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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2021 November 12 at 16^{h} 00^{m}

EMMA BUNCE, *President*
in the Chair

The President. It's really great to see so many of you joining us this afternoon, so welcome to the next instalment of our on-line RAS Ordinary Meeting. It's going to be a really good one — we have two fantastic speakers this afternoon. This meeting is taking place *via* a webinar. Your questions will come to the panellists only and they will be read out and facilitated by our editorial team member, Dr. Louise Alexander.

We have two speakers this afternoon and I'm really pleased to introduce our first speaker, Dr. Alexandra Amon. After growing up in Trinidad and Tobago, Dr. Amon studied at the University of Edinburgh and then was a Kavli Fellow at Stanford University before moving to Cambridge University where she is now a Senior Kavli Fellow. Dr. Amon's research focusses on cosmology and our understanding of the dark universe using a tool called weak gravitational lensing. At present she coordinates the lensing team from the Dark Energy Survey, which is a large international collaboration. I'm sure we'll hear more about that in her presentation. Her doctoral thesis titled 'Cosmology with the Kilo-Degree Lensing Survey' won the Royal Astronomical Society Michael Penston thesis prize in 2018. So I'm really delighted now to hand over to Dr. Alexandra Amon who is going to be talking about 'Shedding Light on the Dark Universe with Weak Lensing'. Over to you, Alexandra.

Dr. Alexandra Amon. Some 13·8 billion years ago the early Universe was hot, superdense and then went through a period of rapid expansion called inflation which left an imprint of the fluctuations at that time. They call this the first light of the Universe, or the cosmic microwave background, or CMB for short. You can measure it as a map of the fluctuations in temperature and density from the early Universe. As the Universe expanded the fluctuations cooled and expanded such that they seeded the large-scale structure which we see in the Universe today. The parts of that soup which were most dense formed the first clumps of particles, eventually the first stars and galaxies, and today, perhaps the biggest galaxy clusters. The random pattern in the CMB is responsible for the random pattern in the large-scale structure that we observe today. There are dark-matter clusters and filaments which form bonds in the Universe on which those galaxies live and stable dark-matter halos that expand far beyond the visible light of the galaxies which live within it.

Dark-matter is crucial to the structure of matter in our Universe — it does the job of glueing the galaxies together. We also know, thanks to supernovae observations published in 1998, that the Universe is expanding and this expansion is accelerating, and we attribute this phenomenon to dark energy which is associated with a cosmological constant in Einstein's equations. The ΛCDM cosmology model, where Λ is the cosmological constant, seems to holds up to whatever is thrown at it, whether it be the observations of supernovae to constrain the distance ladder, through to microwave observations of the CMB, or the large-scale-structure observations of clustering and lensing of galaxies. It is deeply unsettling that the foundation of this model, dark matter and dark energy, comprise most of the Universe and we don't really understand them. Measurements of the large-scale structure measure the late Universe which is dominated by dark energy and which is important for shaping this cosmological model. On the other hand the CMB probed the Universe as it was 13·8-billion years ago, so it measures the imprint of those tiny density fluctuations well before the onset of galaxies and an accelerating Universe and a domination by dark energy. We want to know if we can use the exquisite image of the CMB by the *Planck* satellite to describe the vast structures that formed billions of years later. This is where gravitational lensing comes in and has a lot of power to play.

How does lensing work? The light from a distant background galaxy is distorted with the imprint of the cosmos when it passes close to an intervening galaxy or galaxies. These distortions are called shears. The observations of the shears tell us something about the matter distribution in the region through which the light passes. We use the position and a measure of the shape (essentially a two-component ellipticity) of the lensing galaxies to model our signal. With this shape we determine the shared two-point correlation function between pairs of shapes separated by some angular radius. To model our signal, we also need to know the redshift, z, of the galaxy, and in fact we can only use a distribution of z. We take the volume in which we have observations and slice it up into bins of distance, or z. The correlation functions we measure are directly related to the underlying structure of the Universe. The amount of correlation or lensing we observe is particularly sensitive to Ω_m, the amount of matter in the Universe, one of our cosmological parameters, and σ_8, which is the amount of structure or clumpiness of that matter. Doing the analysis in the redshift bins allows us to determine how structure evolves with z going back in time.

The largest lensing dataset is that from the Dark Energy Survey (DES) project. It was carried out by the *Victor Blanco Telescope* on Cerro Tololo in Chile. It spans 5000 square degrees on the sky and has taken six years to accumulate the observations. We also have data to a much deeper magnitude limit in certain small areas. The lensing data we have been using cover the first three years of observations and covers the whole observed area and contains 100 million galaxies with a mean redshift of 0·6. We have also been using data from the ESO Kilo-Degree Survey (KiDS) which has surveyed 1000 square degrees of sky but has excellent wavelength coverage, and also the *Hyper Suprime-Cam* fitted to the *Subaru Telescope* on Hawaii which covers a small but very deep area. The various teams have worked independently and the results that we find are intriguing. We find that σ_8 varies from that inferred from *Planck*. We find that lensing is consistently and persistently low and measurements are slightly discordant with what the early Universe dictates. It is 1 – 3 σ lower compared to the *Planck* CMB. The low estimates exist in almost every weak-lensing analysis to date but lensing has always been challenging. The data are extremely difficult to wrangle with.

There are three possible explanations for this result. First, the CMB measurements are not quite right. Second, all of the lensing surveys are missing something, but there are many different results pointing at the same thing and these teams have worked independently. Finally, and most exciting, we need some kind of new physics to fill the cracks — extensions to Einstein's theory of gravity, for instance. As lensing is new and the signal is tiny to measure and because it threatens the gold standard represented by the *Planck* CMB map, it is fair to say that our results are under scrutiny.

In practice it is getting increasingly difficult to extract the signal from the images to the precision required. It is hard to measure, calibrate, and validate shapes and distances to galaxies. We did not think that measuring galaxy shapes would be that hard, but many of the 100-million galaxy images are not of *Hubble* quality — most look like fuzzy blobs. We have, apart from modelling the lensing, to deal with the blurring of images by the atmosphere, pixellation of images by detectors, and then there is noise. Once we have measured the shapes we need to estimate the distances to our galaxies or get the redshifts. DES is a photometric survey: we take images of our galaxies in a few bands and it would be much better to take spectra of each galaxy with these limited observations, so there is a huge amount of degeneracy between the type of galaxy being examined and how far away it is. We built an entirely novel framework based on a machine-learning technique of self-organizing maps and we devised methods to account for all our sources of uncertainty. This is all complicated by an effect called blending, because the telescopes are now more powerful and so they are resolving more and more distant galaxies. The fields are getting more crowded so that some galaxy images are projected onto others. How do we measure the shapes and distances of galaxies in this mess? We use image simulation to detect and model the effects of blending, so we can account for that in our analysis.

Finally we need a theoretical model and if we can use our standard model of cosmology we should be able to make predictions as to what our measurements should look like, so computer simulations are crucial here. This is an area in which Stanford plays a big role. Looking at the shear and weak-lensing measurements I'm impressed by how small our residuals are. We do all our analysis with obscured-data results so we don't know whether our data will support a theory for the Universe such as the standard model for describing the early and late Universe or whether we'll find more hints for a new physics. We make our measurements, do our analysis, and fit our model with fake data, and when we are sure we have done it right, we re-run the analysis with real DES data. We find that there is no compelling evidence that we need to deviate from our model. The fact that all the residuals are consistently low suggests possibly a σ_8 tension or hints that we need to keep digging here. We have combined our results with those derived from clustering and the tensions stay about the same. I should also warn that we are using different calibration techniques and different models, so it's not so trivial just to average the points. It is true that each survey has been carried out blindly and it is expected that when we combine them we really will have a significant tension or significant deviation.

At present, we are combining the DES survey with the KiDS data to do a joint analysis. We are currently working on year-six analysis which we expect will take a couple of years, and KiDS has a final dataset which should come out at around the same time. The *Vera Rubin Observatory* opens next year and will map the entire southern-hemisphere sky every few nights for ten years. The year-one dataset will contain more than one billion galaxies. Other forthcoming projects which will produce relevant data include *EUCLID*, and the *Nancy Grace Roman*

Space Telescope being built by NASA which will operate in space and produce better images. The true power of all the datasets will be revealed when we use them all together.

The President. Alexandra, thank you so much for that wonderful talk and for sharing your work with us this afternoon. In the interest of time I'm going to hand straight to Louise and give you the difficult task of picking one or two questions from the list of questions I can see coming in; we won't have time for all of them.

Dr. Louise Alexander. We've only got time for a couple of questions and the first is from Radicchia Praden: "I'm a freshman studying computers and maths, and I have a question related to Hubble Deep Fields. How do we distinguish the astrophysical jets and Hawking radiation from the redshifted star-formation sites in the galaxy images? How does the graph differ in these cases?"

Dr. Amon. That's a good question. Usually, as a cosmologist, I never used to care about these jets or complex processes that are happening in galaxies. We can almost get away, or we used to be able to get away, with treating them just as a number of these galaxies: they were just a shape and a distance and we didn't really need to know very much more about them. Now, as we're getting such powerful data sets, I think we really are limited in that we need to understand the impact of AGNs on the shapes that we measure, on the distances we measure, or on the model that we use. One topical area in our field is being able to use our small-scale measurements, so I'm not sure if you noticed but we end up throwing away most of our data or at least about half of them. This is really quite a shame because we'd have a lot more power if we didn't throw them away, and that's because these complex galaxy processes make it extremely hard to model the measurements on these scales. I think one area that I'm particularly interested in is better understanding the impact of these galaxy-formation aspects on our measurements and on our models so that we can we can actually use those data going forward.

Dr. Alexander. Thank you, and just one more question from Pedro Fanha: "What makes the *Planck* 18 measurements the gold standard? And are there other measurements from the early Universe?"

Dr. Amon. That's a good question. So there are a few other experiments that came before; well there's a couple that came before the *Planck* experiment and now two on-going CMB experiments. But *Planck* really is the state of the art in precision, if you look at their measurement of the power spectrum which is what they measure best on the sky, how much power there is at different scales. The error bars are extremely small which is what I mean by extremely high precision, but more importantly the fit is just beautiful. It is hard to see with *Planck* — which is the gold standard for these measurements — that the model could wiggle or make room for the low-estimate measurements that we're seeing in lensing. I guess it is just widely accepted that this experiment was really excellently done.

Dr. Alexander. Thank you, Alexandra. I'm so sorry we won't be able to take any more questions at the moment and I'm going to pass straight back to Emma.

The President. Now we're going to move straight on to our second speaker and I'm really excited to introduce the award-winning author Dava Sobel. Dava is the author of several books about the history of astronomy including *Longitude*, *Galileo's Daughter*, *The Planets*, *A More Perfect Heaven*, and, most recently, *The Glass Universe*. Dava's book, *The Glass Universe*, refers to the half-million glass plates that Henrietta Swan Leavitt and other women used to document the northern and southern skies. The wonderful thing about Dava's work is that her stories combine real-life drama and historical scientific achievement into a really fascinating literary fusion. I'm really excited to hear your talk this afternoon, Dava, thank you. Dava's going to be speaking about 'The insight of Henrietta Swan Leavitt, adding depth to space'. Over to you.

Ms. Dava Sobel. In the century since Henrietta Swan Leavitt died, the observation that she first published in 1908, then elaborated in 1912, has achieved the status of an astrophysical law, and her quiet life become a topic of interest to many. The yardstick that she discovered for gauging distances across space enabled the first realistic appreciation of the size of the Milky Way, and soon afterward, the breadth of the chasm separating our home galaxy from other island universes.

Very little is known about her personal affairs. Her father was a Congregationalist minister, and the family moved according to his church assignments from Lexington, Massachusetts, where Henrietta was born on 1868 July 4, to the city of Cambridge, to Ohio, and finally to Wisconsin. Henrietta, the oldest of seven children, attended Oberlin College, first as a music student, and later with a concentration on mathematics.

She went back east to live with her uncle and pursue further studies in maths, astronomy, and physics at the Society for the Collegiate Instruction of Women in Cambridge. She volunteered at the nearby Harvard College Observatory while still a student. After her graduation in 1892, she continued assisting at the observatory on and off over a period of years, and finally joined the full-time staff in 1902.

Miss Leavitt did not use any of the telescopes at the observatory, but found her way into deep space *via* a still extant collection of glass photographic plates covering the entire sky.

The idea for the photography project originated with Edward Pickering, who took over as the fourth observatory director in 1877, at age thirty. All astronomers are far-sighted, but Pickering was especially so. The RAS awarded him its Gold Medal twice: in 1886 for the Harvard photometry and again in 1901 for advances in astronomical photography.

Miss Leavitt devoted her efforts to photometry — the assessment of stellar magnitudes from photographs, and also the rectifying of photographic magnitude with observations made *via* specialized instruments in real time. She made her greatest discovery while studying the stars of the southern hemisphere. In an era when only a couple of hundred variable stars were known, she discovered nearly a thousand of them in the Small Magellanic Cloud alone, and published her findings in Volume 60 of the observatory's official *Annals*.

Her paper included 12 pages of numerical tables with a detailed analysis of 16 stars, all Cepheid-type variables, for which she assembled complete light-curves. Toward the end of her report, she commented, "It is worthy of notice that the brighter variables have the longer periods." These words constitute the first formulation of the period–luminosity relation.

The second part of her study, concerning an additional nine Cepheids, followed four years later, published in *HCO Circular* No. 173 on 1912 March 3. This time she declared the relation between period and brightness to be 'remarkable', and referred to it as a 'law', fully a century before the introduction of the term 'Leavitt law' in 2012.

The President. I could listen to you all evening but thank you, that was just so interesting to hear all of that and I'm looking forward to getting a copy of the book myself. I'm going to hand over to Louise and see if we have any questions or comments from our on-line audience.

Dr. Alexander. Thank you Emma, and thank you very much Dava, that was a really fascinating talk; I could have listened to that for a lot longer as well. We've got a comment from Chris Lee who says: "A key takeaway from your book for me was the importance of leadership. Pickering comes across as an exceptional and forward-thinking individual and it was a shame his own centenary passed largely without notice."

Ms. Sobel. I agree. I sometimes feel if I live long enough I would like to write his biography because he was so important and all of his material is at Harvard. They even have letters that he wrote to his mother as a child when he was away for the summer. Alexandra's talk was so interesting, and she ended with that image of the jigsaw puzzle. Pickering was a great lover of jigsaw puzzles and he used to do them by turning the pieces face down so you could not see the picture. He would have been the one to solve the dark matter, the dark universe jigsaw puzzle.

Dr. Alexander. I know that all this work's been done on the digitization but is there ever anything that's exhibited for the public where they can actually go along and look at some of those plates, for example, do you know?

Ms. Sobel. Yes, a lot of the plates are available on the website. The project is called DASCH — Digital Access to a Sky Century at Harvard, and you can look at a lot of the plates there. You can also visit the plate stacks if you're ever in the States. And actually that building is still there, it's practically been swallowed by other structures but it's there and the plates are there and they will give you a magnifying loupe, put some plates on an electric light box, and let you look at them.

Dr. Alexander. That would be really great. We've got one more question; "Are the half-million glass plates at risk of disposal when the digitization project is completed?"

Ms. Sobel. That is my worry. No one has mentioned that word yet, but one has to wonder. Maybe we'll all be volunteering to give them safe haven.

The President. It's a real consideration, isn't it, with the digitization process, but how wonderful to be able to see them actually if you are in the vicinity. I would love to see those. Dava, thank you so much for that wonderful talk. Thank you to both of our speakers and thanks to all of you for joining us this afternoon. Finally I give notice that there will be an additional A&G Open Meeting of the Society next Friday on the 19th of November 2021, so if you are able please come along.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2021 November 19 at 16^{h} 00^{m}

MICHAEL EDMUNDS, *President-Elect*
in the Chair

The Chair. Welcome to the Royal Astronomical Society's Ordinary Meeting, a special one on this 19th of November. This meeting, as you know, is taking place by webinar. We're holding today the 2019 Jeffreys Lecture, obviously carried over because of the pandemic, and I'm absolutely delighted to be able to welcome

Francis Nimmo from the University of California at Santa Cruz, who's going to talk about 'Three surprises from planetary science'. Francis Nimmo received his BA in 1993 and PhD in 1996, both from Cambridge. He was Royal Society University Research Fellow at University College London, before joining the Santa Cruz University of California Faculty in 2005. In 2007, he received the Macelwane Medal of the American Geophysical Union and the Urey Prize from the Division of Planetary Science of the American Astronomical Society. His interests cover the interior and evolution of rocky planets and moons, so it's my great pleasure to introduce Francis to give the Harold Jeffreys Lecture.

Professor Francis Nimmo. [It is expected that an extended summary of this talk will appear in a future issue of *Astronomy & Geophysics*.] The speaker covered three topics in planetary sciences which have evolved significantly in the last twenty-five years. The first was the tendency of planets to re-orientate themselves relative to their spin axis — 'true polar wander'. An example is Pluto, where the large Sputnik Planitia impact basin appears to have caused equator-wards re-orientation. This scenario implies that Pluto harbours a subsurface ocean. The second topic was the discovery of such oceans beneath the ice-covered surfaces of moons in the outer Solar System. Examples were presented of how they are detected, including that of Titan (one of Saturn's moons), which has an axial tilt implying the presence of an ocean. The final topic was the generation of magnetic fields in solid planetary bodies. Rock magnetic measurements have revealed that many bodies, including some asteroids, had dynamos that produced magnetic fields early in their histories. In the case of the Moon, the dynamo may have been powered by the precession of the spin axis, rather than conventional thermal or compositional convection.

Dr. Pamela Rowden. Thank you very much, Francis, and we have a number of questions that have come into the chat. Starting from the top, we have a question from Jerome saying: "Today's lunar core-rotation axis is essentially aligned with the normal to the orbit, so very much tilted. How do you reconcile this precession with your precession mechanism requiring core and mantle rotation to be well coupled to switch off the dynamo?"

Professor Nimmo. I would like to know how the speaker knows that the core rotation axis is aligned with the normal. It's not obvious to me that that's the case. Maybe he can reply and chat and we have a conversation?

Dr. Rowden. Okay, Jerome, if you send another message through Francis will see it. The next question is from Quentin Stanley and he says: "When you mention oceans, I take it to mean more than H_2O, and as such, does the tectonics vary with the type of ocean and thus the dynamo from your argument?"

