THE

OBSERVATORY

A REVIEW OF ASTRONOMY

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EDITORIAL

With the 2025 February issue, *The Observatory* became an on-line-only journal. However, apart from not having to worry about an issue becoming heavy enough to require more postage and the fact that colour is no longer an extra cost, not much else has changed. We do plan to introduce new features in the future, such as DOIs for individual items and references containing links to the corresponding sources, but not too many at once. The first such change will be producing the final PDF from LaTeX. While we will continue to accept formats which we have accepted in the past (*e.g.*, .doc, .docx, .txt, .pdf, .tex), it is preferable to submit items for the *Magazine* using our supported LaTeX macros available at http://www.obsmag.org/templates/ — make sure that you use the latest versions; note that those supersede the older templates in the /old/ subdirectory and are hence preferred, but the older ones are still preferable to non-LaTeX formats. More detailed information is available at the link above and will be updated as needed, so only the most important details, which will also probably not change, are mentioned here.

If an item is essentially plain text with little or no formatting, submitting it as plain text is preferable to doing so in non-LaTeX formats, and only slightly less preferable than submitting it in LaTeX. In particular, PDF-only submissions should be avoided. PDF files are almost always created from some other format; it is preferable to submit that format, though a PDF file could be included as well. The new LaTeX templates allow the user to concentrate on content with the formatting being done behind the scenes, so LaTeX commands within the text of the submission should be used only when absolutely necessary, *e.g.*, for mathematics. We provide a range of examples intended for those unfamiliar with LaTeX (in which case all that is necessary is to place the corresponding parts of the text into the appropriate places in the template) through to experts; choose the most advanced one with which you are comfortable or which is necessary for the submission. Figures should preferably be in PDF or PostScript format and provided as separate files (included within the submission in the standard manner; see the examples). Citations should be provided using the \citep and \citet commands of the natbib package (automatically loaded by obsmag.cls) and not by hard-coding the superscripted reference numbers; references should be provided in BibTeX format; see the examples. (Note that all LaTeX and BibTeX input consists of plain-text files and can be submitted even by those with no access to LaTeX processing, though of course it is preferable to make sure that the submission processes cleanly and produces the desired output before submitting it.)

Send submissions *via* email to submissions@obsmag.org. If there is sufficient demand, perhaps other submission paths can be set up; the same goes for support in Overleaf.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2025 March 14 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

Mike Lockwood, *President*
in the Chair

The President. Welcome to this hybrid meeting. Questions can be put in the Q & A section and they will be read out by Dr. Pam Rowell. Philip Diamond is retiring at this year's AGM after seven years with us, and we thank him for all he has done. He will be replaced by Ian Russell, who will take over on May 1st. The Caroline Herschel Prize Lecture was established by the Herschel Society and it is awarded to UK and German women researchers in alternate years by the RAS and its German equivalent. More details can be found on the RAS website. Unfortunately the current holder, Professor Stefanie Walch-Gassner, who was due to address us, was taken ill at short notice and is unable to be here. Instead I will give a talk entitled 'The Great Aurorae of 2024'.

Last year was a truly remarkable one for aurorae. Aurorae are caused by energetic particles, mostly electrons, hitting our upper atmosphere then precipitating down field lines, hitting atomic oxygen atoms and emitting light. There is a wide range of colours produced: the green appears lower down whilst collisions higher in the atmosphere, due to lower-energy electrons, produce red light. Excitation of molecular nitrogen produces blue light.

Magnetic reconnection happens in the upper atmosphere on the dayside, allowing low-energy electrons to come in down the field lines, producing red aurorae in both hemispheres. Particles can also bounce in the converging magnetic-field lines and end up in the tail plasma sheet; they are accelerated using energy from the solar wind and they give rise to the green aurorae. However, it is particles that come up from the ionosphere that cause most of the aurorae. In quiet periods it is the solar-wind particles that dominate but in disturbed times the major role is taken by the ionosphere, but the energy that comes from the solar wind does always dominate.

Aurorae form an oval around each pole which expands in radius and width, being most intense at the North Cape of Norway, but it can extend to the UK and further south during periods of intense activity. Aurorae often form arches or arcs, if seen from the side, but at lower latitudes the displays are very diffuse and red in colour.

We have conducted a survey of auroral sightings, of which we have 224 870 records going back to 1650, and it appears that most recent sightings are land-based whereas it used to be transatlantic trade and shipping that produced most reports. When you go to Alaska, Iceland, or northern Scandinavia it is very much a cultural activity to go out and observe and record aurorae. At lower latitudes there is intense activity in reporting aurorae and the population density is higher so it is not surprising that auroral sightings correlate with population.

In 2024 there were 4735 reports of aurorae. There was an intense event on May 10/11 and there were four aurorae seen far from the pole in that calendar year. The May 10 event was caused by a coronal mass ejection (CME). It was observed and there was a prediction made about six hours before the first event but, in fact, there were seven CMEs which pummelled the Earth.

It is very tempting to compare the events of 2024 with the Carrington Event of

1859 which was the first to affect directly technology on Earth. The geomagnetic deflection in 2024 May amounted to 400 nT whereas the Carrington event is thought to have reached about 1600 nT. The May 10/11 event is the third lowest latitude reached since records began. In Ontario the aurora was entirely green whereas in Silbury Hill, Wiltshire, we saw red on green with a bit of nitrogen blue in the middle, and in Romania it appeared red over green but here the green formed a narrow band. In Arizona the aurora was almost entirely pure red with a bit of blue. It was also visible from Santa Cruz de Tenerife but the lowest latitude where it was detected was Oman.

The field lines connect to the plasma sheet and the energetic (1 keV) electrons come down the field lines to give a green aurora, then we get energetic particles moving in during the geomagnetic storm from this outer radiation belt and they tip particles that are already there in a low-energy torus called the plasmasphere down onto the Earth and this gives rise to the red colour. High-latitude aurorae are very structured but low-latitude events are very diffuse but more colourful.

In history there are several verses of the *Bible* which are almost certainly descriptions of aurorae. The most interesting is in the second book of Ezekiel where he describes it in such detail and such length that it is almost certainly a red coronal aurora. We think he was living in Nippur, an archaeological site in Iraq. It tallies with Assyrian and Babylonian documents which date it to 567 BC March 12.

Early observers were doctors, clergymen, affluent gentlemen scientists, lighthouse keepers on solitary nights, professional observers, and more recently the latest robotic spacecraft and the public, through citizen science and the social media.

The magnetic pole has moved over time and has affected the appearance of aurorae over the mid-Atlantic and North Africa, neither of which are great places for auroral records. In the 17th Century, Plymouth was a good place to see aurorae but the events slowly went to higher and higher geomagnetic latitudes, whereas the Faroe Islands have moved into the auroral oval and so it is a much better place to see them. Today we have a lot of social media and the modern mobile phone has a great camera for recording aurorae. The eye is as good as a digital camera; if left in the dark for two hours it can detect individual photons, but normally people are not dark adapted.

In terms of the most significant displays, the most intense event was at Khartoum in 1872, followed by one at Panama City in 1859 and one in Oman in 2024, then the Carrington Event of 1859, followed by two events from 2024.

There is some fantastic science to come out. There were two new radiation belts introduced by the May event which was completely unexpected and which are still there.

Professor Mark Lester. Thank you very much, Mike, for speaking to us at such short notice. Are there any questions?

Professor Kathy Whaler. Thanks Mike, really interesting. Do we actually know the magnetic latitude of the site in Iraq in Ezekiel's time?

The President. Will Brown at the BGS did the calculations for me. He used IGRF (International Geomagnetic Reference Field) and then went further back in time by splining it with gufm1 [the model describing the magnetic field at the core–mantle boundary for 1590–1990] and then we used something called a modified quasi-dipole.

Professor Whaler. So you don't actually know it? You are just inferring it as records don't go beyond 1590 or so with gufm1. So, you are extrapolating 1200 years?

The President. We have the IGRF values for the last century but before 1900 we have to use gufm1 and then extrapolate to biblical times.

Mr. Horace Regnart. Thank you. Speaking as a Northumbrian, people might like to know that the first of your photos showed our national tree, the sycamore, against a wonderful aurora. It is now coming back to life. Isn't that wonderful?

The President. It is! That is the best news I've had today. I don't know quite why that upset me as much as the sheer wanton stupidity of it.

Ms. Ana Vitiello. You didn't mention anything about the Southern Hemisphere. Do you have any data on that please?

The President. There are data. The reason we didn't use them in our survey is for two reasons: firstly, an awful lot of the southern hemisphere is water which means that the possibilities are much lower, but, historically, after about 1650, Europe really woke up to measuring around the world and got quite good statistics then, but we don't have any equivalent in the southern hemisphere and so the gradient of the number of potential observers is quite different. And so we decided best just to stick to one hemisphere. There are data and they are quite interesting sometimes.

Mr. Samir Chitnavis. Thank you for a very colourful talk on a Friday afternoon. I research photosynthesis under different coloured stars, which means I get to grow algae under rainbow-coloured lights. I wanted to ask you, are there any observations of animals changing their behaviour during an aurora? Other than humans!

The President. If there are, I would really like to know about it! You raise a very interesting point. One of the big problems now is we get a lot of reports of red aurorae that are actually greenhouses because they use a mixture of red and blue LEDs to make things grow faster, and if it's cloudy it looks like aurorae, and sports stadia where somebody's posted a picture of the aurora at Stamford Bridge. It's where they are using a mixture of lights to get the grass to grow back faster and faster, and so that is an increasing problem of light pollution.

Professor Lester. Thank you again, Mike [applause].

The President. Our next speaker is Andy Smith who is going to tell us about space weather with AI, so he is going to pick up on the sort of applications we are talking about. He was awarded his PhD from Southampton in 2018, and his thesis focussed on physics and plasma environments around Mercury and primarily space weather. He has returned to Earth in every sense and worked at UCL where he combined physics expertise, AI, and interrogative space-weather forecasting methods. In 2022 he was awarded a NERC Independent Research Fellowship which he currently holds at Northumbria University. The title of his talk is 'Space-weather forecasting, geomagnetically induced currents & machine learning'.

Dr. Andy Smith. The take-home message from this talk is that we don't need complex models, we need science.

The aurora is a fantastic manifestation of the interaction of the outflowing solar wind with our geomagnetic environment. The aurora is a manifestation of the ionospheric electrical current that flows in the atmosphere and induces electromagnetic fields and electric fields, and over the past 50 to 100 years we have been putting longer and longer conductors across the Earth which provide very nice avenues to bridge over these geoelectric fields and consequently place geomagnetically induced currents (GICs) in power networks and pipelines. These happen every day but we really feel them when they get really large. They add what is primarily a DC offset into the AC systems — leading to direct damage, hotspots, heating and, ultimately, blackouts.

In Quebec in 1989 a large transformer was blown up thanks to GICs. The province of Quebec lost power for nine hours and it caused millions of pounds' worth of damage, so, ideally, what we want to do is prevent that from happening.

If we know an event is coming there are steps that electricity operators can take to mitigate the effects. New Zealand had a plan which it had agreed with academics and they approved it last May, re-routed power, took things off maintenance, weathered the storm, and then claimed that the plan worked.

Direct GICs are rare and the equipment to measure them is not present in every transformer; they are expensive to install and there is no guarantee that future events would be predictable. We don't measure GICs but we do measure instead the rate of change of the magnetic field. This is the parameter that drives the GICs. To calculate this effect you need to account for the sub-surface conductivity to give you an estimate of the geoelectric field, and knowing the power-network configuration, combining the two allows you to calculate the GICs.

In our studies we concentrate on the geomagnetic field itself, and mostly use the rate of change of the magnetic field. If it gets to 50 nanotesla per minute you are going to get significant GICs. Our study is funded by NERC so we work on impacts on the UK. We have three permanent geomagnetic observatories in the UK from which we have data going back 40 or 50 years. The first is Hartland in Devon which has a current geomagnetic latitude of 48 degrees, with another at Eskdalemuir (55 degrees), and a third at Lerwick (58 degrees).

One process that causes GICs is called a sudden commencement (SC) which, in turn, is caused by the impact of a solar-wind shock in the magnetosphere. It causes a rapid contraction of the geomagnetic field. We have about one to one-and-a-half hours of warning which makes it forecastable. On the ground the magnetic field jumps by several hundred nanotesla in one to two minutes and the effect varies with latitude.

How much does this matter for us? Not much as it turns out. It depends on magnetic latitude and is more important at lower geomagnetic latitudes. However, in the days after an SC we find that we are accounting for 80% of our low-latitude station variability here. Less than 10% of larger magnetic variability is connected with SC events but more than 90% in that three-day interval after. There are two sub-types of SCs — sudden impulse (SI) and storm sudden commencement (SSC). If we see the interplanetary shock rapidly compress the magnetic field and nothing happens then that is classified as an SI. If we see a geomagnetic storm kick off after that, we call it an SSC. We find that the only events we need to care about are those which trigger a geomagnetic storm, so only those SSCs are significant and if we have a three-day warning then we will see the greatest threat to the power networks that we are going to see.

About 30 minutes before the shock impact we see the structure in the solar wind — the solar-wind density increases tremendously, the velocity with which it approaches us drops a lot, the magnetic-field strength increases, and there is a small rotation of the magnetic field so that it points northward. We extract features from the solar-wind parameters and use a series of models invoking linear, non-linear, and ensemble methods to see whether a storm or SSC is going to happen. We restrict the number of parameters we use — most important is the range in B, the magnetic-field strength, followed by the range in particle density and the range in solar-wind velocity. We calculate models using increasing numbers of parameters and we are interested in getting the model reliability — the parameters tell us if something will happen, or won't happen, but how much can we trust it? The second metric is called the skill and how good the model is from picking out events from non-events. We find that we can get all the information from the solar wind using three parameters.

We also ask is there going to be a geomagnetic storm? Again we rank the parameters by importance. This time the most important parameter is B_z, but this time we need seven parameters to describe the shock. What drives the geomagnetic storm and what follows the shock? The four statistical models we use give a different answer which is purely a consequence of the model. A more direct approach is to ask the model what we might see in the future. Instead of predicting the exact shape of a model event, they will be asked whether it will be above a certain level, *i.e.*, a threshold. Three models of increasing complexity were tested and placed into a neural-network model. From the metrics here we can see that the more complex models don't necessarily see the best performance.

In conclusion we note that forecasting GICs is an important space-weather problem. Magnetospheric phenomenon-based forecasting can give an insight and broad warning interval. Direct forecasting can produce a few hours of warning but less insight. We find that simple models perform as well as complex ones but extrapolating the model is dangerous.

Professor Ofer Lahav. Thanks for an interesting talk. I guess those two categories you mention: feature extraction as the more direct one, the second is an example of deep learning. Is this correct? I'm an outsider in this field but in other applications deep learning really does better, even if it is more difficult to understand what it does, so I wonder if you could explain why the deep learning is not doing better, relative to feature extraction?

Dr. Smith. For context, we went back last year and we used methods like SHAP (machine learning) to try and explain why the models are doing what they're doing. It turns out they are replicating the physical understanding that we have, in some ways. I'm still not entirely sure about their extrapolations. However, that's a slightly different question. I think the problem that we're having with deep learning here is that the system is massive and complicated and we're driving it with a single point of input, and that single point of input may not even be that reliable, honestly. It's upstream of the Earth but the entire spatial structure within the solar wind can be very complicated and there's no guarantee that what we're seeing is representative of the phase front of the solar wind as it comes in, for example. So, the models are having to interpret what's going to happen in terms of magnetospheric activity and there's a whole bunch of processes that could happen and then map down to the Earth. It's a complex model that's not fully possible to solve, even with things like numerical physics models of this case. So it's asking for a lot for the model to interpret that, and I think that's the problem.

Professor Tim Horbury. Really nice talk. I'm just going to give a shameless plug, if that's OK? One of the issues in terms of predictability is if you're in the sheath upstream of a cloud, it can be very variable, but if you actually drop into the cloud itself, it's much more predictable. There are ways of diagnosing that, for example, with temperatures or charge states. So that's something that you might want to think about putting into those kind of models. Charge states aren't available at the moment, but *IMAP* is launching in September, and that will have real-time charge-state data, and at that point, we're going to have four spacecraft at L1 with real-time data at once. So, as you mentioned right at the end of that answer, multi-spacecraft here will make a big difference in being able to make accurate predictions in real time, I think. I'm not sure many people are really thinking about it yet, but I think we should really get on and start thinking about how we combine multi-spacecraft L1 data to make better real-time predictions.

Dr. Smith. I absolutely agree, and we've got an ISSI team we put in yesterday to look at things like that, so I hope to review that.

Professor Lester. I'm wondering what would have happened if he said that he could do a shameless plug and I said "No!"

Professor Horbury. I've got the microphone and I'd have done it anyway!

Dr. Smith. The last point on that is that these models are all very data intensive. So, we were training these models on 30 years' worth of data. The problem is that we wouldn't have the historical charge-state data that we may require for that, so it might require some clever thinking maybe to go back and create some sort of substitute pseudo-data that would fill the gap.

Professor Whaler. Thanks very much, Andy. I've probably missed something in your talk but are there any advantages or possibilities of data assimilation from, say, measurements of the magnetic field on the ground, for instance, that might help with the types of models that you've talked about today?

Dr. Smith. Certainly, they definitely do that with things like the ionospheric models that they have. They incorporate data assimilation and that boosts the model performance massively. If we were predicting the ground magnetic field itself, then certainly data assimilation would be an excellent thing. Certainly over the past five to ten years, we're starting to build in more of the kind of techniques that have come in from weather forecasting, for example, leaning heavily upon our friends, such as at Reading. I think that's where we're going in the future.

