hereafter KHS, adopted η instead of the more confusing α or $\tilde{\alpha}$ used by some other authors; since then, some authors other than KHS have also used η instead of α or $\tilde{\alpha}$ for the inhomogeneity parameter.

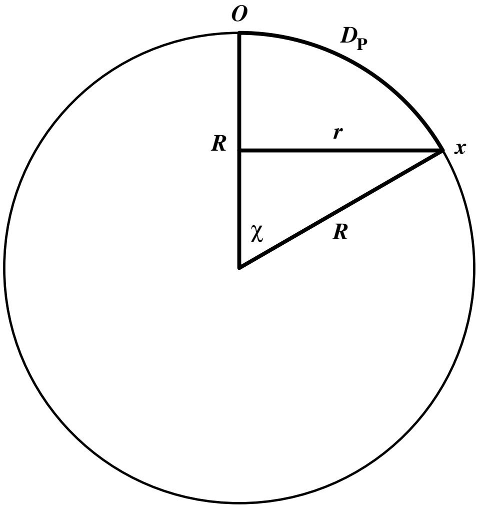

FIG. 1

Although the corresponding definitions are valid for models with k of 0 and –1 (zero and negative curvature, respectively) as well, easiest to visualize are distance definitions for the case $k = +1$ (positive curvature). The universe can be thought of as a curved three-dimensional space, corresponding to the circle. Two dimensions are hence suppressed, so that the two dimensions in the plane of the figure can show the universe and its spatial curvature. R is the scale factor of the universe, as usual chosen to correspond to the radius of curvature. The observer is located at the top of the circle at O and observes an object located at x. D^P, the length of the arc, is the proper distance to that object. For $\eta = 1$, the angular-size and luminosity distances (as well as other distances not discussed here such as the proper-motion distance and parallax distance) depend on $r = R\sin(\chi)$ in a relatively simple manner; see KHS for details. (They depend on r and not D^P for the same reason that the length of a parallel of latitude is less than $2\pi D^P$ where, in the case of the Earth, D^P is the distance along the surface, 'as the crow flies'.) Note that χ is constant in time; one can use it or $\sigma = r/R$, which is also constant in time, as the basis for a so-called co-moving distance.

universe is not flat (see KHS for discussion of various cosmological distances). In a perfectly homogeneous universe, in the general case distances can be calculated *via* elliptic integrals (*e.g.*, ref. 6), though there are simpler solutions for special cases (KHS, Appendix B). Fig. 1 illustrates the definitions in the completely homogeneous case.

Z64 takes a different approach, deriving a differential equation for the separation between two light rays (easily converted to the angular-size distance), which changes due to the expansion of the Universe and due to convergence caused by matter between the two rays (*i.e.*, 'in the beam'). If the beam is under-dense, then the convergence is negative. The effect of matter in the beam is calculated by generalizing the deflection of light by a point mass due to the gravitational-lens effect (*e.g.*, ref. 7) to a smooth distribution. It is noted that for $\eta = 0$ the angular-size distance "increases monotonically right up to the [particle] horizon ($\Delta = 1$) where it reaches the value 2/5"*. (In this paper, all

* $\Delta := 1 - 1/(1 + z)$. For a modern reader, the notation of Z64 is bizarre. See Helbig[8] for a translation into modern notation.

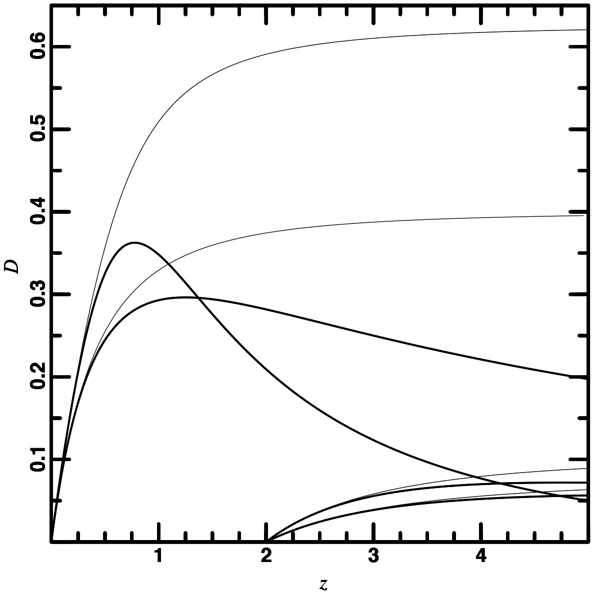

FIG. 2

The angular size distance from the observer ($z_1 = 0$) and from $z_1 = 2$ (lower right) as a function of the redshift z_2 for different cosmological models. Thin curves are for $\eta = 0$, thick for $\eta = 1$. The upper curves near $z = 0$ ($z = 2$ at lower right) are for $\lambda_0 = 2$, the lower for $\lambda_0 = 0$; $\Omega_0 = 1$ for all curves. The angular-size distance D is given in units of c/H_0.

distances are in units of the Hubble length c/H_0 and, unless otherwise specified, the distance is between the observer at redshift $z = 0$ and an object at a redshift $z > 0$; it is sometimes necessary, especially in gravitational lensing, to discuss distances between two non-zero redshifts (*e.g.*, the lens and the source).) Thus, the maximum in the angular-size distance is at $z = \infty$, in marked contrast to the homogeneous case, where there is a maximum ($D^{\mathrm{A}} \approx 0{\cdot}296$) at $z = 1{\cdot}25$ (see Fig. 2).

In addition to the perfect Einstein–de Sitter model and one with all the matter in clumps (galaxies), D^{A} is also calculated for $\Omega_0 = 0$. Since there is no matter at all in such a model, there is no difference between the standard distance (filled-beam) and the empty-beam distance. (It is of course a consistency check that the differential equation for the empty model gives the same result as the standard calculation, *i.e.*, assuming perfect homogeneity.) There are simple analytic solutions for these three cases:

$$D^{\mathrm{A}} = 2\left((1+z)^{-1} - (1+z)^{-\frac{3}{2}}\right) \tag{1}$$

(Einstein–de Sitter model, filled beam),

$$D^{\mathrm{A}} = \frac{2}{5}\left(1 - (1+z)^{-\frac{5}{2}}\right) \tag{2}$$

(Einstein–de Sitter model, empty beam), and

$$D^{\mathrm{A}} = z\left(1 + \frac{z}{2}\right)(1 + z)^{-2} = \frac{1}{2}\left(1 - (1 + z)^{-2}\right) \quad (3)$$

($\Omega_0 = 0$). Note that Eq. (1) is a special case of the Mattig[9] formula

$$D^{\mathrm{A}} = \left(\frac{2}{\Omega_0^2(1 + z)^2}\right)\left(\Omega_0 z - (2 - \Omega_0)\left(\sqrt{\Omega_0 z + 1} - 1\right)\right). \quad (4)$$

Dashevskii & Zel'dovich[10], an English translation of ref. 11, hereafter DZ65, generalize the idea of Z64 to arbitrary values of Ω_0 ($\lambda_0 = 0$ is still assumed). The derivation follows a different route, again an interesting consistency check. In this more general case as well, a completely empty beam puts the maximum in the angular-size distance at $z = \infty$. No analytic solution is given, though one exists[12]; *cf.* KHS, equation (B15) — much more complicated than Eqs. (2) & (3). The angular-size distance for the filled (f) and empty (f_1) beam is plotted as a function of $\Delta = 1 - 1/(1 + z)$ for a few values of Ω_0, and for a few more values of Ω_0, $\Delta_{\max}$ (the value of Δ at which the maximum in the angular-size distance for $\eta = 1$ occurs), and the values of f at $\Delta_{\max}$ and f_1 at $\Delta = 1$ are tabulated. Several interesting features are pointed out in the text and/or are obvious from the figure (if Ω_0 is not mentioned, then the effect is independent of the value of Ω_0):

(*i*) The angular-size distance for $\eta = 0$ increases monotonically with redshift.

(*ii*) The angular-size distance for $\eta = 0$ is less than the light-travel-time distance $c(t_0 - t)$ and larger than the angular-size distance for $\eta = 1$ (at least for $\lambda_0 = 0$).

(*iii*) The angular-size distance for $\eta = 0$ has its maximum value at $z = \infty$.

(*iv*) For $\eta = 0$, $\mathrm{d}D/\mathrm{d}z = 0$ at $z = \infty$.

(*v*) The angular-size distance for $\eta = 1$ has a maximum at $z < \infty$.

(*vi*) The value of the maximum of the angular-size distance for $\eta = 1$ increases with decreasing Ω_0.

(*vii*) The redshift of the maximum of the angular-size distance for $\eta = 1$ increases with decreasing Ω_0.

(*viii*) The angular-size distance for $\eta = 1$ is 0 at $z = \infty$.

(*ix*) Both for $\eta = 0$ and $\eta = 1$, the value of D^{A} at any redshift increases with decreasing Ω_0.

(*x*) For given values of Ω_0 and z, D^{A} for $\eta = 0$ is always larger than D^{A} for $\eta=1$.

DZ65 note that the claim by Wheeler[13] that the maximum in the angular-size distance for $\eta = 1$ occurs only in the case of a spatially closed universe is wrong. While positive spatial curvature can contribute to the maximum, in most cosmological models it is not the main effect[8]. (Spatial curvature can cause a maximum in the angular-size distance for the same reason that the circumference of a parallel of latitude as a function of longitude has a maximum (at the equator), but in most cosmological models the main reason is that the angular-size distance (ignoring curvature effects) is equivalent to the proper distance at the time of emission. At small redshifts, as the redshift increases, the object was farther away (in proper distance) when the light was emitted, thus the angular-size distance increases with redshift. However, at large redshifts, light was emitted when the proper distance was small, long ago, but, due to the more rapid expansion of the Universe in the past, is reaching the observer just now. Referring to Fig. 1, $D^{\mathrm{A}} = Rf(\chi)$, where $f(\chi)$ is $\sin(\chi)$, χ, or $\sinh(\chi)$ for k equal to +1, 0, or −1, *i.e.*, positive, zero, or negative spatial curvature, respectively. At small z, χ is small; at large z, R was small when the light was emitted.)

