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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2020 December 11 at $16^h\ 00^m$
held on-line

Emma Bunce, *President*
in the Chair

The President. Good afternoon everybody and a very warm welcome to you all. We're delighted to bring you the December meeting of the 2020–21 session *via* webinar, and it's great that you can join us for the next instalment of the RAS Ordinary Meetings on-line. First of all, just some housekeeping at the beginning of the meeting. Hopefully, if you look at the top left of your screen, you should see a small green shield, and that symbol means that you're using the most up-to-date version of Zoom and that is secure. I do also need to advise you that this meeting is being recorded, and questions can be asked at the end of the presentations that you're going to see today, but as you will be muted please can you use the Q&A facility that you should find at the bottom of your Zoom screen, and there you can ask your questions. And the questions will go to the panellists and they will be read out today by a member of the RAS editorial team, Louise Alexander. Also, for the purpose of *The Observatory* magazine report, if I could ask you to write your name at the start of your question if you're happy to be included in that report, that would be really helpful, thank you.

The President. On with our programme this afternoon. For our first speaker this afternoon, I'm delighted to welcome Dr. Craig Magee from Leeds; Craig is the recipient of the Fowler 'G' award this year and he's going to be speaking to us this afternoon about 'Seismic-reflection data and space exploration'.

Dr. C. Magee. It is an honour to present my research at an RAS Ordinary Meeting and it offers me an opportunity to engage with a new audience and present some new work. In an attempt to broaden the interest in my talk, I will present work on new research where my colleagues and I have used seismic-reflection data to image structures on Earth that appear similar to those recognized on other planetary bodies, including the Moon, Mars, Enceladus, and various asteroids. Critically, rather than just studying the surface expression of these structures on other planetary bodies, seismic-reflection data allow us to view their 3D form, *i.e.*, it provides ultrasound-like images of Earth's subsurface. In this talk, I will focus particularly on how we can use seismic-reflection data to quantify the geometry and growth of dykes, dyke-induced faults, and pit craters.

Dykes are vertical sheets of magma that play a key role in transporting magma through the crust, to be erupted at the surface. Space for dyke injection is commonly made by moving its wall rock apart, *i.e.*, extending the crust. However, many dykes do not reach the surface and instead cause the overlying rock to extend and fracture (fault). These dyke-induced faults accommodate extension of rock above the dyke and geometrically correspond to two inclined slip surfaces that (*i*) extend from the top of the dyke to the surface; (*ii*) dip towards the dyke (*i.e.*, they create a V-shaped pattern in cross-section); and (*iii*) occur along the length of the underlying dyke. Our work has shown that the identification of dyke-induced faults can be used to map dykes in seismic-reflection data, even when they are poorly resolved by the technique. Associated with dykes and dyke-induced faults are pit craters. Where recognized on other planetary bodies, pit craters can be described as forming relatively small (few hundred metres wide) circular depressions that typically form chains located between the surface location of two dyke-induced faults, and supposedly underlain by vertical pipe-like features; the origin of pit craters is enigmatic and has previously been linked to a variety of processes, including magmatism, faulting, permafrost melting, and cave collapse. Importantly, the surface expression of dyke-induced faults and pit craters mapped and measured on other planetary bodies has been used to make predictions about underlying geology and processes. To test these interpretations of how the geometry of dyke-induced faults and pit craters at the surface relate to underlying structure, we typically rely on laboratory or computational models that attempt to replicate the formation of these features.

Our analysis of buried dykes, dyke-induced faults, and pit craters imaged in seismic-reflection data from offshore NW Australia, allows us for the first time to validate our ideas about how these structures form, and I am going to focus on testing four hypotheses.

Firstly, it is typically assumed that the distance between a dyke-induced fault pair at the surface can be used to predict the depth of the underlying dyke top by projecting their inclined surfaces straight down-dip. Our seismic-reflection data allow us to follow these assumptions and predict dyke depth, but also to measure the dyke depth. We have shown that the predictions and measurements of dyke depth do not always match, principally because faults are curved, *i.e.*, they cannot be projected straight down-dip.

Next, it is also assumed that the extension across a dyke-induced fault pair measured at the surface should relate to the thickness of the underlying dyke. Although it is difficult to estimate dyke thickness from seismic-reflection data, our work shows that extension of dyke-induced faults is mainly accumulated in the subsurface; *i.e.*, the surface extension of dyke-induced faults is minimal and not a good proxy for dyke thickness.

Thirdly, the diameter of pit craters at the surface has been considered to reflect the total vertical height of the pipes expected to underlie them; this assumption has been used to estimate material properties and layer thicknesses of rock and regolith. Our work shows pit craters are underlain by vertical pipes in which material has collapsed, but their height is not simply related to the pit-crater diameter.

Finally, our work confirms suggestions that pit-crater diameter is related to depression depth, meaning we can use this expected correlation to identify where pit craters may have been infilled by later sedimentary processes.

In addition to testing previous assumptions and models, we can compile our observations and measurements to reconstruct how dyke injection occurred.

Because we can recognize surface features related to dyke injection (*i.e.*, pit craters and dyke-induced faults), we can use local well data to date the age of the palaeosurface and show that dyke injection occurred in the Late Jurassic, approximately 150 million years ago. Our measurements indicate that the dykes radiate out and thin away from a central point about 500 km to the south, suggesting they were injected laterally northwards, perhaps in response to mantle plume activity. In detail, we also measure local variations in the offset of sedimentary layers across the dyke-induced faults, suggesting they form in relation to periodic dyke injection.

Overall, the work presented here shows seismic-reflection data is a powerful and unique tool for studying the 3D structure of natural terrestrial analogues of features observed on other planetary bodies.

The President. Thank you, Craig, for that really engaging, very interesting presentation. I'm going to hand over to Louise Alexander who is going to let us know if there are any questions lurking anywhere.

Dr. Louise Alexander. There's a question from Hugh Hudson. "What is the physical reason for the sheet geometry of the dykes? Why is that favoured?"

Dr. Magee. That's actually a really good question. A lot of it comes down to the forces involved. It's a lot easier to fracture a rock and once that rock is fractured — as you know if you hit a brick with a hammer — it splits along the fracture. Once that fracture forms it's then easy for magma to move into that fracture and move up it, opening it up, and that's generally why we get these sheet intrusions.

Dr. Alexander. We've got another question: "Did you test your hypothesis in dykes from the three different dyke-swarm types? Do you think it will make a difference?"

Dr. Magee. Again a very good question. The dyke swarm that we're looking at here was a radial dyke swarm and there have been two or three other papers that have mentioned imaged dyke forms in seismic-reflection data; but then they've only provided a few images. Basically we haven't found the dyke forms yet to test these in other areas. The circumferential dyke swarms are very rare indeed and there are only a few that have been found on-shore, so I suspect that we may see some differences, and this is something definitely to look for; we just don't have the right data or we don't know where they are yet — that is, perhaps, the best way of putting it.

Dr. Alexander. We have one more question from Lyndsay Fletcher: "Do the properties of the dykes and pit craters observed at the surface depend on the physical properties of the material below, or just the geometry, and could this be used to learn about planetary subsurface composition?"

Dr. Magee. This is very much the idea; and for pit craters observed on other planets so far there's been lots of theoretical work on how that structure may inform about the properties of the material that they formed in. One thing that we've yet to do with the work here is to take some of the oil-exploration data from some of the wells in the area where we can actually characterize the physical properties of the rock and understand how that may affect the geometry of the pit craters. We've seen again that that would be a good test for things that we've guessed from other planets but don't really know about, but that is definitely something we will be doing.

Dr. Alexander. The next question is from Don Kurtz: "When you are surveying at sea, do your emitted sounds have impact on marine life?"

Dr. Magee. This is one of the major environmental problems with seismic-reflection data. I'll start by clarifying that I don't do any of the surveying myself. I've never been involved in that. I just take the data and play with it, and there is quite a lot of work done trying to understand the problems associated with this, in particular for animals like whales that rely on sound quite a lot. Seismic-reflection data is really quite damaging but what they often do when they're surveying is find ways of moving the animals away from the area that they're shooting. They have to get special permission from governments' marine protection agencies depending on where the surveys are collected, so it is something that is a problem. It's something that is dealt with as much as possible, but it is definitely an environmental issue where I'm sure more could be done, and at the end of the day I sadly suspect money speaks more than a whale.

Dr. Alexander. We've got time for one more question. It comes from Steve Miller who asks "There are crater trains on Ganymede interpreted as due to fragmented comet impact. Could these be pit craters instead?"

Dr. Magee. Potentially, I guess, although the pit craters that I've looked at have not been related to impacts. There's no sort of impact ejecta. Usually you get these little ejecta rims around them so we can tell they're not related to impacts. There are lots of pit craters that have been recognized on comets, on various other planetary bodies and moons, that are not related to impacts and are probably related to faulting or fracturing in the subsurface. Whether the ones on Ganymede are as well I don't know, I haven't looked at them.

The President. Wonderful! Thank you Louise, and thanks again Craig for a fantastic talk and for answering those interesting questions from the audience.

We now move on to our second speaker this afternoon, Professor Richard Harrison from the Rutherford Appleton Laboratory, and Richard and his team were the recipients of the Group Achievement Award for Geophysics this year. Richard is going to be speaking to us this afternoon about 'Imaging solar coronal mass ejections in the heliosphere, from *STEREO* to *Lagrange*'. Welcome Richard and I will hand over to you.

Professor R. A. Harrison. The solar atmosphere is a truly complex and dynamic environment evidenced by the dramatic images and movies of the Sun taken in extreme-ultraviolet (EUV) wavelengths by imagers aboard spacecraft such as the NASA *Solar Dynamics Observatory*. Such imagers reveal complex hierarchies of magnetic-loop systems, rooted in the body of the Sun, in which are trapped million-degree plasmas, which writhe in response to a combination of motions, such as convection in the Sun and differential rotation of the Sun itself. The major regions of magnetic complexity, the so-called active regions, are the seats of activity such as the solar-flare explosions, and also of eruptions of plasma into space, also well illustrated by EUV images of the Sun. The major forms of discrete eruptive events from the Sun are called coronal mass ejections (CMEs), huge plasma clouds expelled into space as large magnetic systems expand out into space. Each event can carry a billion tonnes of plasma (10^{12} kg) of matter into space, at a speed of anything between a few hundred km/s to a couple of thousand km/s.

We image CMEs using coronagraphs. These are instruments that occult the solar disc in order to image the diffuse structures in the corona around the Sun. Such instruments are aboard the ESA/NASA *Solar and Heliospheric Observatory* (*SOHO*) spacecraft and the NASA *STEREO* spacecraft, and they regularly image CMEs crossing the corona. The first CME observations were made from spacecraft in the early 1970s and, in the last 25 years, such activity has been monitored continuously, particularly by the *SOHO* spacecraft.

However, occasionally a CME will be detected in the coronagraph data that suggests that it is Earth-directed. With a billion-tonne plasma cloud, entrained in an expanding magnetic structure, heading towards Earth it is quite natural to ask the question, what impact can it have on us?

This brings us to the relatively new field of space weather. Space weather is the effect of solar phenomena on human technology and health. There is an increased awareness and concern of such effects because of our increasing reliance on technology. Space weather requires the application of a range of disciplines including solar and heliospheric physics, magnetospheric physics, and ionospheric physics. The kind of effects, or impacts, that we see include damage to spacecraft electronics due to energetic particles, radiation effects on avionics, and geomagnetically induced currents in power-distribution systems. These are just a few examples, and in some cases the impacts can be severe enough, in terms of adverse effects on infrastructure or health, for it not to be a surprise to note that the UK Government has included space weather on the National Risk Register of Civil Emergencies. The Risk Register includes impacts from coastal flooding, river flooding, drought, wildfires, pandemic influenza, storms and gales, and much more, and each item is assessed through a consideration of 'impact severity' and 'likelihood of occurring in the next five years'. Indeed, in terms of these considerations, space weather is cause for significant concern.

Each of the identified risks has a risk owner, which, in the case of space weather, is the Department of Business, Energy and Industrial Strategy (BEIS). In a practical sense, that risk is delegated to the UK Met Office who, in response, have set up a 24/7 space-weather forecasting centre known as MOSWOC (Met Office Space Weather Operations Centre). It is one of only three such centres world-wide, and they work very closely with the US Space Weather Prediction Center in Boulder, Colorado. Quite naturally, the Met Office also work closely with UK research groups involved in the scientific disciplines linked to space weather and to the groups that build and operate space-science instruments that address those disciplines. It is interesting to note that the banks of screens and data being inspected continually at the MOSWOC facility are, in general, the observations from the space-science missions that the research community employs, rather than dedicated space-weather-monitoring missions. So, it has to be noted that, currently, our space-weather predictions in the UK, the USA, and elsewhere, are dependent on rather ageing space-science missions, such as *SOHO* and *STEREO*, and it is well understood that this is not ideal.

The *STEREO* mission consists of two twin spacecraft, launched in 2006, orbiting the Sun in near-1-AU orbits. One spacecraft (*STEREO-A*) was set off ahead of the Earth in its orbit, drifting away at 22·5 degrees per year. The other was set off behind the Earth (*STEREO-B*), drifting away at a similar rate. Thus, they crossed over in superior conjunction, behind the Sun, in 2015, and are on their way back. Unfortunately, *STEREO-B* is not now operational, though we note that the spacecraft were launched 14 years ago for a nominal few-year mission. However, *STEREO-A* is fully operational and is now 60 degrees behind the Earth, approaching us.

The instruments of interest here are the UK-led *STEREO Heliospheric Imagers* (*HI*). There is one *HI* instrument on each of the two spacecraft. The *HI* images are wide-angle images that are directed across the Sun–Earth line. Two cameras on each *HI* instrument record 20 degree × 20 degree and 70 degree × 70 degree images centred on the ecliptic plane. The instrument is offset such that the Sun is just outside the 20-degree field of view. CMEs emerge from the outer edges of coronagraph fields of view and cross the *HI* images. In the same images we see planets, comets, and stars down to 12th magnitude. However, the key feature is the fact that we are actually imaging CMEs in interplanetary space, *i.e.*, crossing the heliosphere between the planets.

Let us consider what this means from a space-weather perspective. CMEs have traditionally been imaged with coronagraphs, as described above, *i.e.*, they are observed crossing the corona, but, from the time they leave the imaged field of view to potentially arriving at Earth, there is a gap of about 200 solar radii where, in the past, we had no observations of the CME. This is akin to observing weather systems leaving the USA eastern seaboard and not monitoring them as they cross the Atlantic, *i.e.*, waiting to see what the impact would be on the UK. Of course, it is logical, if not essential, to image the weather systems to monitor their development and evolution. In the same way, with the *STEREO* observations, from off the Sun–Earth line, it is logical to want to track CMEs through the heliosphere and study their development, to enable better predictions of impact at Earth and elsewhere. In short, the *STEREO HI* instruments have opened a new chapter in terms of observational capability that has practical applications for space weather, as well as for science research. In many of the *HI* images we can actually see the Earth as a single, bright pixel. Thus, on occasions we can witness CMEs passing over the Earth.

We note that the full publication list of research papers known to the *STEREO*/*HI* team can be found at www.stereo.rl.ac.uk, and it includes research not just relevant to CME propagation, onsets and impacts, but to CME–CME interactions (that appear to lead to major particle events at Earth), co-rotating interaction regions (large-scale solar-wind structures in the heliosphere), comets, planets and asteroids, stellar variability, interplanetary dust, and cosmic rays.

NASA's *STEREO* mission has demonstrated the benefits of off-Sun–Earth-line observations, especially in combination with spacecraft observations near the Earth. This has led to a multinational strategy to apply these experiences for space-weather monitoring. The underlying strategy is for the USA, through NASA and the National Oceanic and Atmospheric Administration (NOAA), to maintain dedicated space-weather-monitoring spacecraft at L1. L1 is the so-called Lagrangian point, 1.5 million km sunward of the Earth, where the gravitational forces of the Earth and Sun form a balance. Spacecraft can orbit L1, providing a continuous, uninterrupted view of the Sun. Spacecraft such as *SOHO* have occupied this area of space for many years.

Meanwhile, the other element of the strategy is for ESA to develop a dedicated space-weather-monitoring spacecraft to be stationed at the so-called L5 point. L5 is a gravitational 'well' centred some 60 degrees behind the Earth. Indeed, it is approximately where *STEREO-A* is at the time of writing. L5 provides an excellent location for off-Sun–Earth-line monitoring. This ESA spacecraft is called *Lagrange*.

This strategy recognizes that (*i*) CMEs cause the most severe space-weather effects on human systems and that (*ii*) prediction of CME arrivals at Earth, at this time, are largely based on aging scientific assets. *Lagrange* is set for launch in 2027. It has completed its early design stages, with RAL Space coordinating the remote-sensing instrument-payload development, and the Mullard Space Science Laboratory coordinating the *in-situ* instrument-payload development. With the spacecraft development also centred at Airbus UK in Stevenage, it is clear that the UK involvement and investment in this mission is very significant.

The remote-sensing instrumentation includes a coronagraph and an *HI* instrument to identify CMEs from their earliest stages through the heliosphere to Earth and beyond. Also included is an EUV imager to monitor the magnetic complexity and structure of the corona. Indeed, with the spacecraft at L5, this instrument will see an extra 60 degrees of the solar globe, not imaged from Earth, and noting that the Sun rotates, it is that region that is rotating towards us. This allows inspection of what is to come. The final remote-sensing instrument is a magnetograph. This is a device that maps the Zeeman-splitting effect in the visible surface of the Sun to map solar magnetic fields. Combined with the EUV imager, this provides an excellent facility to study the development of solar activity as it approaches the Earth-facing side. In addition, such magnetic data are commonly used now to model the background solar-wind flows that feed into our space-weather-forecasting models.

The *in-situ* instruments will include devices to sample the local magnetic field and solar-wind plasma at the spacecraft. Other instruments will monitor solar energetic particles and high-energy electrons and ions. Finally, an instrument that measures integrated X-ray flux from the Sun will be used as a solar-flare monitor. All of the instruments have heritage in previous missions, principally through *SOHO*, *STEREO*, and *Solar Orbiter*.

To conclude, this is an area where solar-physics research has fed into an applied field, and it is an area where the UK is particularly strong, both in science and in instrumentation. The heritage from missions like *STEREO* has been core to devising and refining the *Lagrange* L5 space-weather mission, including a fundamental demonstration of the value of off-Sun–Earth-line observations, both for science and space-weather application.

The President. Thank you so much, Richard. Again, a fantastic talk, and I never get tired of seeing beautiful images and movies of the Sun. Thank you for going into some of the details on the results from the *STEREO* missions. I'm going to hand over to Louise if there are any questions from the audience.

Dr. Alexander. I've got a question: "When *Lagrange* is fully operational and we can predict CMEs a lot better, do you think it could also play a role in predicting aurorae for Arctic-Circle tourists and aurora hunters?"

Professor Harrison. Yes it would or it certainly should. If we can identify coronal mass ejections heading our way, and be pretty certain about it, it should certainly have a role to play in that. There is one issue I should point to which I didn't really cover in the talk, and that is, although it sounds silly to say, which way up is the coronal mass ejection? Magnetically it's down to how the ejection links to the Earth's magnetic fields. If the mass-ejection magnetic field is southward-directed in terms of its magnetic polarity, the way it links into the Earth's magnetic field is more far more efficient in generating streams of particles down towards the polar regions that drive the aurorae. As things stand at the moment, the way we would do that is actually try to project it from what we can see at the Sun because the images we have at the moment with coronagraphs and the heliospheric imagers can't actually tell you which way up they are magnetically. So that is one of the big things that we're still grappling with, and we have not really solved in terms of observations in the heliosphere, unless you've got spacecraft everywhere and you can sample these things as they're heading towards the Earth. So I hope that answers the question.