The President. I'm almost shocked by how different the skill-score metrics are in there and what they tell you and which is the right one to use depends on the application. Are you using ones that are guessed to be the best for our network operators? You see what I'm saying?

Dr. Smith. Yes. I'm not sure if there's consensus at this point as to what we should be using. There are some sort of typical ones that people go to and then there's also reasons why they are potentially not the best ones, because of things like unbalanced data sets and we should be using something else. Mike Liemohn has a fantastic paper on metrics and which we should be using, but that mainly focusses on regression rather than classification.

The President. So it is interesting about metrics; I suppose this is true of life, the trick is to choose the one that's right.

Professor Phil Charles. Just a quick one, because I forget whether it was you or Mike who had the table of the top-ten solar-wind events. I was interested to note that 1989 wasn't on there, yet we know it did a lot of damage on the ground, and also, if I remember correctly, it took out several satellites that were operating at the time? How does that correlate with this work?

The President. It's because there's no such thing as a typical storm. A space storm with not a few particles that destroy your satellites and things is rather different from a geomagnetic storm. They do go together but they're not one for one. So, the classic example was 1972, just before the Apollo mission. If it had happened while the Apollo astronauts were out of Earth's magnetic field, it would have killed them. On the ground, that was a very small geomagnetic storm, but it was a massive space storm in terms of that. The only thing it did on the ground was all the American mines laying around harbours in Vietnam exploded and nobody knew why, but there wasn't a major geographic event. It's very varied, so that's part of the problem.

Dr. Smith. There's an entire zoo of processes and what makes a big storm in some senses may not be in others.

The President. Exactly. Again, which metric you used to filter.

The President. We move on now to the Eddington Lecture — 'Reconstructing the history of the Milky Way galaxy using stars'.

Dr. Melissa Ness. (It is expected that a full summary of this talk will appear in a future issue of *Astronomy & Geophysics*.) [The speaker began by stating that astronomy of the Milky Way galaxy has entered a transformative era. The *Gaia* mission and an ensemble of ground-based spectroscopic surveys are delivering element abundances and velocities for millions of stars. These data provide both an opportunity to deepen our understanding of galaxy formation and to test limits of 'the limit of knowledge'.

The speaker continued by summarizing the endeavour of galactic archaeology, whereby we are working to reconstruct the history of the Milky Way galaxy using signatures in its stars. Dr. Ness laid out the data landscape in the 2025 era and highlighted some key results to date from *Gaia* that showcase the differentiating behaviour of different stellar populations in the Galaxy, and then moved on to a discussion of the development of data-driven modelling techniques to derive information from stellar spectra, placing different surveys on the same scale, and talked about the new avenues that data-driven approaches have opened up. This includes enabling spectroscopic ages as well as individual abundances to be inferred from low-resolution, low-signal-to-noise spectra. At the heart of the talk was an exploration into the behaviour of the multitude of element abundances from the large surveys; how they are correlated, what amplitude of intrinsic information they carry, and how much diversity stars show in their abundance patterns (Fig. 1).

There have been several surprises that have come out of the large stellar surveys and data-driven methodologies built to analyse them. We have learned that up to 1 in 100 stars in the disc are 'abundance *dopplegangers*' — chemically identical but unrelated — limiting the prospect of reconstructing the disc's star-cluster building blocks. Furthermore, for stars in the disc, most of the element

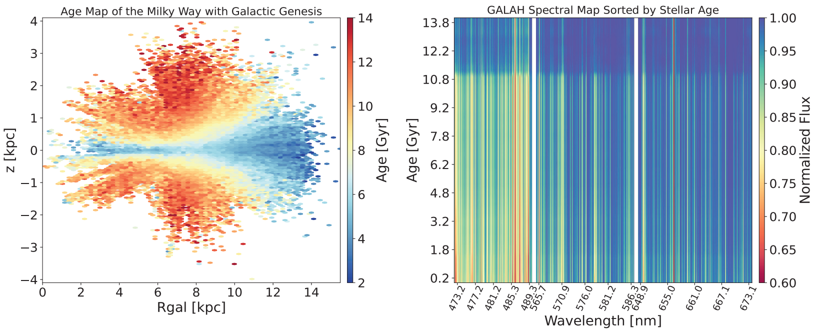

FIG. 1

The left figure shows the age map of the Milky Way, from the Galactic Genesis survey. The right image is a map of continuum-normalized *GALAH* spectra of red-giant stars, with wavelength along the *x*-axis and stars sorted in rows along the *y*-axis in order of ascending age; this summarizes the way that information is encoded in stars; the amplitude of features changes across wavelengths and it changes across stellar age. This is the information we access and interpret, to learn about the formation and evolution of the Milky Way galaxy and map the Galaxy across its spatial extent.

abundances measured for most of the stars can be predicted to a precision of better than 10 percent given only two key abundances. However, this is not the case for stars in the stellar halo. These findings frame how we can most effectively work with the data to turn photons into a quantified description of Galactic history and provide strong constraints on the star formation and mixing processes that have set the Galactic environment.

Dr. Ness concluded by summarizing the remarkable surprises and signatures we have found in the data, and highlighting prospects for chemical tagging in the halo and data-led nucleosynthesis in the disc with the upcoming data from new surveys.]

Professor Richard Ellis. What a beautiful lecture. Thank you so much. Your result on testing chemical tagging is very sad because it is such an elegant idea, but maybe we're being too picky. If you applied chemical tagging to the disc — I mean, with the test that you did: a cluster *versus* the field stars — are you honestly sure we wouldn't learn something just applying it to the field stars? Even if the map of geographical location is slightly blurred, surely there's some benefit and utility in this nice method?

Dr. Ness. I think the power of chemical tagging is not that it works, but it's the method, it's the approach, it's how we're learning so much from the data. So I absolutely think that chemical tagging is incredibly useful as a tool to learn about the data, and I think there is much to do in the abundance space by looking. With the abundances we learn we've basically traced stars back to their birth radius, not to the individual clusters. So the abundances are very discriminative for that. So I'm very interested in taking this to its limits. It's more the theory of chemical tagging — it doesn't matter whether it's successful or not. It helps us enormously.

Professor Claudia Maraston. Thank you very much for this lecture. I'm going to try to export your wisdom to external galaxies, for which we derive metallicities up to very high red-shift from low-resolution spectra. And people, I mean including us, we have done this to attempt to reconcile very-high-resolution abundances to low-resolution abundances. You had a couple of points, but I failed to get the conclusion. When you compare low resolution, like *LAMOST*, with high resolution, what was the result for most elements and also comparing analysis from optical to near infrared, where you notice offsets, which one is better?

Dr. Ness. I won't get into which is better in the sense that we tend to adopt the high-resolution values because they're more precise and I suppose better and they will have different surveys, your *LAMOST* and your *APOGEE* and your *GALAH* have different scales, but if we use a data-driven model and use the styles in common we put them all on the same scale: we have to adopt. So you have to make a decision about which one you want and that's the big question. Which is the more accurate. I think there are tricks we can do; because we have a generative model it should fail to be able to generate the spectra with the wrong labels. I think you can test the fidelity of the labels, which set of labels of which survey is more correct by seeing where you fail to generate a good model of the data. We can talk more about that idea. I'd like to try that. I think it would be fun.

A Fellow. Thanks for the nice talk. I am interested that there are rare events in your list of enrichment sources and less-rare events. So do you see a larger star-to-star scatter in elements that are expected to come from rare events?

Dr. Ness. Good question. So you mean the neutron-capture elements, like some things from r-process?

The Fellow. Yes, something from the neutron-star merger should be rare and I wouldn't expect the whole galaxy to be enriched in the same way by neutron-star mergers.

Dr. Ness. I think there are two points. Yes, all of the neutron-capture elements have higher scatter, but we are predicting on non-neutron-capture elements. I think in the residuals, the fact they're all so correlated, implies that they're all generated from the same underlying 'other source'. I think that we can do that test, but to do that we need really to look at a range of metallicities and look at how many stars are failing our prediction — about 1% fail. In particular, we see things fail in barium and yttrium because that's produced, I think, in stellar-companion mass transfer. I think that we can test that. We just haven't yet.

The President. We should thank Melissa again for a fabulous talk [applause]. I have some questions for you, but I will ask you later today. The next meeting will be 11th April in the Royal Irish Academy, Dublin.

A SIMPLE, STABLE, RAPIDLY-CONVERGING, AND EXTREMELY ACCURATE ITERATIVE SOLUTION FOR KEPLER'S EQUATION

By B. Cameron Reed

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A very straightforward scheme for iteratively solving Kepler's equation is described. The iteration method is the familiar Newton-Raphson technique, augmented with an initial solution estimate based on modelling the sine function as a downward-opening parabola. For even extreme eccentricities, micro-arcsecond accuracy can be achieved with about a dozen iterations. No use is made of 'canned' calculator or spreadsheet root-finding algorithms.

It is well known that it is impossible to obtain a closed-form solution of Kepler's equation for the eccentric-anomaly position angle E of an orbiter as a function of time t. This problem has accumulated four centuries of analysis, and a student or non-specialist researcher who explores the on-line, textbook, and journal literature on it will soon come across intimidating-looking series expansions with coefficients involving Bessel functions, dire warnings concerning convergence instabilities, and a plethora of strategies for generating an initial estimate for E.[1,2,3]

Solving Kepler's equation is now trivial given the root-finding routines available in calculators and spreadsheets. As an instructional strategy, however, defaulting to 'black box' solutions whose inner workings are opaque has obvious disadvantages. The purpose of this note is to describe a very simple, rapidly-converging, iterative solution to Kepler's equation that makes use of an intuitively-appealing procedure for generating an initial guess. The procedure converges to an accuracy of a few micro-arcseconds in about a dozen iterations even in cases of extreme eccentricity at times close to periapsis, when E is evolving rapidly. The iterative engine is the familiar Newton-Raphson method; what may be new (or, more likely, not as well-appreciated as it should be) is the initial-guess procedure. My intent here is not to supersede 400 years of analysis of this problem, but rather to offer a scheme that can be described and implemented in a spreadsheet without appeal to any built-in root-finding routines within an ordinary lecture period.

For an orbit of eccentricity ε and period T, Kepler's equation is

$$f(E) = E + \varepsilon \sin E - 2\pi\tau, \qquad (1)$$

where $\tau = t/T$. In this formulation, the force centre is at the left focus of the ellipse; apapsis corresponds to $E = 0$ at $t = \tau = 0$, and periapsis to $E = \pi$ at $\tau = 1/2$. From the symmetry of an ellipse, we need concern ourselves only with the range $0 \le \tau \le 1/2$ and $0 \le E \le \pi$. For times in the range $1/2 < \tau \le 1$, simply follow the procedure outlined in what follows but use $1 - \tau$ in place of the desired value of τ, and then negate the result for E.

As for generating an initial guess for E, I appeal to the fact that $\sin E$ for $0 \le E \le \pi$ is very similar to a downward-opening parabola. This is illustrated in Fig. 1, where the solid curve shows $\sin E$ and the dashed curve a parabola fit to pass through the end points $\sin E = 0$ at $E = 0$ and π, while having a value of

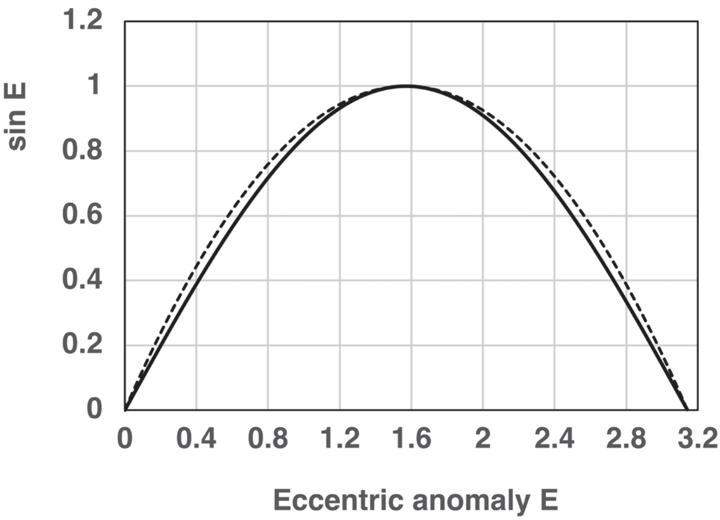

Fig. 1

$\sin E$ *vs.* E (solid curve) and the approximation of Eq. (2) (dashed curve).

unity at $E = \pi/2$. The resulting approximation is

$$\sin E \approx -\frac{4}{\pi^2} E^2 + \frac{4}{\pi} E. \qquad (2)$$

On substituting this into Eq. (1), the result is a quadratic equation in E that can be solved for an initial guess E_0, the 'zeroth' iteration. The form is $AE^2 + BE + C = 0$ with coefficients

$$[A, B, C] = [\frac{4\varepsilon}{\pi^2}, -(1 + \frac{4\varepsilon}{\pi}), 2\pi\tau]. \qquad (3)$$

Once E_0 has been determined, subsequent iterations proceed by the usual Newton method,

$$E_{n+1} = E_n - \frac{f(E_n)}{f'(E_n)}, \qquad (4)$$

where the prime denotes the derivative of Eq. (1) with respect to E, $1 + \varepsilon \cos E$.

Selecting the positive sign in the numerator of the solution of the quadratic for E_0 always gives a value of E greater than π, which can be discarded given the operative range of $0 \leq E \leq \pi$. Although this root does converge to π for $\varepsilon = 1$ and $\tau = ½$ and so might be the root of choice for values of (ε, τ) near those limits, it has the danger of flirting with the divergence of the derivative in Eq. (4) at periapsis. For this reason, I worked exclusively with the negative-sign root, which converges to $\pi^2/4 \sim 2{\cdot}467$ for $\varepsilon = 1$ and $\tau = ½$.

I constructed a spreadsheet to implement this scheme. Experimentation shows that for non-extreme values of ε and τ, micro-arcsecond convergence is reached in two or three iterations. Fig. 2 shows results from running an extreme example, $(\varepsilon, \tau) = (0{\cdot}999999, 0{\cdot}499999)$. The plot shows the logarithm of the change in the number of arcseconds in the estimate of E from the input

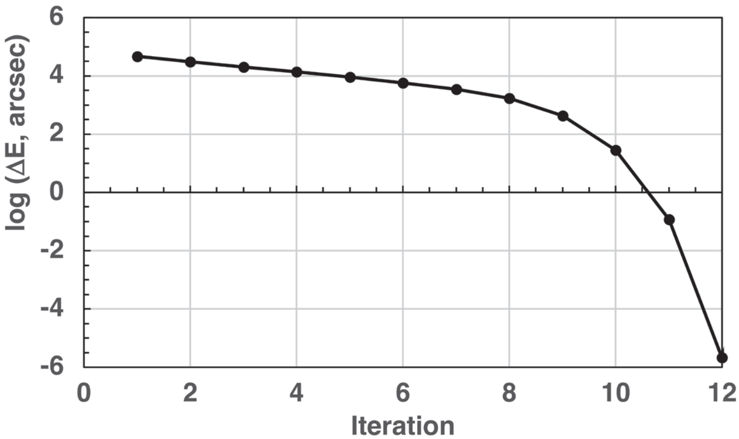

FIG. 2

Logarithm of iteration-to-iteration change in estimate of E in seconds of arc.

value at a given iteration to the succeeding one. The initial estimate is E_0 = 141°·370493, which iterates to E_1 = 154°·443789, for a change of 13°·073296 = 47063·9 arcseconds and a change in the logarithm of 4·673; this is plotted at the location of iteration 1. Arcsecond-level convergence is achieved on going from the 10th to the 11th iteration, and micro-arcsecond convergence on going from the 11th to the 12th; at this point the procedure is running up against the limitation of the computer's accuracy of about 1 part in 10^{15}. At convergence, E = 178°·082209… . The author would be happy to share the spreadsheet with any interested reader.

In conclusion, solving Kepler's equation need not be daunting or mysterious. Sometimes, a simple approach to an old problem can yield perfectly respectable results.

References

(1) https://en.wikipedia.org/wiki/Kepler%27s_equation
(2) See, for example, A. W. Odell and R. H. Gooding, 'Procedures for Solving Kepler's Equation' in *Cel. Mech.*, **38**(4), 307, 1986.
(3) E. D. Charles & J. B. Tatum, 'The Convergence of Raphson Iteration with Kepler's Equation' in *Cel. Mech.*, **69**(4), 357, 1998.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 27: THE TOTALLY-ECLIPSING SYSTEM UZ DRACONIS

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UZ Dra is a detached and totally-eclipsing binary containing two late-F stars in a circular orbit of period 3·261 d. It has been observed by the *Transiting Exoplanet Survey Satellite* in 41 sectors, yielding a total of 664 809 high-quality flux measurements. We model these data and published radial velocities to determine the physical properties of the system to high precision. The masses of the stars are 1·291 ± 0·012 $M_\odot$ and 1·193 ± 0·009 $M_\odot$, and their radii are 1·278 ± 0·004 $R_\odot$ and 1·122 ± 0·003 $R_\odot$. The high precision of the radius measurements is made possible by the (previously unrecorded) total eclipses and the extraordinary amount of data available. The light-curves show spot modulation at the orbital period, and both stars rotate synchronously. Our determination of the distance to the system, 185·7 ± 2·4 pc, agrees very well with the parallax distance of 185·39 ± 0·39 pc from *Gaia* DR3. The properties of the system are consistent with theoretical predictions for an age of 600 ± 200 Myr and a slightly super-solar metallicity.

Introduction

Detached eclipsing binaries (dEBs) are our primary source of direct measurements of the basic physical properties of normal stars[1–3] because their masses and radii can be determined from light and radial-velocity (RV) curves using only geometry and celestial mechanics. Within this class of object, those that have total eclipses are the most valuable because the times of contact during eclipse enable the radii of the stars to be measured to the highest precision[4,5].