Dashevskii & Slysh[14], hereafter DS66, an English translation of ref. 15, generalize the method of Z64 and DZ65 to the more realistic case that the beam is not completely empty, but only for the Einstein–de Sitter model. The empty-beam case is criticized as being too unrealistic, as there will always be some intergalactic matter; this will mean that there will always be a maximum in the angular-size distance. DS66 derive, in their equation (2), the second-order differential equation which is the basis for all further work in this field:

$$\ddot{z} - \frac{\dot{a}}{a}\dot{z} + 4\pi G\rho_{\mathrm{g}} z = 0\,, \tag{5}$$

"which determines the linear distance $z(t)$ between rays", with $\rho_g = \alpha\rho$ (the subscript g refers to the *smooth* component, considered as a "***g****as* at zero pressure that fills all space uniformly" [my emphasis], the rest of the "matter being concentrated in discrete galaxies"); a is the scale factor and G the gravitational constant. Compared to Z64 and DZ65, they allow α (in the notation of KHS, η) to take an arbitrary value $0 \leq \alpha \leq 1$; η is thus completely general. The cosmological model is implicit in the term $\dot{a}/a$, in principle allowing one to study any cosmological model in which $\dot{a}/a$ can be calculated, but DS66 then restrict themselves to the Einstein–de Sitter model for the subsequent discussion, presenting a completely analytic solution for the angular-size distance for this cosmological model:

$$D^{\mathrm{A}} = \frac{1}{2\beta}\left((1+z)^{(\beta-\frac{5}{4})} - (1+z)^{(-\beta-\frac{5}{4})}\right) \tag{6}$$

(modern notation), where

$$\beta := \frac{1}{4}\sqrt{25-24\eta}\,. \tag{7}$$

DS66 point out that, for arbitrary $0 < \eta \leq 1$, the angular-size distance has a maximum at finite z and the angular-size distance goes to 0 for $z = \infty$. Also, the smaller the fraction of homogeneously distributed matter, *i.e.*, the smaller η, the higher the redshift of this maximum. The generalization of the differential equation of Z64 to an arbitrary value of η is obvious; less obvious is the relatively simple analytic solution for arbitrary η for the Einstein–de Sitter model; *cf.* KHS, equations (B18) & (B19).

Dyer & Roeder

Starting with an integral expression (including λ_0) for the angular-size distance in the $\eta = 0$ case, Dyer & Roeder[12], hereafter DR72, give analytic solutions (but now assuming $\lambda_0 = 0$, *i.e.*, the same assumptions as made by DZ65) for the three cases $\Omega_0 < 1$, $\Omega_0 = 1$, and $\Omega_0 > 1$ (though the first is actually not valid for $\Omega_0 = 0$); only the much simpler solutions for $\Omega_0 = 1$ (Z64) and $\Omega_0 = 0$ (ref 9; see also Z64) were previously known. As was common at the time, instead of Ω_0, q_0 was used. In general, $q_0 = \Omega_0/2 - \lambda_0$, so that, for $\lambda_0 = 0$, $q_0 = \Omega_0/2$. The famous result of Etherington[16],

$$D^{L} = (1 + z)^2 D^{A} , \tag{8}$$

where D^{L} is the luminosity distance, is invoked to note that an empty beam leads to a lower apparent luminosity, which leads one to underestimate q_0 if a completely homogeneous universe is assumed; their example has a real value of $q_0 = 1{\cdot}82$ which, if calculated assuming a completely homogeneous universe, results in the value $q_0 = 1{\cdot}40$. The exact numbers are not important; the point is that, to first order, the empty-beam distance is larger than in the standard (filled-beam) case, which is also the case for a lower value of q_0. But this is only to first order; with higher-redshift data, the two effects are not degenerate. It is also shown that, while the difference between the empty-beam distance and the standard distance is non-negligible, there is little difference between the Dyer–Roeder distance and that obtained by numerical integration in a corresponding Swiss-cheese model (see below).

Dyer & Roeder[17], hereafter DR73, can be seen as a combination of DZ65 and DS66, *i.e.*, Ω_0 and η are both arbitrary (though $\lambda_0 = 0$ is still assumed). For the general case, they derive a hypergeometric equation, and present explicit solutions for $\eta = 0$, $2/3$, and 1 as well as $\Omega_0 = 0$ (the second one being new). The special case $\eta = 1$ is the solution derived by Mattig[9] while that for $\eta = 0$ is that derived by DR72. New is a solution for $\eta = 2/3$, which is given for the luminosity distance. For $\Omega_0 = 1$, one has the solution derived by DS66, which is given for the angular-size distance. Differentiation of that equation leads to an expression for the maximum in the angular-size distance, showing that as η goes from 1 to 0, the redshift of this maximum goes from $1{\cdot}25$ to ∞. The point first made by Z64, that the maximum is due to matter in the beam, is emphasized. (Note, however, that an arbitrarily small η will lead to a maximum, though at arbitrarily large z.) They suggest comparing observations with calculations for each of the three values of η for which there is an analytic solution, given the lack of knowledge about intergalactic matter. Finally, as in DR72, they note that calculations for Swiss-cheese models (see below) — interestingly, including $\lambda_0 \neq 0$ — confirm that this is a good approximation, *i.e.*, “the mass deficiency in the beam is in general much more important than the gravitational-lens effect for reasonable deflectors”, at least for “redshifts in the range of interest”.

The distance for an empty or partially filled beam has become known as the Dyer–Roeder distance, although various aspects had been discussed by others before. This is probably due to the fact that the corresponding papers were published in a major English-language journal, used standard notation, and were more concerned with results than with theory. Dyer and Roeder were certainly responsible for putting the topic on the agenda of many astronomers. On the other hand, it seems unfair to neglect the pioneering efforts of Zel’dovich and his colleagues. Hence, in what follows I will refer to the distance calculated based on the above approximation as the ZKDR distance, a term introduced by Santos & Lima[18] and referring to Zel’dovich, Kantowski (see below), Dyer, and Roeder, though I take the ‘D’ to refer to Dashevskii as well, my criterion for being part of the acronym being having (co-)authored at least two papers on this topic, at least one of which was published within ten years of the first paper on this topic (Z64).

Theoretical foundations

Weinberg[19] pointed out that the standard distance formula, *e.g.*, assuming $\eta = 1$, must hold on average if lenses are transparent and there are no selection effects. This is due to flux conservation: the fact that almost all beams are under-dense and hence the average magnification* is less than 1 is offset by the occasional strong-lensing event. Peacock[20] generalized the result of Weinberg[19] to arbitrary Ω_0. Dyer & Roeder[21] considered the effect of a finite source size in gravitational lensing, concluding that, all else being equal, η increases with the size of the source, since the larger the source, the more clumps will lie in front of it, and these will offset under-dense lines of sight. (In the limit, with the angular size equal to the whole sky, then obviously, ignoring absorption, η must be 1, since in this case the average density in the beam is equal to the average density in the Universe. With realistic mass distributions, $\eta \approx 1$ is reached for much smaller angles.) The important quantity is not the size of the source *per se*, but rather the size of the source relative to the clumps; as already mentioned by Weinberg[19], one could think of η increasing with redshift since, due to structure formation, matter was more uniform at high redshift. The fact that the angular size of the beam also increases with redshift (the base of the cone is at the source; the apex at the observer) is an additional effect in the same direction.

Kibble & Lieu[22] also contributed significantly to the understanding of flux conservation in the context of the ZKDR distance. They showed analytically that, under very general conditions (including arbitrary shapes of clumps and strong lensing), the average *reciprocal* magnification in a clumpy universe is the same as that in a homogeneous universe, as long as the clumps are uncorrelated. An important distinction is whether one averages over a set of sources on the unperturbed celestial sphere, or whether one averages over all lines of sight. This is related to whether it is the mean magnification or the mean reciprocal magnification that is the same as in the homogeneous case.

Even if the mean magnification is 1, due to the skewness of the distribution, the *median* magnification is < 1. Clarkson *et al.*[23] pointed out that most narrow-beam lines of sight are significantly under-dense, even for beams as thick as 500 kpc. Although the basic idea of flux conservation is clear (and there are obvious caveats such as non-transparent matter), exact treatments can be very complicated and have led to confusion, much of which has been cleared up by Kaiser & Peacock[24]: Weinberg[19] is essentially right, though one needs to keep in mind the distinction between magnification and reciprocal magnification as discussed above in connection with Kibble & Lieu[22].

Kantowski[25], hereafter K69, took a somewhat different approach to that of Zel'dovich and those who expanded on his ideas, using Swiss-cheese models[26,27]. These are arguably less realistic than the approximation used in the papers discussed above, since in those models clumps of matter are surrounded by voids with $\rho = 0$. Since any spherical distribution of matter is, from outside the sphere, gravitationally indistinguishable from a point source of the same mass (even if it is not static)†, by making clumps out of the matter removed from

*Since gravitational lensing conserves surface brightness, magnification (increase in angular size) and amplification (increase in brightness) are proportional if the former is thought of as the increase in area rather than linear size; thus the two terms are sometimes used interchangeably, though strictly speaking, depending on context, one or the other might be more appropriate.

†The conventional reference is to Birkhoff[28], though the corresponding theorem was actually proved earlier by Jebsen[29].

a surrounding void, the large-scale geometry and dynamics are not changed. Hence, such models are exact solutions of the Einstein field equations and the validity of approximations used to calculate the angular-size distance is not an issue (though, of course, one can question the validity of this approximation to the distribution of matter in our Universe). K69 calculated the apparent bolometric luminosity, which is inversely proportional to the square of the luminosity distance. Since the luminosity distance is larger than the angular-size distance by a factor of $(1 + z)^2$, it is easy to compare his results with those discussed above. K69 points out that in the case that most matter is in clumps (*i.e.*, $\eta \approx 0$), a real value of $q_0 = 2{\cdot}2$ would, were one to wrongly assume the standard distance, appear as $q_0 = 1{\cdot}5$. This foreshadows later work stressing the importance of taking inhomogeneities into account in classical observational cosmology, at least as long as a significant fraction of matter is in clumps and the Universe is similar to the approximations used to calculate distances in such a case.

Dyer & Roeder[30] extended Swiss-cheese models to include cases where $\lambda_0 \neq 0$ and showed that the distances so computed correspond well to those based on previous work (DR72, DR73). Essentially, $\lambda_0 \neq 0$ affects the expansion history of the Universe but nothing else. An important result is that the dependence of the distance–redshift relation on Ω_0 is decreased for $\eta \approx 0$, thus reducing the precision obtainable in practice. Dyer & Roeder[30] is interesting because it presents for the first time distance–redshift relations in a universe with arbitrary Ω_0, λ_0, and η. However, not only because the calculations are based on Swiss-cheese models, no closed formulae are given.

The fact that results are very similar to those based on the simpler assumptions of the ZKDR distance is encouraging, and provides justification for using the simpler approach. It could of course be the case that this approach is too simple for the real Universe, but in that case a Swiss-cheese model would also probably be too unrealistic. Fleury[31] demonstrated with completely analytic arguments the equivalence of the ZKDR distance and that calculated from a certain class of Swiss-cheese models at a well-controlled level of approximation. This had been known for a long time based on comparisons of numerical results, but of course an analytic proof is very important.

Later work

Partially motivated by evidence for $\lambda_0 > 0$ (*e.g.*, refs. 32,33) as well as plans for higher-redshift observations of standard candles[34], it became necessary to calculate the ZKDR distance for $\lambda_0 \neq 0$. The only expression available for $\lambda_0 \neq 0$ was a complicated differential equation derived by Dyer & Roeder[30], but for Swiss-cheese models (see above). No closed solution was presented. Of course, it can be integrated numerically. However, it is rather cumbersome, and the terms do not have an obvious physical interpretation like those in the differential equations of Z64 and DS66. While it was appreciated that Swiss-cheese models are in some sense equivalent to the ZKDR distance derived *via* the Zel'dovich method, this was not shown strictly until much later[31]. Kayser[35] derived a differential equation for the angular-size distance in the style of Z64, DS66, and DR73, but for $0 \leq \eta \leq 1$ and arbitrary values of λ_0 and Ω_0, which he integrated numerically *via* standard but basic means. KHS saw a need for an efficient numerical implementation of that equation, which is the most general equation for the ZKDR distance under the standard assumptions that the Universe is a (just slightly) perturbed FRW model (*i.e.*, no pressure, no dark energy more complicated than the cosmological constant, no back reaction, only Ricci (de)focussing; even today, there is no evidence that the first three are not excellent approximations, and the fourth is as well in many cases). Also, no efficient general implementation existed for the standard ($\eta = 1$) distance. Thus, a description of the differential equation derived by Kayser[35] and the efficient numerical implementation evolved to include a general description of various types of cosmological distances and a compendium of analytic solutions, probably the first time all this information had been presented in a uniform notation.