Professor Nimmo. When I say oceans, I do actually mean mostly water — although there may be other things in them like salt or ammonia, and those contaminants are important because they reduce the freezing temperature, and if you add a contaminant, it actually makes it easier for an ocean to survive. In the case of the induction experiments, it's clear that the oceans have to be salty because a pure liquid-water ocean wouldn't be conductive enough.

Dr. Rowden. The next question comes from John Zarnecki: "If we were to give you one spacecraft, just one, where would you send it and what would it do?"

Professor Nimmo. I think I would go to Enceladus, which is a small moon of Saturn, because Enceladus is blasting water vapour into space. If you really want to understand what the interior of a body is like, you want to go to Enceladus and bring samples back because there you're actually getting free samples from the interior.

Dr. Rowden. The next question is from Simon Josey: "Great talk. Can induction usefully be employed to determine to some extent the chemical composition of the interior ocean moons?"

Professor Nimmo. That's a great question. If you can measure the induction response at several frequencies, then you can get the depth of the ocean and the conductivity of the ocean independently. The problem is relating the conductivity to the composition, because you can imagine there are different contaminants that might give you the same conductivity and so, whilst you can get the conductivity, that's easy, getting the actual composition is harder unless you have extra information, like for instance, spectroscopy at the surface.

Dr. Rowden. Thank you; the next question comes from Stephen King, who asks: "I like the 'cooling-history-infers-oceans' idea. What is the basis for the amount of radioactive heating assumed in your cooling models? How do we think that radioactive elements are distributed through the Solar System?"

Professor Nimmo. The best evidence we have is that if you look at the most primitive meteorites, you can see their elemental concentrations, and if you look at the Sun, the stellar photosphere, you can look at the elemental concentrations there and they are the same, so the elements are in the same ratio in the primitive meteorites and in the Sun, which suggests that that is the original material from which the Solar System was made. If we don't have any other information, we assume that the radioactive elements are present in those proportions, and that's probably a pretty good assumption in the outer Solar System at least.

Dr. Rowden. Thank you. The next question from Paul W. is: "Is there any (externally) detectable frictional heating with subsurface oceans?"

Professsor Nimmo. I'm assuming that this means dissipation in the oceans, just like it is on the Earth. The Earth's oceans dissipate quite a lot of tidal energy. This is somewhat controversial. I think most people have decided that tidal heating inside oceans is not important compared to the tidal heating in the solid objects, but there is not universal agreement on that, if that's what the questioner was asking.

Dr. Rowden. Jerome, who asked the first question, "How do you know it's aligned?", and he's replied and said: "from theory".

Professor Nimmo. I think there's a Goldreich paper slightly after that that looks at exactly this question and concludes that it went from variable precessing to co-precessing with the mantle at some point in its orbital evolution. I can pull out that Goldreich paper; I just don't remember the year off the top of my head.

Dr. Rowden. He's mentioned Poincaré (1910) or Busse (1968).

Professor Nimmo. The Goldreich paper was a little after that.

Dr. Rowden. Richard Katz has asked a question which is: "Regarding Pluto and true polar wander; in your model, the deposit of solid nitrogen seems not to be isostatically compensated. Is that right? Why not? Why would the torque on the ice shell be affected by the denser water that is isostatically up lifted from below?"

Professor Nimmo. That's a good question. What's happening is that, immediately after the impact, you get isostatic compensation, but then if you wait, the shell will cool and become rigid, and then at some later time if you add nitrogen on top, the nitrogen will be supported by a flexure, by the elastic strength of the plate, and so that's how you end up with a positive gravity anomaly. It's not that the torque is acting on the the water itself, it's just that the moment, the degree-two moment, which is what you care about, depends on the overall gravity anomaly, and that's really being controlled by the solid nitrogen. That's where the mass excess is coming from.

Dr. Rowden. Thank you. The last question I have in my list for you is: "Is the tidal heating detectable in the surface anywhere? Is it intense enough?"

Professor Nimmo. Right now there are only two places where we've detected tidal heating directly. One is Io where the surface heat flux is about ten times the Earth surface heat flux, and then the other is Enceladus. The south pole of Enceladus is anomalously hot, so that is the other place where we're actually directly detecting tidal heating being created. So those are the two places where we've actually detected tidal heating.

Dr. Rowden. Cool, thank you. I suppose 'cool' might not be the appropriate phrase where you've got tidal heating, but there you go. My personal question is about Mercury's core. Can you say a little bit more about that please?

Professor Nimmo. The most important thing about Mercury's core is that it's huge. There's only a thin skin of mantle on top, and so we don't actually understand why Mercury's core is relatively so much larger than that of all the other terrestrial planets. That's a big puzzle. The other thing about Mercury's core is that the dynamo it creates is very weird. The centre of the dynamo, as it were, is off-axis, it's off-centre. And that's not well understood. There's something very peculiar about the circulation pattern in Mercury's core that is not well understood.

Dr. Rowden. Thank you, and another question is coming for you, Francis, from Stephen King and it says: "Have you read *20,000 Leagues Under The Sea*? And are you an example of nominative determinism? P.S. Thanks for a great talk and Q&A".

Professor Nimmo. I read *20,000 Leagues Under The Sea* a long time ago and I'm afraid I don't know what nominative determinism means and someone will have to explain it to me.

Dr. Rowden. It means that your name determines your occupation. For instance, a Baker works in a bakery.

Professor Nimmo. People have made jokes about *Finding Nemo* over the years.

The Chair. Can I add my thanks for a very clear, very entrancing lecture, obviously provoking many interesting questions too. Nobody commented on the planets being more complicated than stars. I think we could have an excellent discussion of that one. Anyway, thank you very much for a wonderful night. I give notice that the next A&G Open Meeting of the Society will be on Friday the 10th of December.

THE DEVELOPMENT OF EXTRAGALACTIC ASTRONOMY IN THE UK AS SEEN THROUGH BRITISH PROFESSIONAL JOURNALS: AFTER HUBBLE, PART 2 — 1951–1970

Steven Phillipps

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Hubble's first papers on the distances to M31, M33, and NGC 6822, which conclusively proved for the first time the existence of external galaxies, were published during 1925[1,2]. Following on from an earlier article looking at pre-1925 papers in British journals which turned out in retrospect to be about external galaxies[3], the two parts of the current article review how extragalactic astronomy developed in the UK over the following years, again as seen in the pages of the British professional journals, primarily *Monthly Notices of the Royal Astronomical Society* with a few in *Memoirs of the RAS* and *Quarterly Journal of the RAS* (from 1960) plus *The Observatory*, with its reports of RAS meetings amongst other things. Part 1[4] covered 1926–1950. Here we look at the years 1951 to 1970.

Developments before and after 1950

By 1950, there had been signs of the increased technical capabilities which would feed through into extragalactic studies. The first significant radio observations of sources associated with external galaxies had been made that year[5], and plans for a large optical telescope[6] at a new 'Isaac Newton Observatory' were well under way (though no observations were made with what became the *INT* until late in the time span covered here). As in Part 1, we will take the, somewhat subjective, definition of 'extragalactic astronomy' as including observational (*i.e.*, not purely theoretical) cosmology, but not topics such as individual stars in the Magellanic Clouds. With the (eventual) increase in professional publications in general, and those related to extragalactic astronomy in particular, we concentrate on 'papers', *per se*, rather than reviews or reports, though noting some papers presented at RAS meetings. In addition, only contributions from the UK are now included. Arguably, work emanating from British-linked observatories overseas (the Radcliffe and Cape in South Africa and Commonwealth at Mount Stromlo) could be included, as many (formerly) British astronomers were involved, but there was little movement back into the UK system (Richard Woolley being the important exception). Within these limits, UK papers remained sufficiently thin on the ground during the 1950s that we could continue to consider them individually, but many tend to be related and we group them accordingly (giving representative references). From 1960 the numbers of relevant papers rose sharply (and continued to do so post-1970, of course), so we consider primarily the overall trends, though continuing to note specific influential papers and innovations where appropriate (with apologies to those authors whose papers haven't been individually referenced).

1951–1960

The first relevant *MN* paper[7] in 1951 carried on the new theme of radio astronomy. Hanbury Brown and Hazard discussed 'Radio emission from the Andromeda Nebula', noting that its flux was consistent with that expected if

M31 was similar to our Galaxy. They then attempted to calculate the radio flux expected at the Earth from all the galaxies in the visible Universe. They also studied a bright source they referred to as 'Cygnus (1)', now Cygnus A, though this had not yet been unequivocally identified with a galaxy. Robert Hanbury Brown and Cyril Hazard, then a post-graduate student, were both in Bernard Lovell's group at 'Jodrell Bank Experimental Station' of the University of Manchester. David Dewhirst from Martin Ryle's corresponding radio-astronomy group at the Cavendish in Cambridge was one of the first to show a close match of the radio position for Cygnus A with an optical galaxy in a talk given at the RAS later in the year[8], though comments by Ryle himself and by Hanbury Brown showed that they remained unconvinced.

The other areas of UK involvement continued to be in observational cosmology and galaxy structure. Gerald Whitrow and David Randall[9] showed that in all proposed cosmological models $G\rho t^2$ should be a constant of order unity, where ρ was the mean density of the Universe and *t* its age (related to the inverse of Hubble's constant). They found this difficult to reconcile with the observed values, but while suggesting that unobserved matter might alter ρ did not allow the possibility that H_0 (then thought to be around 500 km/sec/Mpc) might be wrong. The authors were in the Department of Mathematics at Imperial College where Whitrow, a former student of E. A. Milne in Oxford, was a lecturer.

On the structure side, an interesting partnership saw George McVittie co-author an *MN* paper[10] on 'A model of a Spiral Galaxy' with Cecilia Payne-Gaposchkin while he was on leave at Harvard College Observatory from Queen Mary College. They proposed that the stars seen in spiral arms originated from the disintegration of a bar previously in solid-body rotation.

The sole relevant contribution in 1952 came from astrophysicist and philosopher of science Martin Johnson, a physics lecturer at the University of Birmingham, who attempted[11] to explain NGC 5253's unusual emission spectrum as a "recombination afterglow".

In 1953 Hanbury Brown and Hazard[12] returned to the question of identifying resolved radio sources with "extragalactic radiators", noting recent work which appeared to match the bright source in Cygnus to a pair of colliding galaxies, and suggesting that other sources could be associated with galaxy clusters, correctly surmising an identification with the peculiar galaxy NGC 1275 in the Perseus Cluster.

Although obviously not a British contribution, it is noteworthy that the George Darwin Lecture of 1953 was given by Edwin Hubble[13] and edited for publication[14] after his death by Allan Sandage. Entitled 'The Law of Red-shifts', it discussed the discovery of the distance–redshift relation, what Hubble called "Humason's Adventures Among the Clusters" up to 1936, and "attempts at a definitive formulation with the 200-inch reflector", including extending the range to the Hydra Cluster at $z = 0{\cdot}2$ and revising the distances (hence H_0) by a factor of 2. The following year, the RAS Gold Medal[15] went to Walter Baade of Mount Wilson and Palomar Observatory for "his observational work on galactic and extragalactic objects", again emphasizing UK astronomers' interest in extragalactic work even if there was still relatively little actual involvement. (It can be noted, though, that Fred Hoyle, temporarily at Princeton, produced a paper "of a mainly tentative character" in *ApJ*[16] on the hierarchical collapse of galaxies and then stars from large primordial gas clouds.)

In a paper just about reaching the boundary between theoretical and observational cosmology, Reginald Kapp, Emeritus Professor of Electrical

Engineering at the University of London, presented a variant of the Steady State Theory's continuous matter creation whereby galaxies were also sinks where mass disappeared[17], leading to a rapid rise in mass up to a cut-off point where loss overcame growth and hence to a highly peaked galaxy-mass distribution (as was then thought to be the case).

The increasing interest in radio astronomy was indicated by Jodrell Bank holding a symposium[18] with international speakers including van de Hulst, Oort, Bok, and Minkowski. Hanbury Brown discussed the work on emission from external spirals while Hazard suggested that the majority of 'radio stars' were extragalactic. Roger Jennison reported on his interferometric observations at Jodrell Bank, with the then PhD student Mrinal Das Gupta, which suggested that the source in Cygnus comprised two separate emitting regions with the optically identified galaxy in the space in between them. (Their discovery was subsequently published in *Nature*[19]; both the Jodrell Bank and Cambridge radio astronomy groups tended to publish in *Nature* much more frequently than did other astronomers.)

In 1954 there were only two papers. C.W. ('Cla') Allen of UCL, director of the University of London Observatory (the Allen of *Astrophysical Quantities*, for those readers of a pre-internet vintage), presented a statistical paper[20] on determining absolute-magnitude distributions, including extragalactic nebulae in a list of example applications, though with the assumption of a Gaussian shape for what is now termed the luminosity function.

Dirk ter Haar, a physics professor at St. Andrews who mostly worked in statistical mechanics, speculated[21] that the masses of the hierarchy of objects from clusters of galaxies down to stars could be derived on the assumption that they formed from turbulent elements in the primordial gas, as proposed by von Weizsäcker.

Moving on to 1955, we see paper numbers beginning to pick up. Dennis Sciama, then a research fellow at Trinity College, Cambridge, produced a theoretical work[22] on the formation of galaxies in the Steady State Universe, where "any particular galaxy is formed in a universe already full of galaxies", new galaxies forming through gravitational instabilities in the intergalactic gas. He was able to account reasonably well for the typical observed properties of galaxies and their tendency to cluster. (Sciama had, the previous year, also published a paper with Hermann Bondi, then at Harvard, and Tommy Gold, then at the RGO, on the colours of higher-redshift galaxies, but this appeared in *ApJ*[23].)

Eric Lindsay, the director of Armagh Observatory, made a survey of the SMC[24] with the Armagh–Dunsink–Harvard Telescope in South Africa, cataloguing emission-line objects. He later used plates from the ADH telescope to survey star clusters in the SMC, discussing their distribution, magnitudes, and diameters[25]. These were the first modern extragalactic contributions in *MN* from Armagh, despite its historical links to J. L. E. Dreyer of NGC fame[26], most Armagh papers appearing in *The Irish Astronomical Journal*.

An interesting contribution[27] to *The Observatory* on a new topic for the UK came from Peter Fellgett, then Senior Assistant Observer at the Cambridge Observatories, who intervened in the otherwise US disagreement between Neyman & Scott and Limber over the application of fluctuation theory to the study of galaxy clustering. (Neyman & Scott responded in a later issue of *The Observatory*[28].)

Back with the radio astronomy, Hanbury Brown, Henry Palmer, and Richard Thompson[29] attempted to measure the polarization of Cygnus A but found no significant effect down to their instrumental limit. Meanwhile at Cambridge John Baldwin, a PhD student in Ryle's group, compared[30] the extent and emission per unit volume of the Galaxy and M31. Several of the group's members presented a paper at the RAS in 1955 May, read by John Shakeshaft, which was subsequently published[31] in *Memoirs of the RAS* as what became the *Second Cambridge (2C) Catalogue of Radio Sources*. Shakeshaft's talk[32] was the first presentation to the RAS of the steep number counts of the isotropically distributed small sources which, if they were extragalactic, apparently ruled out a Steady State Universe. Unsurprisingly this was disputed by Gold and Bondi (now at King's College London) and defended by Ryle[33].

A further acknowledgement of the importance of radio astronomy came with the award[34] of the RAS Eddington Medal to Henk van de Hulst (Leiden) for his work on the 21-cm line. Indeed, the dominance of radio over optical observation among UK extragalactic astronomers was demonstrated by the talks at a symposium[35] on 'The comparison of the large-scale structure of the Galactic system with that of other stellar systems', held at the Mansion House; the only local speakers in an eminent international line-up were Hanbury Brown and Baldwin who both compared Galactic radio emission with that from M31.

A contribution in 1956 added Edinburgh to the places involved in extragalactic work. Vince Reddish, then a lecturer at the University, calculated the effects on the Cepheid period–luminosity law due to changing the elemental composition, and ruled out large changes in the interstellar gas from which they formed between the inside and the outside of M31[36]. Reddish also sent a letter[37] to *The Observatory*, comparing the integrated colour of the cluster M67, believed to consist of old Population I stars, with those of elliptical galaxies and the centre of M31.

William Bonner, a lecturer at the Department of Applied Mathematics in Liverpool, made two contributions[38] on the border between theoretical and observational cosmology which discussed gravitational instability in very large gas clouds, with "the relevance … to the formation of the nebulae … briefly considered".

Returning to radio astronomy, there were three papers from Cambridge with, for instance, Baldwin and Graham Smith[39] observing the distribution of brightness across M87 and suggesting the presence of a radio halo. The following year George Whitfield[40] determined more detailed spectra of sources including Cyg A and suggested that on average the identified extragalactic sources had steeper spectra than the Galactic ones. Later in 1957, Whitfield was the graduate student who shared with Bruce Elsmore in the first detection and tracking of *Sputnik 1* as it passed over the UK. Meanwhile, Dave Morris, Palmer, and Thompson[41] at Jodrell Bank determined the diameters and brightness temperatures of a handful of intense, small sources, finding support for the view that they might all be the same type as Cyg A.

Despite apparently rather little home-grown effort in the area, Reddish apart, Walter Baade was invited to give the RAS George Darwin Lecture[42] on the topic of stellar populations. He discussed, amongst other things, the colour–magnitude diagrams of Local Group (dwarf) ellipticals and the gas and dust in Andromeda's spiral arms.

In 1958 David Edge, Peter Scheuer, and Shakeshaft[43] produced an *MN* paper on (steep) radio-source counts which very carefully avoids giving its context or implication: the words 'extragalactic' and 'cosmology' appear nowhere! Nevertheless, anyone interested would have known what they meant and Bondi and Ryle predictably argued over the statistics presented by Scheuer at the

RAS[44]. (Tony Hewish also summarized the Cambridge work at an American Astronomical Society symposium, as reported in *PASP*[45], a rare British contribution to an American journal.) Edge and Shakeshaft's survey became part of the *3C Catalogue* which appeared in *MemRAS*[46] the following year.

Also in 1959, we find our first British female extragalactic astronomer publishing in *MN*. Unsurprisingly, given the preponderance of work in this area, Harriet Tunmer[47] was a member of Ryle's group at MRAO, with a studentship from Girton College. As part of a study of the relationship between cosmic radio emission and the cosmic-ray-electron spectrum, she included an application to the radio spectrum of Cygnus A. In addition, Patricia Leslie, of the same group, was an author on a paper in *Memoirs*[48] on the identification of radio sources with distant galaxies.