In this work we present an analysis of the late-F-type dEB UZ Dra, which shows total eclipses and a circular orbit. This analysis is part of our project to redetermine systematically the properties of known dEBs using new space-based light-curves[6] and published spectroscopic results[7].

UZ Draconis

The variability of UZ Dra (Table I) was announced by Pickering[14], following its discovery by Henrietta Leavitt in photographic patrol plates from Harvard. It was awarded the designation 'HV 2972', its range of variation was given as 0·7 mag, and its variability type was described using the phrase "appear[s] to be of the Algol type".

Dugan & Wright[15] found an orbital period of 1·63 d, half the true period because the secondary eclipses were mistaken as primaries. Lacy *et al.*[16] (hereafter L89) state that a doubled period of 3·26 d was adopted by Tsesevitch[17]. This was confirmed and refined by Koch & Koch[18] using brightness measurements from 35-mm film. Gülmen *et al.*[19] collected all times of minimum up to the year 1986.

Imbert[20] presented the first spectroscopic orbits of UZ Dra, obtaining precise velocity amplitudes (K_A and K_B) from 40 RVs per star measured with the *Coravel* cross-correlation spectrometer[21]. Lacy[22] found it to be a double-lined binary system.

TABLE I

Basic information on UZ Draconis. The BV magnitudes are each the mean of 115 individual measurements[8] distributed approximately randomly in orbital phase. The JHK_s magnitudes are from 2MASS[9] and were obtained at an orbital phase of 0·296.

Property	*Value*	*Reference*
Right ascension (J2000)	$19^h25^m55^s.054$	10
Declination (J2000)	+68°56′07″·16	10
Tycho designation	TYC 4444-1595-1	8
Gaia DR3 designation	2261658485914111744	11
Gaia DR3 parallax (mas)	5·3941 ± 0·0115	11
TESS Input Catalog designation	TIC 48356677	12
B magnitude	10·08 ± 0·03	8
V magnitude	9·60 ± 0·02	8
J magnitude	8·616 ± 0·020	9
H magnitude	8·426 ± 0·020	9
K_s magnitude	8·372 ± 0·019	9
Spectral type	F6 + F8	13

L89 presented the first — and so far only — detailed study of UZ Dra. This was based on 35 nights of photoelectric *BV* photometry from Ege University (ref. 19) and 16 high-resolution spectra from two telescopes. Six spectra were obtained with the coudé spectrograph and Reticon detector on the 2·7-m telescope at McDonald Observatory, and the remaining ten with the coudé spectrograph and a CCD detector on the 2·1-m telescope at Kitt Peak National Observatory. From analysis of this material they measured the masses and radii of the component stars to precisions of 1·5–2·3%. They also obtained projected rotational velocities of 20 ± 1 km s^{-1} and 19 ± 1 km s^{-1}, both consistent with synchronous rotation in the assumed circular orbit, spectral types of F7 and G0, and a spectroscopic light ratio of 0·73 ± 0·03 from the 6400 Å-Fe I and 6439·1-Å Ca I lines.

Since that work, Popper[13] has indicated spectral types of F6 and F8 for the two stars, and Graczyk *et al.*[23] have presented updated masses, radii, and temperatures of the stars. A large number of times of eclipse are also available; UZ Dra is a popular target for amateur astronomers.

Photometric observations

UZ Dra has been observed by the NASA *Transiting Exoplanet Survey Satellite*[24] (*TESS*) in an extraordinary 41 sectors to date, due to its placement within the satellite's northern continuous viewing zone. In all cases data are available at 120-s cadence from the SPOC (Science Processing Center[25]). Lower-cadence observations are also available for all sectors but were not used here. The data were downloaded from the NASA Mikulski Archive for Space Telescopes (MAST*) using the LIGHTKURVE package[26].

We used the simple aperture photometry (SAP) light-curves from the SPOC data-reduction pipeline[25] for our analysis, and rejected low-quality data using the LIGHTKURVE quality flag "hard". A total of 664 809 data points survived this cut, coming from *TESS* sectors 14 to 86. These data were converted into differential magnitudes and the median magnitude was subtracted from each sector for convenience.

Fig. 1 shows the light-curve from sector 84, chosen because of its high duty cycle; the remaining sectors are similar so are not plotted. One feature of the light-curve immediately apparent on closer inspection is that the eclipses are total. This seems not to have been noticed previously, which led L89 to use a spectroscopic light ratio to constrain the ratio of the radii of the stars measured from the eclipse shapes.

We queried the *Gaia* DR3 database† for all sources within 2 arcmin of UZ Dra. Of the sources returned — 53 excluding the dEB itself — all are at least 5 mag fainter in the *Gaia* G_{RP} band so should contribute little additional flux to the *TESS* light-curves.

Light-curve analysis

The components of UZ Dra are well-separated so we modelled the *TESS* light-curves using version 44 of the JKTEBOP‡ code[27,28]. We defined star A to be the star eclipsed at the primary (deeper) minimum, and star B to be its

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

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

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

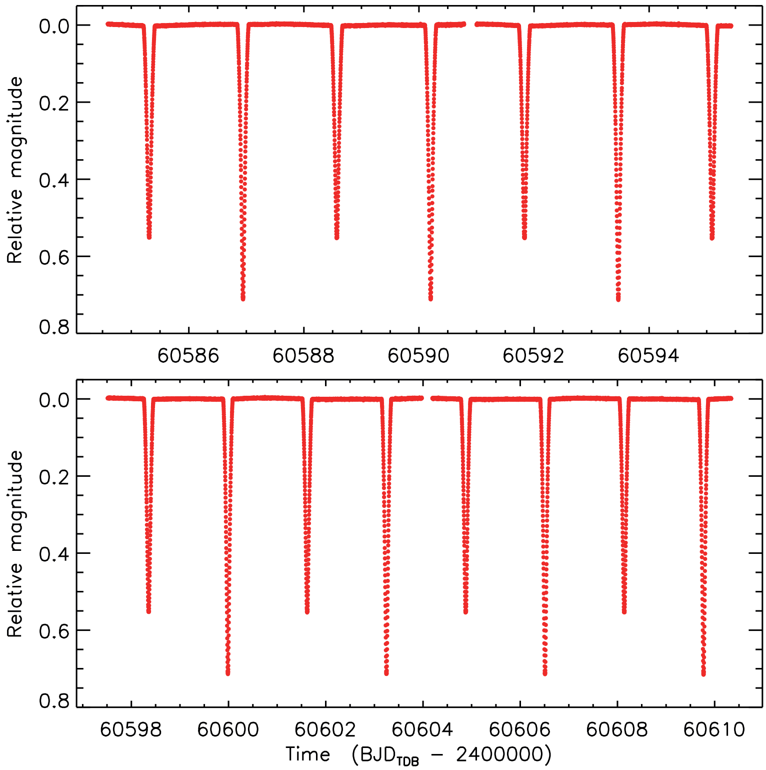

FIG. 1

TESS sector-84 photometry of UZ Dra. The flux measurements have been converted to magnitude units after which the median was subtracted. The other sectors used in this work are very similar so are not plotted.

companion. Star A is hotter, larger, and more massive than star B.

The exceptional amount of data necessitated the analysis of each sector separately, which in turn required the automation of some tasks usually performed manually.

For each *TESS* sector we chose a primary eclipse close to the midpoint of the light-curve, rejected data with large scatter or close to partially-observed eclipses, and defined normalization polynomials to remove slow variations in the measured brightness of the system. A total of 608 575 data points were retained for analysis.

We then fitted the data from each *TESS* sector using JKTEBOP with the following fitted parameters: the fractional radii of the stars (r_A and r_B) taken as the sum ($r_A + r_B$) and ratio ($k = r_B/r_A$), the central-surface-brightness ratio ($\mathcal{J}$), third light (L_3), orbital inclination (i), orbital period (P), and a reference time of primary minimum (T_0). A circular orbit provides a good fit to all data so we assumed an eccentricity of zero; experiments with a fitted eccentricity

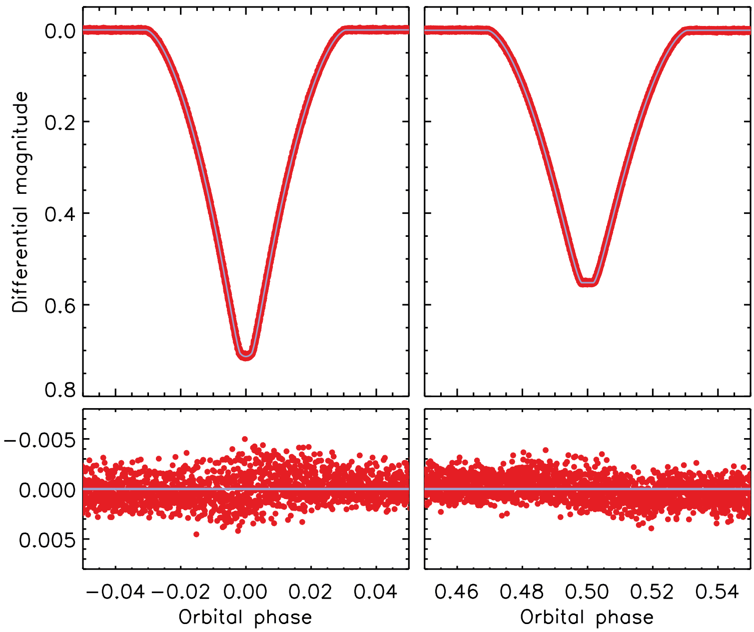

FIG. 2

JKTEBOP best fit to the light-curves of UZ Dra from *TESS* sector 84 for the primary eclipse (left panels) and secondary eclipse (right panels). The data are shown as filled red circles and the best fit as a light-blue solid line. The residuals are shown on an enlarged scale in the lower panels.

caused changes in the measured fractional radii at approximately the 0·004% level. Limb darkening (LD) was accounted for using the power-2 law[29–31], the linear coefficients (c) were fitted, and the non-linear coefficients (α) were fixed at theoretical values[32,33]. The measurement errors were scaled to force a reduced χ^2 of $\chi^2_\nu = 1{\cdot}0$. An example fit is shown in Fig. 2.

Table II lists the results of this analysis. For each parameter we took the final value and error bar to be the unweighted mean and standard deviation of the values from the individual sectors. We did not convert the standard deviation into a standard error because it is already at the limit to which we trust our photometric model for some parameters — in particular the fractional radii in JKTEBOP have been shown to be reliable to 0·1% precision[5] but not beyond.

We also calculated uncertainties using Monte Carlo simulations* to provide error bars on all parameters. The Monte Carlo error bars are smaller than the standard deviation of the values by factors of 1–3 in the case of UZ Dra, likely due to the influence of spot modulation on the light-curve fits (see below).

Fig. 3 shows the variation of the most important photometric parameters with time, with one data point for each *TESS* sector. The small variation in the parameters is striking, confirming the reliability of the solutions for UZ Dra.

*Running 500 Monte Carlo simulations for each light-curve required a total of 40 hours of computing time on a standard consumer-grade laptop.

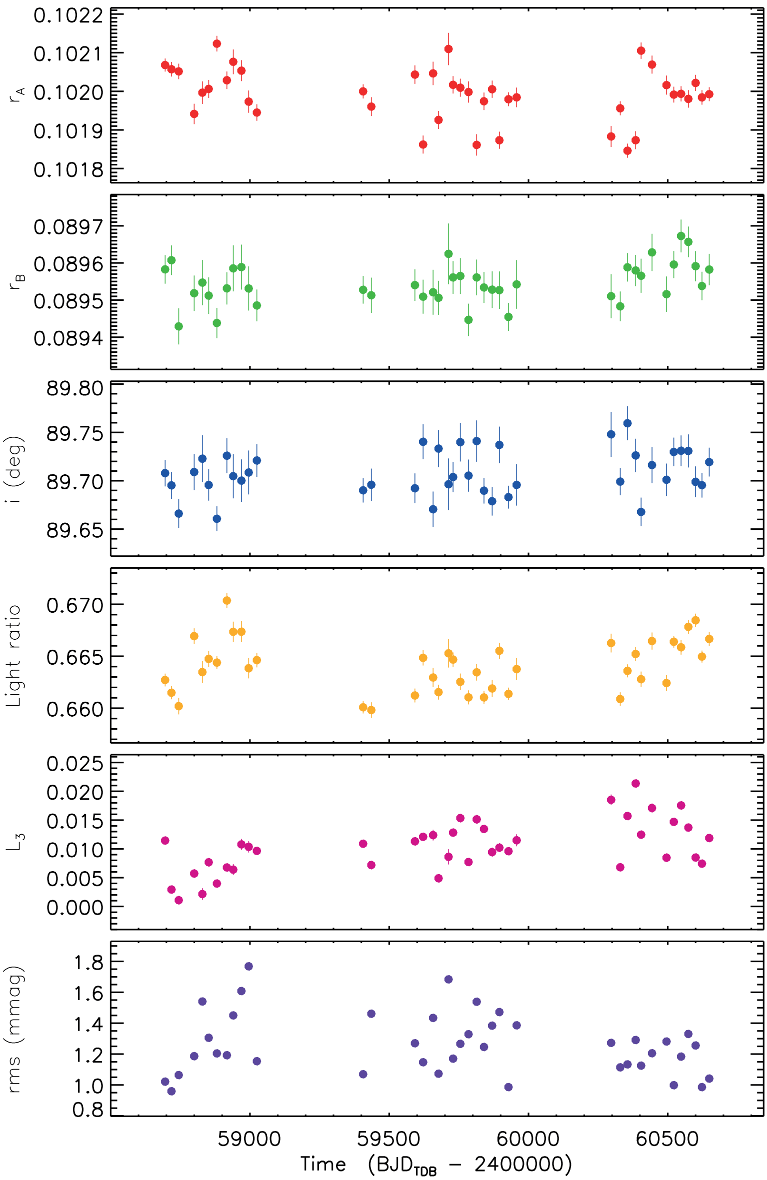

FIG. 3

The best fit to selected photometric parameters of UZ Dra from *TESS* sectors 1 to 86. The times used in the plot are those presented in the next section. The error bars are from Monte Carlo simulations.

TABLE II

Photometric parameters of UZ Dra measured using JKTEBOP *from the light-curves from all 41 TESS sectors. The error bars are standard deviations (not standard errors) of the results for individual sectors.*

Parameter	*Value*
Fitted parameters:	
Orbital inclination (°)	89·708 ± 0·024
Sum of the fractional radii	0·19154 ± 0·00009
Ratio of the radii	0·87795 ± 0·00076
Central-surface-brightness ratio	0·8582 ± 0·0051
Third light	0·0104 ± 0·0045
LD coefficient c_A	0·611 ± 0·013
LD coefficient c_B	0·0568 ± 0·025
LD coefficient α_A	0·4984 (fixed)
LD coefficient α_B	0·5237 (fixed)
Derived parameters:	
Fractional radius of star A	0·10199 ± 0·00007
Fractional radius of star B	0·08955 ± 0·00006
Light ratio ℓ_B/ℓ_A	0·6641 ± 0·0025

No significant slow variations with time are apparent. The Monte Carlo error bars underestimate the true uncertainty in the light ratio, an issue which may be caused by the spot modulation in the light-curve. The third light is not expected to be the same between sectors due to the different pixel position of UZ Dra and pixel mask used each time the telescope is re-orientated.

Orbital ephemeris

Our photometric analysis above yielded a measurement of the mean time of primary eclipse for each *TESS* sector. We fitted a linear ephemeris to these times, obtaining

$$\text{Min I} = \text{BJD}_{\text{TDB}}\ 2459677{\cdot}038365(4) + 3{\cdot}261303037(20)E \qquad (1)$$

in the barycentric rest frame, where E is the number of cycles since the reference time of minimum and the bracketed quantities indicate the uncertainty in the final digit of the previous number. The scatter around the best fit is larger than the error bars suggest, with $\chi^2_\nu = 25{\cdot}4$, likely due to the weak spot activity visible outside eclipse in most *TESS* sectors. The uncertainties in the ephemeris have been multiplied by $\sqrt{\chi^2_\nu}$ to account for this. The individual timings are given in Table III.

The deep eclipses combined with the high quality of the available data yield a very precise ephemeris: the r.m.s. scatter around the best fit is only 2·2 s, and the period is measured to within ±2 ms. We extrapolated it back to the ephemeris given by Gülmen *et al.*[19] (HJD 2446227·4238) and found that it matched to within 18 s, after correcting the HJD to BJD and converting to the TDB timescale[34]. Based on this and our timings, we see no evidence for nonlinearity in the orbital ephemeris. A more robust approach would require assembling the many published times of minimum for UZ Dra, which is beyond the scope of the current work.

TABLE III

Times of mid-eclipse for UZ Dra and their residuals versus the fitted ephemeris.