Dr. Alexander. I've got another question: "Do the electromagnetic emissions from the CME events have any observable effect on Earth prior to the arrival of the particle clouds?"

Professor Harrison. You mean prior to the arrival at Earth?

Dr. Alexander. Yes.

Professor Harrison. We are seeing very diffuse events in white light, visible light, I should say, travelling out from the Sun. If one of those passed over you, for example, and you actually measured the particles, you would see an increase from just a few protons per cubic centimetre, to maybe 15 to 20 protons per cubic centimetre. It is to all intents and purposes a vacuum. But when it hits the Earth, the interaction with the magnetic field is the thing that really drives the activities, the events that we see. Other than streams of energetic particles that can be accelerated in the shock at the front of a coronal mass ejection which certainly can cause impacts on the spacecraft, for example, that you could see (*e.g.*, driving problems with electronics) — beyond that these events are almost invisible, which is why the heliospheric imagers are designed to be sensitive to the very, very, low light levels. I'm not sure that answered the question perfectly but I hope it went some way towards it.

Dr. Alexander. We've got another interesting one from Robin: "How much confidence do we have in predicting impact on technology from coronal mass ejections?"

Professor Harrison. If we have a coronal mass ejection identified in a coronagraph and identified well in heliospheric-imager data, we can, in principle, track these very, very well. The problem with respect to this question is that knowing the likely arrival time is one thing (a valuable thing to know) but predicting the precise impact is another. There have been occasions where a mass ejection arrived at Earth and a particular spacecraft might be damaged — well why was that one damaged and not another one? Predicting the precise impact is extremely difficult, but we do know what could happen and what assets are vulnerable. I suppose the point is that you could say it is our job to say it is coming, it is on its way, it's going to arrive, and this is the time of arrival. Given that information, people running spacecraft operations, power-distribution systems, and so on should be prepared either with particular actions that they need to perform, or putting the A-team on duty at the time of the arrival or whatever it is they need to do to be ready.

Dr. Alexander. We have only got time for one more question, so this is a question from Hugh Hudson: "Are you worried about ESA–UK operational cooperation on *Lagrange*?"

Professor Harrison. That's an interesting question. When you said Hugh Hudson was going to ask a question I thought it was going to be a complicated solar-physics question I'd have a problem with. With regard to ESA and the UK I guess I am not particularly worried. First let me remind people that the UK is and remains a member of ESA. This is nothing to do with the EU. That said, the *Lagrange* concept has grown up since 2009/10 through strategic discussions involving the UK, including ourselves at RAL and the UK Met Office. As the *Lagrange* project developed within ESA, UK teams have led the way in instrument studies and development, and Airbus UK are prime contractors for the spacecraft development. This is a mission to which the UK is heavily committed.

The President. Thank you Louise, and thanks to Richard for answering those questions. To conclude I'd just like to thank both of our speakers this afternoon for their presentations. I'd also like to give you all notice that the next monthly Open Meeting of the Society will be on Friday the 8th of January 2021.

This is obviously the final RAS meeting of 2020. What a year it has been. Thank you all for your support during this difficult year. Thanks for coming to our meetings. I personally would like to wish you all the best, please stay safe and well, and we hope to see you all again very soon.

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EMMA BUNCE, *President*
in the Chair

The President. A very warm welcome to you all, and again we're delighted to bring you the first Ordinary Meeting of 2021 *via* webinar. We're really pleased to have so many of you with us today, and I hope you can all hear me and see me clearly.

I am very pleased to announce the recipients of the Society's awards for 2021. An Honorary Fellowship for Geophysics goes to Professor Walter Mooney from the United States Geological Survey. An Honorary Fellowship for Geophysics goes to Professor Tamaz Chelidze from Tbilisi State University. The James Dungey Lectureship goes to Dr. Karen Aplin from the University of Bristol and the George Darwin Lectureship goes to Professor Filippo Fraternali from the Kapteyn Astronomical Institute at the University of Groningen. The Harold Jeffreys Lectureship goes to Dr. Sanne Cottaar from the University of Cambridge. The Group Award for Astronomy goes to the *Event Horizon Telescope* team. The Winton Award for Geophysics goes to Dr. Julia Stawarz from Imperial College London, and the Winton Award for Astronomy goes to Dr. Cassandra Hall from the University of Georgia. The Fowler Award for Geophysics goes to Dr. Richard Morton from Northumbria University, and the Fowler Award for Astronomy goes to Dr. James Owen from Imperial College London. The Service Award for Geophysics goes to Professor Ian Crawford from Birkbeck College London. The Patrick Moore Medal goes to Miss Sarah Eames from Sandfield Close Primary School in Leicester. The Annie Maunder Medal goes to Professor Robert Walsh from the University of Central Lancashire. The Jackson-Gwilt Medal goes to Dr. Floor van Leeuwen from the University of Cambridge. The Price Medal goes to Professor Emily Brodsky from the University of California at Santa Cruz, and the Chapman Medal goes to Professor Ineke De Moortel from the University of St. Andrews. The Eddington Medal goes to Professor Hiranya Peiris from University College London, and the Herschel Medal is awarded to Professor Stephen Smartt from Queen's University Belfast. This year's Gold Medal for Geophysics goes to Professor Thorne Lay from the University of California Santa Cruz, and this year's Gold Medal for Astronomy is awarded to Professor Dame Jocelyn Bell Burnell from the University of Oxford. Many congratulations to all of this year's winners.

The President. We're now going to hear the James Dungey Lecture for 2020, and this was awarded to — and will be given by — Professor Sarah Matthews from University College London. Sarah Matthews is an expert on the storage and release of energy in the solar atmosphere and has extensively studied the white-light and related sun-quakes in solar flares. Her discoveries have revealed insights into the dominant physical process involved and have shown that white-light flares are not a mere consequence of so-called big-flare syndrome. Sarah is an excellent and enthusiastic communicator of solar physics. I'm very much looking forward to hearing her lecture this afternoon. So I'm now going to hand over to Sarah so hopefully she can share her slides with us and begin her lecture.

Professor Sarah Matthews. [The lecturer reminded us that magnetic reconnection was the term coined by James Dungey in 1958 to describe the process of magnetic-field reconfiguration in which stored magnetic energy, mass, and momentum are released. The work that led him to the identification of this key process, and its role in his seminal work on magnetospheric circulation (the 'Dungey Cycle'), was set in motion as the result of his PhD supervisor's suggestion to investigate whether the magnetic nulls described by Giovanelli in 1948 as the potential source of solar flares might also be responsible for the terrestrial aurora.

In the 2020 Dungey Lecture the role of magnetic reconnection in solar flares was once again considered, and in particular how well the 'standard' eruptive model of solar flares and the conceptual framework that it offers, in which to investigate the global characteristics of the energy release and transport in the context of the magnetic-field configuration, is supported by the increasingly sophisticated observations of the solar atmosphere available to us.

The lecturer focussed in particular on two key elements of the flare process that are not well supported by the 'standard' model — the processes that lead directly to the onset of reconnection, or the so-called flare trigger, and the conditions or processes by which energy can be preferentially deposited in very localized regions within the flaring region, producing localized acoustic disturbances known as 'sun-quakes'. Several studies were described that demonstrated how the use of multi-wavelength spectroscopy, and in particular the enhanced line widths observed in EUV and X-ray spectral lines, can be used to probe signatures of early energy release in the solar transition region and corona and how the location of these enhancements can provide insights into the likely flare-trigger mechanism, as well as the processes involved in the eruption of magnetic-flux ropes.

The second part of the lecture explored some of the evidence amassed so far in order to try to differentiate between the current theories behind the generation of sun-quakes, which include processes such as hydrodynamic shocks, radiative back-warming, energetic-particle precipitation, and magnetic-field transients. Finally, a case study was presented that explored the specific role of the magnetic topology in preferentially focussing energy to a very specific location.

The lecture ended with a brief summary of prospects for future observations that will provide new opportunities to answer some of our remaining questions, including the *Daniel K. Inouye Solar Telescope* (*DKIST*), *Solar Orbiter*, and new magnetic-field diagnostics with the *EUV Imaging Spectrometer* (*EIS*) on *Hinode*. Looking further into the future *Solar-C_EUVST* and the *European Solar Telescope* (*EST*) promise to be invaluable tools for the community.

It is expected that a longer summary of this talk will appear in a future issue of *Astronomy & Geophysics*.]

The President. Thank you so much for that fascinating lecture — I've personally learned a lot. I can see there are some questions coming through. So what I'm going to do now is just hand over to Louise who's going to facilitate the Q&A for us. Thanks, Louise.

*Dr. Louise Alexande*r. I'm going to start with Hugh Hudson but I'm not sure if this is something that you then talked about later in your talk: "As you mentioned, Sarah, the impulsive phase, where energy release is important, may last for a few minutes in a major flare. If we interpret this in MHD, the governing timescale might be the Alfvén crossing time which would be very much shorter. Do you have any view of how this may work?"

Professor Matthews. He's right, of course, Hugh is always right about everything! Yes, it should be the Alfvén crossing time. The very steepest rise of the impulsive phase, where most of the energy release happens, is substantially shorter than a few minutes, but this is one of those cases, I think, of how you define the impulsive phase and maybe we don't have such a consistent way of doing this, even after all these years. So there's clearly continued energy release happening in some of these flares for quite some time, and I think that's another aspect that really isn't completely consistent with that standard model, so something that we do need to understand further. That requires bringing in modelling as well as observation.

Dr. Alexander. Thank you. Francisco Diego would like to know "Are flares always associated with sunspots?"

Professor Matthews. Not always, no, but they are fairly infrequently associated with 'no sunspots', or active regions without sunspots. I certainly vividly remember a spotless flare which was also a white-light flare from my PhD studies. Most of them are associated with sunspots, but we do get flares without sunspots some of the time, yes.

Dr. Alexander. Eamon Scullion is asking "You mentioned the *EST* is expected to have first light in 2027. Is that project now officially funded and going ahead? If not, what is the status of it?"

Professor Matthews. Eamon probably knows the answer to the first part of that question, but the status of it is that we have EU funding to continue the preparatory phase until the end of this year. What we're doing at the moment is finalizing the construction design for the telescope and also working with national partners in order to secure funding to move to the construction phase at the end of two years. Securing funding for these things is always a challenge, and even more so when you have to bring together several nations. The *DKIST* was, I guess, fortunate in that it only had to worry about the US in terms of funding. So the status is that we are still moving forward. We are working to put together a legal framework and also a final construction design.

Dr. Alexander. Stephen King would like to know "How do flare-time-scale models connect current long-term solar magnetic-field models? What causes flares? Do the flux ropes erupt from depth? And if so, how deep?"

Professor Matthews. I'm not sure I completely understand the first part of the question but in terms of what causes flares then that's the question that we're trying to answer. We know that it is the destabilization of the magnetic field. Some recent work by some of our collaborators in Nagoya in Japan has identified that actually some very small-scale magnetic structures around the polarity-inversion line can be, or certainly appear to be, reliable indicators of the beginning of a chain of events that will subsequently lead to a flare as we define it in current terms. However, not all flares involve the eruption of flux ropes, and a significant open question within the community is when these flux ropes actually form. So there are some models where the flux rope is pre-existing and formed by magnetic motions within the photosphere prior to the eruption, and there are some other models where the magnetic flux rope is formed as part of the eruption. One of the questions people are working on to try to understand this is how does that process work and are the processes the same in all cases; and I think the answer to the latter is probably no.

Dr. Alexander. And now a question from Valery Nakariakov: "It is found that very often during the impulsive phase, the non-thermal emission has quasi-periodic pulsations (QPP). We can consider these oscillations as a common and perhaps intrinsic feature of flares. A model of a solar flare cannot be considered as complete if it does not explain those quasi-periodic pulsations. Could you comment on this please?"

Professor Matthews. I agree. I think you're absolutely right. It's become clear that these do appear to be an intrinsic feature and they may well be signatures of oscillatory reconnection. This probably comes back to the fact that the standard model is a very simplistic one. It's a good framework for explaining some of the observations but actually when you start to unpick all of the elements in that, they're hugely complex, so the process of magnetic reconnection is an entire field in itself. The study of waves, in which Valery is an expert, is an entire field on its own. But I agree that our flare models do need to be able to explain QPP because they appear to be ubiquitous and fundamental.

Dr. Alexander. Thank you. We've got time for one last question, and this one's from Lyndsay Fletcher. "What fraction of a flare's energy goes into the sun-quake? What processes could affect that fraction?"

Professor Matthews. It's actually a relatively small fraction of the flare energy budget — as far as we actually know the flare energy budget, because there are significant gaps in our coverage of the spectrum which mean that we don't know that particularly well. The calculations of the acoustic power associated with sun-quakes have some fairly significant uncertainties associated with them. In the majority of cases the power is all around six millihertz or so, but then in other examples we see significant power at seven millihertz and sometimes even at ten millihertz, for reasons we don't yet understand. One of the most recent papers on the topic is starting to look at this ten-millihertz emission. So I'm not sure that we have a very good handle either on the sun-quake energy budget itself or the total flare energy budget but it is actually still a relatively small fraction. I don't think there's any getting away from that.

The President. Thanks, Louise for doing the Q&A, and thanks again, Sarah, for a fantastic talk — it was really very enjoyable. The only thing left for me to do this afternoon is to give notice that the next monthly A&G Open Meeting of the Society will be on Friday the 12th of February 2021. So thanks as always for joining us and I hope to see you all again next time, and please do take good care of yourselves and stay safe and well.

A RECURSION RELATION FOR POWERS OF THE TIME-AVERAGE DISTANCE IN KEPLERIAN ORBITS

By B. Cameron Reed

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This paper derives a recursion relation between three successive powers $\langle r^{n-2}\rangle$, $\langle r^{n-1}\rangle$, and $\langle r^{n}\rangle$ of the time-averaged separation between the two bodies in a Keplerian orbit.

While remarking to students that planetary orbits and hydrogenic wavefunctions both arise from inverse-square forces but have very different mathematical expression and interpretations, I wondered if there is a recursion relation between successive powers of the time-averaged values of integer powers of the orbital radius akin to that for the radial probability distributions of hydrogen-atom states. The answer is yes, and the relationship is surprisingly easy to establish with the help of a table of integrals and a mathematical-physics text. However, this relationship seems not to be well known: I have been unable to find any mention of it in on-line searches or in various mechanics texts. A brief derivation is given here.

Consider a standard Keplerian system comprising two masses. Taking the origin to be located at one of them, the separation as a function of apsidal angle ϕ as measured from periapse is given by the usual equation for an ellipse,

$$r = \frac{a\,(1-\varepsilon^2)}{(1+\varepsilon\cos\phi)}, \qquad (1)$$

where a is the semi-major axis and ε the eccentricity.

If the orbital period is T, the time-averaged n-th power of r will be

$$\langle r^n \rangle = \frac{2}{T}\int_0^{T/2} r^n dt. \qquad (2)$$

The integral need only be taken over half the orbital period because of the symmetry of the problem, and can be cast into an integral over ϕ by invoking conservation of angular momentum L:

$$\frac{d\phi}{dt} = \frac{L}{\mu r^2}, \qquad (3)$$

where μ is the reduced mass. Upon invoking the standard expression for the relationship between LT and the area of the orbit, namely[1]

$$\frac{LT}{2\mu} = \pi a^2\sqrt{1-\varepsilon^2}, \qquad (4)$$

we get

$$\langle r^n \rangle = \frac{a^n\,(1-\varepsilon^2)^{n+3/2}}{\pi}\int_0^{\pi}\frac{d\phi}{(1+\varepsilon\cos\phi)^{n+2}}. \qquad (5)$$

Formula 3.661.4 in Gradshteyn & Ryzhik is exactly what we need[2]:

$$\int_0^{\pi}\frac{d\phi}{(a+b\cos\phi)^{n+2}} = \frac{\pi}{(a^2-b^2)^{n/2+1}}P_{n+1}(x), \qquad (6)$$

where $P_{n+1}(x)$ denotes the Legendre polynomial of order $n+1$. The argument x is

$$x = \frac{a}{\sqrt{a^2-b^2}} = \frac{1}{\sqrt{1-\varepsilon^2}}. \qquad (7)$$

Hence we get

$$\langle r^n \rangle = a^n(1-\varepsilon^2)^{(n+1)/2} P_{n+1}(x). \tag{8}$$

Like expressions for $\langle r^{n-1} \rangle$ and $\langle r^{n-2} \rangle$ can be written down by inspection. Then solve these for the P's and substitute into the usual recursion relation for this family of polynomials to obtain the result

$$(n+1)\langle r^n \rangle = a(2n+1)\langle r^{n-1} \rangle - na^2(1-\varepsilon^2)\langle r^{n-2} \rangle. \tag{9}$$

Explicit expressions for the first few cases are

$$\langle r^1 \rangle = a\left(1+\frac{1}{2}\varepsilon^2\right); \tag{10}$$

$$\langle r^2 \rangle = a^2\left(1+\frac{3}{2}\varepsilon^2\right); \tag{11}$$

$$\langle r^3 \rangle = a^3\left(1+3\varepsilon^2+\frac{3}{8}\varepsilon^4\right); \tag{12}$$

$$\langle r^4 \rangle = a^4\left(1+5\varepsilon^2+\frac{15}{8}\varepsilon^4\right); \tag{13}$$

$$\langle r^5 \rangle = a^5\left(1+\frac{15}{2}\varepsilon^2+\frac{45}{8}\varepsilon^4+\frac{5}{16}\varepsilon^6\right). \tag{14}$$

Computing mean radii in this way avoids any recourse to Kepler's equation, and will always result in closed-form polynomials involving even powers of ε.

I am grateful to an anonymous reviewer whose comments resulted in improvements to this paper.

References

(1) See, for example, Ch. 7 of A. P. Arya, *Introduction to Classical Mechanics*. (Prentice-Hall, Englewood Cliffs, New Jersey), 1990.

(2) I. S. Gradshteyn & I. M. Ryzhik, *Table of Integrals, Series, and Products, 5th ed.* (Academic Press, San Diego), 1994.

LANCASHIRE ASTRONOMERS AND THE EARLY RAS, 1820–1870

By Steven Phillipps

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The Royal Astronomical Society was formed as the Astronomical Society of London in 1820 and continued to be distinctly London-centric even after it was given its Royal Charter in 1831, which confirmed its status as the primary society for astronomers in the UK. Indeed, Fellows living more than 50 miles from the capital were initially in their own category of 'non-resident'[1]. Nevertheless, there were astronomers from the provinces who aspired to membership, or who communicated their contributions to *Monthly Notices* or *Memoirs of the RAS*. In this article we consider those from the present author's home county of Lancashire — as defined by its traditional boundaries — who had an involvement with the RAS during its first half century.