These were two of twelve radio-based extragalactic papers to appear in 1959 and 1960, nine from the recently re-sited and re-named Mullard Radio Astronomy Observatory, Cambridge, and three from Jodrell Bank, the latter including Hanbury Brown and Hazard's work[49] on M31 and M33 using the new 250-foot (now *Lovell*) Telescope.

Somewhat reversing the usual interpretation direction, there was also an RAS report[50] on 'The Galactic System as a Spiral Nebula', using observations of other spirals to assist in interpreting the distribution of matter — mainly the H I — in our Galaxy, but none of the authors or literature cited was British (with the exception of Richard Proctor's paper from 1869[51]).

In observational cosmology, Bill Davidson, a student of Bill McCrea's at Royal Holloway, produced three papers[52]: an updated take on the magnitude–redshift relation allowing for the possibility of both an overall change of luminosity and of spectral shape for distant galaxies in either conventional or steady-state universes, the dependence of number counts (both optical and radio) on secular evolution of the sources and on the curvature of the Universe, and similar effects on angular diameters. Allan Sandage[53] later referred to these as his "marvellously complicated series-expansion papers".

In 1960 we also find a paper[54] from Cambridge doctoral student Donald Lynden-Bell, who demonstrated that a cluster of point masses (stars or galaxies) could be spherical yet still rotate. This problem had been discussed between Lynden-Bell and Astronomer Royal Richard Woolley, amongst others, at the (3rd) Herstmonceux Conference. (The Royal Observatory had moved from Greenwich in 1957.) Woolley himself published[55] colour–magnitude arrays of star fields in the LMC — notably the first RGO entry in our list, though using photographs from the telescopes in Pretoria and the Cape. Sandage and Olin Eggen, the latter then at the RGO, carried out similar work on Magellanic Cloud globular clusters[56,57].

Fred Hoyle, recently appointed Plumian Professor in Cambridge, reappeared[58] with a paper considering synchrotron emission from all types of extragalactic (and Galactic) sources including galaxy clusters and the Universe as a whole. His student Sverre Aarseth[59] constructed a numerical (but not yet N-body) model of a rotating barred galaxy to investigate its stability.

1961–1965

In 1961 we hit a new high of fifteen relevant contributions. Martin Harwit, a NATO fellow at DAMTP, supplied two[60] on 'can gravitational forces alone account for galaxy formation in a steady-state universe'. He had started the work while a student at MIT with Gold and finished it with input from Hoyle and Bondi. Hoyle himself gave a talk at the RAS[61] explaining cosmic radio sources as galaxy-scale flares producing high-energy particles.

Across at MRAO, one of the eight papers produced saw Leslie[62] complete an interferometric survey of the surface brightnesses of radio sources, supporting the idea of two types of radio-emitting galaxies, differing in power by several orders of magnitude. At Jodrell, Hanbury Brown and Hazard[63] worked on a similar point by measuring radio-to-optical flux ratios for galaxies of various types. Leslie, with Elsmore, also studied the Perseus Cluster and NGC 1275[64].

The main radio controversy, though, continued to be the increasingly acrimonious one surrounding the number counts. Ryle and co-authors first specifically examined[65] the predictions of the steady-state theory, concluding that even allowing for source sizes and clustering, there were a factor three more faint sources observed than predicted, and then reaffirmed[66] that the number-count slope was around –1·8. Hoyle and his student Jayant Narlikar responded[67], arguing that the shape of the curve could be changed depending on the probability that galaxies of different ages were radio sources, and by large-scale clustering. Hoyle and Narlikar[68] also refuted a US contribution to *The Observatory*, from Ivan King[69], which suggested that galaxies typically had ages 20–25 Gyr, or twice the Hubble time, which was incompatible with the steady-state (and, though he didn't mention this, with most evolving models, too). Perhaps surprisingly (or perhaps not), support for Hoyle subsequently arrived from the other radio group, Hanbury Brown[70] at Jodrell reckoning that, with a new model of the counts allowing for clustering, it was "premature to attempt to discriminate between various world-models on the basis of simple counts of radio sources".

Another interesting outside contribution to the cosmological debate came from Palomar Observatory when Bill Baum — who had a visiting professorship at Imperial in 1961 — addressed the RAS[71] on what we would now call the photo-*z* technique for faint galaxies, out as far as 3C295, which Minkowski had shown to be at $z = 0{\cdot}44$ (later revised to 0·46). Baum noted that the magnitude–redshift relation appeared linear, implying an acceleration parameter (*i.e.*, $-q_0$ in later usage) around –1 and ruling out the steady-state. Naturally Bondi and Hoyle, who were both in the audience, disagreed, but it was actually Davidson who made the crucial point that an uncertainty in the magnitudes of just $0^{\mathrm{m}}{\cdot}2$ per billion years could reverse the acceleration parameter to +1, the steady-state value. Nevertheless, Davidson (now in the mathematics department of Battersea College of Technology, the forerunner of the University of Surrey) showed in two papers the following year[72] that Ryle's counts, if correct, were incompatible with the steady-state universe and that evolution of radio luminosities was required in any Friedmann–Lemaître model.

On other topics, Tao Kiang[73], then an assistant at the University of London Observatory, produced a paper ahead of its time on 'the galaxian luminosity function', demonstrating the importance of accounting for selection effects. (Most of the paper's citations come from the mid-1970s onwards.) Reddish, who had moved to Jodrell Bank, published a paper[74] in *The Observatory* 'on determining the ages of galaxies' *via* their mass-to-light ratios, assuming a particular initial mass function and star-formation rate proportional to gas mass. He later also noted[75] that the variations in surface density of bright stars in M31 (which should follow the local star-formation rate) did not match up with the variation observed in the H I column density, apparently precluding a simple relationship between SFR and gas density.

Even allowing for papers mentioned already, 1962 saw a lull in paper production and what there was again saw a preponderance of radio astronomy.

For instance, before leaving Jodrell Bank for Australia, Hazard had tested[76] the lunar-occultation method of determining accurate positions for unidentified radio sources on 3C212 (which would later turn out to be a $z = 1$ quasar).

It is interesting that 1962 also saw Astronomer Royal Woolley publish, in the new *Quarterly Journal of the RAS*, a description[77] of the *Isaac Newton Telescope*, already 16 years in the making, which, it was hoped, would be operational at Herstmonceux in 1966. Presumably depressingly for any would-be extragalactic astronomers, the programmes that Woolley listed as suitable for Britain's future largest telescope were exclusively Galactic.

Nevertheless, the 7th Herstmonceux Conference[78] in 1963, reported in *The Observatory*, included talks by a variety of British-based astronomers on extragalactic topics, including Leon Mestel (Cambridge), Harry van der Laan (a PhD student at Mullard), Hoyle, Wal Sargent (then at Herstmonceux), Sciama (DAMTP), McCrea, and Ryle. Mestel[79] created a theoretical model of a galaxy, which, with the appropriate mass and angular-momentum distributions, could contract into a disc with either constant angular velocity or constant rotational velocity, as often seen outside the core of spirals, while van der Laan published two papers[80], one on the interpretation of radio-source data, concluding that "there is not a single well-defined quantitative relation between any two parameters of radio galaxies", and one proposing that radio sources were powered by "a catastrophic event in the nucleus of a galaxy". Hoyle and Willy Fowler (visiting DAMTP from Caltech) explored[81] whether the strong radio sources could be produced by 'stars' of 10^5 to 10^8 solar masses in galactic nuclei.

Indeed, 1963 was another busy year with a total of thirteen papers and a slight majority on the radio side again. Barrie Rowson made high-resolution observations with the Jodrell interferometer[82] of sources including 3C48 (previously identified with a "stellar object") while a Jodrell Bank/Caltech/Mullard collaboration led by Robin Conway[83] produced spectra for sources of various types. Moving on from earlier Manchester work on the H I content of our Galaxy, Rod Davies and colleagues determined[84] "limits to the neutral hydrogen mass of several galaxies".

Sciama joined the dispute over source counts in support of the steady state and against Ryle, proposing that half of the faint sources were actually Galactic[85]. As would be expected this led to considerable dispute when presented at an RAS Meeting[86], the President, Woolley, commenting after Ryle's rebuttal, "This is not a private fight — any fellow may join in!". Bondi, McCrea, Hewish, Davidson, and Kiang, amongst others, took him up on the offer, with Paul Scott[87] following up with evidence against Sciama's model.

On the theory side, Aarseth[88] (now at DAMTP) described "numerical integrations of the classical N-body problem", using between N=25 and N=100 'bodies' to investigate the dynamical evolution of clusters of galaxies. His colleague Christopher Hunter supplied a general solution[89] for the stellar dynamics of self-gravitating flattened-disc galaxies.

The year 1964 saw a variety of papers, with a sudden upturn in observational cosmology. Davidson and Maurice Davies (Reader in Numerical Analysis at Battersea) returned to radio-source counts in evolving universes "of considerable generality", also specifically deducing the evolution of luminosities required for a flat Einstein–de Sitter universe to match the data[90]. Whitrow (appearing here for the first time since 1951) and Bernard Yallop (RGO, a former student at Imperial) had a contribution[91] on the sky background radiation from galaxies and its spectral variation in various cosmologies, and Bonnor[92] (now at Queen Elizabeth College, London) produced a similar work relating to Olbers' Paradox.

Sciama[93] discussed the formation of galaxies and their magnetic fields in a steady-state universe. Ian Roxburgh and Philip Saffman, colleagues of Bondi at King's College, subsequently considered[94] the stability of such models, with respect to the condensation of galaxy cluster size masses. McCrea[95] postulated a steady-state model wherein the continual creation of matter occurred only where matter already existed, *i.e.*, in galaxies. At some point in the growth of a galaxy it would then fission (by some unknown process) to form a new galaxy. Ray Lyttleton (Reader in Theoretical Astronomy in Cambridge) and Bondi[96] considered whether accretion of intergalactic matter could give rise to spiral arms.

The radio observations continued, of course, Margaret Clarke[97] obtaining interferometric positions of 88 sources with small angular diameters and Malcolm Longair[98], also a Cambridge research student at this point, then matching these against galaxies visible on Palomar Sky Survey prints. Similarly, John Pilkington[99] matched Cambridge sources to Abell Clusters.

Probably the most remarkable paper, though, came from dedicated amateur Francis Brown[100]. Brown had first published in *MN* in 1912 and had started studying the inclinations and alignments of galaxies in 1922[101]. He now returned to the scene with a monumental study of '4891 galaxies in a continuous field of 3071 square degrees', measuring their diameters, shapes, and position angles from Palomar Sky Survey prints. [After over 50 years' work he passed his notes on to Richard Ellis in Durham, *c.*1975.]

Though not in a published paper, or indeed reporting British work, what appear to be the first references to quasi-stellar radio sources in British journals (apart from in a review of the recent Texas Symposium[102]) came in talks by Palmer and then Ryle at the 1964 April RAS meeting, as reported in *The Observatory*[103].

The 8th Herstmonceux Conference again had a lengthy session on the *Isaac Newton Telescope*[104], but despite all the activity noted above the only intrusion on the otherwise Galacto-centric plans for its future use came from a radio astronomer, Shakeshaft hoping that it might provide spectra of optically identified radio sources.

In 1965, illustrating relatively new international links, American Peter Goldreich, a visiting post-doc in Cambridge, and Lynden-Bell[105] published their well-known papers on the gravitational stability of rotating discs and the production of spiral arms, while Australian Ken Freeman, then on a Commonwealth Scholarship at DAMTP, discussed gas streaming in barred spirals[106]. E. R. 'Ted' Harrison, 'moonlighting' as a cosmologist from his then day job at the Rutherford High Energy Laboratory (he used his home address, not the Laboratory's), returned to the question of Olbers' Paradox[107], a subject for which he became noted after moving to the USA.

For once, radio observational papers were in a minority, though a new technological development saw Graham Smith[108] use data from the British *Ariel 2* satellite to show that the major contribution to the radio sky brightness below 5 Mc/s was extragalactic. At the September RAS[109], actually held in Dublin, Hubert Gent from RRE, Malvern, and Palmer from Jodrell reported 'new limits to the angular diameters of some quasars' (from a paper that appeared in *Nature*[110]).

UK astronomy in 1966

As we move towards the relatively 'modern' era, it is of interest to consider who was involved in professional astronomy at this epoch. Derek McNally of the University of London Observatory, a well-known advocate for astronomical education, conveniently summed up the situation[111] as of mid-1965 (just prior to the hoped-for inauguration of the *Isaac Newton Telescope* at Herstmonceux). Counting the various parts of the University of London as one, postgraduate studies were possible at 20 universities (and undergraduate astronomy courses were taught at four others, implying at least some academics in each with interests in astronomy) and the three observatories. He estimated that there were certainly no more than 150 post-grads in total. As we might expect from above, a large fraction of these (50) were at Jodrell or Mullard. The number of relevant staff in universities and at graduate level in establishments was counted as at most 140. However, from the above we can see that in the previous fifteen years only eight universities (Battersea, Birmingham, Cambridge, Edinburgh, Liverpool, London, Manchester, St. Andrews) and two observatories had contributed to extragalactic astronomy and observational cosmology. [It is interesting to note that McNally also concluded that "there are at present more places available (or which could be made available) than there are students to fill them, so that further introduction of new astronomy departments would only make the situation more difficult."]

A useful comparison came just three years later with the results of a survey[112] carried out by the recently formed Science Research Council. The Royal Observatories employed 47 Scientific Officers (up from 41), while there were 105 academic staff in universities (compared to about 90), plus 26 working on cosmic rays. There were also 80 of the new breed of Research Assistants ("this class was considered to be quite small", and ignored, in 1965). Research students had risen from about 140 to 185; 46% were now supported by the SRC. Staff members in the radio groups typically had three students each, other academics one. Also noted was that "provision of new facilities by the SRC (the 98-in (2·5-m) *Isaac Newton Telescope*, the SRC lease of the Radcliffe Observatory, the 150-in (3·8-m) *Anglo Australian Telescope*) … makes provision for observational astronomy in a hitherto unprecedented manner".

1966–1970

Returning to the papers, 21 relevant ones appeared in 1966 (17 in *MN*), with MRAO (particularly their students) the largest contributor again with ten, including Jim Gower's 4C source counts[113] and Longair's highly cited paper[114] on interpreting the counts. They were followed by Cambridge theorists, notably Freeman's four contributions on barred spiral galaxies[115] before he left for Texas. Davidson supplied two more cosmological papers[116] on number counts before he, too, moved on, in his case to New Zealand. A paper by Franz Kahn's student Stanislaw Grzedzielski[117] appears to be the first from the University of Manchester outside of Jodrell Bank (which had now become the Nuffield Radio Astronomy Laboratories).

The following year was very similar, virtually half of the 23 extragalactic papers emanating from MRAO, including a number on source spectra and the notable extension to the spectrum of the radio-sky background by Alan Bridle[118]. Ryle & Longair[119] modelled radio-galaxy evolution and Martin Rees at DAMTP (and subsequently at Fred Hoyle's new, but long argued for, Institute of Theoretical Astronomy — from 1972 the Institute of Astronomy) added three theoretical papers[120] on radio-source structure. The keynote papers of the year, though, were arguably that by Lynden-Bell (now RGO) and Jerry Ostriker (Princeton) on the stability of differentially rotating bodies[121] and most definitely the former's groundbreaking paper on 'violent relaxation' in stellar systems[122]. The only specifically optical observational paper came from Kiang[123], on the clustering of Abell Clusters. (Allan Sandage did however win the RAS Gold Medal for his work on stellar populations and galaxy evolution[124].)

There were two important UK conferences in 1968. 'The Physics of Quasars' at Manchester had over a dozen British contributors of talks or at least comments[125], and the 12th Herstmonceux Conference[126], on 'Galaxy Evolution', had around 30 UK participants.

On the other hand, there were considerably fewer papers, just thirteen even including Reddish's introductory lecture[127] for the Herstmonceux meeting and Bernard Pagel's on nucleosynthesis in supermassive objects[128] at the same meeting, which both appeared in *QJ*. Essentially half were again from Mullard, the most cited being Geoff Macdonald, Sidney Kenderdine, and Ann Neville on the structure of 3C sources as measured with the *One-Mile Telescope*[129] and Ryle and Mike Windram on radio galaxies in the Perseus Cluster[130]. Of the remaining four, one was veteran amateur Frederick Brown's final paper on galaxy orientations[131] while another provided the first paper in our list from the recently founded Astronomy Centre at the University of Sussex (with strong links to the RGO), Michael Rowan-Robinson discussing[132] the luminosity–volume test.

The extragalactic astronomers were back in print in 1969 with a total of 24 papers. MRAO was again well represented (nine papers including Craig Mackay with more on the structure of 3C sources[133] and Guy Pooley on M31[134]) with four others from Cambridge theoreticians. There was an increased presence from the RGO with five papers — including the most cited paper of the year, Mike Penston's on isothermal self-gravitating spheres collapsing to form galaxies[135] — but none involved RGO observations, the *INT* having been available for use only since 1967 December.

The 14th Herstmonceux Conference in 1970 was titled 'The Distances and Sizes of Cosmic Objects'. A significant part concerned distances inside the Galaxy, but there were talks[136] on galaxy photometry, on distances to quasars, and on a new topic, the X-ray background, the latter by Longair and by Adrian Webster (Cambridge). At an RAS Meeting[137] Ken Pounds (Leicester) reported on the X-ray detection of M87 (Virgo XR-1) in observations from Skylark rocket flights. The IAU General Assembly was held in Sussex in August and included some extragalactic sessions, but only organizational matters were mentioned at the RAS[138].

Twenty papers appeared in *MN*, *Memoirs*, or *The Observatory* in 1970, with this time Jodrell Bank dominating (seven papers) thanks mainly to Stephen Gottesman's work with Davies on H I in M31 and M33[139]. MRAO contributed five, including a cross-Iron-Curtain collaboration between Longair and Doroshkevic and Zeldovich[140] and the 5C4 survey of the Coma Cluster by Martin Willson[141]. The first extragalactic paper to have used plates from the *INT* appears to be the one by Russell Cannon, Chris Lloyd, and Penston on the ring galaxies I Zw 44 and VII Zw 466[142]. RGO also supplied what appears to be the first UK paper[143] on optical extragalactic astronomy with a female co-author, Keith Tritton and Rosemary Brett's contribution on BL Lac (though technically it was not confirmed as a galaxy at this point), just beating Cannon *et al.*, including Janet Sinclair[144], into print.