Orbital cycle	*Eclipse time (BJD_{TDB})*	*Uncertainty (d)*	*Residual (d)*	*TESS sector*
−301·0	2458695·386152	0·000004	0·000001	14
−294·0	2458718·215246	0·000005	−0·000026	15
−286·0	2458744·305680	0·000006	−0·000016	16
−269.0	2458799·747840	0·000006	−0·000008	18
−260·0	2458829·099615	0·000006	0·000040	19
−253·0	2458851·928689	0·000006	−0·000007	20
−244·0	2458881·280400	0·000005	0·000024	21
−233·0	2458917·154773	0·000005	0·000016	22
−226·0	2458939·983865	0·000007	0·000013	23
−217·0	2458969·335652	0·000006	0·000046	24
−209·0	2458995·426050	0·000007	0·000020	25
−200·0	2459024·777740	0·000005	0·000017	26
−83·0	2459406·350163	0·000004	0·000050	40
−74·0	2459435·701982	0·000005	0·000042	41
−26·0	2459592·244467	0·000005	0·000019	47
−17·0	2459621·596224	0·000005	0·000011	48
−6·0	2459657·470594	0·000007	0·000048	49
0·0	2459677·038369	0·000005	−0·000004	50
11·0	2459712·912675	0·000011	0·000023	51
16·0	2459729·219231	0·000005	0·000018	52
24·0	2459755·309623	0·000006	−0·000014	53
33·0	2459784·661343	0·000005	0·000022	54
42·0	2459814·013130	0·000006	0·000038	55
50·0	2459840·103558	0·000004	−0·000042	56
59·0	2459869·455257	0·000005	−0·000013	57
67·0	2459895·545631	0·000005	−0·000037	58
77·0	2459928·158697	0·000004	−0·000001	59
86·0	2459957·510395	0·000008	−0·000031	60
190·0	2460296·685987	0·000007	−0·000045	73
200·0	2460329·298995	0·000004	−0·000023	74
208·0	2460355·389387	0·000004	−0·000009	75
217·0	2460384·741110	0·000005	−0·000014	76
223·0	2460404·308962	0·000005	−0·000020	77
235·0	2460443·444577	0·000005	−0·000001	78
251·0	2460495·625437	0·000005	−0·000010	80
259·0	2460521·715823	0·000004	−0·000028	81
267·0	2460547·806279	0·000004	−0·000004	82
275·0	2460573·896693	0·000005	−0·000007	83
283·0	2460599·987162	0·000005	−0·000038	84
290·0	2460622·816217	0·000004	−0·000028	85
298·0	2460648·906647	0·000005	−0·000022	86

Radial-velocity analysis

Two prior spectroscopic studies of UZ Dra exist: that by Imbert[20] and L89. The former obtained and analysed 40 RVs for star A and 39 for star B, using the *Coravel* spectrometer. The latter found that Imbert's results were slightly but significantly discrepant with their own measurements, based on 16 high-resolution spectra. This claimed disagreement is sufficient justification for us to revisit the RVs, both sets of which are tabulated in the respective papers.

We first digitized the Imbert RVs then performed two fits with JKTEBOP, one with the same systemic velocity for both stars (V_γ) and one with a systemic velocity per star ($V_{\gamma,\mathrm{A}}$ and $V_{\gamma,\mathrm{B}}$). In both cases we fitted for K_A, K_B, and an

TABLE IV

Spectroscopic orbits for UZ Dra from the literature and from the current work. In each case two sets of orbits are given: where the systemic velocity for the two stars are forced to be the same or allowed to differ. The adopted result is based on all RVs and different systemic velocities. All velocities are given in km s^{-1}.

Source	K_A	K_B	$V\gamma$	$V\gamma_{,A}$	$V\gamma_{,B}$	σ_A	σ_B
Imbert[20]	92·73±0·46	100·51±0·46	−15·29±0·25			1·6	2·5
L89	94·3±0·5	102·6±0·7		−15·6±0·4	−16·8±0·6	1·4	2·0
This work (Imbert RVs)	92·87±0·34	100·50±0·54	−15·45±0·22			1·63	2·57
This work (Imbert RVs)	92·87±0·36	100·52±0·55		−15·71±0·26	−14·80±0·40	1·61	2·48
This work (L89 RVs)	93·96±0·46	102·05±0·64	−15·99±0·31			1·30	1.97
This work (L89 RVs)	94·02±0·48	102·55±0·68		−15·64±0·37	−16·73±0·56	1·28	1·87
This work (all RVs)	93·43±0·28	101·13±0·43	−15·69±0·20			1·61	2·55
This work (all RVs, adopted)	93·40±0·30	101·03± 0·44		−15·84±0·21	−15·33±0·34	1·60	2·50

offset from our ephemeris above (which turns out to be negligible), and assumed a circular orbit. All error bars were obtained using 1000 Monte Carlo simulations[35]; the error bars in the systemic velocities do not account for any systematic bias due to transformation onto a standard system. The two solutions are very similar (Table IV), and confirm the numbers presented by Imbert[20].

We then undertook the same analysis for the RVs from L89. An identical picture emerged: a good agreement between our two solutions and the values given by L89. The phase offset was also negligible, a relevant point because the time-stamps of the RVs are tabulated to only three decimal places (a precision of 86 s) in L89. We therefore confirmed the small but significant discrepancy between the two sets of measurements.

Faced with this choice, L89 opted to use only their own RVs on the basis that previous work by these authors had given results in good agreement with independent measurements for several dEBs. We have used RVs from Claud Lacy several times in the current series of papers: for ZZ UMa[36,37], IT Cas[38,39], IQ Per[40,41], and MU Cas[42,43]. Similarly, we have in the past been happy to adopt RVs from Imbert for AN Cam[44,45] and ZZ UMa[46,37]; the two sources agreed well in the case of ZZ UMa.

We have therefore chosen to adopt spectroscopic orbits from the combined RVs for the remainder of our analysis. Neither source gives uncertainties for their RVs, so we specified uncertainties that give $\chi^2_\nu = 1{\cdot}0$ for each of the four data sets (two per star). Our adopted fit has separate systemic velocities for the two stars, is shown in Fig. 4, and its parameters are given in Table IV. It is, unsurprisingly, intermediate between the spectroscopic orbits from Imbert[20] and L89.

Physical properties and distance to UZ Dra

We calculated the physical properties of UZ Dra using the JKTABSDIM code[48] with the photometric properties from Table II, and the K_A and K_B from the previous section. The orbital period was corrected to the rest frame of the system using a systemic velocity of –15·5 km s^{-1}. The masses are measured to 0·9% precision, and the radii to 0·3%. The radii agree to within approximately 1σ with the measurements from L89, but the masses are slightly lower due to the choices made in the RV analysis. We adopted the effective temperatures of

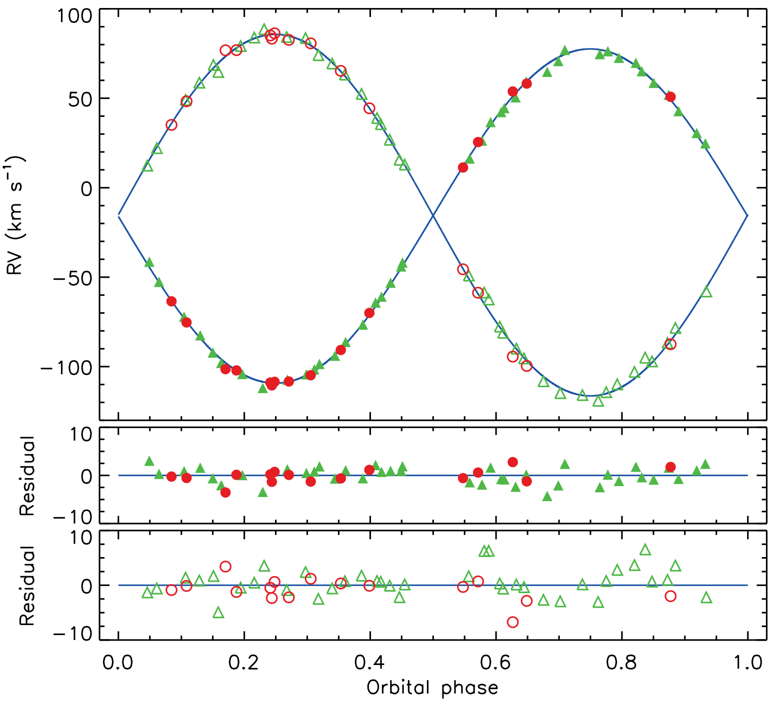

FIG. 4

RVs of UZ Dra compared to the best fit from JKTEBOP (solid blue lines). The RVs for star A are shown with filled symbols, and for star B with open symbols. The residuals are given in the lower panels separately for the two components. RVs from Imbert[20] are shown with green triangles, and those from L89 with dark-red circles.

the stars of 6450±120 K and 6170±120 K, from Graczyk *et al.*[23]. These are significantly higher than the 6200±120 and 5985±110 K given by L89 (see below for justification). For both sets of temperatures, their ratio is in good agreement with the central-surface-brightness ratio in Table II.

The synchronous rotational velocities in Table V are consistent with the projected rotational velocities measured by L89. Inspection of the residuals of the JKTEBOP fits shows that the spot modulation occurs on the orbital period of the system (see next section). We conclude that the system is tidally circularized and rotationally synchronized. There is no evidence for pulsations in the available data.

We determined the distance to UZ Dra using the *BV* magnitudes from *Tycho*[8] catalogue and JHK_s magnitudes from 2MASS[9] given in Table I. We used the surface-brightness calibrations from Kervella *et al.*[49] and found that an interstellar reddening of $E(B-V) = 0{\cdot}02 \pm 0{\cdot}01$ mag was needed to bring the *BV*-based distance measurements into agreement with those from JHK_s. The best distance estimate is 185·7±2·4 pc, which is in excellent agreement with the

TABLE V

Physical properties of UZ Dra defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 47).

Parameter	*Star A*	*Star B*
Mass ratio M_B/M_A	0·9244 ± 0·0050	
Semi-major axis of relative orbit ($R^N_\odot$)	12·533 ± 0·0034	
Mass ($M^N_\odot$)	1·291 ± 0·012	1·193 ± 0·009
Radius ($R^N_\odot$)	1·2783 ± 0·0036	1·1224 ± 0·0032
Surface gravity (log[cgs])	4·3356 ± 0·0020	4·4145 ± 0·0015
Density ($\rho_\odot$)	0·6178 ± 0·0020	0·8438 ± 0·0029
Synchronous rotational velocity (km s^{-1})	19·830 ± 0·056	17·411 ± 0·049
Effective temperature (K)	6450 ± 120	6170 ± 120
Luminosity $\log(L/L^N_\odot)$	0·406 ± 0·032	0·216 ± 0·033
M_{bol} (mag)	3·724 ± 0·081	4·200 ± 0·085
Interstellar reddening $E(B-V)$ (mag)	0·02 ± 0·01	
Distance (pc)	185·7 ± 2·4	

185·39±0·39 pc from the *Gaia* DR3 parallax[10]. In contrast, the temperatures from L89 give a shorter distance and need a slightly negative interstellar reddening to equalize the optical and IR distances.

We compared the measured masses, radii, and temperatures of the stars to theoretical predictions from the PARSEC 1·2 evolutionary models[50]. The best match occurs for an age of 600±200 Myr and a slightly super-solar metal abundance of $Z = 0{\cdot}020$. Thus UZ Dra is a relatively young dEB.

Stellar activity

We obtained a spectrum of the Ca II *H* and *K* lines of UZ Dra to search for evidence of emission caused by chromospheric activity, with the *Intermediate Dispersion Spectrograph* (*IDS*) at the Cassegrain focus of the *Isaac Newton Telescope* (*INT*). A single observation with an exposure time of 500 s was obtained on the night of 2022/06/07 in excellent weather conditions. We used the 235-mm camera, H2400B grating, EEV10 CCD, and a 1-arcsec slit and obtained a resolution of approximately 0·05 nm. A central wavelength of 4050 Å yielded a spectrum covering 373–438 nm at a reciprocal dispersion of 0·023 nm px^{-1}. The data were reduced using a pipeline currently being written by the author[53], which performs bias subtraction, division by a flat-field from a tungsten lamp, aperture extraction, and wavelength calibration using copper-argon and copper-neon arc lamp spectra.

The spectrum (Fig. 5) was obtained at orbital phase 0·887, when the RV difference of the two stars was 126 km s^{-1} (0·17 nm). When compared to a composite synthetic spectrum without chromospheric activity[51,52], the infilling of the *H* and *K* lines is clear. The velocity difference of the two stars is resolved and both show chromospheric emission, most obviously in the *K* line at 393·4 nm.

The *TESS* light-curves show brightness modulations due to starspot activity, visualized in Fig. 6. It can be seen that the variations are on a period consistent with the orbital period of the system, which in the previous section was interpreted as an indicator of rotational synchronization. The variations evolve on a time-scale of roughly two to three times the orbital period and have an amplitude of up to 0·006 mag.

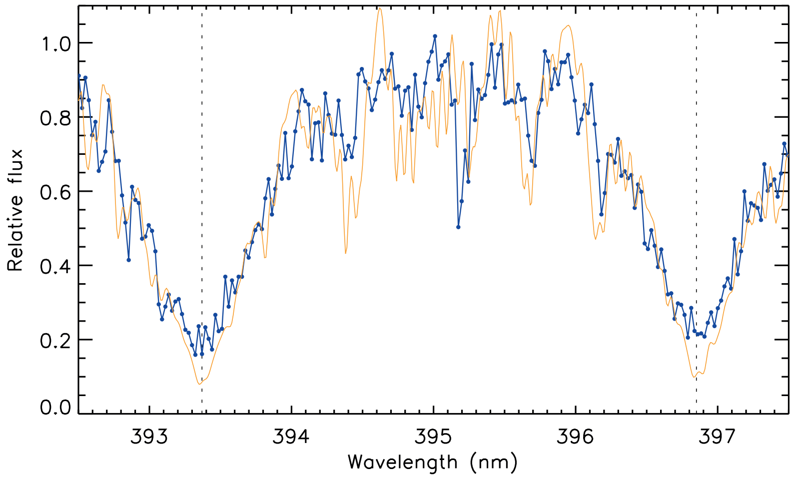

FIG. 5

Comparison between the observed spectrum of UZ Dra and a synthetic spectrum around the Ca II *H* and *K* lines. The observed spectrum has been shifted to zero velocity and normalized to approximately unit flux (blue line with points). The synthetic spectrum is for $T_{\rm eff} = 6450$ K, log $g = 4{\cdot}3$, and solar metallicity from the BT-Settl model atmospheres[51,52] (orange line). A composite synthetic spectrum has been made by duplicating and shifting the original one to the velocities of the two components of UZ Dra then adding them using the light ratio from Table II.

Summary and conclusions

UZ Dra is a dEB containing two late-F stars in a circular orbit with a period of 3·261 d. The most interesting features are total eclipses and a plethora of photometry from *TESS*, which together allow the radii of the stars to be obtained to very high precision. The light-curves also show starspot modulation on the orbital period, indicating the stars are tidally synchronized. We see no evidence for pulsations, orbital eccentricity, or changes in the orbital period.

Two sets of RVs have been published for UZ Dra, and they lead to slightly different measurements for the masses of the components. We are not aware of a reason to prefer one set over the other, so instead combined them to obtain spectroscopic orbits intermediate between the two sets. The uncertainties in $K_{\rm A}$ and $K_{\rm B}$ dominate those in both the mass and radius measurements. *Gaia* Data Release 4 (DR4*) is expected to provide extensive new RVs and thus a casting vote over which set of RVs to use (if either).

The photometric properties of UZ Dra are now extremely well-determined, although the spectroscopic orbits are not. New spectroscopic observations would be useful in determining the photospheric temperatures and chemical abundances of the component stars. The duration of totality is approximately 17 minutes, so a carefully-scheduled observation at secondary eclipse could record the spectrum of star A without contamination by star B.

*https://www.cosmos.esa.int/web/gaia/data-release-4

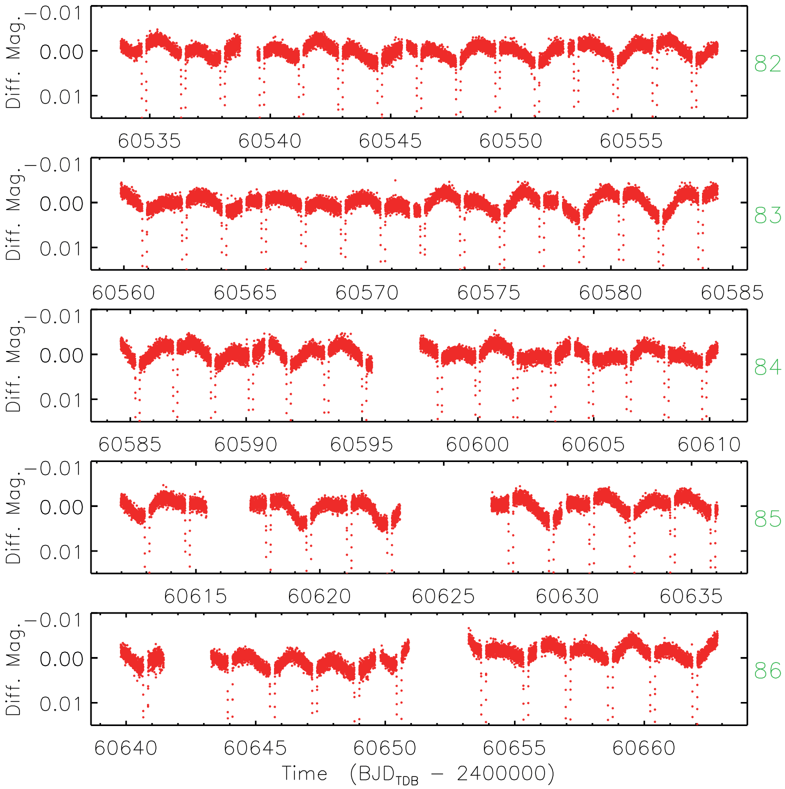

Fig. 6

Differential-magnitude light-curve of UZ Dra from sectors 82 to 86 (labelled on the right of each panel). The *y*-axis has been chosen so the out-of-eclipse variation due to starspots is clear.

Acknowledgements

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This paper includes observations made with the *Isaac Newton Telescope* operated on the island of La Palma by the Isaac Newton Group of Telescopes in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

This work has made use of data from the European Space Agency (ESA) mission *Gaia**, processed by the *Gaia* Data Processing and Analysis Consortium (DPAC†). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. The following resources were used in the course of this work: the NASA Astrophysics Data System; the *Simbad* database operated at CDS, Strasbourg, France; and the arχiv scientific paper preprint service operated by Cornell University.