Kantowski, with collaborators, had returned to the topic of distance calculation in locally inhomogeneous cosmological models[36], coincidentally around the same time that I was writing the code for KHS. Although partially motivated by the *m–z* relation for type-Ia supernovae, further progress was made regarding the theory; in particular, Kantowski *et al.*[37] gave analytic expressions using elliptic integrals for arbitrary λ_0, Ω_0, and $\eta = (0, 2/3, 1)$.

Testing the approximation

Unlike the Swiss-cheese model, the ZKDR distance is an approximation based on various assumptions. While it is reasonably clear that it must be correct in the appropriate limit (*i.e.*, the light propagates *very* far from all clumps, the fraction of mass in clumps is negligible so that it is clear that an FRW model is a good approximation, *etc.*), it is not immediately clear how good the approximation is in a more realistic scenario. One way to test this is to compare the ZKDR distance to an explicit numerical calculation, namely following photon trajectories through a mass distribution produced by a cosmological simulation. Several studies using simple numerical models for the cosmological distribution of matter[38–42] found good agreement between the ZKDR distance and an explicit numerical calculation. More-complicated models still found good agreement[43,44]; for a variety of cosmological models, the discrepancy was less than 1 per cent up to $z = 10$. Mörtsell[45] used essentially the same scheme to investigate the relation between η and the fraction of compact objects. By definition, $1 - \eta$ is the fraction of compact objects f_c in the pure ZKDR case, *i.e.*, only de-amplification due to under-density and no amplification due to gravitational lensing. As expected, taking lensing into account results in $1 - \eta < f_c$. Interestingly, for a variety of cosmological models $((\Omega_0, \lambda_0) = (0{\cdot}3, 0{\cdot}6), (0{\cdot}2, 0{\cdot}0), (1{\cdot}0, 0{\cdot}0))$, for redshifts between 0 and 3, and for various models of the mass distribution (homogeneous and point masses, NFW profiles and point masses), the relation is approximated very well by $1 - \eta \approx 0{\cdot}6 f_c$. Similar results were found by Giblin *et al.*[46], who used a much more realistic model of the mass distribution, based on state-of-the-art simulations, "the first numerical cosmological study that is fully relativistic, non-linear and without symmetry"[47,48]. They stressed the scatter in the distance for a given redshift, which generally increases with redshift and is also dependent on the line of sight.

Classical cosmology

My definition of classical cosmology is the comparison with observations of a quantity the dependence of which on z depends on the values of H_0, λ_0, and Ω_0; such quantities depend on one or more types of distance. Since η influences the dependence of distances on z, it is clear that its effects must be considered when doing observational cosmology.

Magnitude–redshift relation

One of the most important advances in observational cosmology has been the application of the m–z relation to type-Ia supernovae. Goobar & Perlmutter[34] discussed the feasibility of such a programme, and were later involved in the Supernova Cosmology Project, which reported measurements of λ_0 and Ω_0 based on 42 supernovae[49,50], a result confirmed and published slightly earlier by the High-z Supernova Search team[51,52]. While there had been hints, based on joint constraints from several cosmological tests, not only that the cosmological constant is positive but also that it has such a value that the Universe is currently accelerating[32,33], the m–z relation for type-Ia supernovae was the first cosmological test which, by itself, confirmed such a value for λ_0. (Contrary to some claims, this test does not 'directly' measure acceleration in any meaningful sense, even if one does not adopt the extreme view that all that is ever 'really' measured in observational astronomy, whether in imaging or in spectroscopy, are photon counts as a function of position on a detector.) Perlmutter *et al.*[49] also checked for the influence of η, using the FORTRAN code of KHS to compare the standard distance to that of two other models, one with $\eta = 0$ and the other with $\eta = \eta(\Omega_0)$, the latter based on the idea that all matter is in clumps for $\Omega_0 \leq 0{\cdot}25$ and for $\Omega_0 \geq 0{\cdot}25$ the fraction $0{\cdot}25/\Omega_0$ is in clumps, thus $\eta = 0$ for $\Omega_0 \leq 0{\cdot}25$, otherwise $\eta = 1 - 0{\cdot}25/\Omega_0$. Their conclusion, based of course on their data at the time, is that significant differences occur only for models ruled out by other arguments, *i.e.*, $\Omega_0 > 1$.

Kantowski *et al.*[36], still using the soon-to-be-obsolete q_0-notation, had pointed out that η should be taken into account when discussing the m–z relation for type-Ia supernovae. They also presented an analytic solution for $\lambda_0 = 0$ but arbitrary Ω_0 and η, and introduced the parameter ν:

$$\eta = 1 - \frac{\nu(\nu + 1)}{6}, \qquad (9)$$

due to the fact that there are analytic solutions for certain integer values of ν.

Iwata & Yoo[53] assumed a flat universe and, taking Ω_0 from CMB measurements, then calculated $\eta(z)$ such that the cosmological parameters from the m–z relation for type-Ia supernovae agree; this was done for four different scenarios. This is complementary to the work of Helbig[54] (next paragraph) who, at almost exactly the same time, considered only constant η but for arbitrary FRW models, determining the value of η such that the m–z relation for type-Ia supernovae results in the same values for λ_0 and Ω_0 as those derived from the CMB.

Helbig[54] investigated the influence of η, noting that more and higher-redshift data had become available. While the data were not good enough to determine λ_0, Ω_0, and η simultaneously*, the constraints in the λ_0–Ω_0 plane depend strongly on η. Only by assuming $\eta \approx 1$ does one recover the concordance-cosmology values of $\lambda_0 \approx 0{\cdot}7$ and $\Omega_0 \approx 0{\cdot}3$. Since these values are now known to high precision independently of the m–z relation for type-Ia supernovae (*e.g.*, refs. 55–57), one can use the m–z relation for type-Ia supernovae to measure η. The result $\eta \approx 1$ agrees well with other tests to determine η from observations.

*This would imply the somewhat dubious assumption that η is independent of both redshift and the line of sight. Of course, more-realistic models could take such effects into account, but obviously the data would not be able to constrain them since even the simpler model with a constant η could not be constrained.

(While no useful constraints are possible, the global maximum likelihood in the λ_0–Ω_0–η cube also indicates a high value of η.) Unknown to me at the time, very similar results, based on the same data, were obtained by Yang *et al.*[58], Bréton & Montiel[59], and, somewhat later, Li *et al.*[60] (the latter two restricted to a flat universe). While perhaps not surprising, it is of course important in science for results to be confirmed by others working independently. Although they investigated a wider range of models, when restricted to standard FRW models, the results of Dhawan *et al.*[61] are also consistent.

As mentioned above, for objects with an appreciable angular size, it is not surprising that $\eta \approx 1$, since clumps would have to be very big and thus few and far between in order that a relatively thick beam could be under-dense; it is surprising that $\eta \approx 1$ holds for even the very thin beams of supernovae. The supernovae discussed above are at distances of up to a gigaparsec or so, while the physical size of the visible supernovae is roughly the size of the Solar System, so the beams are very thin indeed.

Since the observations indicate that $\eta \approx 1$, one can ask whether this is true 'on average' as discussed by Weinberg[19], or whether each line of sight indicates $\eta \approx 1$. In the former case, one would expect a dispersion in the distance at high redshift. Indeed, the scatter does increase with redshift, but so do the observational uncertainties. Since their quotient is independent of redshift, this indicates that each line of sight indicates $\eta \approx 1$, in other words that all lines of sight fairly sample the mass distribution of the Universe[62].*

One of the basic cosmological tests is the 'standard rod' test, *i.e.*, the comparison of the angular size as a function of redshift of an object of given size to the theoretical expectation derived from the angular-size–redshift relation, which in turn depends on the cosmological parameters. (By the same token, the calculation of the physical size from the observed angular size depends on the cosmological model, and on η.) Although a classic test, no useful constraints have been derived from it — except in the cases of the CMB and BAO, though here the corresponding physical lengths are so large that the ZKDR distance plays no role (*e.g.*, ref. 63) — primarily because of the diffculty in finding a standard rod. Nevertheless, some progress can be made. For example, using a large sample of milliarcsecond radio sources Alcaniz *et al.*[64], assuming a Gaussian prior $\Omega_0 = 0{\cdot}35 \pm 0{\cdot}07$ in a flat universe, found the best fit at $\Omega_0 = 0{\cdot}35$ and $\eta = 0{\cdot}8$ (with no prior on Ω_0, the results were $\Omega_0 = 0{\cdot}2$ and $\eta = 1{\cdot}0$), consistent with the results with respect to the m–z relation discussed above.

Gravitational lensing

In gravitational lensing, it is clear that the approximation of a completely homogeneous universe with regard to light propagation cannot be valid, since otherwise there would be no gravitational lensing. Perhaps for this reason, the ZKDR distance has been used more in gravitational lensing than in other fields.

Asada[65] assumed the validity of the ZKDR distance and used it to investigate how inhomogeneities affect observations of gravitational lenses, in particular bending angle, lensing statistics, and time delay. An interesting analytic result

*This does not imply that the Universe is effectively homogeneous, but rather that the distance calculated from redshift is approximately the same as that which would be calculated in an effectively homogeneous universe.

is that all three combinations of distances* involved in these phenomena are monotonic with respect to the clumpiness for all combinations of λ_0, Ω_0, and source and lens redshifts. The clumpiness decreases the bending angle and number of strong-lensing events and increases the time delay. In the first two cases, decreasing η has the same effect as decreasing λ_0. In other words, using a value of η which is too large (such as the common assumption $\eta = 1$) would lead one to underestimate the value of λ_0.†

At almost the same time (publication was one month later) and completely independently, Helbig[66] investigated not the common gravitational-lensing topics mentioned above, but rather the correlation between image separation and source redshift, in a reply to the work of Park & Gott[67] who had noted a negative correlation. Helbig[66] showed that decreasing η has the same effect as decreasing $K := \lambda_0 + \Omega_0 - 1$ (*i.e.*, this effect is also monotonic in η); also, decreasing η reduces the differences between cosmological models characterized by λ_0 and Ω_0. The strong negative correlation reported by Park & Gott[67], though, seems to be based on an unclean data sample and also is not statistically significant.