Summary and state of play by 1970

Purely in terms of numbers of papers, and for simplicity we will take those in *MNRAS* as our main indicator, across the fifteen years to 1965 there were 87 with UK (based) authors, *i.e.*, about six per year (it was only two or three per year in the 1950s, the same as in the late 1940s[4]), with another 75, or fifteen per year, between 1966 and 1970. This would rise to 40 per year by 1975. (Indeed, David Allen[145], in a letter to *The Observatory* entitled 'Should this Letter have been Rejected', would bemoan the fact that "the rate of publication of astronomical papers is inflating at an alarming rate"). As noted earlier there were also some papers in the non-astronomy-specific *Nature*, the majority of them from the radio groups or the Cambridge theorists; these too increased in numbers, but only from one per year in the 1950s to four per year in the '60s.

In terms of content, it will be evident from the foregoing that extragalactic work in the UK over the period covered was heavily influenced by radio astronomy. In total just over half of the *MN* papers emanated from Mullard or Jodrell Bank (as did many communications in *The Observatory*) and several of the theoretical papers also dealt with the radio number counts. Only about a dozen could be classed as optical observational papers. As regards affiliations, outside of Cambridge and Manchester, even including the contributions in *The Observatory*, we see papers from only the universities of Aberdeen, Battersea (Surrey), Birmingham, Edinburgh, Leicester, Liverpool, London (Observatory, Imperial, King's, Queen Elizabeth, Queen Mary, Royal Holloway, UCL), Reading, St. Andrews, and Sussex, plus the observatories, Armagh, ROE and RGO, and RRE Malvern. The overwhelming majority of the work was carried out by the university groups (though notably, there was nothing from Oxford). One interesting aspect of the authors, compared to the earlier epochs, is the large number of graduate students (particularly in Cambridge). Towards the end of the period we also start to see more collaborative papers between institutes and more non-UK authors in UK institutions. (UK astronomers also now being more likely to spend time abroad, particularly in the USA.)

Looking ahead, plans were, of course, already afoot for future developments during the 1970s. On the radio side, 1971 saw the completion of the 5-km Array, later the *Ryle Telescope*[146], in Cambridge, while an important RAS meeting[147] for the future of UK optical astronomy took place immediately after the time span considered here. The 1971 January meeting was devoted to the work of the Science Research Council's Panel on Instrumentation for Large Optical Telescopes. This discussed instrumentation for the upcoming *Anglo-Australian Telescope* (first light came in 1974). At a later Specialist Discussion[148] on 'The U.K. 48-inch Schmidt Project' it was noted that "Considerable changes have been made in the U.K. commitments in the Southern Hemisphere since 1965 [when the SRC was instituted] … partly in response to the … far-sighted Southern Hemisphere Review". This had led to the joint funding with the Australians of the *AAT* and the SRC was now adding a Schmidt telescope (commissioned 1973) on the same site due to "the pressing need for surveys of the southern sky". X-ray astronomy was also coming to the fore, with the 1972 Herstmonceux Conference 'Cosmic X-ray Sources' summarizing UK work to date and future plans[149]. *OAO-3* (*Copernicus*), with UK involvement, was launched that year while the dedicated UK X-ray satellite *Ariel 5*, first proposed in 1967, was launched in 1974.

Finally, of course, despite McNally and Allen's misgivings, both the number of astronomy groups and the number of papers they produced did continue to grow — as did the size of *Monthly Notices*!

References

(1) E. P. Hubble, *PA*, **33**, 252, 1925.
(2) E. P. Hubble, *ApJ*, **62**, 409, 1925.
(3) S. Phillipps, *The Observatory*, **140**, 185, 2020.
(4) S. Phillipps, *The Observatory*, **142**, 40, 2022.
(5) M. Ryle, F. G. Smith & B. Elsmore, *MNRAS*, **110**, 508, 1950.
(6) RAS Meeting Report, *The Observatory*, **66**, 308, 1946.
(7) R. Hanbury Brown & C. Hazard, *MNRAS*, **111**, 357 and 576, 1951.
(8) RAS Meeting Report, *The Observatory*, **71**, 209, 1951.
(9) G. J. Whitrow & D. G. Randall, *MNRAS*, **111**, 455, 1951.
(10) G. C. McVittie & C. Payne-Gaposchkin, *MNRAS*, **111**, 506, 1951.
(11) M. Johnson, *The Observatory*, **72**, 243, 1952.
(12) R. Hanbury Brown & C. Hazard, *MNRAS*, **113**, 123, 1953.
(13) RAS Meeting Report, *The Observatory*, **73**, 97, 1953.
(14) E. P. Hubble, *MNRAS*, **113**, 658, 1953.
(15) President's Address, *MNRAS*, **114**, 370, 1954.
(16) F. Hoyle, *ApJ*, **118**, 513, 1953.
(17) R. O. Kapp, *The Observatory*, **73**, 113, 1953.
(18) Symposium on Radio Astronomy (R. Hanbury Brown), *The Observatory*, **73**, 185, 1953.
(19) R. C. Jennison & M. K. Das Gupta, *Nature*, **172**, 996, 1953.
(20) C. W. Allen, *MNRAS*, **114**, 387, 1954.
(21) D. ter Haar, *The Observatory*, **74**, 128, 1954.
(22) D. W. Sciama, *MNRAS*, **115**, 3, 1955.
(23) H. Bondi, T. Gold & D. Sciama, *ApJ*, **120**, 597, 1954.
(24) E. M. Lindsay, *MNRAS*, **115**, 248, 1955.
(25) E. M. Lindsay, *MNRAS*, **118**, 172, 1958.
(26) J. L. E. Dreyer, *MemRAS*, **49**, 1, 1888.
(27) P. B. Fellgett, *The Observatory*, **75**, 176, 1955.
(28) J. Neyman & E. L. Scott, *The Observatory*, **76**, 62, 1956.
(29) R. Hanbury Brown, H. P. Palmer & A. R. Thompson, *MNRAS*, **115**, 487, 1955.
(30) J. E. Baldwin, *MNRAS*, **115**, 690, 1955.
(31) J. Shakeshaft *et al.*, *MemRAS*, **67**, 106, 1955.
(32) RAS Meeting Report, *The Observatory*, **75**, 102, 1955.
(33) M. Ryle, *The Observatory*, **75**, 137, 1955.
(34) President's Address (J. Jackson), *MNRAS*, **115**, 202, 1955.
(35) Symposium on the Comparison of the Large Scale Structure of the Galactic System with that of Other Stellar Systems, *The Observatory*, **75**, 192, 1955.
(36) V. C. Reddish, *MNRAS*, **116**, 533, 1956.
(37) V. C. Reddish, *The Observatory*, **76**, 68, 1956.
(38) W. B. Bonnor, *MNRAS*, **116**, 351, 1956 and **117**, 104, 1957.
(39) J. E. Baldwin & F. G. Smith, *The Observatory*, **76**, 141, 1956.
(40) G. R. Whitfield, *MNRAS*, **117**, 680, 1957.
(41) D. Morris, H. P. Palmer & A. R. Thompson, *The Observatory*, **77**, 103, 1957.
(42) RAS Meeting Report, *The Observatory*, **77**, 117, 1957.
(43) D. O. Edge, P. A. G. Scheuer & J. R. Shakeshaft, *MNRAS*, **118**, 183, 1958.
(44) RAS Meeting Report, *The Observatory*, **78**, 93, 1958.
(45) A. Hewish, *PASP*, **70**, 140, 1958.
(46) D. O. Edge *et al.*, *MemRAS*, **68**, 37, 1959.
(47) H. Tunmer, *MNRAS*, **119**, 184, 1959.
(48) B. Elsmore, M. Ryle & P. R. R. Leslie, *MemRAS*, **68**, 61, 1959.
(49) R. Hanbury Brown & C. Hazard, *MNRAS*, **119**, 297, 1959.
(50) J. H. Oort, F. T. Kerr & G. Westerhout, *MNRAS*, **118**, 379, 1958.
(51) R. A. Proctor, *MNRAS*, **30**, 50, 1869.
(52) W. Davidson, *MNRAS*, **119**, 54, 1959; **119**, 665, 1959; **120**, 271, 1960.
(53) A. R. Sandage, M. Livio, S. M. Fall & P. Madau, (eds.) *The Hubble Deep Field*, 1998.
(54) D. Lynden-Bell, *MNRAS*, **120**, 204, 1960.
(55) R. v.d.R. Woolley, *MNRAS*, **120**, 214, 1960.
(56) O. J. Eggen & A. R. Sandage, *MNRAS*, **120**, 79, 1960.
(57) A. R. Sandage, & O. J. Eggen, *MNRAS*, **121**, 232, 1960.
(58) F. Hoyle, *MNRAS*, **120**, 338, 1960.
(59) S. Aarseth, *MNRAS*, **121**, 525, 1960.
(60) M. Harwit, *MNRAS*, **122**, 47, 1961 and **123**, 257, 1961.
(61) RAS Meeting Report, *The Observatory*, **81**, 37, 1961.
(62) P. R. R. Leslie, *MNRAS*, **122**, 51, 1961.
(63) R. Hanbury Brown & C. Hazard, *MNRAS*, **122**, 479, 1961 and **123**, 279, 1961.

(64) P. R. R. Leslie & B. Elsmore, *The Observatory*, **81**, 14, 1961.
(65) M. Ryle & R. W. Clarke, *MNRAS*, **122**, 349, 1961.
(66) P. F. Scott & M. Ryle, *MNRAS*, **122**, 389, 1961.
(67) F. Hoyle & J. V. Narlikar, *MNRAS*,**123**, 133, 1961.
(68) F. Hoyle & J. V. Narlikar, *The Observatory*, **82**, 13, 1962.
(69) I. King, *The Observatory*, **81**, 128, 1961.
(70) R. Hanbury Brown, *MNRAS*, **124**, 35, 1962.
(71) RAS Meeting Report, *The Observatory*, **81**, 113, 1961.
(72) W. Davidson, *MNRAS*, **123**, 425, 1962 and **124**, 79, 1962.
(73) T. Kiang, *MNRAS*, **122**, 263, 1961.
(74) V. Reddish, *The Observatory*, **81**, 19, 1961.
(75) V. Reddish, *The Observatory*, **82**, 14, 1962.
(76) C. Hazard, *MNRAS*, **124**, 343, 1962.
(77) R. v.d.R. Woolley, *QJRAS*, **3**, 249, 1962.
(78) Herstmonceux Conference Report, *The Observatory*, **83**, 150, 1963.
(79) L. Mestel, *MNRAS*, **126**, 553, 1963.
(80) H. van der Laan, *MNRAS*, **126**, 519 and 535, 1963.
(81) F. Hoyle & W. A. Fowler, *MNRAS*, **125**, 169, 1963.
(82) B. Rowson, *MNRAS*, **125**, 177, 1963.
(83) R. G. Conway, K. I. Kellermann & R. J. Long, *MNRAS*, **125**, 261, 1963.
(84) R. D. Davies *et al.*, *The Observatory*, **83**, 245, 1963.
(85) D. W. Sciama, *MNRAS*, **126**, 195, 1963.
(86) RAS Meeting Report, *The Observatory*, **83**, 200, 1963.
(87) P. F. Scott, *MNRAS*, **127**, 37, 1963.
(88) S. Aarseth, *MNRAS*, **126**, 223, 1963.
(89) C. Hunter, *MNRAS*, **126**, 299, 1963.
(90) W. Davidson & M. Davies, *MNRAS*, **127**, 241, 1964; correction in *MNRAS*, **128**, 363, 1964.
(91) G. J. Whitrow & B. D. Yallop, *MNRAS*, **127**, 301, 1964.
(92) W. B. Bonnor, *MNRAS*, **128**, 33, 1964.
(93) D. W. Sciama, *QJRAS*, **5**, 196, 1964.
(94) I. W. Roxburgh & P. G. Saffman, *MNRAS*, **129**, 181, 1965.
(95) W. H. McCrea, *MNRAS*, **128**, 335, 1964.
(96) R. A. Lyttleton & H. Bondi, *MNRAS*, **128**, 207, 1964.
(97) M. E. Clarke, *MNRAS*, **127**, 405, 1964.
(98) M. S. Longair, *MNRAS*, **129**, 419, 1965.
(99) J. D. H. Pilkington, *MNRAS*, **128**, 103, 1964.
(100) F. G. Brown, *MNRAS*, **127**, 517, 1964.
(101) J. H. Reynolds, *MNRAS*, **82**, 510, 1922.
(102) Notes, *The Observatory*, **84**, 40, 1964.
(103) RAS Meeting Report, *The Observatory*, **84**, 125, 1964.
(104) The Eighth Herstmonceux Conference, *The Observatory*, **84**, 169, 1964.
(105) P. Goldreich & D. Lynden-Bell, *MNRAS*, **130**, 97 and 125, 1965.
(106) K. C. Freeman, *MNRAS*, **130**, 183, 1965.
(107) E. R. Harrison, *MNRAS*, **131**, 1, 1965.
(108) F. G. Smith, *MNRAS*, **131**, 145, 1965.
(109) RAS Meeting Report, *The Observatory*, **85**, 231, 1965.
(110) R. L. Adgie *et al.*, *Nature*, **208**, 275, 1965.
(111) D. McNally, *QJRAS*, **7**, 22, 1966.
(112) Meeting Report (D. McNally), *QJRAS*, **10**, 21, 1969.
(113) J. F. R. Gower, *MNRAS*, **133**, 151, 1966.
(114) M. S. Longair, *MNRAS*, **133**, 421, 1966.
(115) K. C. Freeman, *MNRAS*, **133**, 47, 1966 *et seq.*
(116) W. Davidson, *MNRAS*, **132**, 389, 1966.
(117) S. Grzedzielski, *MNRAS*, **134**, 109, 1966.
(118) A. H. Bridle, *MNRAS*, **136**, 219, 1967.
(119) M. Ryle & M. S. Longair, *MNRAS*, **136**, 123, 1967.
(120) M. Rees, *MNRAS*, **135**, 435, 1967 *et seq.*
(121) D. Lynden-Bell & J. P. Ostriker, *MNRAS*, **136**, 293, 1967.
(122) D. Lynden-Bell, *MNRAS*, **136**, 101, 1967.
(123) T. Kiang, *MNRAS*, **135**, 1, 1967.
(124) Presidential Address, *QJRAS*, **8**, 126, 1967.
(125) Manchester Conference Report, *QJRAS*, **9**, 63, 1968.
(126) The Twelfth Herstmonceux Conference, *The Observatory*, **88**, 185, 1968.
(127) V. C. Reddish, *QJRAS*, **9**, 409, 1968.
(128) B. E. J. Pagel, *QJRAS*, **9**, 401, 1968.
(129) G. H. Macdonald, S. Kenderdine & A. C. Neville, *MNRAS*, **138**, 259, 1968.

(130) M. Ryle & M. D. Windram, *MNRAS*, **138**, 1, 1968.
(131) F. G. Brown, *MNRAS*, **138**, 527, 1968.
(132) M. Rowan-Robinson, *MNRAS*, **138**, 445, 1968.
(133) C. D. Mackay, *MNRAS*, **145**, 31, 1969.
(134) G. G. Pooley, *MNRAS*, **144**, 101, 1969.
(135) M. V. Penston, *MNRAS*, **144**, 425, 1969.
(136) The Fourteenth Herstmonceux Conference, *The Observatory*, **90**, 213, 1970.
(137) RAS Meeting Report, *The Observatory*, **90**, 165, 1970.
(138) RAS Meeting Report, *The Observatory*, **91**, 1, 1971.
(139) S. Gottesman & R. D. Davies, *MNRAS*, **149**, 263, 1970.
(140) A. G. Doroshkevic, M. S. Longair & Ya. B. Zeldovich, *MNRAS*, **147**, 139, 1970.
(141) M. A. G. Willson, *MNRAS*, **151**, 1, 1970.
(142) R. D. Cannon, C. Lloyd & M. V. Penston, *The Observatory*, **90**, 153, 1970.
(143) K. P. Tritton & R. A. Brett, *The Observatory*, **90**, 110, 1970.
(144) R.D. Cannon *et al.*, *The Observatory*, **90**, 192, 1970.
(145) D. A. Allen, *The Observatory*, **94**, 320, 1974.
(146) M. Ryle, *Nature*, **239**, 435, 1972.
(147) RAS Meeting Report, *The Observatory*, **91**, 89, 1971.
(148) Discussion Meeting on UK Schmidt Project, *The Observatory*, **93**, 49, 1973.
(149) Sixteenth Herstmonceux Conference, *The Observatory*, **92**, 193, 1972.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 9: THE SOLAR-TYPE SYSTEM KIC 5359678

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KIC 5359678 is a 6·231-d period F-type eclipsing binary system whose component stars both show starspot activity. It was observed by the *Kepler* satellite in long cadence for the full four-year duration of the mission. Wang *et al.*[1] obtained radial-velocity measurements of the two stars and analysed these plus the *Kepler* data to study their spot activity and measure their physical properties, but left several questions unanswered. We have performed an independent analysis and determined the masses (1·252 ± 0·018 and 1·065 ± 0·013 $M_{\odot}$) and radii (1·449 ± 0·012 and 1·048 ± 0·017 $R_{\odot}$) of the stars to high precision. The distance we find to the system is slightly shorter than that from *Gaia* EDR3 for unknown reason(s). We also investigated the precision of the numerical integration applied to the model light-curve to match the 1765-s sampling cadence of the *Kepler* observations. We found that ignoring this temporal smearing leads to biassed radius measurements for the stars: that for the primary is too small by 4σ and that for the secondary is too large by 10σ. Doubling the sampling rate of the model light-curve is sufficient to remove most of this bias, but for precise results a minimum of five samples per observed data point is required.

Introduction

Detached eclipsing binaries (dEBs) are crucial to stellar physics because the properties of their component stars can be measured directly from observed light and radial-velocity (RV) curves[2,3]. These direct measurements can then be used to constrain and to calibrate theoretical models of stellar evolution[4–6]. Many thousands of dEBs are now known[7–10]. Particularly important contributions to the numbers of dEBs for which good light-curves are available have recently been made by space missions such as *CoRoT*[11], *Kepler*[12], and *TESS*[13–15]. An extensive review of the impact of space photometry on binary-star science was given by Southworth[16].