The early RAS

Victorian amateur astronomers came in many varieties, from the 'grand amateur' with their own observatory and major observational research programmes, through 'leisured enthusiasts', to working-class adherents[2]. In addition, there was a small number of professionals, generally academics or assistants at either professional or amateur observatories. It is clear that the *sine qua non* of the grand amateur, in particular, was significant wealth so, given the saying "where there's muck there's brass", we should not be surprised if the rather grimy 19th-Century north west produced numerous amateur astronomers, grand or otherwise, despite the less-than-promising clarity of the atmosphere if too close to a 'dark satanic mill'. There was a good supply of technically literate working men too, but these are notable by their absence in what follows: the RAS was too much of a gentlemen's club to attract their membership and anyway they would have baulked at the two guineas entrance fee and annual subscription[1]. Even Moses Holden (1777–1864), who elevated himself from weaver to lecturer in astronomy at working men's institutes and producer of celestial maps and almanacs, and who was eventually granted the Freedom of Preston for his involvement in the establishment of the Preston Institute for the Diffusion of Knowledge[3], never joined the RAS or contributed to its journals.

The first Lancashire members

There had been significant astronomers in Lancashire prior to the 19th Century, most notably Jeremiah Horrocks of Much Hoole near Preston, who predicted and then observed the 1639 transit of Venus, and his collaborator William Crabtree from Broughton near Manchester, whose joint work has been suggested as the starting point for astronomical research in Britain[4].

However, there was just one man with an address in Lancashire in the original list of members of the RAS (strictly still the Astronomical Society of London at that point) in 1822[5], the Rev. George Burgess Wildig of Liverpool. He had been elected at the very first meeting of the Society in February 1820. Born in Staffordshire in 1784 he entered a mercantile house in Liverpool, but a change of course saw him study in Edinburgh and Cambridge, graduating in 1815 before returning to Liverpool. Entering holy orders he obtained a local curacy but then spent several years as mathematics professor at the Liverpool Institute before becoming a rector back in Staffordshire[6]. He wrote mathematical articles for the *Encyclopaedia Britannica*.

There was one other original 1820 February member who was actually born in Lancashire. Joshua King was born in Ulverston on the Furness peninsular, part of the historic county of Lancashire though now in Cumbria, in 1798, and attended school in nearby Hawkshead. However, he was Senior Wrangler in 1819 and remained in Cambridge for the rest of his life[7].

Rev. John William Whittaker, born in Manchester in 1791, had also been in the first members list (elected 1820 December) and was also at Cambridge at the time. However, by the second list, for 1825, he was back in Lancashire as vicar of Blackburn[8] and obtained his DD in 1830, becoming Rural Dean and Honorary Canon of Manchester Cathedral. He claimed to have reconciled Biblical, geological, and astronomical timescales, but died before publishing the work. By an odd chance, his obituary is adjacent to that of Wildig in *MN*[6].

The third early Lancashire member was Thomas Norris, Esq. of Redvales in Bury[8], elected in 1824. Born in Croston in 1765, he joined a cotton spinning business, subsequently becoming a partner in the firm (along with the father of future Prime Minister Sir Robert Peel). He retired "in possession of a large fortune" in 1821 and from then on made and used a number of telescopes as well as indulging in his many other hobbies, such as natural history and collecting paintings. He may have been Francis Baily's unnamed correspondent who observed the 1822 partial solar eclipse from Bury. He later lived at Howick House near Preston[9].

The first Lancastrian FRAS to carry out astronomical observations in a professional capacity was Captain Henry Foster FRS. He appears in the 1825 membership list[8], where he just recorded himself as "R.N.", with no address. He was born in the village of Woodplumpton, north of Preston, in 1796 and joined the navy in 1812. Between 1817 and 1819 he "visited the Columbia River with the commissioners to establish the boundary line between Great Britain and the United States". He was then part of the British Naval Scientific Expedition to the Arctic in 1823, during which he assisted the astronomer Edward Sabine. He subsequently joined Captain Parry's North West Passage and North Polar expeditions, carrying out astronomical and geomagnetic observations. He was elected a Fellow of the Royal Society in 1824, winning their Copley medal in 1827. From 1828 to 1831, he led an expedition to the South Atlantic, touching upon Antarctica, carrying out gravity measurements with a pendulum[10]. Unfortunately, while continuing his experiments in Central America on the return journey, he was drowned in the River Chagres in Panama after falling from a large canoe, used to reach otherwise inaccessible places[11].

The 1830s

Several Victorian Lancastrians can be ranked firmly among the 'grand amateurs', and pride of place among these has to go to William Lassell[12]. The son of a timber merchant, Lassell was born in Bolton in 1799 and educated at a 'dissenting academy' in Rochdale. After an apprenticeship with a merchant, he set himself up as a brewer in Liverpool. His real interest was astronomy, however, and by 1820 he was already constructing his own reflecting telescopes which he set up "on an equatoreal movement" in his observatory, 'Starfield', in West Derby, a suburb of Liverpool, though he did not become an FRAS until 1839[13]. As his fortune from the brewing business increased, so did the size of the telescopes he built, and by 1844 he had a "two-foot reflector" which he used to discover Neptune's satellite Triton two years later. He also discovered a moon of Saturn and two around Uranus. In 1854 he moved further out of the city, to Bradstones in Sandfield Park, but his next telescope, a 48-inch, the third largest built up to that time, was moved to Malta to take advantage of clearer skies. Besides planetary observations, his main work in Malta was concerned with the detection of new nebulae[14]. On his return to England, he left Lancashire and set up his 24-inch in Maidenhead. He was elected a Fellow of the Royal Society in 1849 and was president of the RAS in 1870–71. A crater on the Moon, a crater on Mars, an asteroid, and a ring of Neptune are all named after him.

Rev. William Rutter Dawes was also born in 1799, the son of Royal Engineers officer William Nicolas Dawes, the first Government Astronomer in New South Wales, who established the original observatory in Sydney at what is now Dawes Point. The younger Dawes was educated at Charterhouse and then St. Bartholomew's to qualify as a doctor. In 1826 he took a practice in Liverpool, resuming an interest in astronomy, but soon became a minister in an independent church in nearby Ormskirk, where he subsequently constructed an observatory. He joined the RAS in 1830. He left the county in 1839 to take charge of "Mr Bishop's observatory in Regent's Park", then built his own observatory in Cranbrook in Kent, later moving it to Maidstone and then to Haddenham in Buckinghamshire, his second marriage, to a wealthy widow, finally enabling him to move properly into the grand amateurs[15]. He co-discovered an inner ring of Saturn with his old Lancashire friend Lassell in 1850 and, starting from his time in Ormskirk, made large numbers of detailed observations of double stars, his work culminating in his *Catalogue of Micrometrical Measures of Double Stars*[16]. Like Lassell he has craters on the Moon and Mars named after him. Dawes was awarded the Gold Medal of the RAS in 1855 and elected an FRS in 1865.

Another friend of Lassell was Alfred King. Although not an FRAS, he is mentioned by Dawes in *MN* in respect of the partial eclipse of 1836: "Mr Lassell and Mr Alfred King were observing from Liverpool; and, having noticed a remarkable appearance during the occultation of this spot, they made diagrams of the phenomenon"[17]. King (born in Liverpool in 1797) was a noted civil engineer: as chief engineer to the Liverpool Gas Light Company for 41 years he was largely responsible for the introduction of gas lighting to the city[18]. In addition, in 1853, in collaboration with John Hartnup (below) he invented the meteorological barograph. His brother Joseph was also an amateur astronomer and their sister Maria married Lassell. An A. Livingston of Liverpool also supplied an observation of the 1836 eclipse to *MN*[19]. This was likely Andrew Livingston, recorded in the Liverpool census as a "Teacher of Navigation", born in Scotland around 1785.

John Chapman Hartnup (born in Kent in 1806) is the first professional astronomer *per se* in our list. He first appears in the annals of the RAS in 1836, when his observations of lunar occultations made at Mr. (later Lord) Wrottesley's observatory in Blackheath were included in *Memoirs*[20]. He also worked as a supernumerary computer at the Royal Observatory in Greenwich. In 1839 there is then an entry in the Society's accounts, "Three quarters, ditto [*i.e.*, of a year's salary], to Mr Hartnup £60". This was in respect of his position as Assistant Secretary to the RAS. In 1843 he was appointed director of Liverpool Observatory, run by the Mersey Docks and Harbour Board, and in 1845 was elected an FRAS. The Liverpool Observatory's original work was concerned with chronometers and longitudes at sea, though Hartnup also observed comets and minor planets[21].

His son, also John Hartnup, (born in 1841 in Somerset House, the RAS 'apartments' at the time), was also a professional astronomer, working as his father's assistant and eventual successor. He was already listed as "astronomer" in the 1861 census when the family home was given as "Waterloo Dock Pierhead, Liverpool Observatory". He became the official assistant observer in 1863 just prior to the Observatory (and the Hartnup family) moving to Bidston on the other side of the Mersey (where their next-door neighbour was the lighthouse keeper). For some reason, though, he was not elected an FRAS until 1886, after taking over as the Observatory director and continuing the work in "chronometrical management". He was for a time vice-president of the Liverpool Astronomical Society (founded in 1881). He was tragically killed in 1892 when falling from the Observatory roof after making some meteorological observations[22].

John Holt Stanway (born Manchester 1799) joined the RAS in 1835, giving his address as "Old Trafford House near Manchester", having acquired part of the estate as a "botanical garden". A commercial broker and accountant, the electoral register for 1836 also records that he held "one moiety of freehold houses and shops". He subsequently had an observatory at his new home, Brookfield, in Chorlton-cum-Hardy. Encountering financial difficulties, and facing potential imprisonment, in the 1840s, he and his family sailed for New York on the *Great Western*, but then headed on to the Republic of Texas, where Stanway adopted a new identity as John H. Smythe Stanley (among others)[23]. He became a photographer and built a new observatory in Houston, contributing articles on astronomy to local newspapers. At various times in America he was referred to as 'Reverend' and 'Professor', though he was neither.

Ebenezer Henderson, the son of a clockmaker in Dunfermline (born 1809), initially followed his father's trade, building an astronomical clock around 1827. Shortly afterwards he moved to the Liverpool area as a clerk in his brother's tannery in St. Helens, subsequently becoming its manager. He also became curator of Liverpool Astronomical Institution and Observatory for a time and gave lectures there[24]. He joined numerous scientific societies and became an FRAS in 1837. He wrote for popular science journals as well as producing books on both horology and astronomy. He was also a notable antiquarian who wrote *The Annals of Dunfermline* and had the Freedom of Dunfermline conferred on him in 1859. He eventually returned to live in Scotland.

The remaining Lancashire FRAS of the 1830s was Peter Clare, elected in 1839. He was born in 1781 in Manchester, where his father, of the same name, was a renowned clockmaker. He carried on his father's business — he constructed the first clock that Manchester Corporation used to keep Greenwich, rather than local, time — and was a long-serving secretary of the Manchester Literary and Philosophical Society from 1821. A fellow Quaker, he was a close friend of Manchester's pre-eminent scientist of the era, the chemist John Dalton[25].

The 1840s

The 1840s saw a number of Lancashire-based amateurs join the RAS. First was John Jesse of Ardwick Green in Manchester in 1841. Born in 1802 and a physician by profession, a member of the Royal College of Surgeons[26], he was also a member of the Linnean Society and became an FRS in 1842, apparently for his astronomical observations from Ardwick: he submitted a paper to the

Royal Society describing his observatory there. He later inherited Llanbedr Hall in Denbighshire[27] and served as magistrate for Derbyshire and Denbighshire, eventually becoming High Sheriff of Denbighshire.

Samuel Elsworth Cottam also joined the Society in 1841 and gave his address as "Athenaeum, Manchester", *i.e.*, the Manchester Athenaeum for the Diffusion of Knowledge[28]. He had been born in Manchester in 1801 and worked for a large mercantile firm in the city. He became secretary of the Manchester Mechanics Institution soon after joining in 1825, lecturing on many scientific topics and arranging exhibitions. He was later a public accountant for large railway companies[29]. His son, Samuel (born in Manchester in 1828), who became head of the accountancy firm, was also an FRAS, elected in 1871[30].

The list of Fellows for 1850 includes one Lieut.-Col. John Hambly Humfrey "late Royal Staff Corps, London Road Station, Manchester"[31]. Humfrey, born around 1801 in Jersey, where his father Lieut.-General Humfrey was commanding engineer officer on the island, started out in the Royal Artillery, transferring to the Staff Corps in 1827. He then served with the British Legion in Spain from 1835 to 1838 and was made a Knight of St. Ferdinand. After being pensioned off he became involved with several railway companies (hence his 1850 address) and became a member of the Institution of Civil Engineers in 1840. His contribution to astronomy is unclear, but he was elected an FRAS in 1844 (when living in Sheffield). An authority on military fortifications and on the Peninsular Wars, writing numerous tracts[32], in 1855 he became a Major Commandant in the British German Legion (a German division in the British Army). From 1862 he was a Captain of Artillery in the Royal Lancashire Militia.

Col. William Assheton Cross from Red Scar near Preston was elected in 1848. Born in 1818, the son of a prominent Preston lawyer and JP, he lived in the family's faux-Elizabethan mansion, Red Scar House. Educated at Rugby and Cambridge he built his own observatory while still at college, obtaining W. R. Dawes' former telescope. He later produced a 15-inch telescope under the guidance of Lassell[33]. In 1871 he listed himself as a magistrate and landowner. His army rank was as an Honorary Colonel in the Lancashire Militia. His brother, the Rev. John Edward Cross (born in 1821, also at Red Scar), was elected an FRAS in 1862. He made some observations from Bolton while he was a curate there in the 1840s, and later had a larger telescope in his observatory in Lincolnshire for which Col. Cross ground the mirrors[34]. A third brother was the Right Hon. Viscount Cross, who twice served as Home Secretary.

Rev. Henry Halford Jones, a Fellow of the RAS from 1848, gave his address in 1852 as the rather ominous "Cemetery, Manchester". He was born near Rugby in 1787 and trained as a Baptist minister. After several positions in the Midlands, in 1823 he was chosen as pastor of a chapel at Styal in Cheshire built for the employees at Quarry Bank cotton mill by owner Samuel Greg. Halford Jones later became Registrar and Chaplain at a cemetery in Manchester. After joining the RAS he contributed the astronomical sections of the *Manchester Almanac* and was appointed Astronomer to Manchester Corporation in 1852, in which position he was responsible for keeping Greenwich Time (see entry for Clare, above)[35].

Perhaps inspired by their pastor, Samuel Greg's family also became involved with astronomy. Son John (born in Wilmslow, Cheshire, in 1801) took over the management of a mill in Caton near Lancaster in 1824 and in 1842 built himself a country mansion, Escowbeck House, to which he added an observatory[36]. (He was later mayor of Lancaster three times.) John's brother Robert Hyde Greg (subsequently an MP) and sons Edward and John Philip were apparently all also interested in astronomy, but the most prominent, and the one with RAS links, was Robert's son Robert Philips Greg (born in 1826). Already studying meteors in the 1850s — a review by Alexander Herschel in *MN* on 'meteoric science'[37] mentions the use of "Mr Greg's catalogue (*Brit. Ass. Report* 1860)" of aerolitic meteors — he was elected an FRAS in 1868, while living in Prestwich. He later contributed several papers to *MN* and *Nature*. He was also a keen mineralogist, treasurer of the Mineralogical Society from 1875 to 1885[38].

Robert Worthington, a solicitor from Altrincham (born in 1805), moved to Crumpsall Hall, which was then outside the conurbation of Manchester, in 1847. The following year he became involved in the Chartist disturbances as a militia commander, rescuing the son of the local MP from rioters. From 1861 he was Registrar to the County Court. Elected an FRAS in 1849, he constructed an observatory at Crumpsall but due to an injury to his eye could not make proper use of it and his friend and neighbour Joseph Baxendell (see below) was invited to make the observations[39]. Worthington later moved his observatory to Ardwick. His son Arthur Mason Worthington (born in 1852) also assisted at the observatory before going to Oxford and studying further at Owens College back in Manchester. He worked as a schoolmaster before becoming professor of physics at the naval colleges at Portsmouth, Devonport, and Greenwich from 1887[40]. An FRAS since 1877, he became an FRS in 1893 for his work on fluid mechanics, as described in his book *The Splash of a Drop*.

Joseph Baxendell, born in Manchester in 1815, went to sea as a youth but returned to the city to become an estate agent. He took up polishing mirrors for his own telescopes and installed them in his friend Robert Worthington's observatory (above), also being chosen as Astronomer to the Corporation of Manchester, succeeding Halford Jones (above) in charge of official time-keeping. Though not an FRAS until 1857, he published his first paper in *MN*, on variable stars, in 1848[41]. Moving his business to Southport in 1871, where he was appointed the Superintendent of the town's Meteorological Observatory, he built his own observatory in Birkdale. He made contributions to numerous learned societies, particularly the Manchester Literary and Philosophical Society (whose proceedings he edited for many years), many of them on links between solar activity and terrestrial weather. He became an FRS in 1884[42] and all told had over 40 papers in major journals, the last a paper in *Astronomical Journal* in 1902. Many of his variable-star observations were published posthumously through the agency of H. H. Turner[43]. His son Joseph (born in 1870) assisted him in his observations as a boy and became a meteorologist in his own right, while Norman Pogson, government astronomer in Madras, was his brother-in-law, and early female RAS member Isis Pogson Kent was his niece.

In a later *MN* contribution[44], Baxendell referred back to an observation he carried out of the 1848 transit of Mercury, which he made with his friend Mr. S. W. Williamson of Cheetham Hill, Manchester. Also, according to Brothers (see below), in an 1866 review of celestial photography, Baxendell and Williamson were "engaged about the same time [the mid-1850s] in producing photographs of the Moon". Samuel Walker Williamson was born in Salford in 1799, and in 1871 recorded himself as "retired ship owner/general merchant". He was a member of the Manchester 'Lit and Phil' but did not become a Fellow of the RAS.

The year 1849 was a busy one for Lancashire amateurs. W. M. Fisher, "Principal, Educational Establishment", was elected in the January along with Rev. Alfred Weld[45]. Scot William McN. Fisher LL.D., born in 1812, was headmaster of a boarding school in the centre of Liverpool. He was also a member of the Lancashire and Cheshire Historic Society.

Father Alfred Weld S.J. was the director of the Observatory at Stonyhurst College, near Clitheroe. Stonyhurst was opened as a Jesuit College in 1794 on land donated by Thomas Weld of Lulworth Castle, the grandfather of Alfred Weld. The latter was born in Leagram in the Ribble Valley in 1823, his family holding the manor. While running the Observatory from 1848 to 1851 (it had been built in 1838) he had five contributions in *MN* and hosted exiled Italian priest Father Angelo Secchi and may have been responsible for inspiring Secchi's later career as a pioneer in astrophysical spectroscopy[46]. After being ordained, Weld resumed charge of the Observatory from 1857 until 1860, participating in the Magnetic Survey of Great Britain. He was made 'Provincial of the English Province' in 1864 and Rector of St. Beuno's Theological College in North Wales in 1871. He ended his days as a missionary in the Eastern Cape[47].

John Ashton Nicholls of Ardwick, Manchester, was another Fellow elected in 1849 (indeed, at the same meeting as Nasmyth, below). Born in Manchester in 1823, he was in the cotton business with his father (a JP and alderman) and had built up his own observatory furnished with a telescope "and other instruments, mostly of the manufacture of Mr Dancer"[48]. However, his health did not allow him to carry out regular observations (he died when only 36) and he instead concentrated on the "moral and social improvement … of the so-called working classes", particularly the education of children now working only half days in the cotton mills. He was Honorary Secretary of the Manchester Athenaeum (see entry for Cottam, above).