The basic observational quantities in a strong (*e.g.*, multiple-image) gravitational-lens system — angles, flux ratios — are dimensionless, except for the time delays between pairs of images[68]. This allows one to determine the Hubble constant from a measurement of the time delay, assuming a mass model for the lens. However, this is true only in the low-redshift limit; at higher redshift, the cosmological model plays a role[69]. The cosmological parameters Ω_0 and λ_0 are now known very well from cosmological tests other than gravitational-lensing time delays (*e.g.*, refs. 55–57); one could thus assume them to be known exactly and use observations related to cosmological distances to determine η (*e.g.*, ref. 54). Within the uncertainties as they were 35–40 years ago, for the angular-size distance, at low redshift the values of Ω_0 and λ_0 are more important, while η becomes more important at high redshift (*e.g.*, see Fig. 2). Due to the different combination of angular-size distances, for lensing statistics the effect of η tends to cancel (*e.g.*, ref. 2), while in the case of gravitational-lensing time delays the importance of η is enhanced even at lower redshift (*e.g.*, refs. 70,71).

Kayser & Refsdal[70] illustrated this dramatically for several world models with $\lambda_0 = 0$, comparing the $\eta = 1$ and $\eta = 0$ cases. For the double quasar 0957+561[72], the cosmological correction factor (which gives the influence of the cosmological model compared to the limiting low-redshift case) was calculated for σ_0 values ranging from 0 to 2 (corresponding to $0 \leq \Omega_0 \leq 4$) with q_0 values of 1·0, 0·5, 0·0, and −1 ($\lambda_0 = \sigma_0 - q_0$). Helbig[71] repeated the exercise for arbitrary combinations of λ_0, Ω_0, and η, again showing the importance of η, which has become even more important now that the values of λ_0 and Ω_0 are so well known.

While the idea is simple in principle[68], in practice many details need to be taken into account when determining H_0 from gravitational-lens time delays (especially if the uncertainties should be small enough to be competitive with

*The combinations are D_{ds}/D_s, $D_d D_{ds}/D_s$, and $D_d D_s/D_{ds}$, respectively. The subscripts refer to the deflector (lens) and source. In the case of only one subscript, it is the second, the first being understood to refer to the observer. This is probably the most common notation. Other schemes explicitly write the first subscript when it refers to the observer as well, use 'l' instead of 'd' to refer to the lens (deflector), use capital letters, or some combination of these. The same subscripts are used to refer to the corresponding redshifts, *e.g.*, z_s, though sometimes z_d is used in the sense of a variable and z_l to refer to the redshift of an explicit gravitational lens.

†Note that this is opposite to the effect in the m–z relation.

other methods), such as measuring the time delay itself and determining realistic uncertainties (*e.g.*, ref. 73), and constructing a realistic mass model for the lens (*e.g.*, refs. 74 & 75). At this level of detail, characterizing the density along the line of sight by a single parameter η, or even $\eta(z)$, is too coarse. Rather, one attempts to measure the mass distribution explicitly, by counting galaxies (*e.g.*, ref. 76) or using weak gravitational lensing (*e.g.*, ref. 77).

Weak gravitational lensing is normally defined as gravitational lensing without multiple images. If the source can be resolved, then information can be gleaned from the distortion of the image. In such a case, however, if the source is at a cosmological distance, $\eta \approx 1$ (because the distance implies a large physical extent near the source, averaging over the matter distribution, and because it appears that, at large redshift, distances behave as if $\eta \approx 1$, as noted above). Relevant for the ZKDR distance with respect to weak lensing is thus weak lensing of point sources.

Wang[78] pointed out that weak lensing leads to a non-Gaussian magnification distribution of standard candles at a given redshift, due to the fact that η can vary with direction. One can thus think of our Universe as a mosaic of cones centred on the observer, each with a different value of η, where there is a unique mapping between η and the magnification of a source. Of course, since the ZKDR distance depends on Ω_0 and λ_0 as well as η, different cosmological models can lead to very different magnification distributions for the same matter distribution.*

Williams & Song[79] took the opposite approach: assuming that the standard distance ($\eta = 1$) is correct, they found that bright SNe are preferentially found behind regions (5–15 arcmin in radius) that are over-dense in the foreground due to $z \approx 0{\cdot}1$ galaxies, the difference between brightest and faintest being about 0·3–0·4 mag. (In other words, the fact that bright supernovae are preferentially found behind over-dense regions indicates that the standard distance is incorrect.) The effect, significant at > 99 per cent, depends on the amount and distribution of matter along the line of sight to the sources but not on the details of the galaxy-biassing scheme.

In a very detailed work, Kainulainen & Marra[80] studied the effects of weak gravitational lensing caused by a stochastic distribution of dark-matter haloes, restricted to flat FRW models and examining those with $\Omega_0 = 0{\cdot}28$ (close to the current concordance model) and $\Omega_0 = 1$ (the Einstein–de Sitter model) as representative examples. In particular, they calculated the difference between the distance in their model and the ZKDR distance for $\eta = 0{\cdot}5$ and $\eta = 0$ for these two models, finding a maximum relative error of only 0·06 for the extreme case of the empty-beam Einstein–de Sitter model at $z = 1{\cdot}6$ (the upper limit of their redshift range). This is yet another example of the proof of the validity of the assumptions underlying the ZKDR distance.

The situation today

The basis of observational cosmology is calculating the dependence of some observational quantity — usually related to some distance — on redshift for a variety of cosmological models, then determining the corresponding cosmological parameters *via* finding the model which gives the best fit to the

*Note that her claim that Perlmutter *et al.*[49] "assumed a smooth universe" is somewhat misleading. While they did not consider a direction-dependent η, they did compare the extreme cases of $\eta = 1$ and $\eta = 0$ as well as the case of an Ω_0-dependent η (*i.e.*, galaxies assigned to clumps and the rest of the matter distributed smoothly, which implies an increase in η with increasing Ω_0), in all cases using the code of KHS.

data. Small-scale inhomogeneities can affect the relation between redshift and distance, thus it at least needs to be investigated whether results depend on the amount of inhomogeneity.

"We are now in the era of precision cosmology" is something that I have heard at many talks and read in many papers. At the same time, one rarely hears about the ZKDR distance today. True, one rarely heard of it 40 years ago, but it was not necessary then since there was essentially no high-redshift observational cosmology involving objects of essentially point-like angular size. Nevertheless, even practical "astronomers at the telescope", as Sandage referred to himself and colleagues[1], were aware of the fact that one sees high-redshift objects by looking between foreground galaxies (due to selection effects or design), and thus the ZKDR distance should be used in those cases. While the main Supernova Cosmology Project paper[49] did look at the influence of η, and (correctly) concluded that it wasn't necessary to take into account with the data they had at the time, after their work such tests were either not done or if so not published until about ten years later. Even then, it was not the teams doing supernova cosmology themselves but rather others re-analysing data from the literature. Perhaps the impression had been created that η didn't need to be taken into account, even though it should have been obvious that one should at least check when higher-redshift data became available. To be sure, many independent investigations had come to the conclusion that $\eta \approx 1$, not just on average, as is to be expected, at least under certain assumptions[19], but also for each individual line of sight, but that does not seem to be the reason for the neglect of η. Perhaps there was a desire to make a clean argument, especially as the results are based on one of *the* classical cosmological tests. Taking η into account weakens the constraints on λ_0 and Ω_0 (even though, in principle, such constraints might be more accurate even though less precise) and also makes clear the approximation — complete homogeneity — used. Of course, the CMB — like baryon acoustic oscillations (BAO) — has more parameters, but these are well understood; η itself is a very rough approximation; the more one thinks about it, the clearer it becomes how rough it is. While one can both see a variation of η among lines of sight as an additional source of uncertainty as well as, at least numerically, use $\eta = \eta(z)$, one doesn't know *a priori* which lines of sight are under-dense (or over-dense) nor the form of the function $\eta = \eta(z)$ (though, as mentioned above, it probably generally increases with z). Indeed, the current practice, for those who care about such details, is to try to *measure* η along a given line of sight and take the value explicitly into account (though this is often expressed as "measuring the convergence"), or even taking individual galaxies along the line of sight explicitly into consideration when modelling a gravitational-lens system (as opposed to just a main lens and some additional convergence and/or shear).

On the other hand, we have been lucky. It seems that, at least to the extent that inhomogeneity can be described by η, observations do indicate $\eta \approx 1$ (at least effectively), so in practice leaving it out of consideration doesn't make a very big difference. It didn't have to be that way. There is no question that the ZKDR distance is appropriate in a universe with a mass distribution corresponding to that on which the assumptions leading to the ZKDR distance are based. However, it seems that our Universe is not like that. Rather, it consists of a 'cosmic web', a large-scale structure of voids, sheets, filaments, and rich clusters of galaxies. There is probably no smooth component on cosmological scales, but a mixture of regions of density which are less than and others which are (very much) more than the average density. For an object distant enough that the inhomogeneity can appreciably affect the distance, the beam traverses such a large portion of the Universe that it is effectively a fair sample, so that the distance calculated from the redshift is roughly the same as the ZKDR distance with $\eta \approx 1$. Also, the classic cosmological tests such as the m–z relation have to some extent been superseded by the CMB, BAO, and weak lensing (of resolved galaxies) which, due to the larger angular scales, are much less sensitive to η. In fact, measuring λ_0 and Ω_0 *via* these other tests allows one to use the classic tests to measure η, rather than it being an additional (nuisance) parameter, which can provide some information on the distribution of dark matter.

Acknowledgements

Fig. 1 is taken from Helbig[8] and Fig. 2 from Kayser *et al.*[3]. This text is an 'executive summary' of and borrows heavily from my recent review of this topic[8] which can be consulted for more details.

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REVIEWS

At the Edge of Time: Exploring the Mysteries of our Universe's First Seconds, by Dan Hooper (Princeton University Press), 2019. Pp. 233, 22·5 × 15 cm. Price £22 (hardbound; ISBN 978 0 691 18356 5).

I thoroughly enjoyed reading this book. Although its title suggests that its principal concern is what happened during the first few moments of the Universe coming into being, it is in fact a brief but comprehensive account of the general development of current cosmological knowledge, written by an enthusiastic expert in the field and easy for the layman to follow. Cosmogony is a hugely interesting subject and I found it refreshing to read this up-to-date account of where we are today and how we got there.

It is also, as it turns out, frustrating, because the author is open in making it clear that our spectacular advances in observational techniques covering both the very large and the very small have so far thrown up more problems than clarity in our scientific comprehension of events. He cites dark matter, dark energy, early cosmic inflation, and the scarcity of antimatter as concepts with which we are still struggling, and points out that our current best mathematical calculations of quark/proton interactions, when applied to the Big Bang, simply do not throw up the atomic situation which we observe.

To put recent developments in perspective, I re-read my copy of George Gamow's 1952 book *The Creation of the Universe*, written when the Steady State hypothesis was still considered a real possibility. Always an entertaining writer, Gamow rather delightfully comments that one of the leading Steady State proponents, the eminent Russian astronomer Vorontzov-Velyaminov, had been obliged to accept it as an essential element of dialectic materialism; but Gamow's whole book is an impressive argument in favour of the Big Bang, or what he refers to as the big squeeze of previous universal matter into a primordial ylem of hot basic particles. This is remarkably similar to Dan Hooper's description in the book under review of an ultra-hot primordial plasma containing all known particle species, and bearing in mind that in 1952 the Cosmic Microwave Background had not become available for analysis and the particle awareness created by accelerators had yet to be developed, Gamow's book was conspicuously prescient in its content. What it did not contain — and here I am back to my use of the word "frustrating" at the beginning of the previous paragraph — was any hint that continuing discoveries would lead to more bewilderment.