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REVIEWS

Einstein in Oxford, by Andrew Robinson (Bodleian Library Publishing), 2024. Pp. 96, 20·5 × 13·5 cm. Price £16·99 (hardbound; ISBN 978 1 85124 638 0).

Ulm, Zurich, Bern, Prague, Berlin, Princeton. Most readers will immediately think of Einstein when encountering the names of those cities in which he lived. But Oxford? Einstein never lived in Oxford, but it is a place which he visited several times, first on his first trip to England in 1921 when he lectured in Manchester and London but also visited Oxford due to the invitation of Frederick Lindemann, professor of experimental philosophy (*i.e.*, physics). He returned at Lindemann's invitation in 1931, 1932, and 1933. Born in Germany, Lindemann was brought up and educated in England, though he returned temporarily to Germany in his teens for some schooling. He thought of himself as more English than the English and, in contrast to Einstein, had very conservative political views, but at the same time great respect for Einstein's science and for him as a person. On the same day I bought this book, just across the street I also saw the famous Einstein blackboard (which contains some mistakes) in the History of Science Museum (whose director, Silke Ackermann, one of many German-born English residents mentioned in this review, provides a foreword), which dates from his Rhodes Lecture in 1931 (which finally took place after several attempts since 1927 to attract Einstein back for a second visit); during that visit Einstein also received an honorary doctorate (with an oration in Latin, putting him into a similar situation as that of those who couldn't understand his lectures in German). The book's preface discusses the blackboard and the first chapter Lindemann and his invitations.

Chapter two discusses aspects of Einstein's work relevant to his 1933 Herbert Spencer lecture. When visiting Oxford, Einstein (sometimes living in Lewis Carroll's former quarters) also indulged his interests besides science, especially music. As the third chapter describes, that was well documented by Margaret Deneke (whose parents had been born in Germany; her mother was also a close friend of Clara Schumann). In addition to playing a borrowed violin, Einstein also sat for a portrait and, in 1933, gave the Deneke lecture on atomic theory. The fourth chapter explores other aspects of Einstein in Oxford, such as writing a (perhaps Carroll-inspired) poem about himself, appearing in a stained-glass window, and Lindemann's attempts to get Einstein elected as a Fellow of Christ

Church, hoping that he would spend a month or so each year there in return for a stipend of £400. He was indeed elected (on 1931 October 21), but Lindemann had to deal both with protests about money going to foreigners and with the tax office. His life in Oxford was not dissimilar to that in Germany, spending time sailing, walking, dealing with female admirers, and discussing politics.

The final chapter discusses Einstein as a refugee from Nazi Germany, making use of his Oxford connections to spend some time there in 1933, arriving from Belgium. Although Einstein noted that his connections with Oxford had grown stronger, he returned to Belgium *via* Glasgow and never came back to Oxford. He did return to England, though, discussing politics with Churchill and later, after hearing of assassination threats in Belgium, hid out alone for a while in rural Norfolk, guarded by Commander Oliver Locker-Lampson. On 1933 October 7, joined by his wife, Einstein boarded a ship in Southampton bound for New York. He never returned to Europe.

The book contains many quotations*, the sources for which appear on seven pages of the now-default small print, followed by two pages with a wide range of suggestions for further reading, a page of acknowledgements, and a three-page index. Robinson has written several books on a wide range of topics, including two others on Einstein; this one is well written and almost free of typos and questionable matters of style. This book provides an interesting glimpse of times and places often mentioned just briefly if not at all in other accounts of Einstein's life. (For an interesting collection of better-known anecdotes, see another book[1] reviewed[2] here not long ago.) Black-and-white pictures of Einstein (and others) in Oxford as well as of his poem (and its translation into English) and of Einstein in a stained-glass window, like William Golding (who was an undergraduate in science before switching to literature and wished that he knew more German) describing his chance meeting with Einstein on a bridge, bring Einstein in Oxford to life. Recommended for those who are interested in more detail on this aspect of Einstein's life, with only a cursory discussion of his science. — Phillip Helbig.

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A Crack in Everything: How Black Holes Came in from the Cold and Took Cosmic Centre Stage, by Marcus Chown (Head of Zeus), 2024. Pp. 350, 20 × 13 cm. Price £12·99 (paperback; ISBN 978 1 80454 433 4).

The late, great Leonard Cohen isn't mentioned directly (nor, as far as I can tell, indirectly) in the book, so I don't know if the title is intended as an allusion ("There is a crack in everything. That's how the light gets in") or is just an illusion. In any case, this book by former Caltech radio astronomer and prolific popular-science writer Marcus Chown is one of a large number of books on black holes, some of which I've reviewed in these pages. Although there is often little overlap between those which I had already read, I asked

*The one on p. 62 contains a sentence starting with "Then in spite of his scientific position he is a poor man", perhaps the first time I have seen 'then' used where today one would use 'for', though the usage was clear due to it being cognate with the German '*denn*', which is used only in that sense. ('Then' in the sense of 'after' is '*dann*'.)

myself whether another book is still needed. The answer is yes. While this book covers relatively standard topics, there is much more emphasis on the scientists involved, often based on interviews (some by the author himself). Many of the topics will be obvious just from the names: Schwarzschild, Chandrasekhar, and Kerr occupy the first three chapters. The fourth concerns Cygnus X-1 (the first black hole detected, by Paul Murdin and Louise Webster) while the fifth takes in several related topics: the discovery of quasars by Schmidt (not neglecting the roles played by colleagues such as Sandage, Oke, and Greenstein), the early efforts of Jansky and Reber, and AGN in general. Although most have heard of Ghez and Genzel in the context of supermassive black holes (SMBH), the corresponding chapter here, before telling their stories, goes into some detail on what came before, a story involving several people working independently or in groups. Once it was clear that supermassive black holes exist, it made sense to try to detect them, with gravitational waves and *via* the *Event Horizon Telescope* (*EHT*); in each case, such detection was possible only *via* a very large collaboration. Primarily observational so far, the ninth chapter delves into the mathematical theory of black holes and modern topics such as holography, the black-hole information paradox, and AdS/CFT correspondence*, but also the formation of the first stars, galaxies, and black holes. The final chapter is a summary of the others except 7 and 8 (gravitational waves and the *EHT*) and also asks whether the Weak Anthropic Principle could explain the relatively low mass of the SMBH in the Milky Way.

Although in all the chapters the scientists feature more strongly than in most books on the topic, they feature more strongly in the earlier chapters than in the later ones (the chapters are more or less in chronological order). Chown not only gets right what some authors got wrong (*e.g.*, Schwarzschild did serve (voluntarily) in World War I but, although he did think about General Relativity then, he did not die in the trenches, but rather after being discharged due to contracting *Pemphigus vulgaris*), but also provides information not easily found elsewhere (*e.g.*, Schwarzschild served not only on the eastern front (which is often mentioned), but also on the western front, and it was in Mulhouse in Alsace (modern north-eastern France) where he first became ill and also from where he corresponded with Einstein).

There are about the usual number of typos and (in my view) questionable style choices as well as a few minor careless errors, but on the whole the book is well written. All the same, Bethe is referred to as an American in the context of work done in 1938, which might be acceptable considering that he arrived there in 1935.† However, Lense, Thirring, and Boltzmann were by any sensible definition Austrian, not German. There are no figures; a few footnotes provide supplementary information; 'endnotes' are references cited in the text; there is a 16-page small-print index.

* Recycling a footnote from an earlier review: AdS/CFT correspondence refers to a popular (more than twenty thousand citations to Maldacena's original paper[1]) conjecture concerning the duality between anti-de Sitter spaces as used in some quantum-gravity theories and conformal field theories which describe elementary particles.

† Nationality is perhaps not well defined in the case of people who live in a country other than that in which they were born, whether or not that is voluntarily and whether or not there is any change in citizenship status, a point made several years ago by Simon Rattle when conducting the Berlin Philharmonic, introducing a piece by the *English* composer Handel (who did become a naturalized British subject in 1727). (In 2021, Rattle became a German citizen in order to be able to work more easily in the EU after Brexit.)

Not only does the book concentrate more on the scientists than do similar books, it also goes beyond the usual familiar narratives, giving credit where it is due and providing more background, and should be valuable to anyone interested in an accurate but non-technical history of astrophysical black holes. — PHILLIP HELBIG.

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The Beauty of Falling: A Life in Pursuit of Gravity, by Claudia de Rham (Princeton University Press), 2024. Pp. 231, 22·5 × 14·5 cm. Price £49·99/$64·99 (hardbound; ISBN 978 0 691 23749 7).

In this book, Swiss-born Claudia de Rham, now a professor at Imperial College, mixes descriptions of her work on gravitation with that of her (initially very successful but ultimately failed) quest to become an astronaut as well as those of other details of her life (*e.g.*, her childhood in several countries, learning her native language French from a Swedish mother in Peru, managing two careers in gravitational physics with her husband Andrew Tolley and their three daughters). The personal details are strewn throughout the book, which is best described as an introduction to the physics of gravitation together with a summary of modern developments, in particular those in which she has been involved (especially massive gravity). Seven chapters cover Special Relativity and the equivalence principle; curvature; tides and gravitational waves; singularities (after more details on her quest to become an astronaut, foiled by a positive test for latent tuberculosis, probably from her time in Madagascar); dark matter, dark energy, vacuum energy, and the cosmological-constant problem; massive gravity (*i.e.*, a theory in which the graviton has a non-zero rest mass); and (possible) tests of massive gravity; a short concluding chapter ends the main part of the book, followed by a two-page bibliography (mostly technical papers) and an eleven-page index, both in small print. There are a few black-and-white diagrams and photos scattered throughout the book (including one of the Einstein equation as graffiti on an abandoned locomotive in Bolivia) and fortunately footnotes rather than endnotes.

Of the many books I've read on General Relativity (GR), this is probably the best non-technical description (there are only very few equations, usually not part of the main narrative) — as simple as possible, but not simpler*. That is partly because she isn't attempting too much, but rather concentrating on aspects which lead up to her own work; it is also because she does a very good job describing a rather technical topic. (Qualitative analogies are always misleading at some level, but she emphasizes the weaknesses of some common qualitative descriptions of GR without finding them totally worthless.) The description of her own work on massive gravity bridges the gap between purely qualitative descriptions and the technical literature; we meet ghosts, extra dimensions, and types of gravitational-wave polarization which don't exist in unmodified GR. However, a common mistake is repeated, namely that Eratosthenes

*A saying attributed to Einstein, who at least said something similar.[1]

demonstrated that the Earth is round. (In fact, his method of measuring the circumference of the Earth requires two assumptions: that the Earth is round and that the Sun is far enough away for its light to be considered parallel. An observer on a flat Earth would see a nearby Sun at a different height above the horizon at noon depending on 'latitude'.) Some order-of-magnitude estimates appear to be wrong probably due to typos or bad editing, but I can't figure out how she could conclude that two astronauts initially one metre apart would, due to their mutual gravitational attraction, be moving as fast as garden snails after only a few milliseconds. (The point was to demonstrate the weakness of gravity; fortunately it is so weak that overestimating it by several orders of magnitude still results in a relatively weak force.) It would have been nice to know why she thinks that the Universe is probably infinite.

Despite my minor quibbles this book was a very enjoyable read and for some could be a good first book on GR, giving not only a broad overview but also highlighting current work in the field and, *via* both unsolved puzzles and the author's own enthusiasm, explaining the beauty of falling for gravity. — Phillip Helbig.

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Space Oddities: The Mysterious Anomalies Challenging Our Understanding of the Universe, by Harry Cliff (Picador), 2024. Pp. 285, 19·5 × 13 cm. Price £10·99 (paperback; ISBN 978 1 5290 9288 2).

Harry Cliff is a particle physicist at the University of Cambridge working on the *LHCb* experiment at CERN. This is his second popular-science book, and his interest in outreach also led to a joint post between Cambridge and the Science Museum in London (2012–2018).

Although David Bowie is not mentioned in the book, the title is an obvious nod to one of his songs. However, not all of the oddities concern space (*i.e.*, astrophysics); there are also chapters on anomalies in particle physics as well as in the overlapping field of astroparticle physics. The book begins with a quote from my childhood hero Isaac Asimov: "The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka' (I found it!) but 'That's funny...'." Or, as Robert Pirsig put it, "The TV scientist who mutters sadly, 'The experiment is a failure; we have failed to achieve what we had hoped for', is suffering mainly from a bad scriptwriter."[1] After a prologue discussing anomalies in general *via* some specific examples — explored in more detail later — and the first chapter on the standard model of cosmology, Cliff takes us on a tour of about a dozen anomalies, starting with two, the anomalous precession of the perihelion of Mercury and the Lamb shift, the resolution of both of which turned out to be new physics (resolution (*a*)). If theory and experiment disagree, there are three possible explanations other than new physics: a mistake in the experiment (*b*), a mistake in the theoretical prediction (*e.g.*, a mathematical error or failing to take a significant effect into account) (*c*), or a statistical fluke (*d*).

The third chapter discusses, in addition to some background on statistics, two claimed detections which do not point to new physics: the *BICEP2* debacle (which was very bizarre but more or less falls into (*c*), though not for the usual reasons) and the *DAMA/LIBRA* experiment (for the direct detection of dark-matter particles in an underground laboratory), which presumably falls into (*b*) because other experiments, including one designed to match *DAMA/LIBRA* closely, have failed to confirm the result. We then move to the story of Linda Cremonisi and *ANITA*, which is a detector mounted on a balloon above Antarctica the purpose of which is to detect radio waves from neutrinos impacting the ice below. *ANITA* can also detect cosmic rays, and the anomaly is one which seems to have travelled through the Earth to emerge from the Antarctic ice. Here, the resolution is not yet clear, but since the *IceCube* detector (photomultipliers in holes drilled into the Antarctic ice) hasn't corroborated the findings, it looks unlikely to indicate new physics.

The unexpected value of the magnetic moment of the muon is an anomaly of which perhaps many have heard. At first, the results from the measurement of the *Muon g-2* experiment increased the discrepancy between theory and experiment. The jury is still out, but there are indications that (*c*) could be the answer here, with more precise calculations involving hadronic vacuum polarization bringing theory in line with experiment. Like the previous chapter on *ANITA*, this one has many details of the day-to-day life of those doing such experiments. The story of neutrino oscillations being the answer to the solar-neutrino problem is perhaps the most recent example of new physics beyond what was then the standard model of particle physics.* That neutrino problem is solved, but another discrepancy between theory and experiment remains unsolved; the rest of the chapter discusses work by Bonnie Fleming and Chris Polly (who was also involved in the *Muon g-2* experiment), again a mixture theory, experiment, and the people involved.

The longest chapter, describing the author's own work, involves anomalies regarding the decay of B-quarks into muons. The resolution here is (*d*). While such a resolution is easy to effect in principle (just get more data), in practice it can consume the careers of several people. It's nice to have a detailed description of an anomaly which went away for a non-dramatic reason, as history tends to concentrate on the spectacular successes (and spectacular failures such as *BICEP2*). Somewhat more familiar to readers of this *Magazine* is the Hubble tension†, the discrepancy between different measurements of H_0, the value of the Hubble constant today, mostly between the value measured *via* 'local' sources such as type-Ia supernovae and the value predicted from the CMB. (The CMB doesn't measure the Hubble constant 'directly'; it is a derived parameter. However, that it can be measured at all involves assuming some cosmological model and calculating what the value should be today based on what is observed at the time of last scattering.) Some who remember when the debate was between values of 50 and 100, as opposed to 67 and 73, though with relatively smaller (claimed) error bars in the latter case (roughly, 1 per cent as opposed to 10 per cent), assume that the current Hubble tension will just go

*Although the mystery wasn't cleared up until 2001 when the results from the *Solar Neutrino Observatory* confirmed indications from *Super-Kamiokande* that the missing electron neutrinos had turned into mu and tau neutrinos (resulting in the PIs of those experiments, Arthur McDonald and Takaaki Kajita, receiving the 2015 Nobel Prize in Physics), in 1994 I had asked John Bahcall (who spent a large portion of his very prolific life on the solar-neutrino problem) at a conference whether he thought the resolution would be a problem with the experiments (*b*) or a mistake in theory such as inaccurate models of the Sun (*c*); he was confident even then that the answer would be new physics (*a*).

†Expect a review of an entire book about the Hubble tension in the next issue[2].

away, like many other anomalies. However, there are important differences. Fifty years ago, the value depended more on the astronomers than on the method, while these days it seems that the difference is due to the method (though of course different groups of people are experts on each method). My own impression is that all involved have also investigated the matter more closely, both their own work and that of those working on the other method. (There is also some tension between various groups working on 'local' methods; Chapter 8 highlights Adam Riess working with type-Ia supernovae (which he also used to measure the acceleration of the Universe, receiving a quarter of the 2011 Nobel Prize in Physics) and Wendy Freedman using the tip of the red-giant branch as standard(izable) candles.) Due to the large amount of data available and the fact that the tension seems to be increasing with time, (*d*) is probably not an option. If (*a*) is an option, that would indicate that something is wrong with the standard model of cosmology, in particular CMB physics. To me, though, that sounds unlikely, as that is well tested in other ways. With multiple observations, (*b*) doesn't look very likely either, though that might be the answer to the tension between various 'local' methods. Option (*c*) is a non-starter because there is no theory which can predict the brightness of standard(izable) candles to sufficient accuracy; those that are used are calibrated. The jury is still out on this one. (My best guess is (*c*) in the sense that a more realistic theoretical model could solve the problem, namely that our local part of the Universe is relatively under-dense. That doesn't seem to be a very popular idea, perhaps because it contains no new physics.)