The "Mr Dancer" alluded to was John Benjamin Dancer, who had been born in London in 1812 but in 1818 moved to Liverpool where his father started a business as an optician and "philosophical instrument maker". The younger Dancer carried on the same trade but then moved to Manchester where he became known for various technical advances, including the development of photographic slides for magic lanterns and improvements in stereoscopes[49]. Albert Brothers (see below) attributed to him the first telescopic photographs of the Moon ever taken in Britain. He became an FRAS in 1855 and supplied an observation of a partial solar eclipse, as seen from Manchester, to *MN* in 1871. He built at least one of the telescopes used by Messrs. Worthington and Baxendell at Crumpsall Hall (see above).

Isaac Waithman Long was elected a Fellow in 1849 at the same meeting as his Manchester compatriot Robert Worthington (above). Born in Yorkshire in 1810, he was a merchant in Higher Broughton, having previously lived in Chorlton-on-Medlock. He later had a villa, 'Hazelcroft', built in Alderley Edge in Cheshire. He was a member of the Manchester Literary and Philosophical Society from 1852. He possessed a 5-inch telescope and made notable observations of Jupiter's belts, one such being recorded in *MN* in 1860[50].

His neighbour, Rev. William Read of Broughton, Manchester, was yet another to join in 1849[51]. He was born in Manchester in 1799 and attended Manchester Grammar School before becoming a tobacco manufacturer. Evidently well-known locally, he was on the committee convened in 1837 to discuss "the importance of establishing an Astronomical Observatory in the vicinity of Manchester" (Dalton, Clare, and Stanway were among the other members). Unfortunately, the proposal to build a "Royal Lancashire Astronomical and Meteorological Observatory" in Broughton came to nothing[52]. He went up to St. John's College Cambridge at the advanced age of 42 and gained his MA in 1848. Almost immediately after joining the RAS he was appointed a deacon in South Mimms in Middlesex and he was a Chaplain in Worthing from 1852.

In his two communications to *MN*, he claimed to have seen "the ceaseless passing of perfect spheres of light in uncountable numbers" while setting up daylight observations of Mercury in 1850. His son William James Read (born in Manchester in 1824) followed in his footsteps, graduating at St. John's just two years after his father. He too was ordained and became an FRAS in 1854[53] when he was a school master in Huddersfield. He later became Archdeacon of Antigua in the West Indies.

The first paper in *Monthly Notices* to discuss (rather than just detect) what are now known to be galaxies[54] appears to have been "Suggestions respecting the Origin of Rotatory Movements of the Celestial Bodies and the Spiral Forms of the Nebulae as seen in Lord Rosse's Telescopes. By James Nasmyth, Esq." in 1855[55]. Nasmyth had first communicated to the RAS in 1843 (*via* Sir John Herschel), an observation of the 'Great Comet', but again was one of those to become an FRAS in 1849. Although born in Edinburgh in 1808, James Hall Nasmyth was at the time the owner of Bridgewater Foundry, which was adjacent to the Bridgewater Canal in Patricroft, near Eccles. He had arrived in Lancashire in 1823, going into business in Manchester making steam engines, and in 1836 moved to Patricroft where he made his fortune. He was best known in engineering circles for his invention of the steam hammer and he also produced a pile-driving machine[56]. He already built his own telescopes at Patricroft — inventing the Nasmyth focus along the way — and retired to Kent in 1856 to concentrate on astronomy and photography, with emphasis on the Moon. Using his engineering skills, he built a mirror-grinding machine powered by a windmill for his observatory at his home, 'Hammerfield', as described in his autobiography[57]. He also collaborated with Lassell (see above) on the construction of the latter's large telescopes.

1850 to 1860

Thomas Turner Wilkinson was elected a Fellow of the RAS in 1850, his one contribution to their journals being his account of the annular eclipse of 1858 as observed at Burnley[58]. He was born in 1815 at Mellor, near Blackburn, and became a schoolmaster, mainly at Burnley Grammar School. He lectured widely at Burnley Mechanics' Institute on scientific matters and also on local history, being vice-president of Burnley Literary and Scientific Club. He co-edited a classic tome on Lancashire folk-lore, *Lancashire Legends, Traditions, Pageants, Sports, &c.; With an Appendix Containing a Rare Tract on the Lancashire Witches &c.*

Dr Hugh Neill became an FRAS in 1851. Born in 1806, he trained in Edinburgh for his diploma from the Royal College of Surgeons which he received in 1827. Three years later he took up a practice in Liverpool and was subsequently a surgeon at the Liverpool Ophthalmic Infirmary, living in Mount Pleasant. He wrote numerous medical tracts, but his main astronomical contribution seems to have been as chairman of the Liverpool Observatory committee while he was on the town council from 1848[59].

John Frederick Stanistreet (born in 1812) was the son of an eminent solicitor in Liverpool and took over his father's position in the firm in the 1830s. However, he was forced to give up his profession through a weak constitution some years later. While sailing to Madeira for his health he taught himself to navigate by the stars and subsequently travelled to view the 1851 eclipse from Trollhattan Falls in Sweden with William Lassell, contributing an account of it to *Memoirs of the RAS*[60]. He became an FRAS in 1852[61]. He also travelled with Lassell to the 1860 eclipse in Santander.

Another Liverpool-based amateur, George Williams, was a member of the same 1851 expedition[62], also publishing his account in *Memoirs*, though he did not join the RAS until 1865 (later reporting in *MN* on his observation of the 1868 transit of Venus). He was born in Bombay (now Mumbai) in 1814, the son of "the Surveyor-General of that Presidency". An architect, he joined a partnership with his brother in Liverpool, where he met Lassell and Stanistreet. He lived in Princes Park, where he had been architect for many of the Georgian-style houses. After retiring he moved to Dolgelley (Dolgellau) where he had an observatory set up[63].

The next Lancastrian RAS member was George Venables Vernon from Stretford in Manchester, born in 1831 and elected a Fellow in 1853. Yet another in the cotton trade (employing 200 hands in 1871), he was primarily interested in meteorology and was an original member of the British Meteorological Society in 1850, as well as a member of the Anthropological Society[64].

Captain Norman M'Leod (*sic*) was elected in 1856[65]. MacLeod worked for the Local Marine Board in Liverpool, with responsibility for the examinations for masters' and mates' certificates. He was also chosen to serve on the Liverpool Compass Committee in their deliberations on the magnetism of ships with the new-fangled iron hulls. Born in Cumberland in 1800, he actually lived on the other side of the Mersey to Liverpool, in Birkenhead in Cheshire.

Father Stephen Joseph Perry S.J. (born in London 1833), having been assistant director from 1856 to 1858, succeeded Alfred Weld (above) as director of Stonyhurst College Observatory in 1860. Perry was subsequently ordained at St. Beuno's in 1866 before returning as Stonyhurst director again from 1868. He was finally elected an FRAS in 1869 and an FRS in 1874[66] producing well over 100 papers, the majority in *MN* (the first, on Winnecke's Comet, in 1869) and *Nature*. He was a regular participant in astronomical expeditions, heading that to Kerguelen Island (aka Desolation Island) for the transit of Venus in 1874. He also observed the 1882 transit from Madagascar. He travelled to several solar eclipses, sadly dying of dysentery on board ship immediately after heroically completing the 1889 observations in the French penal colony of Iles du Salut, French Guiana (which included the infamous Devil's Island which is now a CNES space-agency site)[67]. Perry's deputy as director from 1863 to 1868, and subsequently his assistant and eventual successor, Father Walter Sidgreaves S.J. (born at Grimsargh near Preston in 1837) does not make an appearance in *MN* until 1875 (and oddly was not an RAS Fellow until 1891[68]), so does not technically satisfy our 1870 end point.

Observations of the 1857 occultation of Jupiter and the 1861 transit of Mercury were submitted to *MN* by a Matthew Jee, of Edge Hill in Liverpool, *via* J. C. Hartnup at Liverpool Observatory (see above)[69]. However, he does not seem to have ever joined the RAS. Jee was born in Birmingham in 1790 but was in Liverpool by 1814 when he married an Elizabeth Stanistreet (one might guess a relative of John Stanistreet, above). He was a general broker, though mostly involved in the cotton trade; he was president of the International Cotton Association in 1858. Fellow Liverpool cotton broker John Taylor, active from 1821 to 1857 was also noted "as a poet and as an astronomer", and was known as "Philosopher John"[70]. He was among the original proposers of the Liverpool Observatory, but does not appear to have been connected to the RAS in any way.

The memorably-named Josiah Thomas Slugg began to make telescopes in Manchester in the 1850s. Born in Norfolk in 1814, the son of a travelling Wesleyan preacher, the family moved to Manchester when he was 15. Clearly an entrepreneurial character, he was apprenticed to a druggist and then moved into the manufacture of soda water. Opening shops which covered both these trades in the Hulme district, after attending lectures at Manchester 'Lit and Phil', he then branched out into manufacturing telescopes (and microscopes) as well, advertising their suitability for observing the comet of 1858. They were aimed at a (relatively) mass market, being advertised as the cheapest available ("a marvellously large space will be found between the prices here quoted and the ordinary prices of such instruments"), starting from £2. He also began to produce books and pamphlets, including *The Stars and the Telescope; being a concise description of the starry heavens &c.*[71]. He went on to join the RAS in 1866.

One of his early customers was Rev. Joseph Chadwick Bates of Blue Pits, who became an FRAS in 1863. Chadwick Bates was born in Oldham in 1826 and educated at Manchester Grammar School and Oxford and was ordained in 1850. From 1858 he was the curate in Castleton, then still a separate village outside Rochdale, and was responsible for the building of its impressive parish church by 1862, then becoming its vicar. He built meteorological and astronomical observatories at the vicarage[72].

During the 1850s Nicholas Martindale had an observatory at his residence, 'Holmfield', in Aigburth, Liverpool. In 1860 he purchased a telescope with a high-quality 8-inch object glass made by Alvan Clark from W. R. Dawes (see earlier) for £500. Martindale had been born into a Quaker family in Liverpool in 1822 and in the 1861 census is recorded as a manufacturer of "blacking and Congreve" (the latter being a type of matches) employing 100 men and 200 boys. He joined the RAS in 1862, but he removed his manufacturing to Tonbridge in Kent a year later and did little astronomy thereafter[73]. His 8-inch-telescope lens eventually found its way to Prague, then in Bohemia, and is still in use at Ondřejov Observatory in the Czech Republic[74].

John James Mellor joined the RAS in 1859. He was born in Oldham in 1830 and became chairman of two cotton-spinning enterprises, in Bury and Heywood, as well as having business interests in railway companies. He lived in Bamford near Rochdale in the 1850s and '60s, later moving to Whitefield, south of Bury. He was also an officer in the Volunteers, ending as Honorary Colonel 1st Volunteer Battalion Lancashire Fusiliers, and became MP for Radcliffe-cum-Farnworth in 1895[75]. He was an FRAS for nearly 60 years, but his obituary does not actually mention any astronomical work.

Taking us up to 1860 is Thomas Heelis who became the secretary of the Physical and Mathematics section of the Literary and Philosophical Society of Manchester in 1859 and joined the RAS the following year[76]. He reported on his observations of η Argus (now η Carinae) to the 'Lit and Phil' in 1864. Born in Manchester in 1835 and living in Pendleton, he was an attorney and solicitor, a partner in a long-standing family firm.

Murray Gladstone was also elected an FRAS in 1860. Born in Liverpool in 1816, he spent many years as a railway engineer in England, originally working under George Stephenson, and then as a merchant in the textile trade in Calcutta (now Kolkata). Returning to Lancashire, he went into business as an East India merchant in Manchester and constructed an observatory at his home in Broughton. He later had a country residence built at Penmaenmawr in North Wales where he erected a larger observatory "with all the latest astronomical appliances"[77]. He died in odd circumstances, being found drowned on the beach near his country house. He was the cousin of Prime Minister William Ewart Gladstone.

The half century

A variety of further Lancastrian astronomers appeared in the years up to the 50th anniversary of the RAS in 1870. A "Dr Nottingham, Liverpool" is reported as being elected a Fellow in 1861[78]. Born in Drax in Yorkshire in 1810, John Nottingham trained at Guy's Hospital and in Paris and became house surgeon in Liverpool Infirmary in 1837. He later became a Fellow of the Royal College of Surgeons. Around 1840 he set up in general practice, living in Everton, then a suburb of the city (with a household including a coachman and stable boy). A linguist and avid reader with a huge library, he eventually employed a live-in "polyglot reader" to manage his book collection[79].

William Jackson Rideout was also elected an FRAS in 1861, giving his address as Standish near Wigan[80]. Born in 1823 in Manchester, he was the nephew of the founder of a paper-making company, and managed Farnworth Paper Mill near Bolton, subsequently owning Standish Mill. His introduction to astronomy may well have come *via* this business, as his uncle, with whom he lived, was a close friend of Thomas De La Rue, the head of another paper-making empire and father of subsequent RAS president Warren De La Rue. Rideout later lived in Berkeley Square in London, and in the 1871 census described himself as "land owner, paper manufacturer, cotton spinner (mill not working at present) & employing about 500 hands".

Though not yet an FRAS, Ralph Copeland's first appearance in *MN* came in 1863 when Rev. Dawes reported on his observation of a lunar occultation, made from Manchester[81]. Remarkably, Copeland was born (in 1837) near the same small village, Woodplumpton, as Captain Foster (above). After an adventurous youth as a sheep farmer and gold prospector in Australia, Copeland worked at a locomotive-engineering company in Manchester. Having already made some observations in Australia, he and some other apprentices set up their own observatory in West Gorton. In 1865 he matriculated at the University of Göttingen and also worked at their observatory. After completing his PhD he joined a German Arctic Expedition exploring the east coast of Greenland. On his return, in 1871 he became an assistant at Lord Rosse's observatory at Birr Castle and was then at Dublin University Observatory, Dunsink, being elected an FRAS in 1874[82]. He next became senior assistant at the Dun Echt Observatory of Lord Lindsay (later the Earl of Crawford), making numerous observations of comets, and finally director of the re-founded ROE on Blackford Hill and Astronomer Royal for Scotland in 1889. Of his more than 100 papers, only 24 were in *MN*; the majority were notes in *Astronomische Nachrichten* or in newsletters, as he was "somewhat inclined to postpone the final completion and publication of his scientific work".

1864 saw the election of Rev. William Arthur Darby[83]. Originally from Ireland (born in 1811), he was the Rector of a church in Chorlton-upon-Medlock, near Manchester. His first appearance in the astronomical literature unfortunately appears to have been when the Rev. Dawes berated him in the *Astronomical Register*[84] for errors in his *The Astronomical Observer: A Hand-book to the Observatory and the Common Telescope*. Darby, who had a 9-inch refractor, supplied several contributions on double stars to the *Register*, but none to *MN*. He appears to have been an observing colleague of his Chorlton neighbour Alfred Brothers (below).

Alfred Brothers was born in Kent in 1826. He had various jobs before setting himself up in business as a "photographic artist" in Manchester in the 1850s and living in Chorlton-upon-Medlock. He was the photographer for Queen Victoria and Prince Albert's visit to the Manchester Exhibition in 1857. He applied his expertise to astronomy, and after joining the RAS in 1864 published in *MN*, *Nature*, and other journals until the end of the century, especially on eclipse photography[85]. He wrote the popular book *Photography: Its History, Processes, Apparatus and Materials* in 1892.

Eddowes Bowman of Victoria Park, Manchester, also became an FRAS in 1864. Born in 1810 in Nantwich, Cheshire, he had a rather odd background for an astronomer. He started as an engineer at an iron foundry, then managed coal and iron works in Wales, before deciding to study classical literature at Glasgow University. He became professor of Greek and Latin classics and Greek and Roman history at Manchester New College. However, when the college removed to London he changed tack again and took up natural sciences, giving lectures on many topics at the Royal Manchester Institution. He also acquired a 7¼-inch telescope and built an observatory at his home[86]. A Unitarian dissenter, he wrote numerous articles for the magazine *Christian Reformer*. His father John Eddowes Bowman the elder was an amateur botanist and geologist, while his brothers John Eddowes Bowman the younger and Sir William Bowman FRS were a professor of chemistry and a leading ophthalmologist, respectively.

Rev. Thomas Mackereth of Eccles was elected a Fellow of the RAS in 1865. He had been born "of humble parentage" near Kendall in Westmorland in 1825 and apprenticed to a plumber in Manchester, but decided instead to study for an elementary schoolmaster's certificate. He obtained a post in Salford and took up residence in nearby Eccles in 1860. There he constructed an observatory for his telescope and transit instrument, assisted by his friends Joseph Baxendell and Joseph Dancer (see above). In 1878 he became a pastor in Bolton but continued to observe regularly until retiring to his native county due to ill health. He was also a Fellow of the Royal Meteorological Society[87].

Thomas Glazebrook Rylands was born in Warrington (then in Lancashire, not Cheshire) in 1818, and with his brother took over the family wire-making business in the town. He was mayor of Warrington in 1858–59. Outside business his first interest was meteorology (cataloguing and drawing 43 types of snowflake) before becoming a noted amateur botanist and Fellow of the Linnean Society. In 1865 he built an observatory at his home, 'Heath House', and the following year became an FRAS. In 1871 he had an even larger property, 'Highfields House', built in nearby Thelwall, along with a new observatory on top of a tower. When he became too old to use it, he donated the telescope to the new Liverpool Astronomical Society[88]. He was also an antiquarian and bequeathed his library, containing numerous items from the 16th Century and earlier, to the still relatively new University of Liverpool.

Edward Brailsford Bright of Liverpool used the letters FRAS after his name on the title page of the 1867 edition of *The Electric Telegraph* which he co-authored, though the date of his election is not apparent in the reports of RAS meetings. An electrical engineer (born in London in 1831), he was secretary and general manager of the British and Irish Magnetic Telegraph Company in Liverpool from 1851 to 1868[89], and took out numerous patents in telegraphy with his brother (who worked in Manchester). During this time he was appointed to the Liverpool Observatory Committee, and the Magnetic Telegraph Co. laid cables to link the Observatory to clocks in the city to synchronize them to Greenwich Time. He also had interests in mining and was a director of the British Electric Light Co. from 1878. His brother, Sir Charles Tilston Bright, became engineer-in-chief to the Atlantic Telegraph Company. The latter was also an FRAS, elected 1860, as was his son, also Charles (1892), though this was after they had left Lancashire.

Richard Hooke of Higher Broughton, Manchester, joined the RAS in 1867. Born in Ireland in 1823, but later working in Manchester and living in Kersal Dale for many years, he was a well-known portrait painter[90], many of whose paintings of civic worthies are displayed in Manchester Town Hall. He was also a vice-president of the Manchester Literary Club, contributing numerous articles to the *Manchester Quarterly*, but his astronomical interests are unknown.