Hooper is upbeat about the present problems, and is confident that the steady growth of scientific knowledge will enable us to know all, or at least a great deal more, quite soon; but the cumulative effect of his clear descriptions of currently baffling situations must leave the reader with some degree of doubt as to whether we will ever obtain a comfortably acceptable comprehension of what happened, what will happen, and why. He is forced to be liberal in his range of conjecture, putting forward possible explanations for observed situations — multi-dimensions, multiverses, string theory, M-theory, the Goldilocks argument — but this, while interesting, does not indicate any clear path through the ice, let alone a sight of open ocean ahead.

He is at pains to emphasize the importance of Einstein, Special and General Relativity, and the power and accuracy of its associated equations, but Einstein's explanation of gravity as Hooper summarizes it — "the curvature or distortion of space and time by matter and energy" — has never been as readily comprehensible to the average mind as the idea of Newton's attractive force operating between matter. It is interesting to see that Gamow in his 1952 book described the mathematical apparatus of the general theory of relativity as "nothing but a glorified generalisation of the old Newtonian theory of gravity".

At the root of the problem could perhaps be the fact that mathematics, however elegant and intellectually satisfying, does not necessarily reflect reality. In philosophical terms mathematics, the science of numbers, is a concept different in kind from atomic particles, which like their agglomerations, stars, galaxies, and indeed humans, constitute a different level of reality. In the same way, relativity's treatment of time as the fourth dimension should be tempered by an awareness that time is not a reality in the same class as space. We cannot observe time or mathematics in the same way that we observe planets or particles. But mathematics is such a powerful tool for the scientist, and the elegance of equations so seductive for gifted mathematicians, that their use in extending and confirming hypotheses is inevitable and dominant, nothwithstanding the fact that their alignment with observed realities can become blurred.

Interestingly, Gamow specifically, albeit briefly, raises the point in his book of what led up to the creation of the present Universe, and suggests a squeeze of a previous universe to its ultimate density, while Hooper, understandably enough, does not speculate about what preceded the Big Bang, but provides copious and fascinating details of what was happening immediately afterwards. The fact is, of course, that Hooper has a great deal more information to give us than was available to George Gamow; the initial separation of the four fundamental forces, the stabilization and accretion of elementary particles, spatial inflation; he would be over-egging the pudding by attempting any similar account of what might have gone before, as well as not having the same quality of information on which to base such conjecture.

The reader is inevitably left at the end of the book with a degree of awestruck bewilderment, but this is not the author's fault. Hooper makes it clear that any Grand Unified Theory is at present on hold due to the apparent incompatibility of relativity and quantum mechanics, but he does at the end of his book express the hope that a new theory of quantum gravity will be discovered to supplant General Relativity, a hope which I endorse on the understanding that it will not involve twenty-six dimensions. Perhaps a new form of mathematics which eschews quasi-realities like minus quantities and infinities can be developed.

In any event Dan Hooper has produced a book of thought-provoking interest to anyone attracted to cosmology professionally or as a layman. It is well presented, and includes a helpful diagram of the Big Bang, the value of which increases as the book is read.

In ending this review of a Big Bang-related book I cannot resist expressing my regret that the term Big Bang is now universally accepted. It is ugly and inaccurate — the initial situation was incomprehensibly small and devoid of sound waves — and was of course intended by Fred Hoyle as a term of derision. Something like "Primal Flash" would have been more appropriate and elegant, but it is all too late now! — COLIN COOKE.

What Stars Are Made Of: The Life of Cecilia Payne-Gaposchkin, by Donovan Moore (Harvard University Press), 2020. Pp. 298, 21·5 × 14·5 cm. Price £23·95/$29·95 (hardbound; ISBN 978 0 674 23737 7).

Cecilia Helena Payne (later Gaposchkin) is probably better known now to astronomers and historians of the field than she was for most of her life (1900–1979). Lots of us would now agree with Otto Struve, who said that her PhD dissertation was the most important such in the 20th Century (well, anyhow the first half; he died in 1963). She clearly deserves an outstanding biography, by someone who understands the times, the science, and what sort of person she must have been (I knew her only in the last decade of her life). There have been several attempts[1–8], of which this is the most recent, and author Donovan Moore has had access to those others, as well as archival materials associated with the terms of Harlow Shapley and Donald Menzel as directors at Harvard College Observatory, and a number of other source materials.

Let me give a very quick introduction to her before further exploring the present volume. She was English-born, received a first degree from Cambridge University (when they finally gave women degrees), or at least the equivalent credentials from Newnham College. Arthur Stanley Eddington advised her to go the US if she wanted to be an astronomer. This she did in 1923, completing that thesis two years later. It had the definitive demonstrations that stars are made mostly of hydrogen and helium and that the mix of other elements was much the same in virtually all stars, with the prominence of various absorption lines driven by ionization temperature, with few exceptions.

Henry Norris Russell, Eddington, and other influential astronomers around her in 1925 accepted the latter conclusion, but not the former one until it had been rediscovered by other methods by other people (men of course). She remained at Harvard the rest of her career, finally being named a professor of astronomy and head of department in 1956. Payne became Payne-Gaposchkin in 1934, marrying Sergei Illarionovich, whom she had helped to rescue from Germany, where, as a Russian, he could no longer live safely; nor was Russia willing to have him back. The author has not made use of the 2002-page, three-volume autobiography called *Sergei*, or at least nowhere cites it. I don't know why, since it is delightful reading, salt shaker in hand. The Harvard library surely has copies of all three volumes (as do I).

The present volume focusses heavily on Payne's early life. Half way through the 298 pages of text, she is just negotiating with Shapley to come to Harvard. It includes some marvellous photos of Cecilia that have not appeared in earlier treatments of her life. Many (as well as additional information) came from the Gaposchkins' daughter, Katherine Haramundanis, co-author with her mother of an astronomy textbook, and still to be found in recent directories of the American Astronomical Society. My absolute favourite photo, however, is credited to Smith College Special Collections, and so almost certainly dates from 1943, when Smith bestowed an honorary degree upon her.

During my year on the Smith faculty (1968–69), president Mendenhall asked me for a suggestion of a woman astronomer on whom such a degree might suitably be conferred. My first thought was, of course, CHP-G. But back came the answer "Your person already has one". I cannot remember whether I then proposed Margaret Burbidge, but in fact she already had one too (in 1963).

Author Moore is a writer, not an astronomer, and perhaps has not fully appreciated just how different calibrating brightnesses of variable stars on photographic plates (the task assigned to Cecilia and Sergei by Shapley from the 1930s onward, and by Menzel thereafter) is from measuring line intensities in spectrograms and fitting them with temperatures, pressures, and compositions. Cecilia felt the difference strongly and was never quite happy with the later sorts of tasks. Some howlers that were present in an early draft of the book (which David DeVorkin and I attempted to modify) are gone, though Moore seems to remain of the opinion that Newnham was the only women's college in Cambridge at the time. Girton is indeed a smidge older, though not under that name. And in Cecilia's time, the Girton girls were well known to have nicer legs, because it was a longer cycling distance into town for them than for the Newnham ladies.

Covered in some detail here and not mentioned at all in most of the earlier sources is a few months of intense courtship of Cecilia Payne by Norbert Wiener (father of cyber-everything, 1894–1964). The supporting documentation includes a number of letters from him to his sister, brother, and parents, dated from 1925 June, when they met on board ship, onward. She backs off, and he soon after marries the German-born woman who had previously been his fiancée. His Wikipedia entry says the marriage was arranged by his parents. Payne clearly did not want to be the wife of a professor of science; she wanted to *be* a professor of science! Any woman who is likely to read this will almost certainly concur. His letters are part of the collection of his papers at MIT.

Is this a book to buy? The price is wholly reasonable by current standards, and it should be part of a collection. If you are having only one, I suppose, I would recommend the autobiography[1] (the second edition, with my preface added), and next *The Starry Universe*[2].

One counterfactual question is irresistible: was Cecilia Payne wise to leave England? The careers of Mary Cartwright and Bertha Swirles Jeffreys (also in ref. 5) suggest that women of the same generation could 'make it' at Cambridge. But they were Girton Girls; Cartwright was a mathematician; and Swirles married another, arguably more distinguished, scientist. Clearly we need a larger sample! But I was at Newnham and Girton, for one year each, and survived the experience 50 years later. — VIRGINIA TRIMBLE.

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An article by Katharine Haramundanis in Ref. 2 (pp. 1–66) has 63 figures, including many family and other photos of CHP-G, some with brave and largely successful efforts to identify all the people in conference photos.

Annals of the Deep Sky. A Survey of Galactic and Extragalactic Objects, by Jeff Kanipe & Dennis Webb (The First Seven Volumes) (Willmann Bell), 2019. 23 × 15·5 cm. Price $24·95 per volume (about £19) (paperback; ISBN 978 1 942675 00 6 *et seq*.)

This is a very ambitious project which aims to cover the 88 constellations of the sky to a sufficient depth of detail that would satisfy even the most rabid of observers. The general aim seems to be to compile a more up-to-date version of the well-known and well-loved three-volume set written by Robert Burnham Jr. which was published in 1978. "Amateur observers are curious about all aspects of the celestial objects they observe" say the authors in their introduction to Volume 1. The aim of the series, according to Kanipe and Webb, is "the goal of assisting amateur observers to embark on just this kind of exploration and enrichment by providing, in one place, a broad synthesis of astronomical knowledge that cannot be gleaned except by sifting through hundreds of other sources". The series under review started in 2014 and so far seven volumes of the *Annals* have appeared and they are discussed here. Assuming that each volume covers four constellations (on average), then the project will finish sometime in the 2030s with Volume 22, and will consequently occupy about 24 inches of shelf space.

The latest volume, which takes us as far as Crux, has been authored by Jeff Kanipe only, although Dennis Webb is still helping out with the illustrations. The constellations are being dealt with strictly alphabetically so that southern hemisphere observers will have to wait a while for Sagittarius and Vela. The content appears to have been adjusted so that each volume contains about 350 pages. This does result in a quasi-random set of entries at the end of each volume. Volume 2, for instance, contains about 70 pages of essential terminology, which might have been better included in Volume 1. Volume 3 contains 25 pages on 'The Search for Extrasolar Planets', and Volumes 4–6 have no end article. Volume 7 contains 60 pages on William Herschel and additionally includes 74 finding charts, one for each of the objects discovered by Herschel on 1785 April 11/12, his most productive observing night ever. (It is nice to see that each volume is dedicated to a notable observer; Volume 2 is dedicated to Robert Burnham Jr. and Volume 4 is dedicated to T. W. Webb.)

Each constellation starts with an overview of the historical and mythological background, and notes on the visibility of the constellation from anywhere on Earth and where it fits into the celestial sphere, followed by a selection of objects of interest. Not unsurprisingly these are dominated by deep-sky objects. This is especially true in constellations like Coma Berenices (Volume 6) whose 160 pages are given over to a great deal of detail on the Coma galaxy cluster. The brightest galaxies are extensively described and there are lists of the main component galaxies along with two charts showing, respectively, the inner one degree and inner four degrees of the cluster.