The last of the main chapters introduces the σ_8 tension, though that rather technical term is not used. Basically, some measurements, especially those using the slight distortions of background galaxies due to weak gravitational lensing by foreground matter, indicate that the Universe is less clustered than one might expect from theory or indeed from other observations. (Actually, weak lensing measures a somewhat degenerate combination of the clumpiness parameter σ_8 and the density parameter Ω, so one could also say that the value of Ω from lensing is too low and σ_8 as expected. However, other constraints on Ω are stronger than those on σ_8.) It's unclear what the resolution will be. Since lensing is sensitive to all matter, not just that which is visible, perhaps luminous matter is more clumped relative to dark matter than in the standard model (in which, however, luminous matter is already more clustered than dark matter, a phenomenon going by the name of bias). This chapter ends with the discussion of the BOAT: the Brightest Of All Time gamma-ray burst. The short summary chapter starts off with a brief description of perhaps the most productive anomaly of all time, 'A Measurement of Excess Antenna Temperature at 4080 Mc/s'[3] and concludes with the author's look back on anomalies in physics, not just those mentioned in the book.

After a couple of pages of acknowledgements, the book ends with three pages of 'Notes', which are sources for information in the text, listing the corresponding page. They are not cited in the text, though. There are no figures, no index, and just a few footnotes. I didn't notice any serious mistakes and the number of typos and so on is somewhat less than is usually the case for similar books. (I did chuckle a bit after wrongly parsing a sentence: "A few weeks later, I flew to CERN for the first time after the pandemic had begun to present our results to the outside world.") I really enjoyed reading this book, which takes a somewhat different approach than most popular-science books *via* the scarlet thread of anomalies rather than being about some more or less clearly defined topic. Although of course all the anomalies are documented elsewhere, it's nice to have some of them (there are more, such as the puzzle of different methods to measure the half-life of the neutron giving different values) collected together and presented in a lively manner by someone involved in one of them, already knowledgeable about some others, and having well researched those outside of his field. — Phillip Helbig.

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(1) R. Pirsig, *Zen and the Art of Motorcycle Maintenance* (William Morrow and Company), 1974.
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From the Library

A Fire on the Moon, by Norman Mailer (Penguin Classics), 2014 (originally published 1970 by Little, Brown and Company). Pp. 421 (including 8-page introduction by Geoff Dyer), 20 × 13 cm. Price £10·99 (paperback; ISBN 978 0 141 39496 1).

Yes, *that* Norman Mailer (1923–2007), the great American novelist (by whom I've read one other book[1]). With a degree in aeronautical engineering (Harvard, 1943) and already a reputation as both journalist and novelist, Mailer was certainly qualified to write about the *Apollo 11* mission. The book (finished when *Apollo 13* was returning to Earth) is an expanded version of a three-part series in *Life* magazine, for which Mailer was paid somewhat less than $450 000 ("this ... figure, while certainly too generous, was not vastly inaccurate"). By contrast, in 1969, Armstrong, as a civilian, was paid an annual salary of $27 401, Aldrin and Collins (both Air Force officers) $18 623 and $17 148, respectively (multiply by a factor of 8 or 9 for the modern equivalents). As expected, the book is well written, sometimes reminding me of Dickens, Whitman, or Ginsberg. Mailer (who refers to himself as Aquarius) appears as a character in the book, much of which is in the New Journalism style.

Taking the number of pages and the small size of the print into account, there is very much information in the 15 chapters (grouped into three parts): technical information about the space programme, comments on the social and political situation at the time, long quotations from the radio communications between the astronauts and Mission Control, the geography and hotels of Florida and Texas, contemporary news coverage, and so on, all written essentially as the story unfolded. The first part sets the stage with a broad-brush overview and contains more on Mailer's own perceptions and activities; the second (making up about half of the book) is a detailed chronological account from lift-off to the docking of *Eagle* and *Columbia* after ascent from the Moon; the third (and shortest) includes the splashdown and related events but is more concerned with Mailer's philosophical reflections on the event. Mailer tells the story like a modern myth, except that it really happened. As one of the most significant events of the 20th (or perhaps any) Century, much has been written about *Apollo 11*, both from a technical and from a sociopolitical point of view. Mailer manages to cover both areas seamlessly, and is equally at home whether writing about how liquid oxygen is cooled and transported or about contemporary politics (also in 1969, Mailer finished fourth of five in the Democratic primary for mayor of New York City). As mentioned in another review[2], though I was young at the time I have many clear memories of the Apollo programme, which jibe well with Mailer's much more detailed account. (I noticed only a couple of minor mistakes, almost certainly essentially just typos.)

Already at the time, there were suggestions that the Moon landing was fake, and Mailer debunks them. There are other prescient inklings of what was to become the future: "[c]omputers the size of a package of cigarettes"; the rather quick loss of interest in even such a substantial feat, with "[T]he horror of the Twentieth century [being] the size of each new event, and the paucity of its reverberation". Although many aspects of the book are impressive, perhaps the most impressive is the scope, from the Greek myths through the *Star Trek*-style technical optimism of the 1960s to the different ways (then) future (and now current) society would look back on such a monumental event. The book is not just historical but might prove to be historic, a rare first-hand account of history in the making where the witness understands both the nitty-gritty details and the vast sweep of human history of which it is a part. — PHILLIP HELBIG.

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(1) N. Mailer, *Ancient Evenings* (Little, Brown and Company), 1983.
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ASTRONOMICAL CENTENARIES FOR 2026

Compiled by Kenelm England

The following is a list of astronomical events whose centenaries fall in 2026. Births and deaths of individual astronomers are taken from *Biographical Encyclopedia of Astronomers* (2nd ed., Springer, 2014). This was supplemented by the on-line Obituary Notes of Astronomers and Obituary Lists of RAS Fellows and other societies. For events before 1600 the main source has been Barry Hetherington's *A Chronicle of Pre-Telescopic Astronomy* (Wiley, 1996). For the 17th to 20th Centuries lists of astronomical events came from Wikipedia and other on-line sources, supplemented by astronomical texts made available through the NASA Astrophysics Data System. Discoveries of comets, asteroids, novae, and other objects for 1926 appeared in the February issue of *Monthly Notices of the Royal Astronomical Society* in the following year. There were also references from *Popular Astronomy*, *Journal of the British Astronomical Association*, and *Publications of the Astronomical Society of the Pacific*. Professional discoveries and observations were followed up in *Philosophical Transactions of the Royal Society of London*, *Astronomische Nachrichten*, *Astronomical Journal*, and *Monthly Notices of the Royal Astronomical Society*. Gary Kronk's *Cometography* Volumes 1–3 (Cambridge, 1999–2007) provided details on all the comets. Details on meteorites can be found in the Meteoritical Society's Bulletin Database. Finally, NASA's *Five Millennium Canons of Eclipses* and planetary tables were consulted for information on eclipses and planetary events.

1926

January 3: Death of John Tatlock. Born in 1860, an American astronomer at the Washburn Observatory, then Professor of Astronomy at Beloit College, Wisconsin; then entered insurance and banking; member of the American Astronomical Society; FRAS 1892.

January 9: Death of Thomas Allison. Born in 1858, a New Zealand farmer with an interest in photography and astronomy; FRAS 1920; observed the annular solar eclipse of 1925 July.

January 12: Several predictions were made for the return of Periodic Comet Tuttle in 1926. It was recovered by Wilhelm Heinrich Walter Baade (Bergedorf Observatory, Hamburg) at magnitude 15·5. The comet slowly brightened to magnitude 14 in March and was last observed by Richard Reinhard Emil Schorr (Bergedorf Observatory) as a 12th-magnitude object on April 12. It reached perihelion on April 28 (q = 1·0309 AU) but was not recovered in the Southern Hemisphere [Comet 8P/Tuttle].

January 14: A total solar eclipse was visible across the East Indies, the Indian Ocean, and Central Africa, with a maximum totality of 4 minutes 11 seconds. About fifty astronomers observed the eclipse from Sumatra, Dutch East Indies (now Indonesia). The Dutch expedition in Palambang was mostly clouded out with only glimpses of the eclipsed Sun. At Bencoolen the American and British expeditions had clear weather and photographed the solar corona. Attempts to confirm Einstein's theory of General Relativity failed. An Italian expedition observed the eclipse from southern Italian Somaliland (now Somalia) [Saros 130].

January 15: Death of Arthur Butler Phillips Mee. Born in 1860, a British journalist and amateur astronomer, drawing the Moon, planets, and sunspots; FRAS 1889; founder member of the BAA and the Astronomical Society of Wales.

January 16: Theodore Ballantyne Blathwayt (Braamfontein, South Africa) discovered an 11th-magnitude comet in Hydra and reported it to the Union Observatory. It had already reached perihelion on January 2 (q = 1·3455 AU) but was approaching the Earth and so brightened to magnitude 9·5 on February 10. After perigee on February 5 (0·4520 AU), the comet faded rapidly and was last seen on April 9 by Otto Struve (Yerkes Observatory) [Comet C/1926 B1 (Blathwayt)].

January 20: A bright fireball was seen across Missouri, United States. A single meteorite was recovered from a field 3 km east of Palmyra, Missouri; an L3 chondrite weighing 135g [Palmyra Meteorite].

January 23: Two very large sunspots were observed on the Sun.

January 26: A bright aurora was seen from North America. The magnetic storm affected telegraph and telephone lines.

January 28: A penumbral lunar eclipse was visible from Asia, the Middle East, Europe, Africa, and the eastern side of the Americas [Saros 142].

January 29: Birth of Mohammad Abdus Salam, Pakistani theoretical physicist, studying supersymmetry and the unification of the electromagnetic and weak nuclear forces; Nobel Prize for Physics 1979; contributed to the theoretical study of neutron stars and black holes; promoted Pakistan's space programme; died 1996.

February 23: Another bright aurora and magnetic storm were observed from North America, affecting telephone lines.

March 5: First issue of the science fiction magazine *Amazing Stories*, which included short stories by Jules Verne, H. G. Wells, and Edgar Allan Poe.

March 15: While observing Periodic Comet Brooks 2, Richard Reinhard Emil Schorr (Bergedorf Observatory, Hamburg) reported that it was magnitude 14, considerably brighter than the last observation. It was also 10 arcminutes away from the calculated position. It may have been a completely different object, although it is possible to have been a fragment of Comet Brooks 2, undergoing a sudden outburst. The comet had undergone a major disruption by a close pass of Jupiter shortly before its discovery in 1889.

March 16: Robert Hutchins Goddard (Auburn, Massachusetts) launched the first liquid-fuelled rocket. It reached 12·5 m altitude and landed 56 m away after a 2·5-second flight [Goddard Rocket Launching Site]. Subsequently liquid-fuelled rockets would send spacecraft to the Moon and Mars.

March 26: Birth of Peter Dowling Wroath, a British engineer and amateur astronomer, taking astrophotographs; member of the BAA; died 2008.

April 7: Birth of William Henry Wehlau, an American professional astronomer, Professor of Astronomy at the University of Western Ontario, studying stellar spectra; strove for a large telescope in Canada, leading to the 3·6-m *Canada–France–Hawaii Telescope* on Hawaii; died 1995.

April 16: Death of William James Lewis. Born in 1847, a British mineralogist at the British Museum; Professor of Mineralogy at Cambridge University (1881–1926); observed solar eclipses; FRAS 1873; FRS 1909.

April 16: A stony meteorite, weighing 1·5 kg, was seen to land at Urasaki, Chugoku, Japan [Urasaki Meteorite].

April 18: A small iron meteorite was seen to fall near Tokyo, Japan. The iron octahedrite mass weighed 238 g [Komagome Meteorite].

April 28: Periodic Comet Tempel-Swift returned to perihelion ($q = 1{\cdot}3257$ AU) but was not observed, as this was a very unfavourable apparition. The comet, discovered in 1869 and observed until 1908, remained lost, until it was accidentally recovered in 2001 [Comet 11P/Tempel-Swift-LINEAR].

May 2: A meteorite was seen to land in Khairpur District, Sind, British India (now Pakistan). It is an EL 6 enstatite chondrite weighing 973 g. The Jajh deh Kot Lalu meteorite has undergone extensive scientific investigation on the unusual assemblage of minerals [Jajh deh Kot Lalu Meteorite].

May 9: Maximilian Franz Joseph Cornelius Wolf and Karl Wilhelm Reinmuth (Königstuhl Observatory, Heidelberg) discovered a supernova (mag. 14·3) in the spiral galaxy Messier 61 (NGC 4303) in the Virgo Cluster. There were insufficient observations to define the supernova type [SN 1926A].

May 14: Birth of Brian George William Manning, a British technician and amateur astronomer, telescope maker and discoverer of 19 asteroids; member of the BAA; died 2011.

May 16: Birth of David Aitken, a British physicist at University College, London, developing infrared astronomical observations; FRAS 1969; worked at the Universities of Melbourne and New South Wales, Canberra; studied supernova SN 1987A in the Large Magellanic Cloud in the infrared; died 2021.

May 16: Birth of Joseph Churms, a South African professional astronomer at the Royal Observatory, Cape Town, in charge of the astronomy of stars and comets, discovering two asteroids; FRAS 1951; co-discovered the rings of Uranus occulting the star SAO 158687 in 1977 March; member of the ASSA; President of the ASSA (1969–70); died 1994.

May 17: Birth of Pamela Helen Mary Rothwell Martelli, a professional astronomer, studying cosmic rays at Mont Blanc, Pisa University, and Imperial College London; worked on satellite observations of cosmic rays; FRAS 1964; Upper Atmosphere Research Group at Southampton University (1964–84); died 1991.

May 21: Birth of Michael William Ovenden, a British professional astronomer, Professor of Astronomy at the University of British Columbia, Canada, studying the photometry and spectroscopy of eclipsing binary stars and celestial mechanics; FRAS 1945; member of the BAA; editor of *The Observatory* (1951–2); FRSE 1964; died 1987.

June 9: Periodic Comet Swift 1 returned to perihelion (q = 1·3578 AU) but was not observed. The comet, discovered in 1889, had become hopelessly lost, until it was accidentally recovered in 1973 [Comet 64P/Swift-Gehrels].

June 14: Ida Elizabeth Woods (Harvard College Observatory) discovered a nova in Sagittarius (mag. 10·5) on photographic plates taken at the College's Southern Station in Arequipa, Peru. The nova faded below magnitude 16·5 in 1928 [KY Sagittarii].

June 17: In February 1941 Adriaan van Maanen (Mount Wilson Observatory) found images of a supernova (mag. 14·8) in the spiral galaxy NGC 6181. There were insufficient observations to define the supernova type [SN 1926B].

June 18: Birth of Allan Rex Sandage, an American astronomer at the Palomar Observatory, revising the Hubble constant to 55 km/s/Mpc [currently 72·6 km/s/Mpc by *JWST* observations]; discovered jets coming from the active galaxy Messier 82; compiled two atlases of galaxies; RAS Gold Medal 1967; died 2010.

June 25: A penumbral lunar eclipse was visible from most of Asia, the Middle East, Europe, Africa, and South America [Saros 109].

June 26: Two stony meteorites fell at Lua and one at Dongria, Udaipur State, and another at Dabra, Indore State in Rajasthan, British India (now India). The largest stone 8·63 kg fell at Lua, 9·24 kg in total. It is an example of an L5 chondrite [Lua Meteorite].

June 30: Birth of John Louis Perdrix, an Australian scientist at CSIRO's Division of Minerals and Geochemistry; amateur astronomer with an interest in the history of astronomy; member of the BAA; FRAS 1959; died 2005.

July 8: Asteroid (433) Eros reached opposition. It was studied in preparation for the very favourable apparition in 1931, when it would be observed in order to measure the Astronomical Unit.

July 9: An annular solar eclipse was visible across the North Pacific. As this was only an annular eclipse visible to just a few Pacific islands, no major effort was made to observe it [Saros 135].

July 13: Predictions were made for the unfavourable return of Periodic Comet Kopff, which reached perihelion on January 26 ($q = 1{\cdot}6984$ AU). It was recovered by Max Wolf (Königstuhl Observatory, Heidelberg) near the predicted position but only magnitude 16. Observations were restricted to professional observatories, which followed the comet until November 2 [Comet 22P/Kopff].

July 23: Death of Pietro Paolo Giovanni Ernesto Baracchi. Born in 1851, an Italian astronomer, emigrated to Australia; assistant at the Melbourne Observatory; Government Astronomer of Victoria; founded Mount Stromlo Observatory in 1910.

July 25: A penumbral lunar eclipse was visible from Western Europe, Africa, and the Americas [Saros 147].

July 27: Annie Jump Cannon (Harvard College Observatory) discovered a nova in Sagittarius (mag. 8·6) on photographic plates taken at the College's Southern Station in Arequipa, Peru. She found the nova on a sequence of plates, as it faded to magnitude 11·0 on August 26 and 13·0 on September 9. No further images could be found [FM Sagittarii].

July 28: The Meteor Section of the New Zealand AS observed the δ Aquarid meteor shower and derived a radiant point for the shower.

August 3: Predictions were made for the return of Periodic Comet Finlay, and searches were begun in July. Joachim Otto Stobbe (Bergedorf Observatory, Hamburg) recovered the comet near the predicted position, when it was magnitude 11–12 with a coma 1 arcminute across. Philibert Jacques Melotte (Greenwich) later found an image taken on July 21. The comet reached perihelion on August 7 ($q = 1{\cdot}0611$ AU) and began to fade at the end of August. It was magnitude 12 in September and 14·5 in October. George van Biesbroeck (Yerkes Observatory) made the last observation on November 11 (mag. 17) [Comet 15P/ Finlay].

August 11 & 12: Harold Lee Alden (Yale Observatory Southern Station, Johannesburg, South Africa) observed an enhanced display of the Perseid meteor shower.