John Joynson of Waterloo, Liverpool, was also elected an FRAS in 1867, but an observation of his, of a transit of Mercury, had already been relayed to *MN* by Mr. Hartnup (above) back in 1861[91]. Joynson produced 17 contributions of his own to *MN* between 1865 and 1871, many of them on Mars or occultations[92]. He also submitted reports of observations to the *Astronomical Register*, one of them on the lunar crater Linné made "in company with Mr Williams", presumably the George Williams noted earlier. Joynson had a 6-inch Cooke refractor which was later donated to the University of London Mill Hill Observatory. Born in Liverpool in 1819, remarkably enough, he was baptised by the Rev. Wildig just before the latter became the first Lancastrian FRAS (see above). Joynson made his money as a cotton broker and later lived in nearby Crosby. His near neighbour Richard Coward Johnson of Blundellsands, a "coal proprietor", also contributed observations to the *Astronomical Register* in 1868 but did not join the RAS until 1876[93]. Similarly, Joseph Ridgeway Bridson, who ran the family bleachworks in Bolton, and was a noted photographer[94], subscribed to the *Register* from 1869 but only became an FRAS in 1873.

Charles Barton gave his address as HMS *Conway*, Rock Ferry, Liverpool, when elected an FRAS in 1869. Strictly, Rock Ferry is on the Birkenhead side of the Mersey, but he had previously lived with his uncle, a customs officer, in Liverpool itself. HMS *Conway* was a training-school vessel for the merchant marine and Barton taught mathematics to the cadets and lived on the ship. Born in Chatham in 1840 (or possibly born in Ireland and moving to Kent at a very early age), he had earlier taught navigation at the Royal Hospital School Greenwich[95]. In 1889 Barton proposed Captain A. T. Miller of the *Conway* as an RAS Fellow.

William Garnett of Bashall Lodge, Clitheroe, was elected an FRAS in 1870[96]. He also subscribed to the *Astronomical Register* from 1868. He attended at least one RAS meeting; in 1876 February, "Mr Garnett suggested that some of the earlier volumes of the Notices might be printed, so as to make full sets". Garnett was born at 'Low Moor House' near Clitheroe in 1825, his family owning the adjacent Low Moor cotton mill. (His brother James was a noted diarist, recording the events of the 'cotton famine' brought about by the American Civil War[97].) By 1881, back living in Low Moor, he had 683 employees and was later Lord of the Manor.

Just arriving in Manchester in time for our 1870 endpoint, Balfour Stewart had joined the RAS in 1867. Descended from prominent Scottish (or strictly, Orcadian) families, he was born in Leith in 1828 and studied physics at the University of Edinburgh before joining the university staff in 1856. He became director of Kew Observatory in 1859 where his "attention was principally given to the subject of cosmical physics", particularly the connection of solar and meteorological phenomena. He was elected an FRS in 1862 and won their Rumford Prize for his earlier work on radiant heat[98]. In 1870 he was appointed professor of physics at Owens College in Manchester, forerunner of the University (though he suffered a serious injury in a train crash shortly afterwards). His students included Arthur Schuster and J. J. Thomson. He wrote several textbooks, such as *Lessons in Elementary Physics*. He also produced more philosophical works including *The Unseen Universe*, and was a founder of the Society for Psychical Research.

Summary

Summing up, the largest numbers of our early Victorian Lancashire astronomers were in the clergy, the cotton business, education in various forms, the legal and financial professions, or manufacturing and engineering, with smaller numbers in medical or maritime-related occupations. (Some come into more than one of these categories.) Finally, we have three skilled artisans (clock and instrument makers), an architect, a photographer, an artist, and three professional astronomers (though it could be argued that the Stonyhurst Observatory directors also came into this category). Only Lassell, Dawes, Baxendell, and Nasmyth were grand amateurs in the sense of having large observing programmes and publishing major results from them, with Perry, Hartnup Snr., and Stewart (plus Copeland after leaving Lancashire) the others to regularly publish observations.

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REDISCUSSION OF ECLIPSING BINARIES. PAPER 5: THE TRIPLE SYSTEM V455 AURIGAE

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V455 Aur is a detached eclipsing binary containing two F-stars in a $3^{d}\cdot 15$ orbit with a small eccentricity. Its eclipses were discovered in data from the *Hipparcos* satellite and a spectroscopic orbit was obtained by Griffin[1,2]. Griffin found a long-term variation of the systemic velocity of the eclipsing system due to a third body in a highly eccentric orbit (e = 0·73) with a period of 4200 d. We have used these data, the light-curve of V455 Aur from the *TESS* satellite, and the *Gaia* EDR3 parallax to determine the physical properties of the components of the system to high precision. We find the eclipsing stars to have masses of $1{\cdot}289 \pm 0{\cdot}006\,M_{\odot}$ and $1{\cdot}232 \pm 0{\cdot}005\,M_{\odot}$, radii of $1{\cdot}389 \pm 0{\cdot}011\,R_{\odot}$ and $1{\cdot}318 \pm 0{\cdot}014\,R_{\odot}$, and effective temperatures of 6500 ± 200 K and 6400 ± 200 K. Light from the tertiary component is directly detected for the first time, in the form of a third light of $\ell_3 = 0{\cdot}028 \pm 0{\cdot}002$ in the solution of the *TESS* light-curve. From this ℓ_3, theoretical spectra, and empirical calibrations we estimate the star to have a mass of $0{\cdot}72 \pm 0{\cdot}05\,M_{\odot}$, a radius of $0{\cdot}74 \pm 0{\cdot}05\,R_{\odot}$, and a temperature of 4300 ± 300 K. The inclination of the outer orbit is 53° ± 3°, so the two orbits in the system are not coplanar. We show that a measured spectroscopic light ratio of the two eclipsing stars could lower the uncertainties in radius from 1% to 0·25%. A detailed spectroscopic analysis could also yield precise temperatures and chemical abundances of the system, thus making V455 Aur one of the most precisely measured eclipsing systems known.

Introduction

The study of detached eclipsing binaries (dEBs) is a mature area of research[3–7] that provides foundational measurements of the physical properties of normal stars against which our theoretical understanding can be compared, verified, and improved[8–12]. Many dEBs have long observational histories, stretching in some cases to over a century[13,14]. For these objects, and many others, the on-going NASA *Transiting Exoplanet Survey Satellite*[15] (*TESS*) mission is providing light-curves of previously unobtainable quality. Whilst the *TESS* data are relatively poor in comparison to the NASA *Kepler* satellite[16], they cover a much larger sky area and thus capture information on many more dEBs than *Kepler* did. *TESS* light-curves have been used to provide high-quality measurements of the radii of the components of dEBs[17,18], discover pulsations in well-known dEBs[19–23], obtain eclipse timings[24], study apsidal motion[25], discover multiply-eclipsing binaries[26,27], and investigate 'heartbeat stars'[28].

Within this context we have begun a project to utilise the *TESS* database of time-series photometry to revise and improve the measured physical properties of known dEBs[29–32]. The principal aim is to curate the *Detached Eclipsing Binary Catalogue*⋆ (*DEBCat*) of dEBs with masses and radii measured to precisions of 2% or better[33], by reanalysing existing systems or by adding new dEBs for which good radial-velocity (RV) curves already exist.

V455 Aurigae

In this work we present the first measurements of the masses and radii of the components of V455 Aur (Table I). This object was discovered to be eclipsing by using *Hipparcos* data[35] and given its variable-star designation shortly

TABLE I

Basic information on V455 Aur

Property	*Value*	*Reference*
Henry Draper designation	HD 45191	34
Hipparcos designation	HIP 30878	35
Tycho designation	TYC 3388-1017-1	36
Gaia EDR3 designation	992435451683384320	37
Gaia EDR3 parallax (mas)	12·874 ± 0·052	37
B magnitude	7·71 ± 0·01	36
V magnitude	7·28 ± 0·01	36
J magnitude	6·353 ± 0·019	38
H magnitude	6·132 ± 0·038	38
K_s magnitude	6·082 ± 0·024	38
Spectral type	F5V + F6V	This work

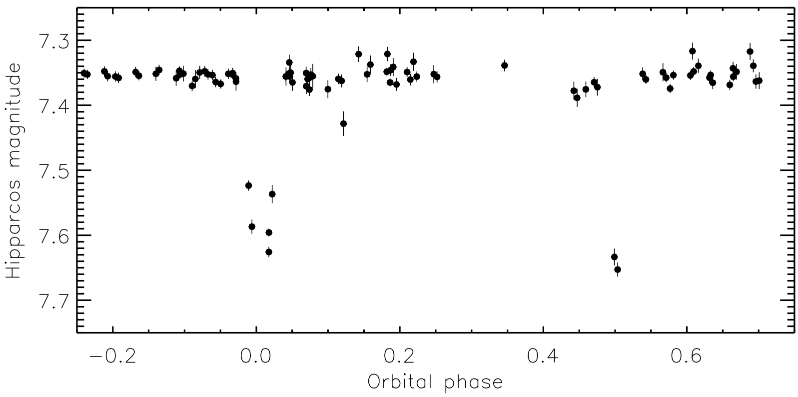

FIG. 1

The *Hipparcos* light-curve of V455 Aur plotted as a function of orbital phase using the ephemeris determined in the current work.

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

afterwards[39]. Fig. 1 shows a plot of the *Hipparcos* epoch photometry. Griffin[1] presented the first spectroscopic orbit of the system, based on photoelectric observations from the Cambridge *Coravel*. A total of 42 RVs were measured for each star. The relatively early spectral type for this instrument proved not to be a problem due to the brightness of the system, although the dips in the cross-correlation functions (CCFs) were only approximately 4% deep (his Fig. 4). The resulting spectroscopic orbits provided the first orbital-period determination for this system plus measurement of the minimum masses ($M_{A,B} \sin^3 i$ where i is the orbital inclination) to better than 1% precision. Griffin[1] noticed a change in the systemic velocity between the two observing seasons during which he obtained data, and surmised the presence of a third star on a wider orbit. He also suggested that the spectral type of F2 from the *Henry Draper Catalogue*[34] was too early, and that a type of approximately F6 V + F7 V better reflected the properties of the system.

Griffin[2] revisited the system with additional RV measurements in order to establish the properties of the outer orbit. From 123 RVs of each of the two eclipsing stars he obtained minimum masses to 0·5% precision and confirmed the small but significant orbital eccentricity of the inner orbit. The outer orbit was found to have a period of 4205 ± 17 d, an amplitude of 5·05 ± 0·20 km s^{-1}, and a high eccentricity of 0·726 ± 0·017. The CCF dips of the two stars have a ratio of 1·21 and this corresponds to a magnitude difference of 0·24 mag. in the V band; this is of course a measure of the relative strengths of the spectral lines of the two stars, not their continuum brightnesses. The mean projected rotational velocities were found to be 17·98 ± 0·17 km s^{-1} and 18·77 ± 0·29 km s^{-1}. Griffin[2] constrained the mass of the tertiary component to be more than 0·5$M_{\odot}$ based on the mass function of the outer orbit, but of spectral type K or later due to the absence of a signal in the CCF.

There are only two other studies that provide relevant information on V455 Aur. Casagrande *et al.*[40] obtained an effective temperature of $T_{\rm eff}$ = 6405 ± 80 K and a metallicity of [Fe/H] = –0·25 for the system using calibrations based on Strömgren photometry. Binarity was not accounted for in the determination of these values, so they should be treated with caution. The $T_{\rm eff}$ listed in the *TESS* Input Catalogue (TIC) version 8·0 (Stassun *et al.*[41]) is 6406 ± 142 K. One time of minimum light has been observed by the BAV[42].

Observational material

The data used in this work comprise a light-curve from camera 1 of the NASA *TESS* satellite[15], which observed V455 Aur in Sector 20 (2019/12/24 to 2020/01/21). The light-curve covers seven primary and eight secondary eclipses. These data were downloaded from the MAST archive* and converted to relative magnitude. We retained only those data points with the QUALITY flag equal to zero. The contamination ratio in the TIC v8·0 is 0·011 which indicates very little contaminating light in the *TESS* photometric aperture.

The *TESS* data were obtained in short-cadence mode, with a sampling rate of 120 s, and include 16412 data points (Fig. 2). They are available, as usual, in two flavours: simple aperture photometry (SAP) and pre-search data conditioning (PDC)[43]. As with previous papers in this series, we have chosen to adopt the SAP data for further analysis. This is because the eclipse shapes are indistinguishable between the two data sets but the PDC data contain jumps and slow undulations that have been introduced by the PDC correction process.

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

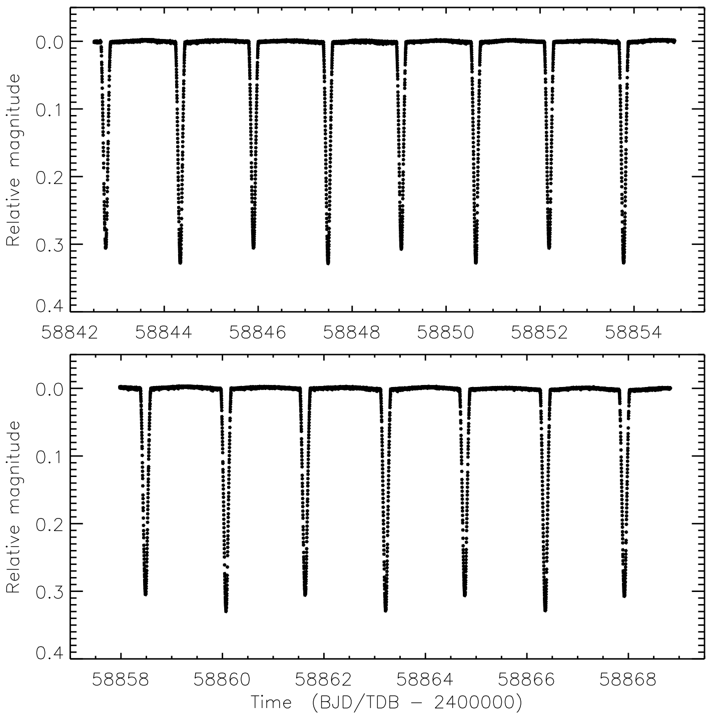

Fig. 2

TESS Sector 20 short-cadence photometry of V455 Aur. The two panels show the data before and after the mid-sector pause for download of the data to Earth[15].

Light-curve analysis

The components of V455 Aur are small compared to their separation so we adopted version 41 of the JKTEBOP* code[44,45] for our analysis of the *TESS* light-curve. JKTEBOP is fast and flexible, and agrees well with more sophisticated codes when the stars are well-detached[17]. We label the star eclipsed at the primary (deeper) eclipse as star A, and its companion as star B; in this case star A is hotter, larger and more massive than star B.

We modelled the *TESS* data and did not consider any additional information such as RVs or times of minimum light. This is because the system has a third body which modifies the observed RVs and times of eclipse of the system, and measuring this change is not a goal of the current work. We fitted for the orbital period and a reference time of primary mid-eclipse. We also fitted for

*http://www.astro.keele.ac.uk/jkt/codes/jktebop.html the fractional radii ($r_A = R_A/a$ and $r_B = R_B/a$ where R_A and R_B are the true radii of the stars, and a is the semimajor axis of the relative orbit), parameterized as their sum (r_A+r_B) and ratio ($k = r_A/r_B$), the orbital inclination, i, and the central surface brightness ratio, $\mathcal{J}$. As V455 Aur is a triple system we also fitted for the third light (ℓ_3) to account for the contribution of the fainter tertiary component; ℓ_3 is defined as the fractional amount of the total light from the system at phase 0·25 that is not contributed by the two eclipsing stars.

The limb darkening was accounted for using the quadratic law[46], for which we took coefficients from Claret[47]. We fixed the quadratic coefficient to the theoretical value but fitted for the linear coefficient, requiring the coefficients to be the same for both stars due to their similarity in $T_{\rm eff}$ and surface gravity. Fixing one of the two coefficients is acceptable as they are strongly correlated[48,49] so any imprecision in one coefficient is easily accounted for by a similar change in the other.

A small but highly significant orbital eccentricity, e, was found by Griffin[1,2] and we find that this is also required in order to get a good fit to the *TESS* data. We accounted for the eccentric orbit by fitting for the parameters $e \cos \omega$ and $e \sin \omega$, where ω is the argument of periastron. Finally, we applied polynomial fits to the overall brightness of the system to deal with any slow changes in brightness, likely of instrumental origin, during the *TESS* observations. We used two first-order polynomials, one for each half of the data (*i.e.*, the two panels in Fig. 2) and fitted the coefficients simultaneously with the other parameters in JKTEBOP.

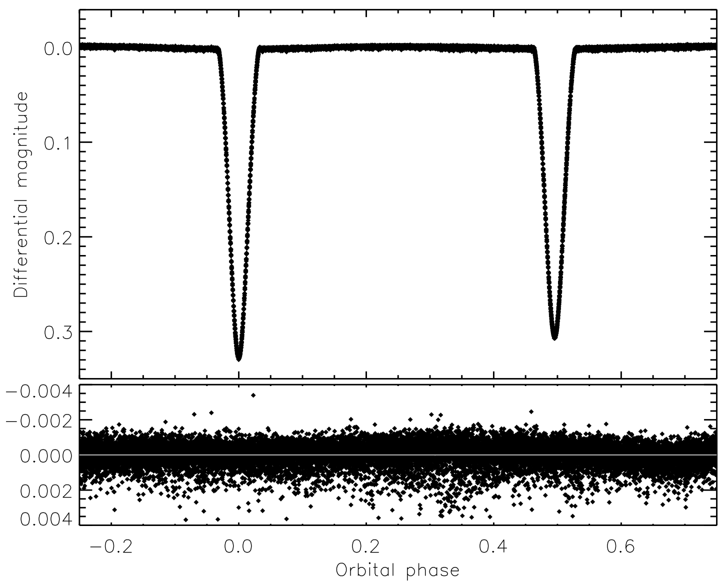

FIG. 3

The *TESS* light-curve of V455 Aur (filled circles) compared to the JKTEBOP fit (solid line, not visible in front of the data). The lower panels show the residuals of the fit with the line of zero residual over-plotted in white for clarity.

The best JKTEBOP fit to the *TESS* data is shown in Fig. 3 and is very good. The residuals have a hint of a non-Gaussian distribution to them — they scatter more to fainter than brighter magnitudes — an effect that we have often seen in *TESS* light-curves. The parameters of the fit are given in Table II. The secondary eclipse occurs at orbital phase 0·4967.

TABLE II

Parameters of the best JKTEBOP fit to the TESS light-curve of V455 Aur. The uncertainties are 1σ. The same limb-darkening coefficients were used for both stars.

Parameter	*Value*
Fitted parameters:	
Primary eclipse time (BJD/TDB)	2458853·778650 ± 0·000008
Orbital period (d)	3·145777 ± 0·000004
Orbital inclination (°)	84·997 ± 0·021
Sum of the fractional radii	0·22018 ± 0·00024
Ratio of the radii	0·949 ± 0·017
Central-surface-brightness ratio	0·9543 ± 0·0011
Third light	0·0282 ± 0·0022
Linear limb-darkening coefficient	0·221 ± 0·012
Quadratic limb-darkening coefficient	0·22 (fixed)
$e \cos \omega$	–0·006803 ± 0·000007
$e \sin \omega$	0·00712 ± 0·00037
Derived parameters:	
Fractional radius of star A	0·1130 ± 0·0009
Fractional radius of star B	0·1072 ± 0·0011
Orbital eccentricity	0·00985 ± 0·00027
Argument of periastron (°)	133·7 ± 1·5
Light ratio	0·859 ± 0·031

Determinacy of the photometric parameters

V455 Aur is a system where one might expect to find significant correlations between parameters, as it exhibits partial eclipses and third light. In addition, it has an eccentric orbit and $e \sin \omega$ is often correlated with the ratio of the radii and the orbital inclination. We therefore explored this in detail.