To give some idea of the relative coverage between Burnham and this publication, I selected at random the constellation Canes Venatici and examined the coverage of this small constellation. Although Burnham dedicates only 27 pages, he does manage to squeeze in entries for 81 double stars, 34 variables, and 16 deep-sky objects, many of which admittedly occupy one line. The *Annals* entry stretches to 110 pages and 'The Featured Objects' includes notes on one double star and 15 deep-sky objects; M51 and its companion galaxy NGC 5195 alone occupy 22 pages.

Double stars are dealt with either as a short one-line list of the brightest and easiest pairs in each constellation marked "for beginners" and plotted on maps of the constellation, or individually as binary systems of particular interest such as zeta Aqr, 36 And, and so on, which attract several pages of discussion. The term 'subcompanion' is used to indicate additional members of the system but I believe the term subcomponent is more generally used.

The books are printed on good-quality paper with (to this reviewer's eyes) a satisfyingly large font, although the relatively small size means that some illustrations need to be considerably reduced; however, everything is clearly reproduced. If your bent runs to deep-sky observing then you will want to obtain these volumes. — ROBERT ARGYLE.

Lectures on Astrophysics, by Steven Weinberg (Cambridge University Press), 2020. Pp. 214, 25·5 × 18 cm. Price £34·99/$44·99 (hardbound; ISBN 978 1 108 41507 1).

This book is based on a course of lectures given by the author in Texas in 2016 and 2017, on 'Stars, Binaries, Interstellar Medium and Galaxies'. The author does not identify the level of the readership, but he does say it should be accessible to anyone with a good undergraduate background in physics and mathematics. Agreed — provided that we put a strong emphasis on 'good', for this is not a book for the B-grader. Much of astronomy today depends upon immense numerical computations. Weinberg's aim is to avoid this as far as possible by developing explicit analytical solutions to astrophysical problems. The only drawback to this is that it often requires a level of mathematical ability with which not all of us are blessed. The author is aware of this, and wisely relegates the more difficult parts (such as, for example, a rapid course in General Relativity) to Appendices to the appropriate chapters. While the mathematics is difficult (often because of unconventional notation), the text between the mathematical parts is exceptionally clear and indeed exciting. Like Lagrange's *Méchanique Analytique*, which famously boasts of having no drawings since it can all be done analytically, this book, too, has no drawings. This is no great disadvantage, and is probably part of the reason why the price is so reasonable.

'Stars' covers most of the standard stuff on stellar atmospheres and interiors, with which many of us will be fairly familiar, but also goes into welcome physical and mathematical detail on less familiar material on white dwarfs, neutron stars, and supermassive stars. Did you know that the Sun rotates at 5×10^{-7} revs per second? And that if you take its size down to a few km, this rate will increase by 10^{10} to thousands of revs per second? And that if it were rotating at such a speed, the centrifugal force at the equator would be greater than the surface gravity, so the star would fly apart, if gravity were the only force keeping it together? And hence if such a rapidly-rotating body of solar mass is rotating at such a speed, there must be some other force holding it together? Such as the residual strong interactions between neutrons, for example? Fascinating! A section that particularly interested me in the chapter on stars illustrates the enormous power of dimensional analysis in stellar theory. Weinberg shows how you can almost predict the Hertzprung–Russell diagram by dimensional considerations alone.

A chapter on 'Binary Stars' does not repeat standard instructions on the determination of orbital elements. Rather it moves on to interesting physics beyond this. This includes a new explicit expression for the volume of a Roche lobe, in which the answer includes the expression $2(\tanh^{-1}2 - \tanh^{-1}\sqrt{3})$, an example of how the mathematics sometimes seems difficult by writing it in an unconventional way. If you can find the numerical value of this expression in less than 15 minutes, your mathematics is probably well able to cope with the book. Those who have studied spectroscopic binaries know that the only information you can get on the masses of a single-lined binary is the 'mass function'. Weinberg goes on to show, however, that if you are gifted at mathematical physics, you can go one better and get the sum of the masses. And if you are *very* gifted you can go yet further and get the individual masses — from a single-lined binary! How? Read the book and find out! Some of the most interesting material on binaries includes the theory of gravitational-wave emission from binary pulsars and coalescing binaries, as well as the detailed theory of the detection and interpretation of such waves. The account here is truly excellent, and makes one believe that such waves really *have* been detected, and how.

The chapter on the interstellar medium, which includes a great deal on atomic and molecular spectroscopy, is the only section on which I felt myself qualified to make a critical judgment, and all I can say is that the spectroscopy is faultless! The most abundant molecule in the interstellar medium is H_2 — but CO is perhaps the most important molecule to help an interstellar cloud to cool to a level in which star formation can begin. Why is this? There are two reasons: CO is heteronuclear while H_2 is homonuclear. And CO has a larger moment of inertia than H_2. What has that got to do with anything? You'll find the answers in the book.

The final chapter is on galaxies. What is the ratio of baryonic to dark matter in galaxies, and in clusters of galaxies? Is it the same in both? Do the spiral arms of galaxies lead or trail? What is their pitch and how tightly wound are they? All of this and more is discussed in quantitative analytical detail.

The book has twelve miscellaneous problems (without solutions). Seeing them made me glad that I no longer have to take exams. To try them, I had to look back into the text and carefully re-read the sections that I had skipped over, and that surely means that they are good and instructive questions.

My search with evil intent for minor mistakes and typos was not very successful and yielded only two minor typos that are unlikely to confuse a reader. My best find, however, was finding six mistakes in the very opening sentence, in which the author has Bessel living from 1766 to 1828 and measuring the parallax of Y Cygni, and Wollaston living from 1784 to 1826 and measuring the parallax of α Centauri. (Bessel measured 61 Cygni in 1838 while he was still alive, and as far as I know the English chemist Wollaston had little if any connection with astronomy.) But don't let this embarrassing initial disaster put you off — the rest is not like that at all!

Bottom line — should you get this book? I would have to say that the stronger you are at mathematics, the more you will get out of the book. But even if you feel that you are not heavily mathematically inclined, the explanatory texts in the equation-free paragraphs are a model of clarity. The book is strong on modern topics, so, if you haven't updated your astrophysics teaching notes for a long time, and you wish to update them with modern topics, this is just the very book you need. — JEREMY TATUM.

Astronomical Data Analysis Software and Systems XXVI (ASP Conference Series, Vol. 521), edited by Marco Molinaro, Keith Shortridge & Fabio Pasian (Astronomical Society of the Pacific), 2019. Pp. 788, 23·5 × 15·5 cm. Price $88 (about £69) (hardbound; ISBN 978 1 58381 929 6).

Astronomical Data Analysis Software and Systems XXVII (ASP Conference Series, Vol. 522), edited by Pascal Ballester, Jorge Ibsen, Mauricio Solar & Keith Shortridge (Astronomical Society of the Pacific), 2019. Pp. 756, 23·5 × 15·5 cm. Price $88 (about £69) (hardbound; ISBN 978 1 58381 931 9).

Astronomical Data Analysis Software and Systems XXVIII (ASP Conference Series, Vol. 523), edited by Peter J. Teuben *et al.* (Astronomical Society of the Pacific), 2019. Pp. 753, 23·5 × 15·5 cm. Price $88 (about £69) (hardbound; ISBN 978 1 58381 933 3).

Anyone who has used an astronomical software package, or explored the website of an observatory or data archive, may have wondered if there was anything newer or better out there. Search engines are not much help with open-ended queries like this, so these volumes might well be a good place to look. One appears annually as a record of an ADASS conference and each contains a hundred or more papers typically four pages long. Some report on progress in large projects such as *ALMA*, *Gaia*, and *LSST*; others describe new software that the authors are usually happy to share; and there are also papers outlining novel astronomical algorithms. In the 28th volume there is a whole section on Machine Learning (what is often mis-called Artificial Intelligence in the popular press). This contains 18 papers on astronomical applications of ML and one on detecting wildlife: 'Saving endangered species with astro-ecology'. I think many astronomers would find it useful at least to skim the table of contents of each volume as it appears. Any library which subscribes to ASP conference proceedings should have them on the shelves, while adass.org makes everything available on-line. — CLIVE PAGE.

Fred Whipple's Empire: the Smithsonian Astrophysical Observatory, 1955–1973, by David H. DeVorkin (Smithsonian Institutions Scholarly Press, Washington DC), 2018. Pp. 401, 25 × 17 cm. Price \$79·95 (about £62) (paperback; ISBN 978 1 944466 18 3).

Once upon a time, astronomical institutions built in the image of a long-term, powerful leader were common. One thinks of Henry Norris Russell at Princeton, Arthur Stanley Eddington at Cambridge (UK), Harlow Shapley at Harvard, and George Ellery Hale at Yerkes and Mt. Wilson Observatories. Fred (Lawrence) Whipple (1906–2004) was among the last of these, holding sway and moulding the Smithsonian Astrophysical Observatory from its 1955 move from the Washington DC area to the environs of Harvard until its merger with Harvard College Observatory in 1973 to form the Center for Astrophysics.

It is the saga of both Whipple and the SAO that author David DeVorkin has told us in this deeply-researched volume. The time frame is very much his own, for he has written previously about Russell, Shapley, Donald H. Menzel (Shapley's successor at HCO), and Charles Greeley Abbot, a long-time champion of SAO and of its programme to measure variability of the solar constant, though you might remember him as the secretary of the US National Academy of Sciences who participated in arranging the 1920 Curtis–Shapley debate. Shapley and Abbot both died in 1973, apparently a bad year for folks involved in those institutions. The successor, first director of the unified CfA, George Field, is happily still with us.

For those of us who remember the period as "the good old days", the major surprise is just how contentious Whipple's arrival and departure both were. Late in the process of unifying HCO and SAO (which Whipple opposed to the last), Jesse Greenstein (Caltech and long a member of the Harvard Board of Visitors) and Alex Dalgarno, who was to head one of the new divisions, looked into finding promising women and minority candidates. The strongest such candidate, Andrea Dupree, was judged not ready for a leadership role. This will come as no surprise to her, as she was one of about 30 (mostly) astronomers with whom DeVorkin conducted oral history interviews between 1969 and 2010, many of the later ones specifically for this project, which, as the author indicates in his acknowledgements, he had been thinking about for some 15 years.

The scope of the volume is broad: one column of the index includes 21 people (all men as it happens), for only 11 of whom could I have told you before reading this book what they did. And there are women in the story, including Katharine Gaposchkin-Haramundanis and her mother Cecilia Payne-Gaposchkin, who both worked on the *Celescope* project and tried to make some use of the ultraviolet data it produced. Brother Michael Gaposchkin was there too for a while, within the Computational Division of SAO. And Sergei was also at Harvard College Observatory from 1934 until his death a few years after Cecilia, but you will not find out from this book what he did. Edward Haramundanis, a mathematician, was also involved.