August 15: Birth of Roy W. Panther, British printer and amateur astronomer; member of the BAA, observing and searching for comets; discovered Comet C/1980 Y2 (Panther); died 2016.

September 1: Antoni Wilk (Cracow, Poland) was making a regular survey of the sky, when he noted a bright, oblong nebulosity of magnitude 6 in Serpens. It was 4 arcminutes long and moving 1 degree in 4 minutes. He reported it as a possible comet, but professional astronomers were unable to confirm this. It is likely to have been a meteor trail, stationary in the atmosphere but moving among the stars.

September 6: A bright fireball was seen across Britain accompanied by a loud detonation.

September 8: Viktor Aleksandrovich Albitzky (Simeis Observatory, Crimea) discovered a nova (mag. 10·5), which appeared on five photographs, the last on September 30. Then the nova faded below the range of the telescope [EY Aquilae].

September 8: Death of Joaquin de Mendizabal-Tamborrel. Born in 1852, a Mexican astronomer; surveyed the border between Mexico and Guatemala (1878–83); astronomer at Tacubaya Observatory and the Military College of Chaputtepec; represented Mexico at international conferences; FRAS 1892.

September 14: Death of John Louis Emil Dreyer. Born in 1852, a Danish astronomer in Ireland at the Birr Castle 1874, Dunsink 1878, and Armagh Observatories 1882; FRAS 1875; completed the *New General Catalogue of Nebulae and Clusters* (*NGC*) in 1888 and the *Index Catalogues* (*IC*) in 1895 and 1910; President of the RAS (1923–4).

September 16: Birth of Henry Proctor Palmer, a British astronomer at the University of Manchester; involved in radio astronomy at Jodrell Bank (1952–79), studying radio sources (quasars); FRAS 1957; died 1990.

September 19: Birth of Masatoshi Koshiba, a Japanese physicist at the Universities of Chicago and Tokyo, Professor of Physics at the University of Tokyo (1970–89); involved in the detection of neutrinos with the *Kamiokande* and *Super-Kamiokande* detectors; Nobel Prize for Physics 2002; died 2020.

October 9: It was predicted that there could be a display of the Draconid meteor shower, associated with Comet 21P/Giacobini-Zinner. William Frederick Denning, John Philip Manning Prentice, and A. King (BAA Meteor Section) observed a number of bright meteors. One particularly bright fireball was widely seen, leaving a trail visible for 30 minutes.

October 16: Predictions were made for the first favourable return of Periodic Comet Giacobini-Zinner, discovered in 1900 and 1913. Several searches began, until Friedrich Karl Arnold Schwassmann (Bergedorf Observatory, Hamburg) recovered the comet in Ophiuchus (mag. 14). Later, he found images on photographs taken on October 6 and 8. It slowly brightened in October and November, reaching perihelion on December 11 (q = 0·9937 AU). In 1927 George van Biesbroeck (Yerkes Observatory) continued observing the comet, taking the last photograph on March 4 (mag. 15·5) [Comet 21P/Giacobini-Zinner].

October 28: Death of William Joseph Hussey. Born in 1862, an American professional astronomer; worked on the *American Ephemeris and Nautical Almanac*; Professor of Astronomy at Leland Stanford Junior University Palo Alto; astronomer at Lick Observatory, observing comets and planetary satellites; observing double stars and discovering 1327 new ones; Lalande Gold Medal 1906; Professor of Astronomy at the Universities of Michigan (1905–26) and La Plata (1911–17).

November 4: Birth of John Paul Cox, an American professional astronomer at Cornell University and the Courant Institute at New York University; Professor of Physics and Astrophysics at the University of Colorado Boulder (1963–84); studied the mechanism of pulsation in variable stars; FRAS 1965; published *Principles of Stellar Structure*; died 1984.

November 5: Josep Comas Sola (Fabra Observatory, Barcelona) found a 12th-magnitude comet on photographic plates taken to record asteroids. A slightly earlier image was recorded by Grigory Nikolayevich Neujmin (Simeis

Observatory, Crimea). A number of astronomers observed it in the next few nights and at the end of November. The comet remained about magnitude 12 into 1927 February. It reached perihelion on March 22 ($q = 1{\cdot}7725$ AU) and then slowly faded until the last observation on May 31. This was a new short-period comet with an orbital period of 8·5 years [Comet 32P/1926 V1 (Comas Sola)].

November 5: Periodic Comet Neujmin 2 was discovered in 1916 but missed at its first return in 1921. Calculations for the return in 1927 led to Grigory Nikolayevich Neujmin (Simeis Observatory, Crimea) finding the comet in Leo (mag. 14·5). It slowly brightened and reached magnitude 11·6 at the beginning of 1927 February. It was at perihelion on January 16 ($q = 1{\cdot}3382$ AU). Then the comet faded and became more and more diffuse, being last photographed on March 9. Despite efforts to recover the comet in 1932, 1943, and 1948, it has never been seen again and presumably broke up at the end of the 1926–7 apparition [Comet 25D/1926 V2 (Neujmin 2)].

November 8: Death of George Morham. Born in 1845, a British engineer and amateur astronomer; observed Donati's comet in 1858; observed the total solar eclipse of August 1905 but was prevented from travelling to Riga for the eclipse in 1914 August by the outbreak of the Great War; FRAS 1921.

November 24: Birth of Lee Tsung-Dao, a Chinese-American physicist; wrote PhD thesis 'Hydrogen Content of White Dwarf Stars' (1950); Professor of Physics at Columbia University (1953–2012); Nobel Prize in Physics 1957 for work on Charge Conservation Parity violation; studied statistical mechanics, astrophysics, and black holes in the 1980s and 1990s; died 2024.

November 29: Birth of Dilhan Eryurt, a Turkish astrophysicist, studying the formation and evolution of the Sun and main-sequence stars; worked at NASA's Goddard Institute for Space Studies; returned to Turkey at the Middle East Technical University, Ankara; died 2012.

December 9: A very bright fireball was seen across Arizona, including the Lowell Observatory at Flagstaff. The meteor broke up in flight and there was a loud sound.

December 10: A meteorite was seen to land near Ojuelos Altos, Andalucia, Spain, 60 km northwest of Cordoba. It is an L6 chondrite weighing 5·85 kg [Ojuelos Altos Meteorite].

December 15: Periodic Comet de Vico-Swift, discovered in 1844 and 1894, returned to perihelion ($q = 1{\cdot}7137$ AU) but was not observed. Despite extensive searches in 1907, the comet remained lost until 1965 [Comet 54P/de Vico-Swift-NEAT].

December 17: Birth of Allan Verne Cox American geophysicist on Earth's plate tectonics and magnetic reversals; Professor of Earth Sciences at Stanford University (1967–87); died 1987.

December 19: A penumbral lunar eclipse was visible from Siberia, Europe, a large part of Africa, and the Americas [Saros 114].

December 29: Birth of Michael William Feast, a South African professional astronomer, Director of the South African Astronomical Observatory (1976–92); studied the structure of the Milky Way and the Magellanic Clouds; Professor of Astronomy at the University of Cape Town; Honorary FRAS 1980;

FRSSAf; died 2017.

Ten novae in the Andromeda Galaxy were recorded by the 100-inch telescope at the Mount Wilson Observatory during the year.

An iron meteorite was found near Okahandja, South West Africa (now Namibia), 67 km north of the capital Windhoek. It is an Iron IIAB meteorite, weighing 6·58 kg [Okahandja Meteorite].

An iron meteorite was found in Red River County, Texas, 3·1 km west of the town of Rugby. It is an Iron 1AB – sLL weighing 15 kg and heavily weathered. It was one of the first meteorites in the collection of the amateur astronomer Oscar Edwin Monnig (1902–99), founding member of the Society for Research on Meteorites (now The Meteoritical Society) [Deport Meteorite].

Two youngsters found a triangular shaped metallic mass on the surface of the ground 15 km northeast of Oakley, Cassia County, Missouri. It is an Iron IIIF meteorite weighing 111 kg. It had been heavily weathered but still had an intact fusion crust. The meteorite now resides in the U.S. National Museum, Washington [Oakley (iron) Meteorite].

Wolfgang Pauli used quantum mechanics to derive the observed spectrum of the hydrogen atom.

Albert Einstein received the RAS Gold Medal.

A 41-inch (104 cm) lens was manufactured in England for a large refractor at the Simeis Observatory, Crimea, but failed its optical tests.

Thea von Harbou's science-fiction novel *Metropolis* was published in book form (it appeared as a serial in 1925). It was made into a film by her husband, film director Fritz Lang, which was released in 1927.

1826

January 4: Death of Nicolas Fuss. Born in 1755, a Swiss mathematician, assistant to Leonhard Euler at St. Petersburg, Russia; worked on the mathematics and optics of microscopes and telescopes; Secretary to the Imperial Academy of Sciences (1800–26). His son Georg Albert Fuss (1806–54) was an astronomer at the Pulkovo and Vilnius Observatories.

February 6: Birth of Joseph Winlock, an American astronomer, 3rd Director of the Harvard College Observatory (1866–75); involved with the *American Ephemeris and Nautical Almanac*; observed the total solar eclipses of 1869 August and 1870 December, photographing the corona; father of the Harvard astronomers Anna Winlock (1857–1904) and Louisa Winlock (1860–1916); died 1875.

February 15: Birth of Emmanuel-Benjamin Liais, a French astronomer at the Paris Observatory in charge of the meteorology service and magnetic observations; observed the total solar eclipse of 1858 September in Brazil and discovered Comet C/1860 D1 (Liais); Director of the Imperial Observatory, Rio de Janeiro (1874–81); speculated that dark features on Mars were due to vegetation; died 1900.

February 15: Birth of George Johnstone Stoney, an Irish physicist; assistant to Lord Rosse at Birr Castle (1848–50); Professor of Physics at Queen's College, Galway; researched into the kinetic theory of gases, relating to planetary atmospheres; FRAS 1860; FRS 1861; died 1911.

February 27: The Austrian military officer Wilhelm von Biela (Josephstadt, Austria) discovered a comet as a small, round nebulosity with a faint central point in Pisces. The following night it had moved one degree east. It was independently discovered by Jean Félix Adolphe Gambart (Marseilles, France) on March 9 and also recorded in Chinese texts. European astronomers followed the faint comet across Aries and Taurus during March. It reached perihelion on March 18 (q = 0·9024 AU) and was closest to the Earth on April 19 (0·9599 AU). The last observation was made by Carlo Brioschi (Naples) on May 9.

Von Biela calculated the orbit for the comet and found that it was very similar to the orbits of comets seen in 1772 and 1805. The same conclusion was reached by Gambart and Heinrich Wilhelm Matthias Olbers. Periodic Comet Biela was the third periodic comet to be recovered in 1832 September [Comet 3D/1826 D1 (Biela)].

March 12: Birth of Col. Michael Foster Ward, a British military officer, interested in meteorology and astronomy; observed the Andromedid meteor storm on 1885 November 27 from Germany; FRAS 1863; died 1915.

March 29: Honoré Flaugergues (Viviers, France) was informed of the discovery of Biela's comet and observed a nebulous object in Orion. He followed the comet for most of the nights until April 6. He thought that it was a different comet and calculated a parabolic orbit. It remained on the list of comets until 1914, when Walter Hassenstein found that Flaugergues had misidentified the comparison stars and that this was indeed Biela's comet. [Comet 3D/1826 D1 (Biela)].

May 3: A bright meteor was observed over Sicily. The meteorite fell at a farm near the Sicilian town of Mineo, forming a small crater and making a loud sound. This was a rare pallasite, but only 42g of samples remain at the University of Perugia [Mineo Meteorite].

May 10: Birth of Henry Clifton Sorby, a British amateur scientist, who studied rocks in thin section, first terrestrial samples and then meteorites; died 1908.

May 19: A meteorite was seen to fall near the city of Pavlograd, Dnepropetrovsk Oblast, Russian Empire (now Ukraine). About 40 kg of a L6 chondrite was recovered [Pavlograd Meteorite].

May 19: A meteorite was seen to fall near the town of Galapian, Aquitaine, France, just twelve years after another meteorite had landed, killing an ox. This meteorite is an H6 chondrite weighing 132·7 g [Galapian Meteorite].

May 21: A total lunar eclipse was visible from Asia, the Middle East, and a large part of Africa [Saros 116].

May 21: Death of Georg Friedrich von Reichenbach. Born in 1771, a German scientific instrument maker in Munich; supplied transit circles to observatories.

May 26: Birth of Richard Christopher Carrington, British astronomer with an observatory at Redhill, Surrey; studied northern circumpolar stars; FRAS 1851; RAS Gold Medal 1859; made long-term observations of the Sun, including the major solar flare of 1859 September 1 [Carrington Event]; died 1875.

June 5: A partial solar eclipse was only visible from southern South America [Saros 144].

June 7: Death of Joseph von Fraunhofer. Born in 1787, a German glass-lens maker of exceptional skill, making some of the finest telescope objectives; discovered dark (absorption) lines in the solar spectrum in about 1814 [Fraunhofer Lines].

June 17: Birth of Rev. Joseph Chadwick Bates, a British vicar with interests in astronomy, meteorology and geology; FRAS 1863; FGS; died 1901.

June 21: Birth of Georg Balthasar von Neumayer, a German polar explorer and meteorologist; founded the Wilhelmshaven and German Maritime Observatories; co-founded the International Polar Commission 1879 and organized the (First) International Polar Year (1882–3); died 1909.

July 5: Birth of Amédée-Victor Guillemin, a French journalist and author of popular books on physics and astronomy, including large numbers of illustrations; died 1893.

July 5: Birth of James Breen, Irish computer at the Royal Observatory at Greenwich (1840–6), assistant at the Cambridge University Observatory (1846–58); observed the total solar eclipse in Spain in 1860 July; FRAS 1862; died 1866.

July 7: Birth of Sir Charles Todd, a British-Australian astronomer; assistant at the Cambridge University and Royal Observatory; Director of the Adelaide Observatory (1855–1906); FRAS 1864; FRMetS; observed the transits of Venus in December 1874 and December 1882; FRS 1889; KCMG 1893; died 1910.

July 22: Death of Giuseppe Piazzi. Born in 1746, an Italian monk, teaching mathematics and astronomy; founded the Palermo Observatory in 1789, cataloguing 6748 stars; discovered the first asteroid Ceres on 1801 January 1; discovered the 'flying star' 61 Cygni's rapid motion; reformed the standards of weights and measures for the Kingdom of the Two Sicilies.

August 7: Jean Louis Pons (Florence, Italy) discovered a faint comet in Fornax, which was also discovered by Jean Félix Adolphe Gambart (Marseilles, France) on August 15. The comet was quite well defined in September and was closest to the Earth on September 14 (0·5212 AU). It was followed in October despite interference from the Full Moon. The comet was last seen by Leopoldo Del Re (Naples) on December 11. The orbit was essentially parabolic with perihelion on October 9 ($q = 0{\cdot}8529$ AU) [Comet C/1826 P1 (Pons)].

August 7: Birth of James Bourdan, an American politician, Governor of Massachusetts (1785–7); interested in astronomy and electricity with Benjamin Franklin; supported an expedition to Newfoundland to observe the transit of Venus in 1761 June; 1st President of the American Academy of Arts & Sciences (1780–90); FRS 1788; died 1790.

August 14 & 15: J. Graziani (Rome, Italy) observed the Perseid meteor shower, describing that "there were more than 50 per hour in the two nights indicated." Observing from 10 pm to midnight, he noted that most of the meteors moved from northeast to southwest.

October 22: Jean Louis Pons (Florence, Italy) discovered another comet in Boötes, which was independently discovered by Thomas Clausen (Hamburg) on the 26th and Gambart (Marseilles, France) on the 28th. The comet became a naked-eye object at the beginning of November and transited the Sun on November 18 when at perihelion (q = 0·0269 AU). It reappeared in the morning sky at the end of the month, when it displayed a bright tail 8 degrees long. The comet was followed until 1827 January 6 [Comet C/1826 U1 (Pons)].

October 31: A partial solar eclipse was visible only from Antarctica [Saros 111].

November 14: A total lunar eclipse was visible from North America, Asia, the Middle East, Europe, and Africa. The eclipse was widely observed [Saros 123].

November 23: Death of Johann Elert Bode. Born in 1747, a German astronomer, discovered the galaxy Messier 81 in 1774 and Comet C/1779 A1 (Bode); Director of the Royal Observatory, Berlin (1787–1825); edited the *Astronomisches Jahrbuch*; compiled the star atlas *Uranographia* (1801), including Herschel's nebulae, clusters, and double stars; noted the gap between Mars and Jupiter (Titius–Bode Law) and became involved in the search for asteroids.

November 29: A partial solar eclipse was visible from the Middle East, Europe, and North Africa [Saros 149].

December 4: Birth of Col. Arthur Swann Howard Lowe, a British army officer, interested in meteorology and astronomy; FRMetS; FRAS 1857; died 1888.

December 11: Birth of Georg August Dietrich Ritter, a German physicist, who studied the structure of stars, including the pulsation of stars, but his work was relatively ignored; died 1908.

December 16: Birth of Giovan Battista Donati, an Italian astronomer, who discovered five comets C/1855 L1 (Donati), C/1857 V1 (Donati-van Arsdale), C/1864 O1 (Donati-Toussaint), C/1864 R1 (Donati), and particularly the spectacular comet C/1858 L1 (Donati); Director of the Pisa University Observatory (1864–72), studying stellar spectra; observed the total solar eclipse of 1860 July; died 1873.

December 26: Jean Louis Pons (Florence, Italy) discovered a comet in Hercules, also found by Jean Félix Adolphe Gambart (Marseilles, France) on December 27. Bad weather and bright moonlight interrupted observations at the beginning of 1827 January and the comet was last seen by Jakob Schwarzenbrunner (Kremsmünster, Austria) on January 26. It reached perihelion on February 5 (q = 0·5062 AU) but was in conjunction with the Sun [Comet C/1826 Y1 (Pons)].