First, we determined the uncertainties in the photometric parameters using three approaches: the Monte Carlo and residual-permutation algorithms in JKTEBOP[50,51], and by fitting subsections of the light-curve in isolation. For the Monte Carlo and residual-permutation algorithms we calculated 10 000 individual solutions. For the fitting-subsections approach we broke the *TESS* data into five sets, each containing three consecutive eclipses, and modelled each in the same way as for the whole dataset. As a result, each fitted and derived parameter had three estimates of its uncertainty, and we simply adopted the largest of the three possibilities (see Table II). All three error estimates were reassuringly similar for all parameters (except the orbital period for obvious reasons), supporting the reliability of the error estimates. The fractional radii are the most important parameters from this analysis and the largest uncertainty estimate for them came from the fitting of subsections of the light-curve. They are determined to approximately 1% precision, which is a good result for a partially-eclipsing system with an eccentric orbit and third light.

We find an extremely good agreement with the results from the RV observations by Griffin[2] for those parameters in common. They comprise the orbital eccentricity (0·0099 ± 0·0012 from Griffin *versus* 0·0099 ± 0·0003 here), argument of periastron (132° ± 7° *versus* 133°·7 ± 1°·5), and the period ($3^{d}·1457741 \pm 0^{d}·0000012$ *versus* $3^{d}·145777 \pm 0^{d}·000004$). We also detect the third light to high significance, with a value approximately 13 times its uncertainty, which is the first detection of light from the tertiary component of the system.

To illustrate the situation further we have plotted the results from the Monte Carlo (left panels) and residual-permutation (right panels) algorithms in Fig. 4. An immediate conclusion is that the Monte Carlo algorithm appears to be better behaved, although this is illusory. The paths traced by various solutions in the residual-permutation panels are a result of correlated noise moving gradually

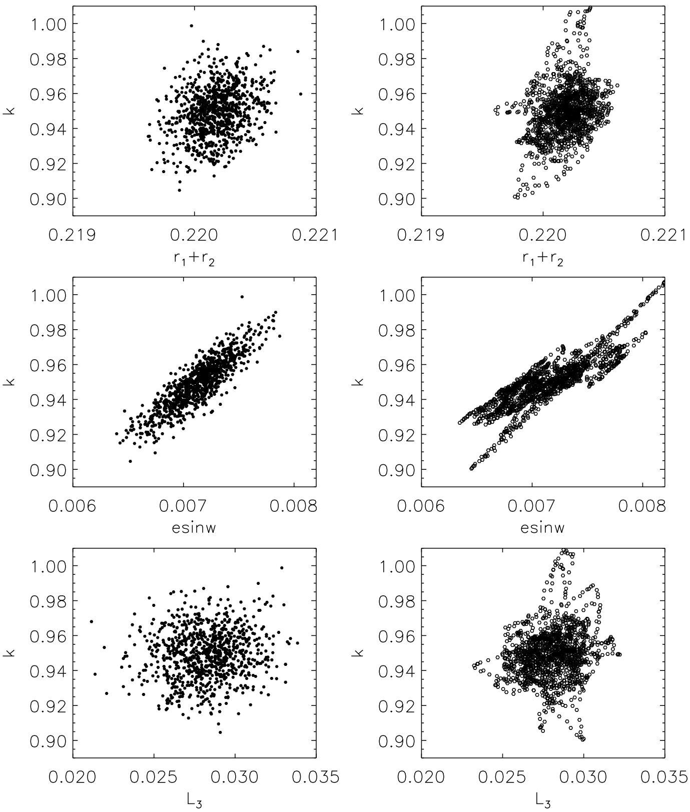

FIG. 4

Correlation plots for selected photometric parameters. The panels on the left show results from the Monte Carlo analysis, and on the right from the residual-permutation analysis. Each point corresponds to the best fit of one of the synthetic datasets generated during the error analyses. For clarity, only the first 1000 points are shown in each case.

through the light-curve, meaning successive residual-permutation solutions are closely related. This does not happen for the Monte Carlo solutions, leading to the smoother appearance of the correlation plots from that algorithm.

Fig. 4 also shows that the sum and ratio of the radii are almost uncorrelated (which is the reason why the fractional radii are parameterized as such in JKTEBOP), but there is a clear correlation between k and $e \sin \omega$. Third light is surprisingly not correlated with the ratio of the radii, but in the case of V455 Aur it is correlated with the orbital inclination and the sum of the fractional radii (not shown).

The primary indeterminacy in the solution is best seen with the ratio of the radii (Fig. 5), which is strongly correlated with the light ratio and thus the surface-brightness ratio. Because $r_A + r_B$ is known very precisely from the eclipse durations (its uncertainty in Table II is only 0·1%), k is correlated with r_B and anti-correlated with r_A. The net result is that the fractional radii of the stars are correlated with the light ratio, and thus a more precise measurement of r_B and r_A could be obtained if an external constraint on the light ratio of the system were available. We find that if a light ratio with an uncertainty of 5% were available, the precision of the measurements of r_B and r_A would be improved from 0·8% and 1·0%, respectively, to 0·25% for both. Such a constraint could be obtained spectroscopically[51,48], helped by the temperatures of the stars being

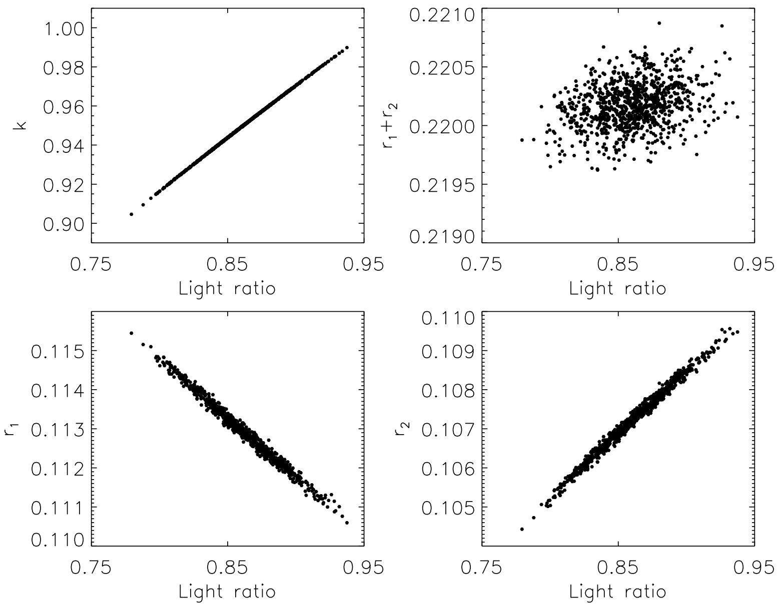

FIG. 5

Correlation plots for selected photometric parameters. Each point corresponds to the best fit of a synthetic dataset during the Monte Carlo analysis.

similar. Another possibility is an interferometric measurement, as achieved for the dEB V1022 Cas[52,31]. From the physical properties of the system and the *Gaia* EDR3 parallax we find that the angular separation of the stars is 0·735 ± 0·003 mas. This is within the limits of optical interferometers such as that operated by CHARA, but difficult and thus less likely to be achieved *versus* a spectroscopic measurement of the light ratio.

Properties of the third component

Griffin[2] observed the orbital motion of the tertiary star but not its light. He found that it had to be at least 0·5 $M_{\odot}$ in order to cause the observed orbital motion, but of spectral type K or later to remain undetectable in the cross-correlation functions. Now that we have a direct measurement of its light — from the third light of ℓ_3 = 0·028 ± 0·002 found in the JKTEBOP analysis — it is worth revisiting the topic. This amount of third light is small — especially considering the relatively red response function of *TESS* — so a low-mass third body is expected.

We began by estimating a mass for the tertiary component. The mass was used to predict the radius and $T_{\rm eff}$ of the third body using the empirical polynomial calibrations* presented in equations 2 and 3 of Southworth[53]. Its surface gravity was calculated from its mass and radius. We then interpolated the ATLAS9 synthetic spectra from Castelli *et al.*[54] to the $T_{\rm eff}$ and gravity values of the star.

The $T_{\rm eff}$ values of the eclipsing stars were initially taken to be 6340 K and 6240 K based on the spectral types advanced by Griffin[2] and the tables of Pecaut & Mamajek[55]. These values were subsequently revised to 6500 K and 6400 K in a second iteration. Synthetic ATLAS9 spectra were interpolated as for the third star, using their surface gravities from Table III. The three sets of synthetic fluxes were converted to relative light contributions using the radii of the three stars, and then passed through the response function of the *TESS* instrument[15]. The third-light value was calculated as the fraction of the combined light of the three stars that is emitted by the third star.

TABLE III

Physical properties of V455 Aur defined using the nominal solar units given by IAU 2015 Resolution B3 (Ref. 62).

Parameter	*Star A*	*Star B*
Mass ratio	0·9557 ± 0·0027	
Semi-major axis of relative orbit ($R^{\rm N}_{\odot}$)	12·295 ± 0·017	
Mass ($M^{\rm N}_{\odot}$)	1·2887 ± 0·0063	1·2316 ± 0·0050
Radius ($R^{\rm N}_{\odot}$)	1·389 ± 0·011	1·318 ± 0·014
Surface gravity (log[cgs])	4·2626 ± 0·0070	4·2887 ± 0·0089
Density ($\rho_{\odot}$)	0·480 ± 0·012	0·538 ± 0·017
Synchronous rotational velocity (km s^{-1})	22·38 ± 0·18	21·20 ± 0·22
Effective temperature (K)	6500 ± 200	6400 ± 200
Luminosity log($L/L^{\rm N}_{\odot}$)	0·492 ± 0·054	0·419 ± 0·055
$M_{\rm bol}$ (mag)	3·51 ± 0·13	3·69 ± 0·14

*In Southworth[53] calibrations of mass *versus* radius and mass *versus* $T_{\rm eff}$ were obtained from stars of masses 0·21 $M_{\odot}$ to 1·59 $M_{\odot}$. The first calibration was used but the second calibration was not; it was retained in that publication in case it became useful in future.

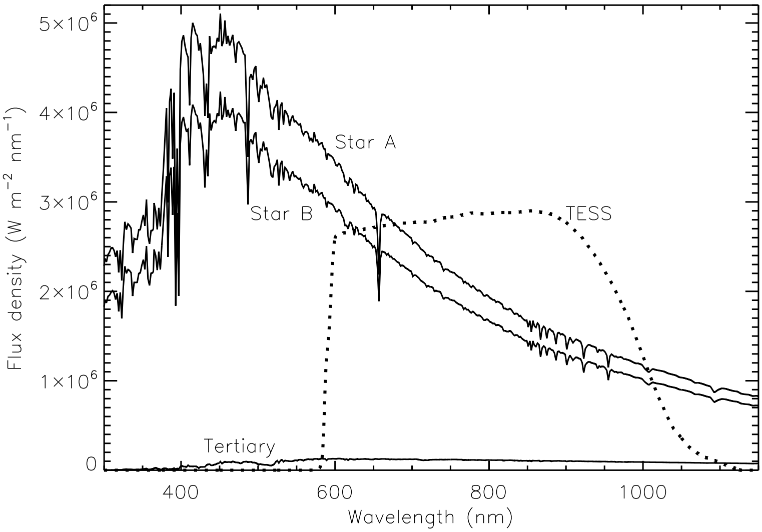

FIG. 6

The synthetic spectra of the two eclipsing components (labelled Star A and Star B) and of the third body (labelled Tertiary) from ATLAS9 model atmospheres and adjusted for the radii of the stars. The passband response function from *TESS* is also shown, using dotted lines, and has been arbitrarily scaled to half the full height of the plot.

We then adjusted the estimated mass of the tertiary component until the predicted amount of third light matched the ℓ_3 measured from the light-curve. In the following section we use the properties of the third star in the process of determining the $T_{\rm eff}$ values of the two eclipsing stars. Once this was completed, we re-ran the analysis above with the new $T_{\rm eff}$ values in order to arrive at consistent values for the properties of the tertiary component.

We found that the tertiary star has a mass of $0{\cdot}72 \pm 0{\cdot}05 M_\odot$, a radius of $0{\cdot}74 \pm 0{\cdot}05 R_\odot$ and a $T_{\rm eff}$ of 4300 ± 300 K, where the error bars include contributions from the third light and also the scatter in the empirical calibrations. The numbers quoted here are those obtained after the iteration to the final $T_{\rm eff}$ values of the two eclipsing stars (see below). A representative plot of the theoretical spectra and the *TESS* passband is shown in Fig. 6. With this mass the inclination of the third orbit is 53° ± 3° which implies this triple system is not coplanar.

Using Kepler's third law we find the semi-major axis of the outer (relative) orbit to be 7·6 AU and thus the maximum separation between the eclipsing and the tertiary components is $r_{\rm max} = a(1 + e) = 13{\cdot}0$ AU. At a distance of 78 pc (see below) this corresponds to an angular separation of $0''{\cdot}17$. This is resolvable using high-resolution imaging or integral-field spectroscopy of the type often wielded in the detection of close binaries and young planets[56–58]. Obtaining the spectrum of the third star, or its apparent magnitudes in multiple passbands, would provide additional constraints on its $T_{\rm eff}$ and thus mass. This will be easier at infrared wavelengths due to the brightness of the third component relative to stars A and B: we find that the value of ℓ_3 is only 0·015 in the *V*-band but increases to 0·082 in the K_s-band.

Physical properties of the eclipsing system

We used the JKTABSDIM code[59] to calculate the physical properties of the eclipsing system and its two components. As input to this we used the fractional radii, orbital period, inclination, and eccentricity from the photometric analysis above. To this we added the velocity amplitudes measured by Griffin[2], K_A = 96·27 ± 0·16 km s^{-1} and K_B = 100·73 ± 0·23 km s^{-1}, on the grounds that there was no clear reason to repeat his analysis rather than just adopt his results. We confirmed that the RVs were correctly attributed to the two stars, as it is possible that the photometric primary star (the star obscured at the deeper eclipse) is not the spectroscopic primary star (the star which is brighter or has stronger spectral lines); for examples see Paper IV of this series[32] and Themeßl *et al.*[60]. The masses and radii of the stars obtained in this way are measured to precisions of 0·5% and 1·0%, respectively, which can be attributed to the quality of the RVs from Griffin[2] and the light-curve from *TESS*.

The remaining quantities to be determined are the $T_{\rm eff}$ values of the three stars detectable in the light-curve. This can be done by matching the distance from the *Gaia* EDR3[37] parallax, 77·68 ± 0·31 pc, to that obtained from the radii, $T_{\rm eff}$ values, and bolometric corrections of the stars. For this we used the bolometric corrections in multiple passbands from Girardi *et al.*[62]. We accounted for interstellar reddening of the system by including an estimate of $E(B-V)$ = 0·002 ± 0·002 mag obtained using the STILISM* on-line tool (Lallement *et al.*[63,64]).

The *BV* and *JHK* apparent magnitudes of V455 Aur, given in Table I, include the light from all three components but we have the relative light contributions in only the *TESS* passband. We therefore used estimates of the $T_{\rm eff}$ values of the three components and propagated their relative light contributions in the *TESS* band to the other bands[65,66] using ATLAS9 synthetic spectra[54]. The $T_{\rm eff}$ ratio of the two eclipsing stars is tightly constrained by the surface-brightness ratio from the JKTEBOP analysis. This process was iterated once in order to ensure consistent properties for all three stars (see previous section). Additional iterations were not needed because the third body contributes only a small amount of light to the system. Once these relative light contributions were determined, we calculated the apparent magnitudes and distance of the eclipsing system. By requiring the distances to be consistent in different passbands and with that from the *Gaia* EDR3 parallax, we determined the $T_{\rm eff}$ values of the eclipsing stars by iterative manual adjustment.

We find the $T_{\rm eff}$ values of the two stars to be $T_{\rm eff,A}$ = 6500 ± 200 K and $T_{\rm eff,B}$ = 6400 ± 200 K. These correspond to spectral types of F5 V and F6 V, respectively[55], which is closer to the F6 V + F7 V favoured by Griffin[2] than the F2 in the *Henry Draper Catalogue*[34]. A detailed spectroscopic analysis to determine precise $T_{\rm eff}$ values and chemical abundances would be very beneficial in improving our understanding of this system[67,68].

*https://stilism.obspm.fr

Summary

The V455 Aur system comprises a double-lined spectroscopic binary with a lower-mass third star on a wider orbit. The inner binary was found to be eclipsing from its *Hipparcos* light-curve. Extensive RV measurements by Griffin[1,2] yielded precise measurements of the masses of the two eclipsing stars and the first determination of the period of the outer orbit. Prior to the current analysis, however, no photometric study of the system was available. In this work we have studied the high-quality light-curve of V455 Aur obtained by the *TESS* satellite, which covers seven orbital periods of the inner eclipsing system. We determined precise fractional radii for the two stars and also detected the light contribution of the third star to high confidence. Combining our photometric results with the spectroscopic quantities from Griffin[2], we have determined the masses and radii of the eclipsing stars to precisions of 0·5% and 1·0%, respectively. We have shown that the radius measurements could be further improved by obtaining a spectroscopic light ratio.

The T_{eff} values of the dEB were measured by forcing the distance to the system (determined from the stellar radii and T_{eff} values) to match that found from the *Gaia* EDR3 parallax. As part of this process we subtracted the contribution of the third star from the apparent magnitudes of the system in the *BV* and *JHK* bands, and accounted for interstellar extinction using reddening maps[63,64]. The mass, radius, and T_{eff} of the tertiary was obtained from empirical calibrations based on dEBs[53] adjusted to match its light contribution to the *TESS* light-curve. Its mass is significantly above the minimum mass from the outer spectroscopic orbit, suggesting that the two orbits are not coplanar.

We have made a brief comparison of the properties of V455 Aur AB to the predictions of the PARSEC theoretical stellar models[69]. We find that the masses, radii, and T_{eff} values are reasonably well matched for a fractional metal abundance of $Z = 0{\cdot}017 \pm 0{\cdot}003$ and an age of $1{\cdot}8 \pm 0{\cdot}2$ Gyr. The model predictions are slightly too shallow to match the observed mass–radius relation of the two stars, with an agreement at the level of roughly 2σ. This should be investigated in more detail in future, once further constraints have been placed on the physical properties of V455 Aur.

With these new results V455 Aur can be added to the *DEBCat* catalogue[33]. A detailed spectroscopic analysis of the system is advocated, in order to provide better T_{eff} measurements of the stars as well as a light ratio (helpful in measuring their radii) and photospheric chemical abundances (useful for a comparison with theoretical models). The complication caused by the presence of the third body means this is not a benchmark binary system, as the third light affects the photometric analysis, but the non-coplanarity of the two orbits is interesting from a dynamical viewpoint[70].

Acknowledgements

The current work presented a detailed analysis of an eclipsing binary system that was only made possible by the extensive and impressive RV dataset obtained by Roger Griffin. This work was begun shortly before Roger passed away at the age of 85. I wish to dedicate this paper to Roger, who provided an extraordinary example of what can be achieved *via* careful analysis of many objects as part of a long-term project. Whilst I never met Roger, I have had the privilege of several lengthy email exchanges with him as well as a brief tour of 'his' 36-inch telescope at Cambridge.

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REVIEWS

Vera Rubin: A Life, by Jacqueline Mitton & Simon Mitton (Harvard University Press), 2021. Pp. 309, 24 × 16 cm. Price £23·95/$29·95 (hardbound; ISBN 978 0 674 91919 8).