Other initiatives supported by Whipple have been great successes, for instance, the *Multi-Mirror Telescope* (actually now a monolith) on the relatively dark site of Mt. Hopkins in Arizona. The Observatory now carries his name. Another success was the *Large Optical Reflector*, a mosaic to catch Cerenkov radiation when high-energy gamma rays hit the Earth's atmosphere. Trevor Weekes and Giovanni Fazio were among the others associated with that innovation, and it was Whipple Observatory results that persuaded many astronomers that ground-based gamma-ray astronomy made sense and cygnettes did not exist. Whipple was also an early enthusiast (by American standards at least) for radio astronomy. He and Greenstein wrote a 1937 paper which confessed in effect that they did not understand the large radio fluxes coming from the Milky Way that had been detected by Karl Jansky and Grote Reber. Whipple, however, favoured a really big radio dish in the American North East over the plan for the *Very Large Array* in the American South West. The *VLA* was the winner, both politically and scientifically. It had the additional advantage of being capable of piece-by-piece construction, usable as it went. European astronomers exploited this merit in constructing the *Very Large Telescope* of four mirrors in Chile, but seem to have forgotten it.

It came as a surprise to me, who had known Fred only in his later life as a kindly, seemingly-serene gentleman, who continued to send real paper birthday cards when others were resorting to email, to learn that he had suffered a major breakdown in 1942, which was treated over months by repeated rounds of electro-shock therapy.

Despite the richness of information in this book, I still have at least one question. Fig. 47 shows Dave Latham and Robert Stefanic at the 61-inch telescope at Oak Ridge, MA, with one of their 'digital speedometers', used to obtain highly precise radial velocities. How did it work, and was it in any way related to the radial-velocity spectrometer developed at Cambridge (UK) by Roger Griffin in the same time frame?

Conflict of interest: not only was my copy an autographed gift from the author, but we have been friends since we were undergraduates together at UCLA in the early 1960s. — VIRGINIA TRIMBLE.

Astrophysics of Planetary Formation, 2nd Edition, by Philip J. Armitage (Cambridge University Press), 2020. Pp. 332, 25 × 18 cm. Price £59·99/$79·99 (hardbound; ISBN 978 1 108 42050 1).

An astronomical advance is made. The cry goes up "the text-books will have to be rewritten". This is rarely the case but there are exceptions, and cosmogony is one of them.

The watershed was the mid-1990s. Before then we knew of nine planets; our nine. The Solar System was flat, the orbits near-circular, and the division into terrestrial and gas giants seemed reasonable and temperature dependent. Most folk who studied the possible origin processes believed that the planets were coeval with the Sun, and formed by the condensation of a nebular cloud left behind after the solar collapse. Victor Safronov's monograph *Evolution of the Protoplanetary Cloud and Formation of the Earth and the Planets* was always close to hand.

But then came a huge change. By 2020 March 1 astronomers had discovered 4187 exoplanets, in 3105 systems. The majority of these systems had Sun-like central stars. High metallicity was important. But the big surprise was the number of hot Jupiters. Many of the newly-found systems had massive planets in Mercury-like orbits close to the central star. Clearly there was a huge variety of systems out there, and there must be diverse origin processes.

Philip Armitage taught a graduate course on the subject at the University of Colorado in Boulder. One of the results was the text-book under review. It is accurately targeted at advanced students proficient in astronomy, physics, and mathematics. The first edition was published in 2009. Since then NASA's *Kepler* mission has dramatically increased our knowledge of the small planetary population, and the *ALMA* radio telescope has provided many detailed images of protoplanetary discs.

The first chapter discusses the relevant characteristics of our planetary system, how exoplanets have been discovered, and the properties of these extrasolar systems. Chapter 2 reviews the observed properties of protoplanetary discs. Radial temperature profiles, vertical structure, ionization states, and condensation sequences are considered. Chapter 3 concentrates on disc evolution and topics such as magnetohydrodynamic angular-momentum transport, disc winds, and disc dispersal are considered. The next two chapters investigate the production of planetesimals. After the formation of these 100-m- to 100-km-sized bodies gravitational accretion takes over. Collisions, coagulation, accretion, and drag are all important. By Chapter 6 we have reached the giant planets and topics such as core formation and hydrostatic growth become significant.

Finally comes the topic of migration in what remains of the gaseous nebula and the importance of interplanetary resonances, and the Nice Model.

The end product is an absolutely first-class text-book. Armitage always has the needs of his students firmly in mind. His exposition is comprehensive, detailed, thorough, concise, and clear. This is coupled with the fact that the book is beautifully produced, and well-illustrated, and referenced. It will do much to encourage more scientists to move into this fascinating field. — DAVID W. HUGHES.

THESIS ABSTRACT

NEW AVENUES IN ATMOSPHERIC MODELLING OF EXOPLANETS

By Siddharth Gandhi

In this thesis I explore various aspects of atmospheric characterization of exoplanets with the primary goal of understanding their chemical compositions and physical processes. My research led to the development of new, self-consistent models of exoplanetary atmospheres, a new paradigm for atmospheric retrievals of thermal-emission spectra, as well as chemical detections using both high-resolution Doppler spectroscopy as well as low-resolution transit spectroscopy.

I firstly computed the molecular and atomic cross-sections of various species prevalent in the atmospheres of such exoplanets in order to compute their spectra. The absorption cross-sections were calculated through the broadening of spectral lines obtained from high-resolution line lists. These cross-sections

and subsequent spectral models have led to the detections of numerous chemical species (HCN, TiO, Li, Na, K, CO, and H_2O) in the atmospheres of several exoplanets.

Recent advances in observations have heralded the need for accurate models of exoplanetary atmospheres. I have built a new self-consistent atmospheric model, GENESIS, custom built for exoplanets and demonstrated for irradiated and non-irradiated atmospheres over a wide range of atmospheric parameter space. The model treats line-by-line radiative transfer through the Feautrier method and radiative–convective equilibrium through the Rybicki Complete Linearization method in a plane-parallel atmosphere. This model allows for a detailed exploration of radiative processes and chemical compositions and their effects on observed emission spectra. I compared this model against several others in the literature and found good agreement between the atmospheric properties and emission spectra.

Thermal inversions have been seen on the dayside atmospheres of some hot Jupiters and have been predicted to be caused by TiO or VO due to their visible opacity. I used the GENESIS model to investigate the effect of visible opacity and deduced that many new species (AlO, CaO, NaH, and MgH), hitherto unexplored, are also capable of causing thermal inversions on hot Jupiters. I have explored the effect of these species as a function of their overall atmospheric abundance as well as determining the required abundance for each of these species to form an inversion. Secondly, I show that a low infrared opacity caused by a low H_2O abundance can also lead to strong thermal inversions even with sub-solar abundances of these visible absorbers due to the change in infrared opacity. As a demonstration of this work I have shown that the thermal inversion on WASP-121b can be explained by all the visible absorbers listed above. These thermal inversions are of great importance as the species responsible may be observed with current observational capabilities, thus providing testable observations for these species.

I have also developed a new hybrid retrieval method for exoplanetary emission spectra, HyDRA. This uses the latest atmospheric modelling tools to fit the observed spectra of exoplanet atmospheres. We explore a wide range of parameter space and determine the temperature profile and abundances of various species present in the dayside atmosphere through the emission spectra. These retrieved abundances are then used to explore disequilibrium processes which may be present through integration into the GENESIS self-consistent model. Such a framework allows constraints on departures of the temperature structures from radiative–convective equilibrium as well as chemical compositions from thermochemical equilibrium. I explored *HST* and *Spitzer* observations of WASP-43b and confirmed that the data were in agreement with radiative–convective equilibrium in the dayside atmosphere.

The HyDRA retrieval framework has also been extended to model the atmospheres of ultra-hot Jupiters with temperatures in excess of 2500 K. Such high temperatures can cause molecular species such as H_2O to dissociate thermally and for ionic species such as H^- to form. Such effects have been used to explain the largely featureless *WFC3* spectra seen for many ultra-hot Jupiters. I have included both of these effects into the HyDRA retrieval model to retrieve the atmosphere of the planet WASP-18b. I find that the retrieved abundances for H_2O and CO and the thermal inversion in the atmosphere do not change significantly compared to previous retrievals of WASP-18b which did not include thermal dissociation or H^- opacity. I also see no significant evidence for H^- or thermal dissociation in the atmosphere. With future instrumentation we may be more likely to constrain such effects in the emission spectra.

I have also used the HyDRA retrieval framework to perform a set of homogeneous retrievals for eight well-known hot Jupiters with high-precision *HST WFC3* spectra. These planets all also have *Spitzer* observations which I also used to explore the atmospheric temperature profile and chemical composition, in particular to explore the H_2O abundance. The eight explored planets span a wide range of equilibrium temperatures, including four which fall into the category of ultra-hot Jupiters. We find that the coolest planets in the study generally have better constrained H_2O abundances near solar composition due to strong H_2O absorption features. On the other hand, three of the hottest exoplanets exhibit thermal inversions and indicate very poorly constrained or sub-solar H_2O abundances. This study shows that even currently explored exoplanets exhibit a wide range of atmospheric properties and that we will be able to explore this diversity further with more exoplanetary spectra coming up in the next few years.

Finally, I have used the GENESIS model to enable chemical detections of molecular species using high-resolution Doppler spectroscopy of hot Jupiters. I generated high-resolution emission spectra of the hot Jupiters HD189733b and HD209458b for cross-correlation with the data obtained with the *VLT CRIRES* spectrograph. This helped us find evidence for H_2O, CO, and HCN in the atmospheres of both planets. In the future this method has great potential for new chemical detections due to its sensitivity to trace species, and shows great promise in the detection of biosignatures on smaller rocky planets.

— *University of Cambridge; accepted 2019 July*.

OBITUARIES

Derek Hugh Powell Jones (*1934–2020*)

Derek was born in Pinner, Middlesex, in 1934, the younger son of an architect, Leonard Jones. His mother, Ethel, worked for the 'friendly society' associated with the Transport & General Workers Union, which was absorbed into the Ministry of Labour after the Labour Government reformed National Insurance following WW II. At the start of the Second World War he was evacuated, age six, to a host family in Kelowna in the Okanagan valley, British Columbia, Canada. Although unrelated, he and his brother Bryan always referred to their hosts fondly as Uncle and Aunt, and Derek went back to visit them in Canada on several occasions. It was the tradition there for children to sleep on the porch in the hot summer where it was cooler. Derek, now aged 10, soon discovered a love for the stars and astronomy made visible by the dark skies, although this was somewhat obscured by the metal screening there to protect them from mosquitoes.

Once back in England, aged 11, Derek continued his education at the Royal Masonic School, Bushey, Hertfordshire, where he won a number of books as prizes, including one entitled *Building your own Telescope* which he duly did. At 18 he obtained state scholarships in pure and applied mathematics securing him a place at Christ's College, Cambridge.

Before starting at Cambridge, Derek had to undertake two years' National Service in the RAF. Considering his academic skills he was enlisted in the scientific advisory branch in High Holborn, London. His maths was used statistically to place new candidates in suitable posts, based on their application questionnaire and often using Brunsviga mechanical calculators.