KIC 5359678 was found to be a dEB using data from the *Kepler* satellite[12,17–19] with a morphology value of 0·27 which indicates that it is well-detached[20]. Armstrong *et al.*[21] determined effective temperature ($T_{\rm eff}$) values for the two components of 6713 ± 405 K and 6237 ± 623 K. Qian *et al.*[22] determined the $T_{\rm eff}$ of the system to be 6510 ± 70 K and its spectral type to be F5 from a medium-resolution (R = 1800) spectrum obtained using the *LAMOST* spectroscopic telescope[23] survey of the *Kepler* field[24].

Wang *et al.*[1] (hereafter W21) presented a detailed study of KIC 5359678 which concentrated on the characteristics of the starspots on the stellar surfaces. To determine the physical properties of the stars, W21 modelled the light-curve from the *Kepler* satellite together with RVs from a set of 58 medium-resolution (R = 7500) *LAMOST* spectra[25] using the PHOEBE2 code[26]. They gave two sets of physical properties for the system, for eccentric and circular orbits, which are formally identical but with error bars differing by as much as a factor of three. They also quoted no error bar for the mass of the secondary star, and did not mention whether they accounted for the cadence of the observations obtained by the *Kepler* satellite. For these reasons, and to see if the properties of the system can be established to a precision of 2% or better[2,27], we present below a reanalysis of KIC 5359678. Basic information on the system is summarized in Table I.

TABLE I

Basic information on KIC 5359678

Property	*Value*	*Reference*
Kepler Input Catalog designation	KIC 5359678	28
Kepler Object of Interest designation	KOI 6569	29 and updates
Gaia EDR3 designation	2101510803402761344	30
Gaia EDR3 parallax	0·6151 ± 0·0135 mas	30
B magnitude	14·905 ± 0·023	31
V magnitude	14·209 ± 0·056	31
H magnitude	12·927 ± 0·029	32
K_s magnitude	12·862 ± 0·030	32
Spectral type	F5	1

Observational material

The *Kepler* satellite is a 0·95-m Schmidt reflecting telescope with a focal plane containing 42 CCDs, launched by NASA in 2009 March and placed into an Earth-trailing heliocentric orbit[33,34]. Its mission was to obtain photometric observations of a single patch of sky (the *Kepler* Field) for four years in order to find transits of extrasolar planets. Due to a limit on the amount of data that could be returned to Earth, *Kepler* could only be used to observe 170 000 objects simultaneously. Consecutive observations were summed into single 'long cadence' observations with an effective duration of 1765·5 s, and the count rates of pixels in the region of selected targets were transmitted to Earth. A subset of 512 of these targets could be observed in 'short cadence', where individual observations were summed into data with an effective duration of 58·8 s. *Kepler* observations were divided into quarters (three months) due to the rotation of the spacecraft around its optical axis to keep its solar panels illuminated by the Sun. These data were reduced by the *Kepler* mission Science Operations Center (SOC)[35].

KIC 5359678 was observed for the entirety of the *Kepler* mission, from quarters Q0 to Q17, in long cadence. The first data point was taken on 2009/05/13 and the last on 2013/05/11. Small gaps occured within this time interval when *Kepler* paused observations for technical reasons or to transmit data to Earth. The data were downloaded from the MAST archive* and converted to relative magnitudes. Rejection of unreliable data (typically represented by 'Inf' or 'Nan') left 64 073 measurements. We chose to work with the standard aperture photometry (SAP) rather than the pre-search data conditioning (PDC) data, after verifying that the differences were negligible for our purposes. An example light-curve, chosen at random to be from Q10, is shown in Fig. 1.

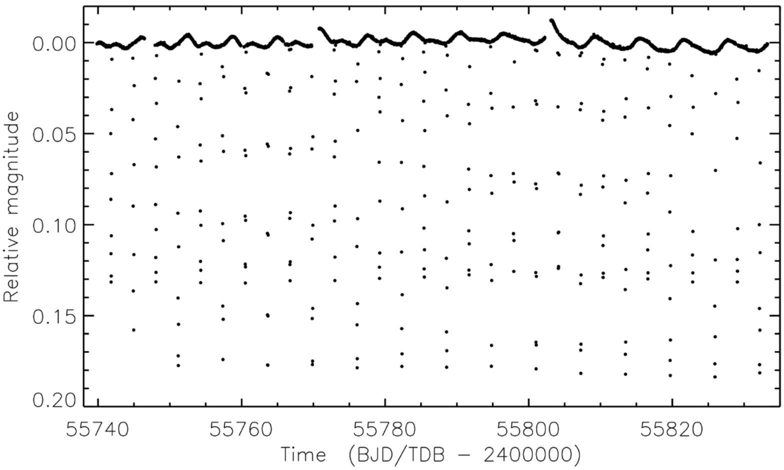

Fig. 1

Kepler quarter-10 light-curve of KIC 5359678. The spot activity can be seen as continual variations in the data outside eclipse, and two jumps in the data are also visible after short interruptions to the observations.

Analysis of the Kepler light-curve

The majority of the photometric observations occur outside eclipse, so hold negligible information on the physical properties of the stars. The starspot

* Mikulski Archive for Space Telescopes,
https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

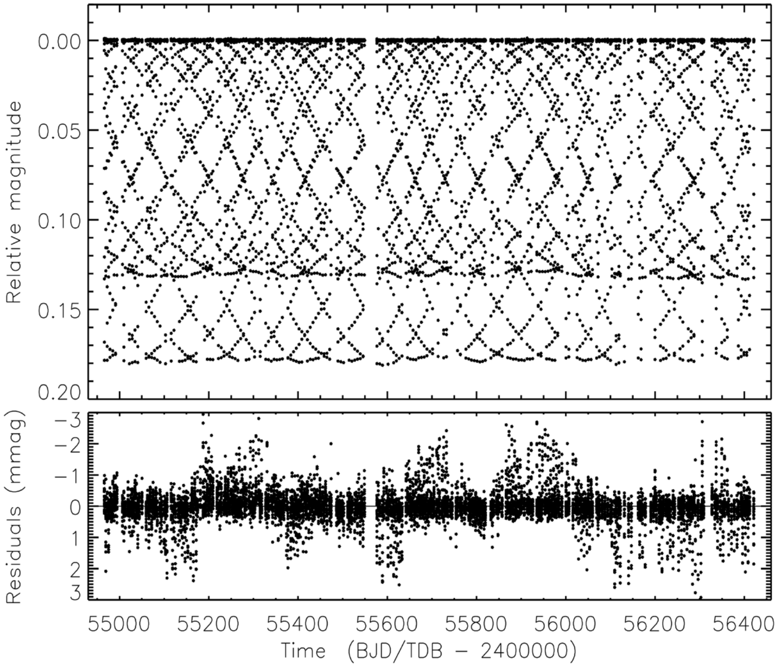

FIG. 2

The *Kepler* light-curve of KIC 5359678 as analysed (top panel) with the residuals of the best fit for a circular orbit (lower panel).

variation also affects the brightness of the system during eclipse but occurs on much longer time-scales. We tackled both problems by extracting the data around each eclipse from the overall light-curve, fitting a polynomial to the out-of-eclipse data, and subtracting the polynomial (in magnitude units) to remove the slow variations due to starspots and instrumental effects. All eclipses were manually inspected and those with insufficient data either before or after, or with more than two data points missing, were rejected. This left a total of 8106 observations with the main effects of spot activity removed (Fig. 2).

We then proceeded to analyse the data with version 41 of the JKTEBOP* code[36,37]. Fitted parameters included the sum and ratio of the fractional radii ($r_A + r_B$ and $k = \frac{r_B}{r_A}$ where $r_A = \frac{R_A}{a}$, $r_B = \frac{R_B}{a}$, R_A and R_B are the radii of the stars, and a is the semi-major axis of the relative orbit), the orbital inclination (i) and period (P), a reference time of primary minimum (T_0; when star A is eclipsed by star B), and the central surface-brightness ratio of the two stars ($\mathcal{J}$).

For limb darkening (LD) we adopted the quadratic law, fitted the linear coefficient for each star (u_A and u_B) and fixed the quadratic coefficients (v_A and v_B) to theoeretical values from Sing[38]. We found third light to be very small so fixed it at zero. One important consideration is the long sampling cadence — one observation every 1765 s — and we accounted for that by numerically integrating the model light-curve to match the observed one[39].

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

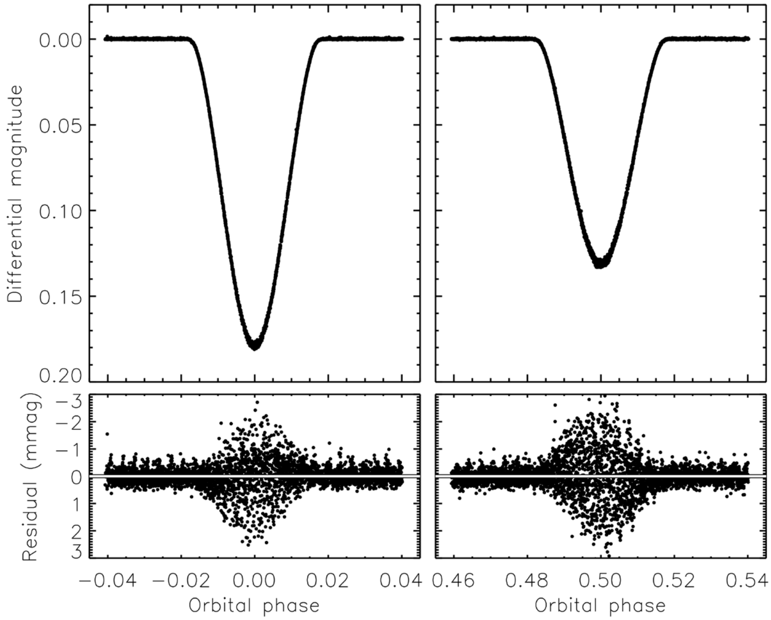

FIG. 3

The *Kepler* light-curve of KIC 5359678 (filled circles) around the primary (left) and secondary (right) eclipses. The best fit is not plotted as it is indistinguishable from the data. The lower panels show the residuals of the fit with the line of zero residual overplotted in white.

We obtained solutions for a circular and an eccentric orbit. In the latter case we fitted for $e \cos \omega$ and $e \sin \omega$ where e is the orbital eccentricity and ω is the argument of periastron. In both cases we included the RV measurements of the two stars published by W21 in order to measure the masses and radii of the stars. The error bars on the three datasets (light-curve, RVs of star A, RVs of star B) were each scaled to give a reduced χ^2 of $\chi^2_\nu = 1$ for that dataset.

The best fit to the light-curve for the circular orbit can been seen in Fig. 2. The residuals in this figure show systematic trends with time which occur because our approach to dealing with the spot activity does not account for the partial obscuration of spots during eclipses. Our best fit therefore systematically over- or under-predicts the eclipse depth in a way which changes on a characteristic time-scale of approximately 200 days. This is much longer than the rotation period or the time-scale over which individual starspots appear and disappear (see Fig. 1), but is much shorter than the time interval covered by the data.

Another visualization of the situation is shown in Fig. 3, where the data have been converted into orbital phase and shown in close-up around the eclipses. The best fit is clearly a good representation of the data, but the residuals significantly increase during both eclipses. As changes in eclipse depth are driven primarily by spots on the surface of the eclipsed star, this tells us that both stars show spot activity and that their activity levels are comparable.

TABLE II

Parameters of the JKTEBOP best fits to the Kepler light-curve and published RVs of KIC 5359678. The uncertainties are 1σ and are the larger of the Monte Carlo and residual-permutation options for each parameter.

Parameter	*Circular orbit*	*Eccentric orbit*
Fitted parameters:		
Primary eclipse (BJD/TDB)	2455402·26675 ± 0·00002	2455402·26670 ± 0·00002
Orbital period (d)	6·23060994 ± 0·00000024	6·23060991 ± 0·00000028
Orbital inclination (°)	85·537 ± 0·042	85·527 ± 0·049
Sum of the fractional radii	0·13246 ± 0·00044	0·13255 ± 0·00049
Ratio of the radii	0·724 ± 0·022	0·732 ± 0·027
Central surface-brightness ratio	0·7324 ± 0·0015	0·7253 ± 0·0129
Third light	0·0 (fixed)	0·0 (fixed)
Linear LD coefficient star A	0·293 ± 0·008	0·297 ± 0·011
Linear LD coefficient star B	0·318 ± 0·009	0·307 ± 0·023
Quadratic LD coefficient star A	0·31 (fixed)	0·31 (fixed)
Quadratic LD coefficient star B	0·29 (fixed)	0·29 (fixed)
$e \cos \omega$	0·0 (fixed)	0·000035 ± 0·000048
$e \sin \omega$	0·0 (fixed)	−0·0010 ± 0·0017
Velocity amplitude star A (km s^{-1})	70·14 ± 0·34	70·15 ± 0·37
Velocity amplitude star B (km s^{-1})	82·49 ± 0·56	82·50 ± 0·58
Systemic velocity star A (km s^{-1})	−29·19 ± 0·14	−29·19 ± 0·28
Systemic velocity star B (km s^{-1})	−29·30 ± 0·21	−29·30 ± 0·28
Derived parameters:		
Fractional radius of star A	0·07685 ± 0·00053	0·07655 ± 0·00091
Fractional radius of star B	0·05561 ± 0·00085	0·0560 ± 0·0014
Orbital eccentricity	0·0 (fixed)	0·0009 ± 0·0012
Argument of periastron (°)	n/a	272 ± 92
Light ratio	0·381 ± 0·028	0·388 ± 0·028

The uncertainties in the fitted and derived parameters were estimated using Monte Carlo and residual-permutation simulations[36,40]. The Monte Carlo algorithm requires the data errors to be of a correct size, which was achieved by the scaling to force $\chi^2_\nu = 1$. The residual-permutation algorithm successively shifts the residuals of the best fit along the data strings before refitting, so is by design sensitive to red noise and eclipse-depth variations. The larger of the two error bars was adopted for each parameter. Table II gives the best-fitting parameters and their uncertainties for modelling runs assuming a circular or an eccentric orbit. Fig. 4 shows the RVs and the fitted circular orbits. The parameter values for the circular- and eccentric-orbit cases are almost identical, and their error bars are similar, so we adopt the circular orbit as our final result. Inspection of the Monte Carlo and residual-permutation results shows that there is a very strong correlation between the ratio of the radii and the light ratio of the system, as is normally seen in cases where eclipses are shallow and partial (*e.g.*, V455 Aur[41]). The radius measurements could be improved by obtaining a spectroscopic light ratio, although this will need a large telescope given the relative faintness of KIC 5359678.

How much numerical integration is needed?

The *Kepler* long-cadence light-curve of KIC 5359678 is sampled at a cadence of $t_{\rm samp} = 1765{\cdot}5$ s (Borucki[34]) so each eclipse of this EB is covered by only nine or ten data points. It is therefore important to account for this when

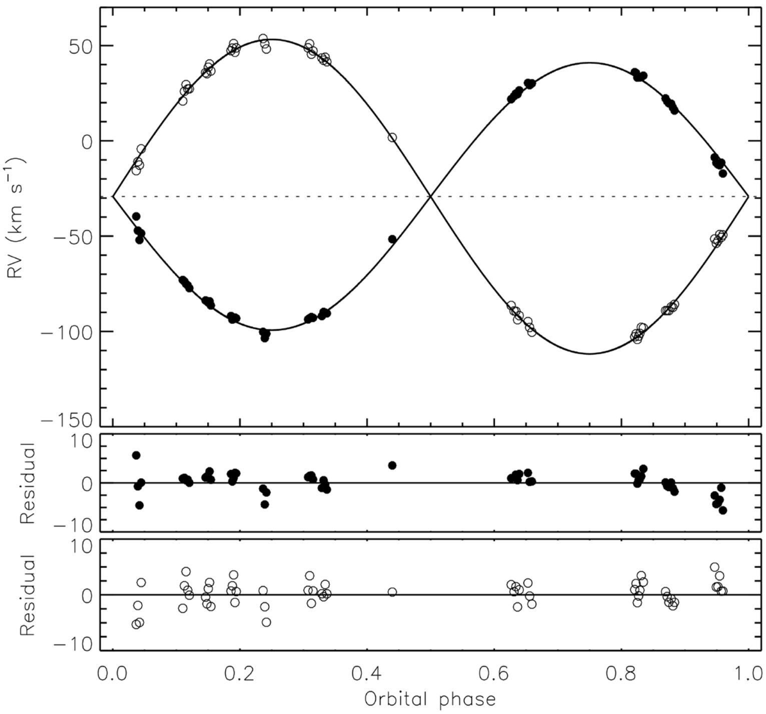

FIG. 4

The RVs of KIC 5359678 from W21 for star A (filled circles) and star B (open circles) plotted *versus* orbital phase. The solid curves give the best-fitting circular orbits, which are visually indistinguishable from the best-fitting eccentric orbits. The lower panels show the residuals of the fits for the two stars individually.

fitting the data, by numerically integrating the model light-curve. The method implemented in JKTEBOP is to divide each data point up into $n_{\rm samp}$ time intervals of equal duration $t_{\rm dur} = t_{\rm samp}/n_{\rm samp}$, calculate the model light-curve at the midpoint of each time interval, and then take the mean of the $n_{\rm samp}$ fluxes as the predicted value for that data point[39]. An obvious question is: what is a suitable value of $n_{\rm samp}$? Smaller values risk undersampling the light-curve and biassing the best-fitting parameters, whereas larger values take proportionally more computing time. A value of $n_{\rm samp} = 9$ was used in the JKTEBOP analysis above.