This has been a wonderful year for Vera Rubin (make that Vera Florence Cooper Rubin) watchers! First this charming, interesting, and mostly very accurate book, its cover bearing a photograph of the then Miss Cooper at the eyepiece of a Vassar College refractor in 1948. The very same image appears on page 7 of 'Technology Quarterly' on light in the 2021 January 19 issue of *The Economist*, in connection with the enormous detector array being constructed for the *Vera C. Rubin Observatory* (the name since 2020 January of what we had been used to calling the *Large Synoptic Survey Telescope*). On page 165 of the biography is Dr. Rubin "measuring photographic plates at DTM [the Department of Terrestrial Magnetism] in 1972." And that same photo is on page 21 of the 2021 February 13 issue of *Science News*, as part of a box called "An expanding picture" (which runs from Hubble in 1929 to the Bullet Cluster in 2006) within a feature on "Our Wild Universe". *Science News* has her measuring "rotation rates of stars", rather than rotation rates of galaxies, using emission lines from gas heated by stars. The Mittons got this right, though neither text points out that the measuring engine she was using was distinctly old-fashioned, even in 1972. She is looking into a microscope rather than at the screen of a Grant spectrocomparator, and I don't think it automatically punched the IBM cards with wavelengths and positions on the plate either. Well, the Grant machine I used in 1965–68 was modern for its time!

Let me get a few of the mistakes out of my system before turning to the 'Aha!'s, Wows, and all. Vera Rubin did not (page 225) "chair" the IAU Commission on Galaxies; she was President of it, 1982–85, the second woman to hold the position (yes, Margaret Burbidge was first (1970–73), and I was third (1994–97)). Palomar Observatory (page 116) was not part of the Carnegie Observatories; rather Mt. Wilson and Palomar together made up the Hale Observatories, Palomar having originally been a Caltech appendage. Dark matter was not (page 169) nameless in 1970. The English words had already been sanctified by use in the 1927 *Astronomy* (volume 2) by Russell, Dugan & Stewart in connection with the plane of the Milky Way. And you are now all shouting "*dunkle Materie*, Fritz Zwicky 1933". Yes, true, though also "*dunkle Materie*" in galaxies from Knut Lundmark in 1932. Antoinette de Vaucouleurs was not precisely (page 94) "her husband's life-long collaborator" since she pre-deceased him by about eight years, he remarried (Elysabeth Bardavid), and his work continued, with, for example, the *Third Reference Catalogue of Bright Galaxies* appearing in 1991.

Now for some things that are right in the present volume and not always elsewhere. Vera was absolutely a pioneer in opportunities for women astronomers. In particular, she was the first woman actually assigned time in her own right at Palomar, for fall 1965, by the then-new director Horace W. Babcock, who held the job 1964–78, in succession to Ira S. Bowen, director of the combined Mt. Wilson & Palomar Observatories (1948–64) who declined to assign observing time officially to women astronomers. I had always thought Vera had been the 200-inch observer on her first run in 1965 November, but in fact she used the 48-inch Schmidt to image the Galactic plane to look for intrinsically bright and faint OB stars. (I was assigned 48-inch time starting in 1966 November to image the Crab Nebula.)

Probably the most important 'choice' anyone makes is choice of parents. Vera's were excellent — Pesach Kobchefski (later Philip Cooper, but always called Pete) and Rose Appelbaum Cooper. He had a degree in electrical engineering from the University of Pennsylvania, and she had attended South Philadelphia High School for Girls, before going to work for the Telephone company (Bell in those days and places). They valued education and interest in numbers for both daughters, Vera's sister Ruth being the elder, though only a couple of years so, and provided enormous assistance to Vera and her husband while they were raising their four children.

Yes, the second most important choice in life, at least for most women (and women astronomers; yes, I was lucky here, too) is choice of spouse. Believe it or not, Vera Cooper and Robert Rubin were introduced by their mothers! They married in 1948 June, soon after her 1948 May graduation from Vassar. Bob pre-deceased Vera, dying of multiple myeloma in 2008. Yes, the committee that awarded her the Gruber Cosmology Prize in 2002 knew of his illness, and wanted her to have the prize — which she would surely have won in due course anyway — while they could both still enjoy it. Physicist Robert was an absolutely equal partner in raising their four children, daughter Judith Cooper Young sadly also pre-deceasing her mother in 2014 (but she and her significant other had been there in the gardens of 813 Santa Barbara Street to help Vera celebrate the Gruber). The three Rubin sons are still very much with us, mathematician Karl a colleague here in the University of California Irvine.

Is having an early female mentor important in the development of a woman astronomer? Well, maybe. Remarkably, Vera and I had the same one about 15 years apart, she at Vassar, I at the University of California Los Angeles: Maud Worcester Makemson (1891–1977), whose life was another remarkable story, but not to be told here. She taught 'practical astronomy' at UCLA, the first course astronomy–mathematics majors were expected to take.

We come now, skipping over many fascinating aspects of Vera's life (buy the book; read the book), to the questions most folk ask. Did Rubin discover dark matter? Was she ever nominated for the Nobel Prize for this? Was she ever actively considered for the Prize? The answers, properly, are 'no', 'yes', and 'yes', but we need some details. The Mittons make clear that Vera first started looking at rotation of (mostly) spiral galaxies in the hopes of understanding the physics of galaxies, the range in their forms, sizes, colours, and all the rest. This led to flat rotation curves and the eventual conclusion that, as you move out from the centres of most galaxies, the ratio of dark to luminous material gradually increases. The Mittons quote science writer Dennis Overbye (*New York Times* obituary) quoting J. P. Ostriker, that "Vera's work ... clinched the case for dark matter for most astronomers." (Some of us had been clinched somewhat earlier by papers coming in 1974 from Ostriker, Peebles, and Yahil, and from Einasto, Kaasik, and Saar.) And there was contemporaneous work on radio (H I) rotation curves, velocity dispersions in clusters of galaxies, and the development of large-scale structure in the Universe.

Now about that prize. The Mittons say that no one can know until the records of nominations and deliberations are unlocked in 50 or 60 years after the event. But, of course, some folks have known all along. No, I did not nominate Vera for a Nobel, but I was asked at one point in time, by those folk in Stockholm, to evaluate two nominations of her "for the discovery of dark matter", and even paid for my report. So, yes, she was nominated, and yes she was taken somewhat seriously as a candidate. But truthfully, the nominations did not give adequate credit to precursor and contemporary work on the subject nor, indeed, to Robert Rubin's enormous contributions to their family life which made her intense involvement in astronomy possible. He was, through most of his career, basically a physicist (some of whom at least make good husbands for women astronomers). What did I write? You can guess: Zwicky & Sinclair Smith; Babcock on the rotation curve of M 31; and Holmberg on binary galaxies (I did not then know about the 1932 Lundmark paper).

Back to the Mitton book and a few more interesting tidbits. Vera seems never to have thrown away a letter she received, a copy of one she wrote, or observing records. The material is all in the Library of Congress, Jacqueline and Simon had access to it all, and found many interesting things that most of us hadn't realized. She did her PhD at Georgetown University, the only one in the Washington DC area that had an astronomy programme — she knew already that physics was not her destiny! She completed it actually working with George Gamow at George Washington University (easy to confuse the two) but under the official supervision of Dr. Father Francis J. Heyden, SJ, who aspired to develop a large graduate programme there. This eventually failed. Vera remained at Georgetown for a number of years, overburdened with assorted teaching and administrative tasks, before finally fleeing to DTM quite near the Rubins' Chevy Chase DC home. The Georgetown astronomy department eventually closed, and their books and journals ended up in the astronomy library at the University of Maryland, where I found early issues of *Astronomische Nachrichten* and IAU assorted proceedings very useful.

Among other close friends revealed by the archived letters were Allan Sandage, who urged her to apply for observing time at Palomar, and Dr. Father

Martin F. McCarthy, SJ, himself a Georgetown graduate, who was back there in 1962–63 and shared observing techniques and other astronomical wisdom with the younger Dr. Rubin. Their friendship, both professional and personal, remained close for decades, and McCarthy was often a guest in the Rubins' home. George Coyne, SJ, is also a part of this story, though not as central: Vera and Martin McCarthy were the joint examiners of his Georgetown PhD dissertation on the spectrum of moonlight. I knew first-hand that Father McCarthy and Father Coyne had great gifts of friendship, which extended to include female colleagues. Indeed this is so of every Jesuit astronomer I've encountered, including a younger one who is my 'go to' person for questions like, can communion be validly received if the officiant and the communicant are not physically in the same space at the same time (probably not, though there are relevant things that can be done in the home). Such questions would not have interested Vera Rubin, who recognized that religion is an important part of life, but not so much of her life. She and Bob sometimes attended a reform synagogue, Temple Sinai, in Washington DC, but were not observant and did not insist on a Jewish education for their children.

Quite a few other women astronomers move through these pages, most notably perhaps Sandra Moore Faber, who worked with and published with Vera (as Sandra Moore) at DTM in the summer of 1966 before starting graduate school at Harvard. Faber spent much of the last two years of her graduate career again at DTM under Vera's wing, before going on to the University of California Santa Cruz, and a truly spectacular career. Yes, VT is there too, not in a terribly flattering light, and I will say only, in partial exoneration, that the paper concerned was the very first (of a long series it later turned out), for which I had really expected only one reader, who was indeed male. I owed Vera Rubin many other favours, of which the two purely professional were (*i*) appointment to head a revived Supernova Working Group (under Commission 28) in 1982 which led in due course to Presidency of that Commission and of two different IAU Divisions, and (*ii*) nomination for the J. Murray Luck Prize in Scientific Reviewing of the US National Academy of Sciences (which gave me a chance to meet Lynn Margulis, and the NAS President Frank Press the chance to insult me in public).

This has been a small, very personal selection from among the gems to be found in the Mittons' biography of Vera Rubin. Buy it (a smidge less than 10¢ a page); read it; and please let me know what you think are the highlights! — VIRGINIA TRIMBLE.

Zwicky: The Outcast Genius Who Unmasked the Universe, by John Johnson Jr. (Harvard University Press), 2019*. Pp. 352, 24 × 16 cm. Price £28·95/$35 (hardbound; ISBN 978 0 674 97967 3).

A work colleague many years ago told me that a boffin was a "Brainy Old Fellow Full of Ingenious Notions" (I think he maybe had an alternative version of 'Fellow'); I suppose a modern equivalent is someone who 'thinks outside the box'. Well, if one were looking for the perfect example of such a person,

*Having been published toward the end of 2019, it might have been expected that an earlier review would have been forthcoming. I have to relate that the original copy of the book was sent to Leonard Matula — a regular reviewer in these pages in recent years — who had a strong interest in Zwicky and his works. Tragically, Leonard passed away on 2021 January 9, a victim of Covid-19.

none would be better than Fritz Zwicky. This remarkable character, born in 1898 in Bulgaria of Swiss parents, was perhaps the most significant gadfly to inspire, annoy, challenge, and provoke astronomy in the 20th Century. I first came across the name in my final undergraduate years at St. Andrews (where, it turns out, one of Zwicky's daughters also studied) when I undertook a project on supernovae. So far as I recall, there were then five classes of such brilliant objects, and Zwicky seemed to be discovering most of them.

However, his career didn't start there. His early life was spent in Switzerland where he excelled at school (and also became a passionate mountaineer), before enrolling at the famous ETH (Swiss Federal Institute of Technology), where Einstein had once taught. Meanwhile the First World War raged around neutral Switzerland and Zurich became a hotbed of intrigue and political ferment; Lenin & Trotsky lived there but clearly had no influence on Zwicky who developed an anti-communist stance.

In 1925 Zwicky was recruited to a two-year fellowship at Caltech, swayed more by the prospect of mountains than by astronomy. However, he also liked the ambience in Pasadena and under Millikan's tutelage he stayed on, eventually getting sucked into the exciting beginnings of cosmology, as we now understand it, developing on Mt. Wilson. This brings us to that long turbulent era, when Zwicky rose to prominence with pronouncements on a number of hot topics: the expansion of the Universe, dark matter, neutron stars, gravitational lensing, faint blue stars and quasars; and then managed to fall out with a number of leading astronomers over matters of priority, the correctness of ideas, and personality. John Johnson covers all of this with what seems to me a fair balance.

But non-astronomical matters are also treated in depth. During the Second World War, Zwicky played a major role in the development of rockets for the American military, which led to him being included in the mission to 'rescue' a number of experts from Germany at the end of hostilities — including, of course, Wernher von Braun — and the growth of the Aerojet company, later a major force in the US's missile programme. While you might think that that, together with his anti-communist sympathies, would have made for an easy ride through the McCarthy era, his refusal to abandon his Swiss citizenship caused problems, including eventually the loss of his position at Aerojet.

It's clear that Zwicky was certainly opinionated, stubborn, and not always easy to deal with. But on the domestic and personal level, he shines through as a more reasonable character — a good husband, father, and socially responsible citizen of the world. I ended my read through Johnson's book glad that, from time to time, such mavericks come along to create a bit of intellectual chaos. — David Stickland.

Pioneer of Galactic Astronomy: A Biography of Jacobus C. Kapteyn, by Pieter C. van der Kruit (Springer), 2021. Pp. 305, 24 × 16 cm. Price £27·99/$39·99 (paperback; ISBN 978 3 030 55422 4).

This follows on from a biography of Kapteyn by the same author in 2015, entitled *Jacobus Cornelius Kapteyn: Investigator of the Heavens* and reviewed in these pages by my late, lamented friend and colleague Derek Jones[1]. The question might be asked — was it worth devoting two volumes to the subject? The answer has to be yes and with the centenary of Kapteyn's death coming up next year this is as good a time as any to do it. Van der Kruit is in an excellent position to tackle this project. As a professional astronomer and teacher at Groningen, where Kapteyn spent so much time, he has had access to the considerable archives that exist, and he is also Dutch and therefore able to access the primary sources in the language in which they were written. He also co-authored the proceedings of a symposium on Kapteyn which was held in Groningen in 1999[2], and was a student of J. H. Oort, about whom he has also written[3].

Surprisingly, there had been no serious attempt to write a comprehensive biography of Kapteyn even though several people (including Willem de Sitter) had planned to carry out such a project. In 1928, Kapteyn's daughter published a biography but van der Kruit points out that this is naturally inclined towards the family aspects of life with her father.

When he was 14, Kapteyn was given a star chart by his older sister and this inspired him to construct his own star chart which still exists but is poorly reproduced in the book. This interest in astronomy led to his father getting him 'a big telescope'. Kapteyn passed the entrance exam for the University of Utrecht when he was 16 but did not enter the University until a year later. He went on to study the physics of vibrating membranes as a PhD topic, but in his defence of his thesis he also had to discuss a series of 18 propositions, six of which were astronomical in nature including one about the average of proper motions of stars of different apparent brightnesses. Kapteyn graduated in 1875 at which time only 20% of published astronomical research involved the sidereal universe and this was largely star cataloguing.

With his mathematics degree Kapteyn applied for and obtained the post of *observator* (observer) at Leiden Observatory where he began to use the meridian circle for measurement of stellar positions. In 1877 Groningen created a chair of astronomy to which Kapteyn was appointed in 1878 and gave his inaugural address on 'The annual parallaxes of the fixed stars'. He was to remain on the staff of Groningen for the remainder of his life.

Kapteyn started on his great investigation of the spatial distribution of stars in the early 1880s and involved himself with the meridian circle at Leiden to measure some stellar parallaxes. This was no mean feat as it involved timing the passages of stars across a wire to an accuracy of a few hundredths of a second of time. This work was followed by a collaborative project with David Gill to measure plates from the Cape Photographic Durchmusterung project which occupied him for six years, and later by the Carte du Ciel project, an extension to the whole sky and reaching fainter magnitudes than the CPD.

Kapteyn also directed a number of students, including Willem de Sitter whose PhD thesis concerned the satellites of Jupiter but who is now remembered for his work on relativity and cosmology, and Jan Hendrik Oort who made significant contributions to our understanding of the Milky Way and was a pioneer of radio astronomy, although Oort actually completed his thesis under Pieter van Rhijn.

Kapteyn realized that the minute size of stellar parallaxes meant that he would need to use statistical methods to estimate the distances of the stars. This led to the concept of star streams which he announced in St. Louis in 1904, and later to the idea of selected areas in which Kapteyn suggested that 206 small areas of sky, evenly distributed on the sky, would be used to conduct a stellar census. This drew a lot of support, especially from the United States in particular, and led to an enduring relationship between Kapteyn and George Ellery Hale. It resulted in a number of annual visits by the Kapteyns to Mount Wilson in the years before the First World War.

Towards the end of his life Kapteyn worked on the relation of the gravitational attraction of the stars on each other and their velocities, a topic which he called mechanics. In 1915 September he wrote to Hale and said "Even more important than the central position of the Sun seems to be that our result for the first time shows the existence of a force in the great Sidereal System. A rough computation leads to the conclusion that at a distance corresponding with a parallax of 0″·2 the stars are under the action of a force equal to the attraction of a central mass having 5 million times the Sun's mass".

Van der Kruit writes compellingly about the life and work of Kapteyn and intersperses within the text some charming episodes from his personal life. — ROBERT W. ARGYLE.

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Chinese Astrology and Astronomy: An Outside History, by Xiaoyuan Jiang, translated by Wenan Chen (World Scientific), 2021. Pp. 312, 23·5 × 16 cm. Price £115 (hardbound; ISBN 978 981 122 345 7).

In the historical pre-20th-Century quest to understand the celestial universe it is quite clear that Europe dominated. In a list of ancient astronomers, for example Hipparchus, Ptolemy, Copernicus, Tycho Brahe, Kepler, Galileo, and Newton, there is a notable absence of other cultures, including Chinese names. Were the Chinese too busy doing other, seemingly more important, things? Did their concentration on astrology fetter them to be merely interested in the prediction of solar, lunar, and planetary movement over the future few decades, the typical lifetimes of the interested parties? Maybe their insistence that celestial matters be strictly restricted to court astronomers did not help. There was also the lack of competition. The Chinese had a strong self-belief and self-interest and seemed disinterested in what other nations were up to.

Jiang Xiaoyuan is the Dean of the Department of the History of Science and Philosophy at Shanghai Jianotong University, and a well-known expert on ancient Chinese astrology and astronomy texts. We are treated to a detailed review of the literature and an overview of the slow progress that Jesuit missionaries made, starting at the beginning of the 17th Century, to influence Chinese thought. Emperors like Kangxi were very interested in astronomy, but also very reluctant to allow that interest to be passed on to others. In pre-Ming times it was a felony for the general public to interpret heavenly events. The Chinese seemed also to be very reluctant to accept the fact that the Earth was spherical, and also much smaller than the Universe. The operational mechanisms of the Universe seemed to be of very little concern.

Observing the sky was important, as was the recording of comets and novae and the prediction of eclipses. The official observers had high status. Much time was devoted to interpreting what was seen, in order to predict such things as floods, droughts, good harvests, and famines. There was also a strong political and militarist aspect. The success or failure of military campaigns were thought to be influenced by the celestial situation. Unfortunately for the astronomers, obvious predictive inaccuracies could lead to the death penalty.