As a student at Cambridge, Derek utilized his interest in maths and astronomy continuing with the RAF reserves as a trainee navigator. He regularly flew in Avro Ansons from Marshall's airfield, Cambridge, as well as joining in larger NATO operations. One of his most memorable operations was flying from Kinloss in Scotland up the Norwegian coast as part of an exercise to track naval movements in the area. He recalls vividly flying through spectacular northern lights as well as witnessing St Elmo's fire from the aircraft propellers.

Whilst at Cambridge he also answered an invitation from Dr. Richard Woolley to attend a summer course at the Royal Greenwich Observatory (RGO) at Herstmonceux. Dr. Woolley had recently arrived from Australia to lead the observatory but found it to be a moribund institution so was on a campaign to fill it with bright, young, keen astronomers. It was while Derek was here he met Thelma Anne Gray, also attending an RGO summer course from St Andrews University, and they later married in Herstmonceux church in 1960, with the reception in the castle as a special favour from Dr. Woolley. They went on to have five children: Timothy (born in the USA), Elizabeth (in the UK), Penelope and Thomas (both in South Africa), and Naomi (in Australia). His career in astronomy gave him children born on four different continents.

After graduating from Cambridge as a Senior Optimes in mathematics, Derek took a full-time job at the Royal Greenwich Observatory as a scientific officer, joining the team using the 28-inch refractor for the observation of visual double stars led then by Dr. Woolley. He demonstrated the telescope to the Duke of Edinburgh when the Duke visited the RGO in 1958. Derek was then given a Commonwealth Fund Fellowship to Caltech and Mount Wilson in California for 21 months, observing red-dwarf stars which later became the topic of his PhD thesis. On return to England he successfully defended this thesis in 1965. He then joined the 36-inch-*Yapp*-reflector team led by now Sir Richard Woolley, and from 1965 to 1969 Derek and his new young family moved to the observatory then run by the Radcliffe Foundation in Pretoria. His work there was on regular Cape observations of radial velocities and also on the occasional observations of RR Lyrae stars. He was invited to the Australian National University's Mount Stromlo Observatory from 1969 to 1972, where he continued work on RR Lyrae variables and branched out into various topics in stellar kinematics. During this time his family lived in university housing in Hughes, Australian Capital Territory.

Returning to RGO Herstmonceux in 1972 he worked on the *Isaac Newton Telescope* (*INT*) in conjunction with K. F. Hartley and Jeremy Bailey (then a student) on interfacing signals from the *INT* to a digital computer. Jeremy Bailey also worked on the magnetic variable AM Herculis and another student Romylos Korakitis worked on the timings of the Crab Pulsar. During the 1970s Derek was captain of both the Observatory Hockey Team and the Observatory Quiz Team.

He was an active member of the Royal Astronomical Society, editing the *Monthly Notices* from 1977 to 1982 and *The Observatory* magazine from 1973 to

1977. He was also a Council Member from 1979 to 1982 and Vice-President in 1981.

The *INT* was moved to Newcastle-upon-Tyne in preparation for the Northern Hemisphere Observatory on Roque de los Muchachos, La Palma in the Canary Islands. In 1975 Derek undertook one of his first trips to the observatory at Izaña on Tenerife, run by Imperial College London. With the confirmation of the Roque de los Muchachos observatory, his work became more and more devoted to building it. He spent the 1980s focussed on the construction and operation of the 1-metre *Jacobus Kapteyn Telescope*. On completion of the observatory he engaged a further generation of students who worked on cataclysmic variable stars and who went on to distinguished careers. He lived on La Palma from 1988 to 1991 and again from 1993 to 1994, at the same time as he and the RGO moved to Cambridge, and before his retirement in 1994.

Following his retirement, he was active in supporting amateur astronomical societies and also delivered a course for 13 years at the University of the Third Age called 'Astronomy is Looking Up'. His last talk to the University of the Third Age was 'Our Crazy Calendar' in the summer of 2019.

His generous and unstinting guidance was appreciated by his many co-workers and students, one of whom characterized him as "one of the last gentleman astronomers", a compliment that described him perfectly. — THE JONES FAMILY.

Gordon Ernest Taylor (*1925–2020*)

Gordon was born in Birmingham and spent his early childhood there. His father died when he was 12 and his mother moved the family to Bristol where he attended Cotham School. Quite when his interest in astronomy began isn't clear but it was obviously well established by 1943 when he was one of the co-founders of the Bristol Astronomical Society, a connection he maintained for the rest of his life, latterly as a vice-president. On leaving school he worked at WD & HO Wills tobacco company before being called up for his National Service in the RAF. He was posted to The Gambia in West Africa where he received training as a meteorologist. When he was released from the RAF he continued to work for the Air Ministry making routine meteorological observations in Swansea. In early 1948 Gordon set in motion moves which resulted in the establishment of the Swansea Astronomical Society. The public lecture he gave in March to "stimulate enthusiasm for astronomy" was evidently successful since the society prospered then and is still active today. However, Gordon's time in Swansea as the society's Director of Observations was short-lived; by the time of their second AGM in 1949 September he had applied, and been accepted, for a job in the Nautical Almanac Office, still in its wartime location in Bath, and followed the office to its new home reunited with the observatory at Herstmonceux later that year. At lunch in the canteen on his first day he met Miss Violet Strong who worked in the General Office; they married two years later.

He was assigned to the Occultation Department, a circumstance which was to lead to a lifelong devotion and a high-profile international reputation. In order to monitor the fluctuations in the Earth's rate of rotation required to provide corrections to the Universal Time scale (aka GMT in the UK), the NAO had for many years been concerned with predicting and reducing the timings of occultations of stars by the edge of the Moon. These early predictions were made by means of an ingenious analogue device known as the 'Occultation

Machine' which simulated the passage over the Earth of the shadow of the Moon as cast by a star. Input settings represented the angular position and motion of the Moon with respect to the Earth, and the shadow was represented by a cylinder of light that moved over the surface of a terrestrial globe on which the positions of observers had been marked. The operator turned a handle to move the 'shadow' and rotate the Earth; the time at which the edge of the 'shadow' passed over each observer was read from a dial. In later years digital computers were programmed to make the predictions, although there was at first a period of overlap with the occultation machine.

Gordon took a particular interest in grazing occultations where a star viewed by an observer situated at the northern or southern limits of the Moon's shadow path sees the star disappear behind the lunar mountains and reappear through the valleys. Such observations required very accurate predictions, which Gordon made, and then deployed two or three van loads of observers and their telescopes to relevant locations across southern England, having first forewarned the local police of strange nocturnal activities! In addition, Gordon was one of the pioneers in predicting and analysing the times of occultations of stars by planets, asteroids, and comets. In these cases, accurate timings could be used to determine the sizes and shapes of the occulting objects, especially important for asteroids. A major success arose from Gordon's 1973 prediction that Uranus would occult the 8th-magnitude K5 star SAO 158687 on 1977 March 10 which, despite a deal of scepticism in some quarters, it duly did and revealed for the first time the presence of thin rings around the planet. As a result Gordon appeared as Patrick Moore's guest on *The Sky at Night*.

As asteroid ephemerides improved and better star catalogues became available Gordon led the international moves to expand the numbers of predictions. From the early 1950s until the mid-1970s he had done virtually all the work on asteroidal and planetary occultations himself. Eventually international collaboration was formalized in 1983 with the formation of the International Occultation Timing Association (IOTA). One innovation pioneered by Gordon was use of the 13-inch Astrographic telescope at Herstmonceux to improve the predictions when asteroid and star to be occulted were close enough for both to be photographed on one plate. The technique was taken up by US workers resulting in an increase the numbers of asteroidal occultations successfully observed. Gordon led expeditions to various parts of the world in order to make observations. In recognition of his key contributions as the "Father of asteroidal occultations, his role in predictions for both lunar and planetary events, and for truly pioneering occultation work since the 1950s" IOTA gave Gordon its prestigious David E. Laird Award in 2014. Gordon was also active for many years in the work of Commission 20 of the International Astronomical Union, 'Positions and Motions of Minor Planets, Comets and Satellites'.

From 1957 the NAO took on the task of providing predictions for Earth orbiting satellites. Gordon did the bulk of the work and made nightly observations. In his *Personal History of HM Nautical Almanac Office* Donald Sadler, then Superintendent, says "Over the years Taylor was the most prolific observer of artificial satellites."

In addition to his professional work Gordon had a long and fruitful connection with the British Astronomical Association which he joined in 1945. His early occultation work enthused many amateur observers to participate with timings. In due course Gordon became a senior figure in the affairs of the Association, most notably as Director of the Computing Section for a record 36 years (1974–2009), and also as President (1968–70). The Computing

Section is responsible for the production of predictions of various astronomical phenomena and with the preparation of data for the annual *BAA Handbook*. In this role Gordon followed in the footsteps of three other NAO staff members: L. J. Comrie (1919–22), H. W. P. Richards (1935–36), and J. G. Porter (1938–59). Gordon received the BAA's Merlin Medal and Gift in 1962 and again in 1979. In 1982 Minor Planet 2603 was named Taylor in his honour. He was elected a fellow of the Royal Astronomical Society in 1955.

Already an instigator in the establishment of the two astronomical societies mentioned above, in the early 1960s Gordon was instrumental in the formation of a third: the Crayford Manor House Astronomical Society, now one of the foremost societies in the south of England. It was here that his wide general knowledge of astronomy and gift for clear exposition came to the fore. Despite the travel involved he gave courses there for many years, creating a group of extremely knowledgeable and enthusiastic members who have since proved a challenging audience for subsequent speakers. It was here in 2010 he was presented with a special BAA award, an engraved plaque, in recognition of his outstanding contributions to astronomy for over 50 years, with particular mention of his key role in the 1977 occultation of Uranus. Closer to home, and in retirement, Gordon joined the Eastbourne Astronomical Society in 1997, serving on the committee between 1999 and 2013, and regularly provided information about what would be visible in the night sky at various society and public viewing evenings.

Another of Gordon's enduring interests was sundials, a number of which he designed for commercial companies at home and abroad, one example being the six-sided sundial pillar for the Seven Dials Trust at Covent Garden. His *pièce de résistance*, and lasting memorial, is the imposing *Tercentenary Sundial* (inaugurated by HRH The Princess Anne on 1975 July 18) in the formal gardens at Herstmonceux Castle, unusual in that it has a reclining equiangular dial with a vertical gnomon.

Outside work Gordon was a keen table-tennis player who represented the Observatory first team, the RGO Stars, competing in division 1 of the Eastbourne league, and was himself Eastbourne champion on three occasions. In his later years he also took to running: initially, before retirement in 1984, the five miles to and from work, and then in senior races thereafter.

I am indebted to Mrs Violet Taylor for family information; to Leslie Morrison, David Dunham (Gordon's long-time US collaborator at IOTA), and Bernard Yallop for detailed insight into Gordon's work; and to Peter Standen. — ROGER WOOD.

Here and There

SO LONG, AND THANKS FOR ALL THE FISH

We will continue to have an image of the Rosse telescope as the Society seal ... — *A&G*, **60**, 4, 2019.

FOR THE ABSOLUTE BEGINNER

Finder chart for Betelgeuse – page 48. — *BAA Variable Star Section Circular* 183, 2020 March.