We therefore ran a set of solutions of the *Kepler* light-curve (eclipses only) with $n_{\rm samp}$ running from one (equivalent to no numerical integration) to nine (the value used for the main analysis). The results are shown in Fig. 5 for the radii of the stars, in the expectation that these are the properties whose measurement is most affected by the sampling rate of the observations. It can be seen that ignoring numerical integration leads to results that are very biassed: $R_{\rm A}$ is too small by $4{\cdot}1\sigma$ and $R_{\rm B}$ is too large by $10{\cdot}6\sigma$. This arises because the smearing of

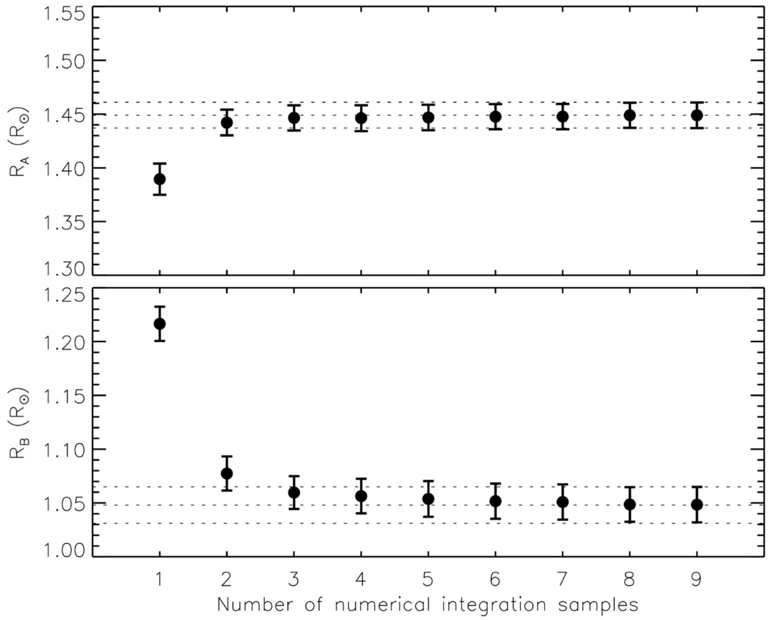

FIG. 5

Best-fitting radii of the stars (star A in the top panel and star B in the bottom panel) with varying amounts of numerical integration. Error bars from Monte Carlo simulations are shown. The values and uncertainties found in the current work are indicated with dotted lines.

the eclipse shape is best matched using a larger k and a slightly smaller i. Using $n_{samp} = 2$ immediately leads to a big improvement in the results, and $n_{samp} = 3$ is sufficient to bring both radius measurements within the error bars of the final result. Larger values of n_{samp}, perhaps 5 or 8 depending on one's science goals, are needed to measure reliable parameter values. However, the error bars are reliably measured for much coarser sampling: $n_{samp} \geq 2$. It is therefore acceptable to measure parameter values with a larger n_{samp}, but then run the error analysis algorithms with a lower n_{samp} to save computing time.

These conclusions are specific to KIC 5359678 but are likely to hold for most EBs with eclipses of similar duration. They are comparable to what Southworth[39] found for the synthetic light-curve of a transiting extrasolar planetary system resembling Kepler-6. Similar conclusions were also reached by Kipping[42]. The most important point is that if the data have been temporally averaged then the model one fits to it must be treated in the same way.

Physical properties of KIC 5359678

To determine the physical properties of the KIC 5359678 system we used the values and uncertainties of r_A, r_B, P, i, K_A, and K_B from Table II. The calculations were performed with the JKTABSDIM code[43], which calculates the physical properties using standard formulae and propagates uncertainties *via*

TABLE III

Physical properties of KIC 5359678 defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 47). The T_{eff}s are from W21.

Parameter	*Star A*	*Star B*
Fitted parameters:		
Mass ratio	0·8503 ± 0·0071	
Semi-major axis of relative orbit ($R^N_\odot$)	18·854 ± 0·081	
Mass ($M^N_\odot$)	1·252 ± 0·018	1·065 ± 0·013
Radius ($R^N_\odot$)	1·449 ± 0·012	1·048 ± 0·017
Surface gravity (log[cgs])	4·214 ± 0·007	4·424 ± 0·013
Density ($\rho_\odot$)	0·412 ± 0·009	0·924 ± 0·043
Synchronous rotational velocity (km s^{-1})	11·76 ± 0·10	8·51 ± 0·14
Effective temperature (K)	6500 ± 50	5980 ± 70
Luminosity log ($L/L^N_\odot$)	0·555 ± 0·014	0·103 ± 0·025
M_{bol} (mag)	3·353 ± 0·037	4·483 ± 0·061
Distance (pc)	1534 ± 27	

perturbation. We adopted the T_{eff} values of the stars from W21, but increased the error bar for star B because the quoted value is measured relative to the T_{eff} of star A so therefore should include its uncertainty. The ratio of the T_{eff}s is consistent with the surface-brightness ratio measured from the light-curve (Table II). The results are given in Table III.

To determine the distance to the system we used its apparent magnitudes in B and V from APASS DR9 and in H and K from 2MASS (see Table I); the 2MASS J magnitude is unreliable[32]. The interstellar extinction was estimated as $E(B-V) = 0·07 \pm 0·03$ mag obtained using the STILISM* on-line tool (Lallement *et al.*[44,45]). Its distance of 1534 ± 27 pc was calculated using the surface-brightness method from Southworth *et al.*[43] and the K-band surface-brightness calibrations from Kervella *et al.*[46]. This is significantly smaller than the distance of 1626 ± 36 pc from the parallax of the system in *Gaia* EDR3[30].

We are unable to deduce the reason why our distance is discrepant with that from *Gaia*. The 2MASS apparent magnitudes are single-epoch so may have been obtained at a time of particularly strong starspot activity — we have no data available to provide an independent cross-check but the required change of approximately +0·1 mag in K is much larger than the brightness modulation due to starspot activity seen in Fig. 1. The 2MASS observations were taken at phase 0·9801 ± 0·0001 based on our ephemeris in Table II, which is close to but confidently outside primary eclipse (see Fig. 3). The APASS BV magnitudes come from six epochs so are very unlikely to be made significantly fainter by eclipses. A larger set of T_{eff} values allied with stronger reddening also requires implausible changes — increases of 1300 K in both T_{eff}s and 0·23 mag in $E(B-V)$ — to fix the discrepancy. Stellar radii larger by 5% would also be sufficient, but far beyond our 1σ error bars in Table III and significantly greater than those found by W21. We leave this mystery for future study.

Summary and conclusions

KIC 5359678 is a dEB containing two F-type stars that both show brightness variations due to starspots. We have extracted the data around eclipse from the

*https://stilism.obspm.fr

light-curve of this system obtained using the *Kepler* satellite and fitted them with JKTEBOP to determine the photometric properties of the system. Numerical integration was used to account for the low sampling rate of the *Kepler* long-cadence data. We included published RVs for the two stars to determine their masses and radii. With the inclusion of spectroscopic measurements of the T_{eff}s of the two stars, we determined their luminosities and the distance to the system. The distance measurement is slightly shorter than that from *Gaia* EDR3 — at the level of 2·0σ — and we have not found a good explanation for this minor discrepancy.

We investigated the amount of numerical integration needed to fit the *Kepler* data for KIC 5359678. We found that ignoring the sampling rate leads to radius measurements that are wrong by −4σ (for R_A) and +10σ (for R_B). These biasses are fixed by the application of only a small amount of numerical integration to the model light-curve during the fitting process: merely doubling the model sampling rate is sufficient for approximate solutions but more precision is needed for final results.

We can now turn to the original prompt of this work: the analysis of W21 presented very different error bars for circular- and eccentric-orbit solutions; no uncertainty was given for the mass of star B; and there was no mention of the sampling cadence. For the first point, we find very similar results for the two options and adopted the circular-orbit results for our own calculations. For the second, the uncertainty in the mass of star B is 1·2%. For the third, the results of W21 are much closer to our own when we used numerical integration, so we conclude that they did account for this effect in their analysis.

A wider comparison between the results of W21 (adopting the circular-orbit values) and our own shows good agreement for the radius of star B: 1·048 ± 0·017 $R_\odot$ (this work) *versus* 1·05 ± 0·03 $R_\odot$ (W21); but not star A: 1·449 ± 0·012 $R_\odot$ (this work) *versus* 1·52 ± 0·03 $R_\odot$ (W21). The reason is not clear but could be related to the different ways in which the spot activity was accounted for. Our mass measurements, though, are in unexpectedly poor accord: 1·252 ± 0·018 $M_\odot$ *versus* 1·32 ± 0·02 $M_\odot$ for star A, and 1·065 ± 0·013 $M_\odot$ *versus* 1·12 $M_\odot$ (W21, no error bar quoted) for star B. As the mass measurements are primarily dependent on the RVs, and both studies used the same ones, it is not clear how this discrepancy could have occurred. Our results have come from extensively-tested codes and analysis methods[37,48,49] so should be reliable.

The final motivation for the current study was to see if the available data were sufficient to establish the masses and radii of the component stars of KIC 5359678 to 2% or better. Table III shows that it was indeed possible. This dEB has now been added to the *Detached Eclipsing Binary Catalogue* (*DEBCat*⋆, ref. 50) and can in future be used to help calibrate theoretical models of stars with masses close to that of our Sun.

Acknowledgements

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

References

(1) J. Wang *et al.*, *MNRAS*, **504**, 4302, 2021.
(2) J. Andersen, *A&ARv*, **3**, 91, 1991.
(3) G. Torres, J. Andersen & A. Giménez, *A&ARv*, **18**, 67, 2010.
(4) A. Claret & G. Torres, *ApJ*, **859**, 100, 2018.
(5) G. Valle *et al.*, *A&A*, **615**, A62, 2018.
(6) A. Tkachenko *et al.*, *A&A*, **637**, A60, 2020.
(7) C. L. Watson, A. A. Henden & A. Price, *Society for Astronomical Sciences Annual Symposium*, **25**, 47, 2006.
(8) N. N. Samus *et al.*, *Astronomy Reports*, **61**, 80, 2017.
(9) T. Jayasinghe *et al.*, *MNRAS*, **477**, 3145, 2018.
(10) H. B. Thiemann *et al.*, *MNRAS*, **502**, 1299, 2021.
(11) M. Deleuil *et al.*, *A&A*, **619**, A97, 2018.
(12) B. Kirk *et al.*, *AJ*, **151**, 68, 2016.
(13) A. B. Justesen & S. Albrecht, *ApJ*, **912**, 123, 2021.
(14) L. W. IJspeert *et al.*, *A&A*, **652**, A120, 2021.
(15) A. Prša *et al.*, *ApJS*, in press, arXiv:2110.13382, 2021.
(16) J. Southworth, *Universe*, **7**, 369, 2021.
(17) A. Prša *et al.*, *AJ*, **141**, 83, 2011.
(18) R. W. Slawson *et al.*, *AJ*, **142**, 160, 2011.
(19) J. Debosscher *et al.*, *A&A*, **529**, A89, 2011.
(20) G. Matijevič *et al.*, *AJ*, **143**, 123, 2012.
(21) D. J. Armstrong *et al.*, *MNRAS*, **437**, 3473, 2014.
(22) S. B. Qian *et al.*, *ApJS*, **235**, 5, 2018.
(23) X.-Q. Cui *et al.*, *Research in Astronomy and Astrophysics*, **12**, 1197, 2012.
(24) P. De Cat *et al.*, *ApJS*, **220**, 19, 2015.
(25) W. Zong *et al.*, *ApJS*, **251**, 15, 2020.
(26) A. Prša *et al.*, *ApJS*, **227**, 29, 2016.
(27) J. Southworth, *The Observatory*, **140**, 247, 2020.
(28) T. M. Brown *et al.*, *AJ*, **142**, 112, 2011.
(29) W. J. Borucki *et al.*, *ApJ*, **728**, 117, 2011.
(30) Gaia Collaboration *et al.*, *A&A*, **649**, A1, 2021.
(31) A. A. Henden *et al.*, in *American Astronomical Society Meeting Abstracts*, vol. 225, p. 336.16, 2015.
(32) R. M. Cutri *et al.*, *2MASS All Sky Catalogue of Point Sources* (NASA/IPAC Infrared Science Archive, Caltech, US), 2003.
(33) W. J. Borucki *et al.*, *Science*, **327**, 977, 2010.
(34) W. J. Borucki, *Reports on Progress in Physics*, **79**, 036901, 2016.
(35) J. M. Jenkins *et al.*, *ApJ*, **713**, L87, 2010.
(36) J. Southworth, P. F. L. Maxted & B. Smalley, *MNRAS*, **351**, 1277, 2004.
(37) J. Southworth, *A&A*, **557**, A119, 2013.
(38) D. K. Sing, *A&A*, **510**, A21, 2010.
(39) J. Southworth, *MNRAS*, **417**, 2166, 2011.
(40) J. Southworth, *MNRAS*, **386**, 1644, 2008.
(41) J. Southworth, *The Observatory*, **141**, 190, 2021.
(42) D. M. Kipping, *MNRAS*, **408**, 1758, 2010.
(43) J. Southworth, P. F. L. Maxted & B. Smalley, *A&A*, **429**, 645, 2005.
(44) R. Lallement *et al.*, *A&A*, **561**, A91, 2014.
(45) R. Lallement *et al.*, *A&A*, **616**, A132, 2018.
(46) P. Kervella *et al.*, *A&A*, **426**, 297, 2004.
(47) A. Prša *et al.*, *AJ*, **152**, 41, 2016.
(48) P. F. L. Maxted *et al.*, *MNRAS*, **498**, 332, 2020.
(49) J. Southworth, *The Observatory*, **141**, 234, 2021.
(50) J. Southworth, in *Living Together: Planets, Host Stars and Binaries* (S. M. Rucinski, G. Torres & M. Zejda, eds.), *Astronomical Society of the Pacific Conference Series*, **496**, 321, 2015.

CORRESPONDENCE

To the Editors of 'The Observatory'

Other Losses

After the recent review[1] of a book by Steven Weinberg, a note was added pointing out that he had died between the writing and publication of said review. In addition to the points which Trimble mentions in that context, I note that, although many have worked on some combination of particle physics and astrophysics, Weinberg is one of the few to have worked on non-astronomical particle physics and non-particle-physics astronomy. Although probably best known for his work in particle physics (his 'A Model of Leptons'[2] having been cited over five thousand times and leading to a Nobel Prize), apart from his books on cosmology, relativity, and gravitation, Weinberg also wrote a few important papers in cosmology, such as, while based at the CfA, 'Apparent Luminosities in a Locally Inhomogeneous Universe'[3], which is still relevant (ADS lists eight citations in the past two years), and his classic paper on explaining the value of the cosmological constant *via* the weak anthropic principle[4]. In 2003 Weinberg noted "I've gone over completely to cosmology. ... Cosmology is fantastically exciting. So it was an obvious choice. I think I can go on making some interesting contributions in cosmology ... ."[5] He never stopped teaching even long after retirement age, teaching courses and writing books as a method of learning more, *e.g.*, his book[6] on the discovery of modern science, reviewed in these pages[7].

Weinberg seemed to know almost everything about most of physics (not to mention other topics); that was also the case with Thanu 'Paddy' Padmanabhan (1957 March 10 — 2021 September 17), whom we also lost recently, at the age of just 64. I first encountered him *via* his review article 'Inflation for Astronomers'[8]. His books on the history of science[9], quantum field theory[10], theoretical astrophysics[11–13] (reviewed here[14]), structure formation[15], and gravity[16] demonstrate the vastness of his knowledge. His way of looking at physics is well documented in a book[17] reviewed here[18]. He is one example of my impression that most really smart people are also very considerate human beings.

Trimble pointed readers to proper obituaries for Weinberg. One can also easily find many for Padmanabhan as well. My goal here is not to write yet another one, but rather to share with readers my own sense of loss of those from our community with whom, however tangentially, I had some contact. Many readers here are of an age at which the passing of those we have learned from will become more and more frequent; many will have noticed that, just four days before Padmanabhan, Antony Hewish also passed away, though at the ripe old age of 97.

Yours faithfully,
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References

(1) V. Trimble, *The Observatory*, **142**, 305, 2021.
(2) S. Weinberg, *Phys. Rev. Lett.*, **19**, 1264, 1967.
(3) S. Weinberg, *ApJ*, **208**, L1, 1976.
(4) S. Weinberg, *Phys. Rev. Lett.*, **59**, 2607, 1987.
(5) J. Riordon, *APS News*, **12**, no. 8, 3, 2003.
(6) S. Weinberg, *To Explain the World: The Discovery of Modern Science* (Allen Lane), 2015.
(7) P. Helbig, *The Observatory*, **136**, 82, 2016.
(8) J. Narlikar & T. Padmanabhan, *ARAA*, **29**, 325, 1991.
(9) T. Padmanabhan, *The Dawn of Science: Glimpses from History for the Curious Mind* (Springer), 2019.
(10) T. Padmanabhan, *Quantum Field Theory: The Why, What and How* (Springer), 2016.
(11) T. Padmanabhan, *Theoretical Astrophysics: Volume I: Astrophysical Processes* (Cambridge University Press), 2000.
(12) T. Padmanabhan, *Theoretical Astrophysics: Volume II: Stars and Stellar Systems* (Cambridge University Press), 2001.
(13) T. Padmanabhan, *Theoretical Astrophysics: Volume III: Galaxies and Cosmology* (Cambridge University Press), 2002.
(14) A. Heavens, *The Observatory*, **121**, 197, 2001.
(15) T. Padmanabhan, *Structure Formation in the Universe* (Cambridge University Press), 1993.
(16) T. Padmanabhan, *Gravitation: Foundations and Frontiers* (Cambridge University Press), 2009.
(17) T. Padmanabhan, *Sleeping Beauties in Theoretical Physics* (Springer), 2015.
(18) P. Helbig, *The Observatory*, **136**, 39, 2016.

The Invention of the Printing Press

One of the centenaries to be celebrated in 2022 is the birth of William Caxton in 1422 who, in these pages[1], was credited with the "invention of the printing press using movable type". While his work was certainly important in the development of printing, especially in England where he produced *Dictes and Sayenges of the Phylosophers* in 1477, the first dated book printed in English, it seems probable that the inventor of movable type was actually Johannes Gutenberg (or more elaborately Johann Gensfleisch zur Laden zum Guttenberg, died 1468) who produced the Gutenberg Bible in about 1455, which is believed to be the first book printed with movable type in the West. It may be, however, that similar methods were already employed in the Far East by that time.

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(1) K. England, *The Observatory*, **141**, 318, 2021.

REVIEWS

The Invisible Universe: Why There's More to Reality than Meets the Eye, by Matthew Bothwell (Oneworld), 2021. Pp. 305, 23·5 × 15·5 cm. Price £18·99 (hardbound; ISBN 978 0 86154 124 9).

I remember a time when the invisible universe meant radio astronomy or infrared astronomy or perhaps ultraviolet astronomy or even cosmic rays. What a difference now! Not only can we observe a large fraction of the electromagnetic spectrum, we can detect gravitational waves and we are aware of the looming existence of dark matter and dark energy. Our eyes sample only a tiny fraction of what is out there. We may well marvel as we look up at the stars glittering in a clear night sky, and it is a glorious sight, but very much just the icing on a very large cake.