James South was awarded the Royal Society's Copley Medal for his work on double and triple stars.

John Frederick William Herschel, James South, and Friedrich Georg Wilhelm Struve received RAS Gold Medals.

Thomas Keith published *A New Treatise on the Use of the Globes*, a text on geography and astronomy.

W. H. Prior published *Lectures on Astronomy*. At this time a number of lecturers were giving popular lectures that packed out some of the largest theatres in Britain.

1726

January 25: Death of Guillaume Delisle. Born in 1675, a French cartographer; member of the Académie Royale des Sciences; observed the total solar eclipse of 1724 May in Paris; brother of the astronomers Joseph-Nicolas Delisle (1688–1768) and Louis de L'Isle de la Croyère (1685–1741).

April 2: An annular solar eclipse was visible from Southwest Africa and the South Atlantic. The partial phase was visible from Africa and part of South America [Saros 115].

April 7: Birth of Charles Burney, an English musician, composer, and historian of music; interested in astronomy, writing 'An essay towards a history of the principal comets that have appeared since 1742' (1769); FRS 1773; died 1814.

April 16: A partial lunar eclipse was visible from the Americas, Asia, and the Middle East [Saros 127].

June 14: Birth of James Hutton, a Scottish geologist, who developed the principle of uniformitarianism in geology and the concept of Deep Time; FRSE founding member 1784; died 1797.

September 25: A total solar eclipse was visible from West Africa and northern North America. There were several observations of the partial phase from Western Europe [Saros 120].

September: Birth of Thomas Melvill, Scottish natural philosopher, interested in spectroscopy and astronomy; experimented with kites to study the atmosphere; died 1753.

October 11: A partial lunar eclipse was visible from the Middle East, Europe, Africa, and the Americas. A number of astronomers observed the eclipse [Saros 132].

October 29: Birth of Daniel Melanderhjelm, a Swedish mathematician and astronomer, Professor of Astronomy (1761–82); knighted 1778; secretary of the Royal Swedish Academy of Sciences; published books on astronomy, the motion of the Moon, the transits of Venus, and the atmospheres of the planets; died 1810.

John Harrison developed the gridiron pendulum for clocks to compensate for variations in temperature.

Sir Isaac Newton published his final version of *Philosophiae Naturalis Principia Mathematica* (*The Mathematical Principals of Natural Philosophy*).

Posthumous publication of David Gregory's *Astronomiae physicae et geometricae elementa* (*Elements of Physical and Geometrical Astronomy*)

Giuseppe Lorenzo Stecchi (Florence) published *Delle Meteore* in three volumes, describing atmospheric and celestial phenomena in verse.

1626

February 11: Death of Pietro Antonio Cataldi. Born in 1548, an Italian mathematician, who taught mathematics and astronomy at Bologna.

April 9: Death of Francis Bacon. Born in 1561, an English philosopher of science, who developed a geocentric model of the Universe in 1611, already outdated by telescopic observations of the planets.

May 8: Death of Baldassarre Capra. Born in 1580, an Italian mathematician and astronomer, observed the supernova in Ophiuchus in 1604 October;

accused by Galileo of plagiarizing his work on geometrical dividers.

October 30: Death of Willebrord Snell. Born in about 1580, a Dutch mathematician at the University of Leiden; discovered the law of the refraction of light (Snell's Law).

November: Birth of Jeremy Shakerley, an English astronomer, who promoted the work of Jeremiah Horrocks, predicted and observed the transit of Mercury on 1651 October 24 from Surat, India; died 1655.

December 10: Death of Edmund Gunter. Born in 1581, an English mathematician and astronomer; developed the Gunter's quadrant for navigation at sea; noted the change in declination of a magnetic compass with time; Gresham Professor of Astronomy (1620–26).

Birth of Pietro Mengoli, an Italian mathematician, Professor of Mathematics at the University of Bologna (1647–86); wrote on mathematics, cosmology, and music theory; died 1686.

Thomas Fale published a second revised edition of *Horologiographia*, a pamphlet on constructing sundials.

1526

March 11: Birth of Heinrich Rantzau, German writer, patron and astrologer; associate of Tycho Brahe; died 1598.

May 23: Transit of Venus

June 14: Birth of Taqi al-Din Abu Bakr Muhammad ibn Zayn al-Du Ma'ruf al-Dimashqi al-Hanafi, Arab astronomer and astrologer; director of the short-lived Constantinople Observatory (1579–85); made astronomical observations and calculations, extensive writings; died 1585.

Death of Abd al-Ali ibn Muhammad ibn Husayn al Birjandi, an Islamic astronomer at Samarkand; wrote commentaries on astronomical texts.

1326

Spring: Death of Robert of Reading, an English Benedictine monk and chronicler at Westminster Abbey; observed and recorded the bright aurora of November 1322.

1226

March 4: A conjunction between Jupiter and Saturn occurred just before dawn.

September 13: A comet appeared between Boötes and Coma Berenices.

Birth of Gregory Abu'l-Faraj Bar Hebraeus, Bishop of the Syriac Orthodox Church; polymath; wrote numerous books, including *Hewath Hekmetha* (*Butter of Wisdom*) on Aristotelian philosophy and *Suloqo Hawnonoyo* (*Ascent of the Mind*), an essay on astronomy and cosmography; died 1286.

1126

July 19: Chinese astronomers discovered a 'broom star' in the Draco–Ursa Minor–Camelopardalis region, recorded in several texts. On July 22 the

Japanese saw the comet in the north with a tail three degrees long, recorded in *Dainihonshi*.

Birth of Abu al-Walid Muhammad ibn Ahmad ibn Muhammad ibn Rushd al-Hafid [Averroes], Spanish-Arab Aristotelian philosopher and astronomer, wrote commentaries on Aristotle's works and Ptolemy's Almagest; died 1198.

1026

Birth of Wilhelm Abbot of Hirschau Abbey, Bavaria; taught mathematics and astronomy and wrote on astronomy and music; constructed astronomical instruments and a stone astrolabe; died 1091.

Adelard of Bath translated mathematical and astronomical works of Muhammad ibn Musa al-Khwarizmi into Latin.

926

March 31: Flodoard of Rheims recorded in his *Annals* that a total lunar eclipse was observed from Paris. The eclipse, dated as April 1, was visible from the Middle East, Europe, Africa, and the Americas [Saros 95].

July 22: The Chinese observed that "many stars flew, crossing each other", recorded in *Ssu-tien-k'ao*. An enhanced display of the Perseid meteor shower.

There is a report that fiery rays of light appeared in the northern sky. This was a bright display of the aurora borealis.

826

May 7: The Chinese observed that "within the Sun there was a black vapour like a cup", recorded in *Hsin T'ang Shu*.

May 24 & 26: The Chinese observed that "within the Sun there was a black spot", recorded in *Hsin T'ang Shu*. This was probably the same sunspot seen earlier in the month rotating back into view.

Birth of Al-Sabi Thabit ibn Qurrah al-Harrani, Arab doctor, mathematician, astronomer, and astrologer, court astronomer at Baghdad, wrote many astronomical works, including published solar observations in *Kitab fi Sanat al-Shams* (*Book on the Solar Year*); died 901; father of the court astronomer Sinan ibn Thabit ibn Qurra (880–943) and grandfather of the court astronomer Ibrahim ibn Sinan ibn Qurra (908–46).

726

December 13: A total lunar eclipse was observed from Ireland, recorded in the *Annals of Ulster*. The eclipse was visible from Asia, the Middle East, Europe, Africa, and the Americas [Saros 85].

Theophanes the Confessor recorded in his *Chronographia* that a very bright meteor was seen from Constantinople.

626

March 26: Chinese astronomers discovered a 'sparkling star' between Aries and the Pleiades, recorded in *Chiu T'ang Hui Yao* and *Hsin T'ang Shu*. On March 31 the comet had moved to Perseus. At Constantinople "an exceedingly bright star appeared for four days in the west after sunset" during March according to the *Chronicon Paschale* [Comet X/626 F1].

The Chinese astronomer Fu Jen-chun collected astronomical observations of the ancients during the year.

526

September 22: Elias recorded a solar eclipse. It was annular/total across Central Africa, but the partial phase was visible from South Asia, the Middle East, Southern Europe, and Africa [Saros 91].

AD 126

March 23: The Chinese observed a 'guest star' in the Virgo–Coma Berenices–Leo region, recorded in *Hou Han Shu*. This may have been a nova or a tailless comet.

275 BC

Ptolemy II Pharaoh of Egypt founded the Museum of Alexandria, including the Library.

375 BC

(about) Birth of Philippus of Medma, Southern Italy, Greek astronomer and mathematician; made observations from the Peloponnese and Locris, Southern Italy, used by later astronomers.

475 BC

(about) Death of Xenophanes of Colophon. Born in about 571 BC, an early Greek poet and philosopher in Sicily and Southern Italy; recognized the Earth's water cycle; made early speculations on the nature of the Universe.

675 BC

October: The Babylonian scribe Asaredu the Younger recorded that "if a comet becomes visible in the path of the stars of Anu (the Pleiades?): there will be a fall of Elam in battle."

975 BC

The Roman writer Pliny the Elder recorded in his *Natural History* that in this year "a comet appeared all on fire and was twisted in the form of a wreath and had a hideous aspect; it was not so much a star as a knot of fire."

1375 BC

May 3: A total solar eclipse was visible from North and Central Asia and the Middle East [Saros 16]. This may be the eclipse mentioned in a cuneiform document from the Western Palace Archive in Ugarit, Syria (KTU 1·78): "the Sun was put to shame; went down in daytime." It continued, "on the 6th. hour of the day of the new moon in the month Hiyaru the Sun went down. Its gatekeeper was Rsp." Rsp would then be Aldebaran in Taurus or an eclipse comet. The general view is that the document refers to the total solar eclipse of 1223 BC March 5 [Saros 20] with Rsp being Mars, then at superior conjunction.

THESIS ABSTRACTS

The Structure of Extrasolar Planetesimal Belts in Images

By Yinuo Han

Solid bodies in the form of planets and planetesimal belts familiar to us in the Solar System are also a prevalent feature around other stars. Their great diversity highlights a lack of complete theories for how they formed, which is further complicated by observational challenges to understand their full architecture in the first place. Currently, our best observational constraints on the outer planetary system come from imaging the planetesimal belts that populate this region, known as debris discs. As planets dynamically interact with the disc throughout their formation and evolution, structures reflecting their history are imprinted on the disc. In this thesis, I develop systematic and unbiassed methods to recover the three-dimensional structure of debris discs from their images applicable to a versatile range of imaging modes. By removing assumptions on the functional form of the disc structure, this method provides unbiassed constraints on disc substructures with realistic uncertainties that enable us to interpret dynamical interactions shaping the planetary system. I apply this method to a sample of debris discs with resolved imaging to infer general three-dimensional structures of debris discs and their implications for planetary-system formation. For the archetypal edge-on debris disc of β Pictoris, for which multiple epochs of high-resolution mid-infrared and millimetre images are available, I model in detail its vertical structure for different grain sizes and any variations in azimuthal substructures across time, constraining dynamical scenarios that could be shaping the evolution of the system. The approaches developed in this work to model debris-disc structures from images will be important for interpreting upcoming observations with *ALMA*, *JWST*, and the next generation of observatories at high sensitivity and resolution. — *University of Cambridge; accepted 2024 August.*

Constraining Reionization: Evidence from 21-cm Limits Predictions for Fast Radio Bursts

By Stefan Heimersheim

In this thesis, I explore multiple constraints on the properties of early galaxies, the reionization history, and the global 21-cm signal. Specifically, I use upper limits on the 21-cm power spectrum measured by the *HERA* (*Hydrogen Epoch of Reionization Array*) interferometer, current and future measurements of the global 21-cm signal, and forecasts for high-redshift Fast Radio Bursts (FRBs).

Firstly, I examine the influence of cosmic reionization on FRBs. They are recently discovered extra-galactic sources of strong radio signals, and the dispersion measure of these signals is sensitive to the ionization state of the intergalactic medium. (This analysis has previously been done only for specific reionization models; I propose using a model-independent parameterization of reionization.) I employ synthetic data of future FRB measurements at high redshifts, $z > 5$, to show that (*i*) the model-independent method removes a significant bias in the inferred optical depth, and (*ii*) that the observation of high-z FRBs can facilitate direct and model-independent measurements of the reionization history and associated cosmological parameters.

Secondly, I use Bayesian methods for a model-independent parameterization of the sky-averaged 21-cm signal. One of the biggest challenges in that field is identifying the cosmological signal among other systematic contributions and foregrounds. In my work, I compare two model-independent methods to fit the 21-cm signal and to separate out the foregrounds: (*i*) a Gaussian process modelling the foreground-orthogonal component of the data, and (*ii*) a spline-based FlexKnot interpolation utilising Bayesian evidence to find the simplest signal (agnostic of its cosmological or systematic nature) that fits the data. I apply these methods to both a synthetic validation data set and the *EDGES* (*Experiment to Detect the Global EoR Signature*) observations. I find that both methods fully recover the foreground-orthogonal component of the signal and that the FlexKnot method is able to separate the signal from the foreground in the synthetic data. Using this novel analysis I discover a set of four different shapes that can explain the *EDGES* observations, only one of which resembles the originally reported absorption signal.

Finally, I derive constraints on the astrophysical properties of early galaxies using 21-cm power-spectrum observations from the *HERA* telescope. I derive a likelihood function to compare the data with cosmological models, develop a neural-network emulator to speed up the computation of those cosmological models, and analyse the measurements of two *HERA* data releases. I derive constraints on astrophysical parameters based on semi-numerical models, in particular focussing on models with non-standard radio backgrounds. The main constraint I find is that early galaxies cannot simultaneously produce low X-ray and high radio emissions, as such scenarios would produce a signal larger than the upper limits set by *HERA*. — *University of Cambridge; accepted 2024 January.*

Unveiling Fundamental Physics with High-Resolution X-Ray Spectroscopy of Active Galactic Nuclei

By Júlia M. Sisk-Reynés

This doctoral thesis explores the use of high-resolution spectroscopy of active galactic nuclei (AGNs) to probe fundamental physics. It focusses on the study of axion-like particles (ALPs) and the spin of supermassive black holes (SMBHs).

Chapter 1 starts with a review of black holes as mathematical and astronomical objects and provides an account of the knowledge of the physics of the accretion flow onto SMBHs in AGNs as revealed by X-ray observations of AGNs. This is followed with a discussion on the use of X-ray reflection spectroscopy as a probe of the spin of moderately accreting SMBHs, and the use of spin diagnostics to probe the growth of SMBHs over cosmic time-scales. Summaries of the Standard Models of cosmology (or the ΛCDM paradigm) and particle physics are provided. Evidence of the need for physics beyond the Standard Model

(BSM) is presented. This introductory chapter concludes by highlighting the role of ALPs as generic predictions in BSM theories and as compelling dark-matter candidates and is accompanied by a description of plausible techniques towards their detectability with astronomical sources.

Chapter 2 begins our discussion on astrophysical ALP searches by presenting the tightest bounds to date on the coupling of light ALPs to electromagnetism based on a spectral analysis of high-resolution archival *Chandra*/Grating observations of the luminous cluster-hosted quasar H 1821+643.

Chapter 3 provides an exploration of how the next-generation *Athena* X-ray flagship observatory will improve on the current most sensitive limits presented in Chapter 2. A promising technique to mitigate the effect of previously ignored systematic uncertainties is discussed. ALP projections from the *AXIS* probe-class concept proposed to NASA for a 2032 launch are also introduced.

The future of ALP searches with upcoming missions is encouraging due to advances in detector technology. These advances include improvements in effective area, spatial resolution, and spectral resolution when compared with current observatories. In future, probing light ALPs with observations of bright AGNs located at the centres of rich clusters may be the only plausible observational test of string theories and will complement the search for ALP dark matter at light ALP masses.

Chapter 4 presents the application of state-of-the-art X-ray reflection models on the *Chandra* spectral view of H 1821+643 introduced in Chapter 2, pointing out that its colossal, central SMBH is rotating at moderate speeds. This chapter concludes by presenting the observed population of SMBHs whose spin has been estimated from such models.

The observed population seems to feature two sub-populations: a population of low-mass SMBHs with maximal-to-extreme spins and a high-mass population of SMBHs whose spins cluster at moderate values. This notion is aligned with the predictions of semi-analytic and numerical models of hierarchical structure formation and black-hole evolution over cosmic time-scales. Therefore, assessing this hypothesis with Bayesian statistics may eventually help confirm what drives SMBH growth over cosmic time-scales and help distinguish between the relative importance of growth powered by coherent and incoherent accretion and SMBH–SMBH mergers.

Chapter 5 presents closing remarks and outlines possible future research directions. — *University of Cambridge; accepted 2024 July.*

Here and There

THE PANDEMIC WAS RESPONSIBLE FOR MORE THAN WE THOUGHT

A few weeks later, I flew to CERN for the first time after the pandemic had begun to present our results to the outside world. — *Space Oddities* (Picador), p. 193, 2024.

Advice to Contributors

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where the items in square brackets are required only when citing an article in a book. Authors are listed with initials followed by surname; where there are four or more authors only the first author '*et al.*' is listed. For example:

(1) G. H. Darwin, *The Observatory*, **1**, 13, 1877.
(2) D. Mihalas, *Stellar Atmospheres (2nd Edn.)* (Freeman, San Francisco), 1978.
(3) R. Kudritzki *et al.*, in C. Leitherer *et al.* (eds.), *Massive Stars in Starbursts* (Cambridge University Press), 1991, p. 59.

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