This is a rather strange book, clumsily translated and lacking in relevant illustrations. It assumes that the reader has a considerable background in Chinese history. What was written about astronomical sightings and interpretations is well recorded, and the source of Chinese astrology is investigated, but the reader gets far too little insight into why the Chinese seemed to ignore the physics and mathematics behind it all. There is no mention of telescopes. It seems that even when the Chinese learnt about the existence of astronomical telescopes they showed little interest in what they might reveal. We are also left wondering why the Chinese found astrology so important, and maintained their interest long after other civilizations relegated the subject to its rightful insignificance. — DAVID W. HUGHES.

Neutron Stars: The Quest to Understand the Zombies of the Cosmos, by Katia Moskvitch (Harvard University Press), 2020. Pp. 296, 22 × 15 cm. Price £23·95 (hardbound; ISBN 978 0 674 91935 8).

This book is probably not the best available layman's guide to neutron stars, what they are and how they work, but it contains a lot of information of interest to anyone eager to learn about current astronomical activity and the people who are involved in it, and its particular target is the developing study of neutron stars.

The author is a science journalist and writes in an informal style, as is indicated *ab initio* by the subtitle 'The quest to understand the Zombies of the Cosmos'. She has visited many of the astronomical observation sites around the world and has met and talked with many of the professional astronomers who work there and/or are prominent in current neutron-star research, and she provides the reader with much interesting information about the localities and equipment involved and about the lives and background of the people concerned.

For those who are eager to learn about the stars themselves, this approach is initially disconcerting, because facts about them are interposed between the copious amount of personal-lifestyle and topographical information provided. The text certainly contains a lot of information about our current general awareness of cosmological concepts, although it is not set out as clearly as perhaps it might have been. Degenerate stars are not mentioned as such, and the basics of the situation as presently understood do not leap out of the text. In other words, the battle between the space required by atoms and the desire of gravity to destroy it, and the success of the latter in its creation of white dwarfs, neutron stars, and black holes (though the black-hole situation could be regarded as something of a Pyrrhic victory) could have been put before the reader more succinctly. Electrons, protons, and neutrons are of course mentioned, but the most fascinating aspect of neutron stars, their mass–size ratio, only becomes clear when the reader is well into the book (page 71 for mass and page 153 for radius).

The development of our knowledge of atomic physics is recounted in the book, with reference to famous names such as Eddington, Chandrasekhar, and Zwicky; Einstein, relativity, gravity being a manifestation of the distortion of spacetime by matter, the particular involvement of quantum principles in neutron stars, and fast radio bursts are all mentioned, so readers are getting a lot of information for their money. The prime value of the book, however, seems to me to be the vivid and interesting descriptions of modern multi-messenger observatories, and its insight into the personalities of leading players in current astronomy.

The book contains 15 colour plates, mainly of important modern observatories, together with illustrations of some key astronomical personnel, and an intriguing if rather speculative diagram of a neutron star. It also contains a great number (more than I have encountered in any other book) of acronyms, but these are, I suppose, inevitable in a profession where special structures and new phenomena need to be rapidly referenced. A certain inconsistency is shown here, as, for example, by *LIGO* (*Laser Interferometer Gravitational-Wave Observatory*) and *Virgo* (named after the Virgo Cluster), both of which identify gravitational-wave observatories; but the book has a good index of such terms to aid the reader. A clearer distinction between the different kinds of detectors required for electromagnetic radiation, for gravitational waves, and for neutrinos, and their locations at ground level or in space or below ground would be of help to the lay reader, and I should have liked the author to have included a neutrino detector in her admittedly extensive — at least ten sites around the world — visiting list.

Throughout the book there is a noticeable dichotomy between the factual certainty of the text relating to people and observatories and the more diffuse text containing neutron-star explanatory material, but the author cannot be blamed for the current complexities of cosmology, and her determination to make the subject interesting and exciting excuses the odd reference to voodoo and well reflects her own enthusiasm for the subject and her wish to pass it on to her readers. — Colin Cooke.

Cosmic Pinwheels: Spiral Galaxies and the Universe, by Ronald James Buta (World Scientific), 2021. Pp. 469, 23·5 × 16 cm. Price £95 (hardbound; ISBN 978 981 121 668 8).

According to the preface, the author "would like to take the reader into the fascinating world of spiral galaxies". This is a laudable aim, of course, but who is "the reader" supposed to be? The book itself is an eclectic, even idiosyncratic, take on the subject, well written and beautifully illustrated, as one would expect from the author. It is part astrophysics textbook, part illustrated galaxy atlas, part history of science, part personal memoir, and perhaps also part homage to the author's mentor Gérard de Vaucouleurs.

As a textbook, the absence of mathematical content (inasmuch as there are no equations) would probably rule it out as a university text on this side of the Atlantic, if not on the other. It is also quite a long read at nearly 470 pages. It is strongly biassed towards the author's speciality of galaxy morphology, and particularly to bars and rings. To be fair, these are often given fairly short shrift in other textbooks, so this is a useful source of detail on such topics from an expert. In addition, references to original technical papers are given throughout which makes the book a handy introduction to the literature (which students may well find useful). Spiral arms are also extensively discussed, but nuclei, for instance, are covered in just 13 pages.

The subject history is somewhat affected by a (presumably unconscious) US-centric viewpoint. For instance, neither the pre-Hubble contribution of Sweden's Knut Lundmark to the velocity–distance relation, nor his detailed discussion of the existence of brighter "upper-class" novae (aka supernovae), are mentioned. Estonian Ernst Öpik's famous determination of the distance to M31 by dynamical means is likewise absent. Similarly, in more modern times, the work by Dutch radio astronomers, particularly Albert Bosma and Piet van der Kruit, on H I rotation curves, carried out at the same time as US work on optical rotation curves in the late 1970s, does not rate a mention. On the other hand, there is such a thing as too much detail. Apart from a professional historian of science, it is not clear who needs to know the average number of nights in a given month that Lord Rosse's assistants were able to observe with the Leviathan.

Personally, I enjoyed the "ah yes, I remember having to do that" moments in the author's reminiscences on observing techniques of years ago (I actually met de Vaucouleurs in Edinburgh in 1976, but that's another story), but again, does anyone who is not a somewhat-elderly fellow professional astronomer really want to read about this?

The text is almost free of typos (I noticed just two). One Americanism caught my eye, though: I don't think you will reach the site of Herschel's former observatory if you ask for directions to "Sloo", the pronunciation suggested by the author.

In summary, many people may find something interesting in the book, but probably rather few will find all of it interesting. The size and price of £95 then become rather an issue, though I notice that Amazon will sell you a version for your Kindle for only £38·36. — Steve Phillipps.

Molecular Astrophysics, by A. G. G. M. Tielens (Cambridge University Press), 2021. Pp. 654, 25 × 17·5 cm. Price £69·99/$89·99 (hardbound; ISBN 978 1 107 16928 9).

As Professor Tielens points out in the introduction to this massive book, "we live in a molecular Universe: ... a Universe where molecules are abundant and widespread; a Universe where molecules play a central role in key processes that dominate the structure and evolution of galaxies ...". He also notes that "our progress in understanding the molecular Universe is greatly aided by close collaborations between astronomers, molecular physicists, astrochemists, spectroscopists, and physical chemists ...". It is these collaborations that bring not only great pleasure to those working in this field at what can be achieved, but also a responsibility to understand at a reasonably high level the challenging range of subjects that necessarily arise in these collaborations. This large, comprehensive, and up-to-date volume will meet the needs of most researchers in molecular astrophysics to have to hand a reliable, wide-ranging, and accurate overview. Professor Tielens is a well-known researcher who has been active in molecular astrophysics for many years, and this volume is based on his years of experience in teaching at summer schools,

About half of the book deals with essential but fairly standard knowledge, including spectroscopy, thermodynamics, and chemical processes in the gas phase and on surfaces. This foundation is exploited in the second half of the book with applications to the study of diffuse and molecular clouds, star-forming regions, and what Tielens calls the "aromatic Universe". In the chapter on diffuse clouds there is a useful summary of the present work on the so-called Diffuse Interstellar Bands. This is a problem that has been requiring a spectroscopic solution for many years. The chapter on star formation is particularly comprehensive, telling the whole dynamical story from pre-stellar cores to masers. The final chapter discusses aromatic molecules as found in the interstellar medium, including large PAHs (polycyclic aromatic hydrocarbons) and cage molecules such as C_{60}. This is an area in which Tielens has been particularly active, and this final chapter is a valuable review for all researchers working in this area.

The book is well supplied with tables and diagrams in black and white, not always legible; however, all the figures are reproduced as colour plates, all located together in the middle of the book. I didn't find this practice very convenient. Each chapter is provided with further reading, exercises, and bibliography. I am confident that this book will become an essential standard reference book for researchers in molecular astrophysics. It seems good value at present prices. I recommend it to all molecular astrophysicists. — David A. Williams.

Physics and Evolution of Supernova Remnants, by Jacco Vink (Springer), 2020. Pp. 521, 24 × 16 cm. Price £109·99/$149·99 (hardbound; ISBN 978 3 030 55229 9).

Author Jacco Vink of Amsterdam has written the book he says he wishes had existed when he began graduate work on supernova remnants in 1995. A book from that era could not, of course, have contained a large fraction of the information now available, if only because Vink's first-author papers make up 22 of the references cited (out of 1284, ranging from A. Aab *et al.* to V. N. Zirakashvili *et al.* (from which you may deduce that Fritz Zwicky appears only as Walter Baade's junior author from 1934)). There are many good things to be said about the book, but unfortunately also some not so good. The summary chapter lists 16 take-away points that the author regards as well-established. An important one is that it is now possible to distinguish remnants of thermonuclear SNe Ia from those of core-collapse SNe, for young remnants. Chemical composition from X-ray data is an important discriminant. The developing remnant of SN 1987 A gets a detailed treatment, though unfortunately it is a very atypical core-collapse SN II, whose remnant core has yet to reveal itself. The data shown (neat coloured images) end in 2016 and "… neutron stars are born with a variety of spin periods and magnetic fields. We will have to be patient to see what the properties are of the compact object star in SN1987A." Yes, absence of proof-correcting is a problem, OH maser emission is fairly common in older remnants, collisionally rather than radiatively excited, including in the new class of mixed-morphology SNRs with both shell emission and a pulsar-wind nebula. To clarify by example, the Cygnus Loop is a shell type; 3C 58 a plerion or pulsar-wind nebula; Kes 75 is a composite SNR, and W 28 mixed morphology. Kurt Weiler and Nino Panagia coined the name 'plerion' in 1978.

Another take-away concerns magnetars, neutron stars whose spin-down rate implies magnetic fields approaching or exceeding 10^{14} Gauss. (Incidentally, Vink's units are astronomical, kiloparsecs, and cgs erg s^{-1} all the way.) The takeaway is that the neutron stars were probably not very rapid rotators to begin with, on the grounds that the associated supernova remnants had low explosion energies. The catch? The two largest slow-down rates (strongest magnetic fields) belong to SGR (soft gamma repeater) 1866–20 and SGR 1904+14, for which there are no associated SNRs. Those two spin-down rates were measured by Chryssa Kouveliotou and her associates in 1998–99, and I remember sitting on a sunny porch somewhere while she explained to me that nothing other than monumental magnetic fields could fit the data. The name, however, was coined earlier and by others, by analogy with quasar, pulsar, and so forth (my suggestion that certain other kinds of systems should be called 'gravars' has never caught on).

In addition to the 16 take-aways there are 14 "open standing science issues." Two of them live in territories I have defended over the years. First, the Crab Nebula suffers from "the sigma problem", having its magnetic-field energy "low compared to the energy in relativistic electrons/positrons." Building on a model coming from Charles Kennel and Ferd Coroniti (then both at UCLA) in 1984, the relatively slow velocity, 0·3 *c*, of the "thin wisp of Scargle" (1969, Jeffrey Drexel) implies that the real sigma there must be much less than unity, says the author. On the other hand, extrapolating outward from the known field of the pulsar, leads to a prediction of that ratio, sigma, much greater than one. Various fudges are suggested as solutions, none of which seem to appeal very much to the author. My only contribution is that, for the nebula as a whole, the two energies are probably comparable.

A second puzzling topic is the progenitors of Type Ia, thermonuclear SNe. Are they single white dwarfs, driven to distraction and to the Chandrasekhar limit by accretion from a close-binary companion, or are they double, paired degenerates which spiral together and in sum exceed a threshold for igniting carbon and oxygen detonation or deflagration? The conflicting observational evidence is presented correctly in Chapter 9. Unfortunately in the summary we are told, "For a number of Type Ia supernova remnants evidence is found for ambient gas modified by stellar wind outflow, suggesting single-degenerate systems; but the lack of surviving donor stars in supernova remnants suggest a single-degnerate scenario." Clearly 'double degenerate' is meant in the last clause, and the slight non-agreement of subjects and predicates in number is one of many examples throughout the volume, but the error of the main point leaves this reader just a bit worried about trusting other items. I am, incidentally, a double-degenerate person, following the inspiration of the late Bohdan Paczyński.

Those 1284 references are a bit of a challenge. They are listed alphabetically at the end (without paper titles) and numbered in that order. Citations within the text are only by the number, so there is no very easy way to tell what a given author or paper is being given credit for. I'm there (1968) probably for the distance to the Crab; Scargle for the semi-relativistic wisps. Kennel and Coroniti as noted. Goldreich and Julian for their aligned-rotator model, but not Gunn and Ostriker for their oblique rotator. Woltjer, who wrote the first-ever Crab Nebula thesis, appears only for an *Annual Review* article (a good many others of those are also invoked). And Robert E. Williams who wrote the second-ever Crab thesis does not appear at all. A handful of other 'historical' papers are mentioned, but the author has not intended to cover that topic in any detail.

Rather, he states, the several chapters are of two kinds: textbooks (but no problems at the end) and review articles. Among the former are shock physics and cosmic-ray acceleration (with SNe and SNRs apparently not able to reach the highest energies that are thought to be galactic), and a very fine chapter on radiation mechanisms, pointing out, for instance, that the expressions for inverse Compton radiation and synchrotron are almost the same, except for involving the energy density in photons in the former and the energy density in magnetic fields in the latter. The colour images come from *Chandra*, *HST*, and the *VLA*; many of the explanatory graphs are the author's own drawings. The colour coding varies from image to image, but is always explained in the captions. Other items are less easy to interpret. For instance, again on the 'single- *vs*. double-degenerate' issue does "mass lass consistent" mean mass loss consistent, or mass less consistent? Probably "mass loss" but I read it the first time as "mass less".

I could not possibly have written this book (nor, truthfully, wanted to), and it took Dr. Vink from 2015 to early 2020. He credits some of his students and postdocs with having proof read chapters, but it really needed a paid professional with a clear understanding of both the subject and the technical language of astrophysics. Still if somebody gives you a copy, thank them heartily and make use of whatever parts fit with your interests. — Virginia Trimble.

Elementary Cosmology: From Aristotle's Universe to the Big Bang and Beyond, Second Edition, by James J. Kolata (IoP Publishing), 2020. Pp. 153, 26 × 18·5 cm. Price £30 (hardbound; ISBN 978 0 7503 3613 0).

Although the book is part of the 'AAS–IOP Astronomy ebooks' programme, I am reviewing what looks to be a traditional hardbound book. (Additional ISBN numbers do indicate, though, that it is available in various electronic formats as well.) We are told that "AAS–IOP Astronomy ebooks is the official books program of the American Astronomical Society". The author is an emeritus professor of nuclear physics at Notre Dame, and the book is based on a course of the same name which he taught there. The name is apt, as it is much more basic than other cosmology textbooks[1–5] I've reviewed in these pages[6–10]. It is broad, covering nearly all the topics expected in an introductory cosmology course, but of course at the expense of depth; the average length of chapters is eight pages, and about one-third of the length of the main text is taken up by figures and their captions. There is a slight emphasis on particle-physics aspects (early Universe, inflation, even string theory) and hot topics (neutron stars and black holes, gravitational radiation) at the expense of traditional observational cosmology. Those interested in cosmology will surely have other sources for the more traditional topics, and it is nice to have newer material presented well and at a uniform level. The figures, most in colour, many of which I have seen before, either in identical or similar versions, complement the text well. (While attributions are important, they should have been collected into 'picture credits' in the back matter. Often, the acknowledgement is longer than the rest of the caption, and the reader really doesn't need to be told in the main text that "[t]he author is stated to be Headbomb" or "MissMJ".)

The main problem is with the more traditional topics. While not the author's area of research, a book at this level should be able to get everything right. I've seen similar goofs elsewhere, but expected more from a book published under the aegis of the American Astronomical Society. A few examples (there are others; these can be described briefly): wrong definition of equant, Kepler described as Austrian rather than the more correct (but still anachronistic) German, one at least has the impression that elliptical orbits are needed to explain retrograde motion, blue stars stated categorically to be bigger than red stars, Goodricke appears to have discovered δ Cephei (rather than just its periodic variability), supernovae classified *via* light-curve shape (rather than spectrum), visible light has the wavelength range 300–600 nm, Special Relativity cannot handle acceleration, the static Einstein universe described as the steady-state model, the fraction of metals (in the astronomical sense) among the elements in the Universe is only 0·01 per cent. There are also a few simpler obvious mistakes which any proof reader should have caught, such as "constellation Vega". It should go without saying that the treatment of the flatness problem is very shallow, though that is a mistake committed by most authors[11].

After about half-way through, there are practically no such mistakes. Those in the first half are easy enough to correct. There is a reasonably good book here waiting to get out, but marred by easy-to-fix problems. Someone with only basic knowledge of cosmology might notice some of the mistakes then wonder what else is wrong but not easily spotted, but that is not something which the target readership can judge. There seems to be no reason why the pages are numbered as m–n, where m is the chapter number and n the page number in that chapter. In the list of links to about a couple of dozen astronomy and cosmology websites, about half-way through one has only the titles but not the URLs.

Otherwise, there are relatively few typos and so on. The sixteen main chapters are followed by three more: further reading, the list of websites mentioned above, and a list of abbreviations. (The last is useful in a book like this, but it is a bit confusing that the author uses 'BBNS' for 'big-bang nucleosynthesis' instead of the usual 'BBN'. Also, the relatively uncommon abbreviations 'BBH' and 'BNS' for 'binary black hole' and 'binary neutron star' are neither in that list nor is it explained in the text that the (first) 'B' is for 'binary'.) There are neither footnotes nor endnotes nor an index.

In considerably less time than it took to write and produce the book, all of the mistakes could have been caught and corrected by someone familiar with the subject matter. That criticism applies to other books as well, though in this case I found more and expected fewer. My guess is that, now that publication itself has become less expensive, it has become too expensive for publishers to do proper proofreading (much the same as the lack of good meals on cheap flights), but many authors still assume that they do. — PHILLIP HELBIG.

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CORRIGENDUM

On page 148 in the 2021 June issue appears a very positive review of *Cosmic Odyssey* by Linda Schweizer. However, the Editors blundered in their rendering of the subtitle to the book: they have credited the advances made at Palomar to 'Infrared Astronomers' rather than to the 'Intrepid Astronomers' who observed at many wavelengths! For this they apologise sincerely.

Here and There

ARMLESS SPECULATION

The Sun, along with its Solar System orbits the Milky Way Galaxy — our Solar System forms one of its arms. — *What Does Rain Smell Like?*, 535 Books, 2019, p. 12.

HMMM

Quick Quiz Question No. 3: To the nearest whole number, how many parsecs are there in a light year? Answer: 3 — *New Scientist*, 2021 January 9, p. 52