It is the invisible cake itself that Matthew Bothwell describes in this book, and I have seldom read such a well-written and imaginative account. He starts with a clear and broad-ranging discussion of the nature of light, introducing the paradox of whether it is a wave or a particle and including a final note on scientific notation for the large numbers that occur everywhere in astronomy. From there he moves on to a more detailed account of what infrared and microwave observations reveal, in both cases starting with an informal account of what these regions of the spectrum are and how we can observe them through 'windows' in our absorbing atmosphere. Microwaves are introduced through the accidental discovery of the microwave background by Penzias and Wilson, which allows him to introduce cosmology, mentioning also the rather inconclusive 'Great Debate' in 1920 between Shapley* and Curtis. The rest of that chapter spells out the development of modern cosmology, from Hubble's expanding universe through Hoyle's steady-state model with continuous creation to the Big Bang model, and the confirmation of the latter by *COBE* measurements of the spectrum of the microwave background. *COBE*'s successors, *WMAP* and *Planck*, also revealed the tiny fluctuations in density that eventually led to star and galaxy formation; the *Planck* map can be seen in one of the 14 colour plates in the centre of the book.

The remaining chapters cover more esoteric topics. Sub-millimetre observations have revealed the giant galaxies that underwent great bursts of star formation in the early Universe, hidden from optical observations by vast clouds of dust and gas but eventually becoming the dead, red, giant elliptical galaxies we see today after all their gas has been used up or ejected. Black holes are next introduced, including the 2019 first image of one (or at least of its shadow). Radio astronomy, introduced by the stories of Jansky and Reber (the latter described as "the only radio astronomer in the world" for some ten years), brings in a discussion of pulsars and the implications of their very rapid spin in terms of objects of enormous density, but also introduces the use of the 21-cm line of hydrogen to map gas distribution in the Milky Way and other galaxies.

What else is out there? The last three chapters discuss dark matter, gravitational waves, and finally dark energy, which is aptly described as "deeply weird". All of these topics, like the earlier ones, are described in the informal, conversational style that characterizes this book and makes it so easy to read. There are clear discussions throughout of the difficulties in obtaining observational results and a sensible stress on the many uncertainties. Bothwell also manages to convey the excitement in the search for new techniques and results.

*He mentions here, in a footnote, that Shapley is his academic great-great-grandfather. This prompted me to a similar exercise, which revealed that my academic grandfather was Fred Hoyle.

These days, I normally don't read the whole of any book I am reviewing, using judicious sampling instead. This book was different — it sucked me in and I found myself reading and savouring every page. Aimed at a popular readership, the book is so well written and so full of little insights that any astronomer would enjoy reading it. I strongly recommend it. — ROBERT CONNON SMITH.

Shapley's Round Table: A Memoir by the Astronomer's Daughter, by Mildred Shapley Matthews, edited by June L. Matthews & Thomas J. Bogdan (self-published), 2021. Pp. 299, 23 × 15 cm. Price $20 (about £15) (paperback; ISBN 978 1 09838 356 5).

I was struck, while first reading the memoir of the long-time director of the Harvard College Observatory, Harlow Shapley, how accomplished he was, not only as a scientist who calibrated what we now call Leavitt's Law, the period–luminosity relation for Cepheids, but also how widespread his influence was, not only at Harvard but also worldwide.

Perhaps my favorite story was when Nehru came to Harvard in 1955 and met with various deans and other muck-a-mucks (p. 171). Only after the luncheon was Nehru asked what he wanted to do next, and he said, "I want to see the astronomer, Shapley"! And together, at the Observatory, they watched Donald Menzel's movies of eruptions on the Sun, which were to play an important role in my own career.

Shapley's name may be best known among astronomers and astronomy students as one of the two protagonists of the 1920 'Shapley–Curtis Debate' on whether the spiral nebulae exist as 'Island Universes' that we now call galaxies. It turns out that the scientific essence was debated in print after the somewhat superficial on-site discussion at the National Academy of Sciences, and that Shapley turned out to be wrong about galaxies but with better reasoning than Curtis. The memoir discusses the events and the circumstances.

Or perhaps Shapley is best known for realizing that the globular clusters he was studying were almost all in one direction in the sky, and that therefore the centre of our galaxy must be in their centre rather than centred on our own Solar System. Or perhaps Shapley should be given credit even with today's Astronomy 101 undergraduates for calibrating the period–luminosity relation, even though the original idea that brighter Cepheids took longer to go through their periods than fainter ones was Leavitt's, since she correctly assumed that they were all at approximately the same distance from us, given that the ones she studied were in the Small Magellanic Cloud. The distinction between Cepheids and RR Lyrae stars was not yet appreciated, and Shapley actually used the latter.

As I prepared to write this review, the February issue of *Astronomy Magazine* arrived, with contributing editor Michael Bakich's list of the 50 greatest astronomers of all time — and Shapley came in 9th! With Herschel, Copernicus, Tycho, and Galileo holding down the top four spots, that's quite a vote for Shapley's importance.

Only once did I meet Shapley, when I was a graduate student at Harvard and he came down from his retirement home in New Hampshire to have one of his famous 'Hollow Squares', arranged in the then-library of the Harvard College Observatory. He had retired from the directorship of HCO in 1952 (leaving my mentor, Donald Menzel, to become director in 1956, prior to my arrival as a first-year student in 1959), and died twenty years later.

The memoir under review was written by his daughter, the late Mildred Shapley Matthews (who got too busy to carry it further with her work as editor of 30-or-so volumes for the Lunar and Planetary Laboratory), and updated and published by his granddaughter June L. Matthews, a retired MIT professor and former Director of the MIT Laboratory for Nuclear Science, in collaboration with the science-writer and historian Tom Bogdan. I guess we have to thank amazon.com and other on-line sites for making it easy for readers to get a copy, in turn allowing them to publish this memoir themselves (with the help of BookBaby) while having it easily accessible to prospective readers.

I knew about the Hollow Square, but I have now learned about Shapley's circular desk, with sections devoted to various topics under investigation, easily available as the desk rotated. The desk itself was rescued by Sara Schechner, the Wheatland Curator of Harvard's Collection of Historic Scientific Instruments, and her husband, Ken Launie, both active in the Antique Telescope Society. According to Mildred Shapley Matthews's description "Sometimes on Sundays we would go over to his office in Building C for a ride on his merry-go-round desk, a huge circular revolving table with space to spread out twelve different jobs. With a slight spin of his desk he could go from one piece of work to another without disturbing any job. In the center of this remarkable table was a cylindrically shaped bookshelf that also revolved. In addition, he had a revolving chair so that he could turn his back on his desk and its twelve projects and face a conventional table which was covered with even more work ... . But there was always space made amidst the piles of papers large enough for one of us to sit happily while he spun the merry-go-round (pp. 25–26)."

And in the memoir, I learned of the lively time when the Director's House (from the 1840s, expanded around 1900, with about 20 rooms) was still standing, attached to the dome of the Great Refractor (15-inch lens, matching that of Leningrad's Pulkova Observatory's), all part of the reaction of Harvard and Boston to Williams College — where I have taught for 50 years —having an observatory in place (since 1836) before Halley's Comet went by in 1843. It sounded wonderful for the children to have the run of the big house, and for after-work activity by the observatory scientists, including the famous 'computers'. And I learned of both domestic and scientific participation of Mrs. Shapley, the former Martha Betz.

As a Gilbert & Sullivan fan, I especially liked the story and the full quotation of *The Observatory Pinafore*, where the 1879 original version was resurrected for the New Year's Eve festivities as 1928 turned into 1929 (pp. 146–154).

Interestingly, my wife and I have sat in the Shapleys' high-backed dining-room chairs, left them by their predecessor, Edward Pickering, since the set was rescued by Prof. William Yandell Elliot when the house was torn down (too expensive to maintain, was the excuse, a pity), and now resides in his son's home in Claremont, California, Ward Elliot having served as a Kirkland House tutor overlapping with me there in the 1970s.

I learned of Shapley's other fascination besides astronomy: ants. He studied ants and their trails around the world. Harvard professor E. O. Wilson died just last week as I write this, so I can't ask him anymore about any 'ant' discussions he may have had with Shapley, though their interchange from the 1950s is described in the Notes (pp. 271–2). Unbelievable but testifiably true is the story of Shapley collecting an ant from Stalin's dinner table in the Kremlin, preserving it in vodka on the spot, and later lending it to Wilson, who never got around to returning it.

I loved reading about Annie Cannon at the Shapley observatory (and her Star Cottage 'little house' nearby), and her first impression: "At first we thought he was a visiting college student ... before we were introduced ... . But we immediately liked him because he was so friendly and enthusiastic, and really interested in our work."

How did Harlow Shapley become an astronomer? "'Journalism and a surrounding general education was my goal,' my father went on, 'Science I would avoid. But the best laid plans certainly went wrong. When I showed up ... to be a freshman in Journalism, I discovered they had decided to postpone by one year the starting of the school ... . I got ahold of the big catalogue of courses, alphabetically listed, and started at the beginning. Here in first place was the word a-r-c-h-e-o-l-o-g-y. Sounds good but how do you pronounce it? Is the c-h- hard or soft? In southwest Missouri we did not have that word, and I was too vain or shy to ask.'"

"'So, you became an astronomer because it began with A!' I couldn't resist getting ahead of the story."

"'So, I turned the page and thereby turned my life. For the next category in the catalogue was a-s-t-r-o-n-o-m-y, and I could pronounce it, even though I knew nothing about the subject.'"

I found myself so fascinated by the memoir that by the time I got to Chapter 4 on 'The Universe Explored and Debated', I was hooked. And then Chapter 5 on 'The Young Director', from 1921 on, and Chapter 6 on 'The Golden Era of the Harvard College Observatory'.

I knew that Menzel had observed the 1932 total solar eclipse from Maine, but I hadn't realized that the International Astronomical Union had met that summer in Cambridge soon thereafter.

For this astronomical readership of *The Observatory*, I will leave the readers (may there be many) to, well, read. But I note that Shapley was an internationalist, and got into trouble ("good trouble" as the late congressman John Lewis called some activities) with the House Un-American Activities Committee. Some of it was merely for associating with the Russian astronomers at the Pulkova Observatory and elsewhere after World War II. During the war, for example, they couldn't use the clearing house of astronomical events centred at Harvard and "cable the station in South Africa: 'NOVA EXPLOSION PUPPIS SHOOT NIGHTLY,' though 'MAKE SYSTEMATIC OBSERVATIONS OF BRIGHT NEW STAR IN CONSTELLATION PUPPIS...' was satisfactory."

I enjoyed (p. 161) the story of the celebration of the 400th anniversary of the 1543 publication of Copernicus's masterpiece in Shapley's quoted words, "We rented Carnegie Hall in New York and filled it ... . A committee of big shots helped in choosing these revolutionaries. First, of course was Einstein — then Henry Ford, the geneticist Thomas Hunt Morgan, Igor Sikorsky of the helicopter, and Walt Disney; but no politicians ... . Einstein's brief speech in his pidgin-English was incomprehensible — so everybody loved it and him. The affair was a complete success — another good offering of internationalism."

Don't miss Chapter 7 on 'Internationalism', or Chapter 8 on 'Assault on the Unknowns' (with a mention of the book entitled *Climatic Change* that he edited in 1953) or the Afterword on the family over the last fifty years. Twenty-four pages of Notes by Tom Bogdan, edited by June, are followed by a selected publications list. A ten-page appreciation called 'Harlow Shapley's Impact' by Harvard astronomer and historian-of-science Owen Gingerich follows. The book ends with the acknowledgments, credits, biographies of the contributors, and a useful index.

Literally, I couldn't put it down once I started reading this fascinating memoir. I recommend it wholeheartedly to everyone. So do the five leading astronomers, authors, and historians who provided the back-cover blurbs, four of whom are credited with adding accuracy and encouragement to the narrative: Dava Sobel, David DeVorkin, Marcia Bartusiak, Virginia Trimble, and Robert Kirshner. — Jay M. Pasachoff.

ExoFrontiers: Big Questions in Exoplanetary Science, edited by Nikku Madhusudhan (IoP Publishing), 2021. Pp. 256, 26 × 18·5 cm. Price £120/$190 (hardbound; ISBN 978 0 7503 1470 1).

In the current era of widespread on-line meetings, a boring/relevant/important/critical (delete according to taste) choice is of one's background. The first option is to select one of the electronically-superimposed virtual alternatives and, software edge-detection algorithm allowing, project an image of oneself on a tropical beach, in a minimalist office space, inhabiting a Peppa Pig cartoon, or any of many other possibilities. One could instead adopt a non-virtual approach and actually allow the camera to capture real objects behind oneself. Alternatives here are either utilitarian ("I'm in my kitchen in front of a fridge and kettle") or to suggest a more cultivated persona ("I'm very intelligent and intend to prove this by positioning myself in front of a shelf of thick books with obscure philosophical, literary, or scientific titles"). The egomaniac can deliberately insert one's own book carefully into the vista, partly-obscured in the hope of it appearing accidental. This reviewer prefers the impressive-book-collection approach and my students do seem to notice. The book under review is a valuable addition to such a library background, having a satisfyingly chunky appearance (at least in hardback form), a light-blue colour on the spine that will stand out, and a proper high-brow scientific title. It therefore is highly recommended.

Oh, hang on, I forgot to cover one minor aspect of the book. Its contents ... are a compilation of 24 essays about a wide range of areas within the field of exoplanetary science. Each chapter provides an introduction to the area of study, a discussion of the current state of the art and important questions, and lists of the opportunities and challenges. The publication has been curated by Nikku Madhusudhan, who also contributes the excellent opening chapter ('The Exoplanetary Landscape'). The other 23 works provide a reasonably comprehensive and predictable survey of the field, and the contributing authors could be characterized (without being disparaging) as 'the usual suspects'. All are well written, although in some cases the particular agendas and projects of the authors are given plenty of visibility. I found quite a few chapters to be particularly informative and interesting, examples being (in page order): Nikku's introduction; 'Radial Velocity Surveys', by Debra Fischer; 'Small Satellites for Exoplanet Science', by Fossatti, McCullough & Parry; 'Orbital Dynamics and Architectures of Exoplanets', by Dan Fabrycky; and 'Exoplanetary Habitability', by James Kasting. Overall this book is a useful and informative addition to the literature on extrasolar planets, and I foresee turning to it quite often in search of particular ideas or references. The presentation is also very good, with almost no typographical or grammatical errors. The worst I could find was a reference within the text to "Sydney (2003)" whereas the bibliography of that chapter had the correct "Barnes (2003)". The paper quality is a bit lower than expected, given the price, which is a problem in a few diagrams where small fonts have become blurred. Which brings us to the fact that it costs £120. At this price, it is unlikely to grace the bookshelves of amateurs or students. However, it is more aimed at professional astronomers who can put a book like this on expenses or suggest it as a library purchase. So will I contribute the review copy to my university library? No — I've got a video-conference background to maintain. — John Southworth.

Annual Review of Astronomy and Astrophysics, Volume 59, 2021, edited by E. van Dishoeck & Robert C. Kennicutt (Annual Reviews), 2021. Pp. 488, 24 × 19·5 cm. Price from $496 (print and on-line for institutions; about £372), $118 (print and on-line for individuals; about £89) (hardbound; ISBN 978 0 8243 0959 6).

Somewhat thinner than the *Reviews* of the last couple of years, and in a much darker blue livery than sits comfortably with the previous 58 volumes on my shelves, the latest *ARAAp* nonetheless contains a fascinating biographical chapter and ten reviews on an interesting range of topical issues.

The book opens with an account of the growth of radio astronomy in India by one of its founding fathers, Govind Swarup. It is sad to relate that the author passed away in 2020, so we are fortunate to have this personal and scientific autobiography. He was responsible in large part for the development of the *Ooty Radio Telescope* and the *Giant Metrewave Radio Telescope*.

On then to the reviews and, starting relatively close to home, we have an important discussion of the Carrington Event of 1859 in which the Sun briefly flexed its muscles and showed us something of our vulnerability. It is compared with other, more recent, studies of stellar variability and does not make comfortable reading for us terrestrials. But if we are ever moved to vacate Earth, would we want to venture as far out as the Kuiper Belt? See what's there in a review of trans-Neptunian space. Perhaps we should be thinking more in terms of a habitable exoplanet, so the statistics of what's available are also covered.

The fact that we exist at all hinges on chemical elements rather more exciting than hydrogen, and so mass loss from cool, old stars and novae have a part to play, and are both treated in some detail. The wonderful results from *Gaia* add to our understanding of stars and their evolution to the point of contribution to the chemical enrichment of space (or not, depending on mass), and highlights from that mission and future possibilities are examined.

Black holes are also on the menu and we read of the damage that massive ones can do to nearby stars; *ROSAT* was a pathfinder for this topic but it's now a multi-wavelength adventure. The spin of black holes is also considered in depth. Another popular pursuit these days seems to be multi-messenger astronomy, and here we find the practice applied to neutron-star mergers.

And right on the frontier of astronomy is a discussion of a light boson as a candidate for dark matter; I don't expect to be still writing reviews if and when this nut is finally cracked. — David Stickland.

Decoding Astronomy in Art and Architecture, by Marion Dolan (Springer), 2021. Pp. 343, 24 × 17 cm. Price £27·99/$39·99 (paperback; ISBN 978 3 030 76510 1).

The architecture and art in this book are ancient, at least five hundred years old. We zoom around the world glimpsing wonders like the Lascaux Cave paintings, Göbekli Tepe in Turkey, Newgrange in Ireland, Stonehenge, Angkor Wat in Cambodia, Borobudur Mahayana in Java, the Ajanta caves in India, the Forbidden City in Beijing, the Temple of Apollo Delphi, Greece, the Khazneh at Petra, the Pantheon in Rome, Hagia Sophia in Istanbul, the Scrovegni Chapel in Padua, Chartres Cathedral, the Sistine Chapel, Teotihuacan in Mexico, the

Peruvian Nazca Lines, the Inca king Pachacuti's Cuzco and Machu Picchu. The superb colourful illustrations make you itch to head for the nearest airport. But the travelogue text does not encourage you to decode the astronomy.

The American art historian Marion Dolan seems to assume that astronomy was of paramount importance to all the relevant artists and architects. Well, it is encouraging that our subject is given such a prominent role; but I need to be convinced that this is justified. The book insists that specific buildings are orientated to significant horizon positions, spots where the Sun rises or sets on certain days, and certain star groups such as the Pleiades have heliacal risings and settings. But let's face it, *all* buildings have facets that point at certain horizon declinations, even my house. I need to be convinced of the significance. Fair enough, if you want to organize a party to celebrate the winter solstice you need to know when this will happen. But do you need the timing to be accurate to the nearest hour, or day, or will a week do?

Cardinality is stressed, and it is hinted that the east is associated with dawn and birth, and the westerly setting Sun points to our deathly destination. But we are given no indication as to how accurate the orientation needs to be, and no indication as to how the planning was executed. The importance of flat horizons is ignored. Much is made of how sunbeams fall on specific days and at specific times, but every building with windows lets in the Sun, and with our typical weather few rely on sunbeams as calendrical markers. The snag is that none of the relevant civilizations left any written records. We look at their ruins, and we make up their motivations.

I enjoyed reading this book. I revelled in the ancient art, I was amazed by many of the old buildings, I was pleased to see the extensive lists of references to the hard work of archaeologists and archaeoastronomers. But I was left wondering whether the town planners, the artists, or the architects (or even the present-day art historians) knew much about astronomy. Did the predictability of certain astronomical events really have any serious significance in those distant chaotic times? The reader needs convincing before trying to decode something that might not even be present. — David W. Hughes.

Conversations on Quantum Gravity, edited by Jácome (Jay) Armas (Cambridge University Press), 2021. Pp. 717, 25 × 18 cm. Price £39·99/$49·99 (hardbound; ISBN 978 1 107 16887 9).

In 2010, after spending most of his evenings co-managing a cocktail bar and art gallery during his time as a PhD student at the Niels Bohr Institute, Armas moved to Copenhagen's renowned hippie commune Christiania, where he co-ran a cinema for several years and decided to compile this book. He began it during a long-term visit to the Tata Institute of Fundamental Research in India. He is now an assistant professor at the University of Amsterdam, working on topics such as "forced fluid dynamics from blackfolds in general supergravity backgrounds"[1]. The book is a labour of love consisting of well-edited interviews* of varying length (from one (Ed Witten) to 39 (Abhay Ashtekar) pages) with 37 physicists who work(ed), in one way or another, on the topic of quantum gravity. They took place, mostly in person, between 2011 and 2020, though those interviewed had the opportunity to modify the edited transcripts; both the original date and the date of the last edit are noted. Interestingly, while some spent much time on checking and updating their transcripts, most saw no need for an update, as their views hadn't changed.

*As such, it is similar to two other books[2,3] reviewed in these pages[4,5].

Some of those interviewed will be familiar because they are (also) astronomers, astrophysicists, cosmologists, or generally famous or both (*e.g.*, Gerard 't Hooft, Juan Maldacena, Roger Penrose, Carlo Rovelli, Lee Smolin, Leonard Susskind, Steven Weinberg, Edward Witten, some of whom have had books reviewed in these pages). All are well known in the world of quantum gravity; not working in that field, I recognize about half, have heard talks by about a quarter, and have met and have read books (some reviewed in these pages) by about an eighth each. The interviews vary not only in length but also in depth and breadth, some discussing technical points of their work while others concentrate more on an overview. Amazingly, the technical level and the general style are very uniform; were it not for the disagreements, one could have the impression that all was said by the same person. The first and last questions are almost always the same: "What are the main puzzles in theoretical physics at the moment?" and "What is the role of the theoretical physicist in modern society?". Weinberg notes that 'puzzle' implies not just an open question but something we know about but don't understand, offering the spectrum of quark and lepton masses as an example. Witten notes that he "would like to understand what string theory really is", which probably implies that at least most people probably never will. Most were also asked what had been the biggest breakthrough in theoretical physics in the thirty years before the interview and why they chose to do physics. The other questions depend on the person interviewed and their answers to previous questions. Many agree that the main puzzles are quantum gravity, dark matter, and the cosmological constant and thus relevant to astrophysics and cosmology even though the technical work of most is in other areas. The detection of the cosmological constant is also cited by many as a breakthrough (though that is more observational than theoretical, but of course severely constrains theory), as are AdS/CFT correspondence* and string theory (but the last also as a puzzle). Some puzzles, such as the measure problem in cosmology (Carlip), were mentioned by only one.

There are many differences of opinion. On the correct theory: "String theory is the only idea about quantum gravity with any substance" (Witten). "[Loop quantum gravity] has not given any new insights into quantum gravity" (Arkani-Hamed). "[S]tring theory is the only theory at present that got this far" but "[m]y main point of criticism towards string theory is that it is venerated as a kind of bible" ('t Hooft). "There are good things in both loop quantum gravity or string theory but in each of them I can see some basic problem" (Connes). "All [predictions of string theory] contradicted by experience. ... String theory ... has failed the goals that it set itself" (Rovelli).

On the cosmological constant: "[T]he main puzzles include the cosmological constant problem" (Carlip). Giddings sees "the smallness and origin of the cosmological constant" as a "prominent problem". Arkani-Hamed sees it as completely solved by Weinberg (his description is too long to quote here, but should be required reading for all physicists). "I do not consider that dark energy constitutes a puzzle since at the moment there is a simple explanation in terms of the cosmological constant" (Ashtekar). "The dark energy issue is overrated. I do not think it is such a big mystery" (Rovelli).

On breakthroughs: "The holographic principle. There is no doubt about it" (Susskind). "Ads/CFT. No question about it" (Arkani-Hamed). "[String theory

*AdS/CFT correspondence refers to a popular (more than twenty thousand citations to Maldacena's original paper) conjecture concerning the duality between anti-de Sitter spaces as used in some quantum-gravity theories and conformal field theories which describe elementary particles.

is] about everything interesting that happened in the past 30 years (laughs)" (Gross). "In the past 30 years .... not much (laughs)" (Carlip). (Yes, there is much laughter, indicated in the transcripts, in one case even noting two separate laughs.) "I do not think that there is anything which we already recognise clearly as a major breakthrough in the past 30 years" (Rovelli). "[N]othing has happened in the past 30 years which I consider to be at the same level of the commutation relations of quantum physics or the gauge principle" (Wilczek).

Of course, one cannot even attempt to summarize such a massive tome in a short review, but I hope that the quotations above convey some of the flavour. Most of the discussion is somewhat more technical (though there is no proper equation in the entire book), but needs more context in order to be appreciated. Armas has added citations to the interviews at appropriate places within the text, referring to the (usually several pages of) references after each interview which were also added by him. Like old-fashioned conference proceedings which contain questions and answers for each talk, this book indicates perhaps better than their technical papers what the people involved were actually thinking about, but the references provide a link between the two.

There are no figures. A few footnotes were added by Armas for clarity. The main text is followed by a four-page small-print index. There are few typos and the book has a uniform feel, despite having been written by thirty-eight people. The book is neither an introduction to nor a review of quantum gravity, and not at all a textbook. Considering the length and quality, it is reasonably priced. As the title states, it consists of experts discussing their research, but at a level which should be accessible to all physicists who have a basic idea as to why a theory of quantum gravity is worth looking for. I recommend it highly to those and to future historians who want to know what those people were *really* thinking. — Phillip Helbig.

References

(1) J. Armas *et al.*, *Journal of High Energy Physics*, **10**, 154, 2016.
(2) M. D'Onofrio, P. Marziani & J. W. Sulentic (eds.), *Fifty Years of Quasars: From Early Observations and Ideas to Future Research* (Springer), 2012.
(3) M. D'Onofrio, Roberto Rompazzo & Simone Zaggia (eds.), *From the Realm of the Nebulae to Populations of Galaxies: Dialogues of a Century of Research* (Springer), 2016.
(4) P. Helbig, *The Observatory*, **133**, 302, 2013.
(5) P. Helbig, *The Observatory*, **137**, 185, 2017.

Introduction to Turbulent Transport of Particles, Temperature and Magnetic Fields: Analytical Methods for Physicists and Engineers, by Igor Rogachevskii (Cambridge University Press), 2021. Pp. 261, 25 × 19 cm. Price £110/$140 (hardbound; ISBN 978 1 316 51860 1).

Turbulence remains one of the most difficult and fascinating unsolved problems in physics and applied mathematics, and is fundamental to planetary science and astrophysics. This book sheds considerable light on this topic using analytical methods, and it may surprise some readers to discover how much can be learnt through these. The focus is on the role of turbulence in transporting physical properties such as particles and temperature and — importantly for many astrophysical applications — magnetic fields. The style is very much aimed at a reader wishing to study the topic in depth; very helpfully, all mathematical derivations are written out clearly, so that the reader can follow the steps, and there is no resort to "it can be shown that…". Thus, the book is an ideal text for graduate students, or advanced undergraduates, as well as more experienced researchers wanting to develop their understanding of turbulence. Furthermore, there is a really useful set of practice problems, as well as skeleton solutions. Although focussing on analytical methods, applications, particularly to geophysical and astrophysical dynamos and to planetary oceans and atmospheres, are also described, and there are wide-ranging 'further reading' sections which guide the reader to recent research in these fields. The book lacks any figures or diagrams, which might have made it a little more accessible; however, there are some helpful tables, and I especially liked the footnotes giving brief biographical information about the key scientists involved in this long story. — Philippa Browning.

More From the Library

Our colleagues at the American Association of Variable Star Observers (AAVSO) passed through two traumas in 2021 (besides the pandemic). First, they sold their building at 49 Bay State Road in Cambridge, Massachusetts, intending to move to smaller, rented premises. Second, their director, Stella Kafka, resigned to take up a somewhat similar position at the American Meteorological Society, also headquartered somewhere around Boston. Part of the outcome was an auction to dispose of items, including books, for which there would no longer be storage space, the books being distinctly mixed bags, grouped by who had previously owned them. I bid on three lots (plus some earrings, which are a different story) and, as the sole bidder, ended up with two of the lots, previously owned by William Tyler Olcott and Clinton B. Ford, though I chose for what I was pretty sure would be interesting books I hadn't read before.

Eight or nine of the volumes met expectations, having publication dates from 1843 (a century before my birth) to 1937. The authors include Sir James Jeans, Agnes Mary Clerke, Charles Greeley Abbot, Ormsby Mitchel, and C. E. K. Mees. All of them have been scanned, each has revealed items both more or less expected and quite unexpected, and my intention is to submit short introductions to them, one at a time, sporadically, for the Editors to treat as they see fit, but with the hope that other readers might be inspired to share with us all some of the classic volumes they might own. — Virginia Trimble.

The Sun, by Charles G. Abbot, S.M., Director of the Smithsonian Astrophysical Observatory, Washington DC (D. Appleton and Company, New York and London), 1911. Pp. 448, 19·5 × 13 cm, "with numerous illustrations." From the William Tyler Olcott collection of the American Association of Variable Star Observers, sold at auction in 2021. A gift to WTO from S. C. Hunter, dated 1911 November 20.

Charles Greeley Abbot (1872–1973), who had been the Home Secretary of the US National Academy of Sciences in 1919–20, was the longest-lived and last surviving participant from the Curtis–Shapley Debate of 1920. He was born the year newspaperman Horace Greeley lost the US presidential election to Ulysses S. Grant, though that was not the reason for his middle name*; rather his mother had been born Carol Ann Greeley.

*In contrast, Hjalmar Horace Greeley Schacht, who stabilized the German mark after the run-away post World War I inflation, was named for the democratic presidential candidate, having been born while his parents were briefly in the US.

Abbot's own astronomical territory was the Sun, and he described his volume as a successor to Professor (Charles A.) Young's *The Sun* "now out of print"*, which he quoted *in extenso*. It is, of course, trivially easy to go through such a volume saying "no, no, no. well sort of, no, no, reluctantly yes, no, no." I won't try to do that. Instead, I would like to focus on some aspects of the astronomical community of the time, a few of Abbot's own strengths and contributions, and on what he regarded as the most important unsolved problems of solar physics at the time.

In an acknowledgements paragraph, he thanks W. W. Campbell of Lick, G. E. Hale and the staff of the Mt. Wilson solar observatory, E. B. Frost of Yerkes, people from the US Naval Observatory, the US Patent Office, and the US Department of Agriculture. Two implications, I think: astronomy was still a very small community by our standards, and specialization was still wide enough to allow scientists to take a professional interest in more than one subject.

Abbot begins a section on the structure of the Sun by précising what Young had written, and then other models from Halm, Schmidt, and "W. H. Julius of Utrecht". Who? Well, Halm has an entry in the *Biographical Encyclopaedia of Astronomers* (*BEA*, ed. T. Hockey *et al.*, 2014) and had measured solar rotation, which Abbot found very important, during 1901–06. Julius is not there, and Schmidt cannot be any of the several of that surname who are. In contrast, Abbot then describes his own model, saying it has its grounding on work by Secchi, Schuster, and K. Schwarzschild. Them I have heard of, and you probably have too. What does this mean? That being credited by Abbot enhanced an astronomer's reputation and improved his chances of making it into *BEA*? Probably not. More likely, there was a discernible track that led toward what we now think about the Sun; Abbot was on it, and cleared the path ahead of where his predecessors had gone. Remarkably, Abbot found one paper by the infamous Thomas Jefferson Jackson See worth citing.

Now about Abbot's own contributions as he describes them in *The Sun*. First and foremost he was certain that the photosphere was purely gaseous, not some mix of clouds or mists of dust or liquids, but dense enough to provide a continuous spectrum and a sharp-appearing edge. He knew about, and approved of, Fabry–Pérot interferometers, and was a strong supporter of the direct use of solar energy. Some of his 16 patents were for that purpose. He also took a serious interest in how plants of various sorts make use of sunlight (hence those 'thank you's to the US Patent Office and Dept. of Agriculture). He recognized that sunspots are cooler than the rest of the photosphere and the only place where spectra show significant molecules. Abbot's Sun was, however, purely radiative (and earlier even than the 'Eddington standard model' built of polytropes), with a temperature that declined monotonically from photosphere outward. Thus his brave attempts to account for the spectra of the chromosphere (flash spectrum) and corona and the motions of prominences (for which he had hold also of some dubious data) were doomed to failure.

But he listed three most important unsolved problems: What is the corona? What causes sunspots? And what is the source of solar and stellar energy? Travelling back in time, we can happily assure him (*i*) it's hotter than the

*H. N. Russell, R. Dugan & J. Q. Stewart described their two volumes of *Astronomy* in 1926–27 as a revision of Young's *Manual of Astronomy*. Perhaps it helped sales.

photosphere (though exactly how this is achieved is still a hot topic, as it were), (*ii*) you need both a convective atmosphere and a global magnetic field, as well as the local, sunspot one that Hale had recently found (and again "more work is needed"), and (*iii*) the relevant revolutions in physics were, just barely, underway in labs in Europe, but will lead to new forces, new energy sources, and ways of both recognizing the great age of the Solar System and providing energy for it on beyond the theory of contraction

Now, if someone would just slip me a copy of *The Observatory* from 2133 … . — VIRGINIA TRIMBLE.

THESIS ABSTRACTS

THE INFLUENCE OF PLANETARY AND STELLAR COMPANIONS ON DEBRIS DISCS

By Ben Yelverton

Around 20% of main-sequence stars are known to host debris discs composed of planetesimals and the dust produced in their collisions. The structures of these discs can be constrained through spectral-energy distribution (SED) modelling or direct imaging of the dust. Gravitational perturbations in a system containing planets or multiple stars can influence the evolution of a disc and leave observable signatures in the disc's structure, potentially allowing the inference of companions which are not directly detectable. Additionally, one might expect the properties of discs to be related to the properties of massive companions at the population level, either because companions are linked to planetesimals through common formation conditions, or because of their gravitational influence following their formation.

In this thesis, I explore several issues relating to the connection between debris discs and massive companions. Motivated by the discovery of several discs with gaps, I begin by investigating one mechanism which may produce such gaps: eccentricity excitation through secular resonance with a two-planet system. I use Laplace–Lagrange theory to illustrate how the properties of undetected planets in a system with a gapped disc may be constrained within the secular resonance model, then use N-body simulations with collisional post-processing to show that the model can produce a gap at a specified location, but with inevitable asymmetries. Next, I study a sample of 341 multiple-star systems, using their SEDs to identify and characterize their debris discs. I find that the stellar-separation distributions of disc-bearing and disc-free systems differ with 99·4% confidence. No discs are detected for separations between 25 and 135 AU, likely because such systems dynamically clear out circumstellar material at an early stage. Finally, I compare the disc properties of 201 stars with known planets and 294 without. I find no evidence for a statistical difference in the disc fractional luminosity or temperature distributions of the two samples, once differences in binarity, spectral type, and dust sensitivity are accounted for. — *University of Cambridge; accepted 2020 July.*

Data-Driven Discovery of Transients in the New Era of Time-Domain Astronomy

By Daniel Muthukrishna

Time-domain astronomy has reached an incredible new era where unprecedented amounts of data are becoming available. New large-scale astronomical surveys such as the Legacy Survey of Space and Time (LSST) are going to revolutionize transient astronomy, providing opportunities to discover entirely new classes of transients while also enabling a deeper understanding of known classes. LSST is expected to observe over ten-million transient alerts every night, at least two orders of magnitude more than any preceding survey. It has never been more important that astronomers develop fast and automated methods of identifying transient candidates for follow-up observations.

In this thesis, I tackle two major challenges facing the future of transient astronomy: the early classification of transients and the detection of rare or previously unknown transients. I detail my development of a number of novel methods dealing with these issues. In the first chapter, I provide an introduction to the field of transient astronomy and motivate why new methods of transient identification are necessary. In the second chapter, I detail the development of a new photometric transient classifier, called RAPID, that is able automatically to classify a range of astronomical transients in real-time. My deep-neural-network architecture is the first method designed to provide early classifications of astronomical transients. In Chapter 3, I identify the issue that, with such large data volumes, the astronomical community will struggle to identify rare and interesting anomalous transients that have previously been found serendipitously. I outline my novel method that uses a Bayesian parametric fit of light-curves to identify anomalous transients in real-time. In Chapter 4, I highlight some issues with current photometric classifiers and improve upon RAPID so that it is capable of dealing with real data instead of just simulations. I present classifiers that perform effectively on real data from the *Zwicky Transient Facility* and the *PanSTARRS* surveys. Finally, in the last chapter, I discuss the conclusions of my work and highlight some future opportunities and work needed in preparing for discovery in the new era of time-domain astronomy. — *University of Cambridge; accepted 2021 July.*

Here and There

THE OLD METHODS ARE CLEARLY THE BEST

[Olbers'] lifelong concern with comets dates from January 1779, when he used his observations of Bode's comet to calculate its orbit according to Euclid's method. — *Dictionary of Scientific Biography*, edited by C. C. Gillispie, Vol. X, p. 197, 1974.

A VERY CLOSE SHAVE INDEED

A NASA spacecraft has officially "touched" the Sun, and got to within about eight miles of its core. — *The Week*, 2022 January 8, p. 13.